ALTERNATIVE GENERATION TECHNOLOGIES

ANALYSIS OF THE INNOVATION LANDSCAPE

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		Approved By :	Chris Critchley
		Signed :	*Signed on Original*

Originating Office: FRAZER-NASH CONSULTANCY LIMITED
The Cube, 1 Lower Lamb Street, Bristol, BS1 5UD
T: +44 (0)117 9226242 F: +44 (0)117 9468924 W: www.fnc.co.uk

EXECUTIVE SUMMARY

Background

Wave Energy Scotland (WES) has commissioned this landscaping study with the aim of identifying and analysing potential alternative generation technologies which may provide opportunities for use in wave energy and provide a step change reduction in the delivered cost of energy.

The key objectives of this landscaping study are to:

- Identify alternative technologies which have potential to output electricity in a wave energy generation environment.
- Assess key physical and functional characteristics, to assess the capabilities, limitations, applications, and potential opportunities offered by each alternative technology.
- Identify which technologies may present an opportunity to deliver a step change reduction in the Levelised Cost Of Energy (LCOE).
- Identify the development challenges which would have to be overcome to realise the potential for each technology.

This study considers the potential of the alternative technologies within the context of the technology achieving utility scale wave energy generation within 25 years. For this study utility scale is considered to be a 100MW farm with a 20 year lifespan after 1GW of wave energy has been installed globally. This represents a significant growth beyond that seen in the last 10 years.

The Process

The process below was applied:

- **Assessment Criteria Development**: Developed a set of requirements and criteria for a common assessment baseline across technologies. Also developed Technology Readiness Level (TRL) definitions.
- **Fundamental Energy Interactions:** Created a structure of the types of energy that exist and fundamental physical principles that allow conversion to help ensure that all generation technologies were identified.
- **Technology Research:** Identified generation technologies from all industries/research through public data, industry/academic engagement, idea generation and horizon scanning techniques. Technologies with a wave energy TRL of 7 or more were considered as “conventional” to form a baseline and all others were considered “alternative”.
- **Technology Assessment:** Used the Technology Research, assessment criteria and TRL definitions to characterise the feasibility and opportunity of technologies and captured this in technology capture sheets. The technologies that had the best feasibility and opportunity were agreed with WES and down selected for further study.
- **Concept Development:** Developed artist’s impressions of some potential wave energy devices using the down selected technologies. These were used to explore feasibility, costing and opportunity arguments.

- **Cost Influence:** Developed cost metric information for the conventional technology baseline and alternative technologies using public data, industry/academic engagement and scaling arguments. Developed arguments for future performance to consider LCOE for the target deployment.
- **Technology Development Routes:** Used the outputs from the Technology Research and Concept Development stages to identify the technical issues and uncertainties that require resolution before the alternative technologies could be successfully deployed.

Architecture and Terminology

To ensure clarity of communication, this report uses the key terms defined below. A more complete set of terminology definitions is found in Section 1.1.

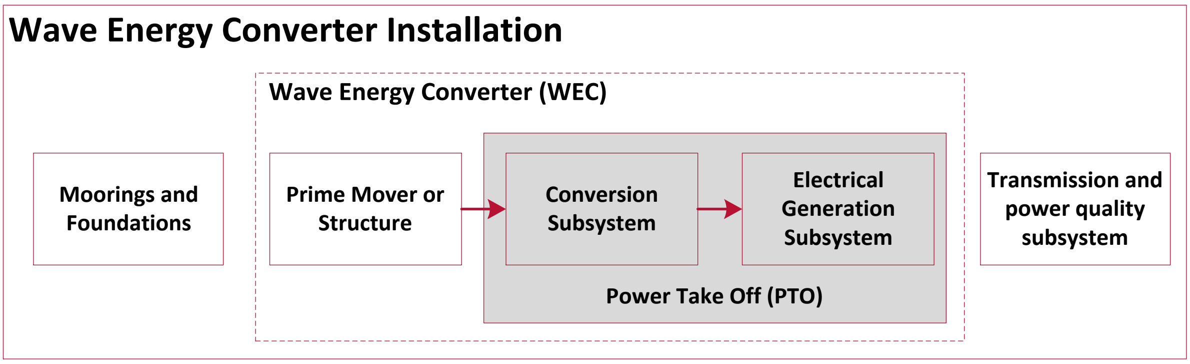


Figure 1 – System Architecture of a Wave Energy Converter Installation

- **Wave Energy Converter Installation**: This is considered to be the whole system which is required to keep a Wave Energy Converter (WEC) on site and connect it back to shore. A typical WEC will require moorings and foundations of some description to remain on station, and an electrical connection to shore or an intermediate hub. Some WEC types have been developed which pump water to shore rather than using an electrical connection.
- **Wave Energy Converter (WEC)**: A integrated device comprising the prime mover and the required sub-systems to capture energy from the wave, convert it to mechanical energy and then to electrical output.
- **Prime Mover**: In some device architectures, this is a structure or mechanism that first converts wave energy to another form of energy. Typically it converts wave energy to rigid body kinetic energy.
- **Power-Take Off (PTO)**: The subsystem(s) which is/are used to convert the output from the prime mover into electricity. Typically converts a form of rigid body kinetic energy to a form of AC electricity. In Figure 1, the PTO is comprised of the Conversion and Electrical Generation Subsystems.
- **Generation Technology:** A technology that outputs electricity, as a part of the Electrical Generation Subsystem in Figure 1.

Results

Baseline Technology

A broad range of technologies have been developed to quite high technology maturities in a wave energy context, however many of these are Prime Movers or Conversion Subsystems. Investigation into Electrical Generation Subsystems has not advanced as far, with rotary and linear generators being the only technologies currently used in mature wave energy devices.

The conventional baseline to assess the alternative generation technologies against was developed from rotary induction generators. The baseline developed during this study was a CAPEX of £200k/MW, OPEX of £14k/MW/year and peak generator efficiency (rotational input to electrical output) of 95% (Section 7.5).

Alternative technology

The assumptions used to project future cost or performance improvements for the alternative generation technologies are gathered from public sources, such as academic papers or funded project details. These assumptions account for a level of future development, however this could be greater if there is additional research effort or funding of these technologies due to interest from other industries. Their attractiveness to the wave energy sector can be strongly influenced by their applicability to other industries, especially if they are considered game-changing or enabling technologies. While projections in this report are optimistic, collaboration with other organisations will likely be required to ensure the most promising are kept in consideration for their marine energy potential.

This report helps to identify the nascent technologies which show promise for the wave energy sector and opportunities for future development considered.

8 alternative generation technologies were identified that have a wave energy TRL of 6 or lower. This is in contrast to applications outside their use in a wave energy environment where some alternative technologies have a TRL of 9.

Although identified as “alternative”, most of the technologies have already been considered in wave energy to some degree already, but not to the same level as wave devices using conventional rotary electrical generators. This suggests that:

- The wave energy industry has been good at trying to innovate around the technology over the decades it has been considered, and/or;
- Many novel technology developers recognise that wave energy is an industry that is looking for new ideas.

The alternative technologies that were downselected as those most likely to be feasible to generate at scale and to provide economic opportunity for the timescale of interest were triboelectrics, piezoelectrics, dielectric elastomers (DEGs) and magnetostrictive generators (Section 5).

These technologies form the Electrical Generation Subsystem. A generic WEC’s PTO consists of a Conversion Subsystem and an Electrical Generation Subsystem (as shown above in Figure 1). Due to the requirement for a frequency input that is orders-of-magnitude greater than provided by waves for efficient generation, it is considered necessary to include a Conversion Subsystem for triboelectrics, piezoelectrics and magnetostrictive generators. These technologies are also unlikely to remove the need for other WEC subsystems, therefore economically they can be considered as direct replacements for the conventional Electrical Generation Subsystem.

DEGs do not necessarily need a Conversion Subsystem and it is possible that there are architectures using DEG that could reduce the amount of supporting structure required. Therefore while DEGs can be considered as replacements for conventional generators, they are more economically promising as a technology because they may allow for the removal of other subsystems.

Alternative technologies that were not considered further at this time included magnetohydrodynamic, thermoelectric, electrokinetic and electrohydrodynamic generators, primarily due to their poor efficiency or low power density when compared with alternatives. These technologies may be viable for use in a wave energy system following a successful development programme, however they were assessed to be less viable (both now and in the future) than the 4 downselected technologies.

Most of the Electrical Generation Subsystem technologies require an additional Conversion Subsystem for frequency step-up/changing the range of movement. This is similar to the conventional generation requirement for an intermediate system (gearbox/hydraulics), therefore the economic comparison could be done considering a replacement of the Electrical Generation Subsystem.

Economic Impact and Technical Feasibility Evaluation

The technical and economic aspects of the assessment have been developed based on the information gathered from public data and from industry engagement.

The economic impact results show that:

- Alternative generation technologies (at least over the next 25 years) will not deliver a step change reduction in the cost of energy when used as replacement of the Electrical Generation Subsystem alone, with the exception of DEG.
- If an alternative technology could remove or replace other subsystems such as the Conversion Subsystem or Structure, there is potential for further reductions in the LCOE.
- DEG could eliminate the Conversion Subsystem and remove the need for some amount of Structure, however this would be dependent on the architecture. A bulge wave is one example of such an architecture.
- There are high values of uncertainty in the predicted future costs due to current data immaturity and the amount of time to elapse before the target case (i.e. 25 years). This means that future performance could be significantly higher or lower than that predicted.
- The key driver of poor economic performance is poor power density compared to conventional generators. Lower power density requires a larger amount of generation material. For a given generation material this means more is required, increasing the cost.

The technical feasibility results show that:

- None of the technologies appear highly likely to be technically feasible to generate power at the commercial scale of interest to WES.
- Magnetostriction has been demonstrated to the highest TRL of the alternative technologies.
- Magnetostriction and DEG are the technologies that are most likely to be technically feasible for power generation at scale.
- Low power density is a key issue across technologies, making it more difficult for devices to achieve the absolute level of power output required. Technology development programmes may improve the power density of the materials considered.
- Other aspects of concern are resistance to loading (fatigue and extreme), environmental impact of large devices (where much larger devices may be required, meaning that more area is obstructed by an array), manufacturability and material cost.

The alternative technology that appears to have the best mix of technical feasibility and economic opportunity, in the target scenario, is DEG (particularly when considered in an architecture where there is potential to remove some subsystems compared to conventional architectures).

Key economic results are presented in the table on Page 10.

Technical Development Challenges

The key technology development challenges are:

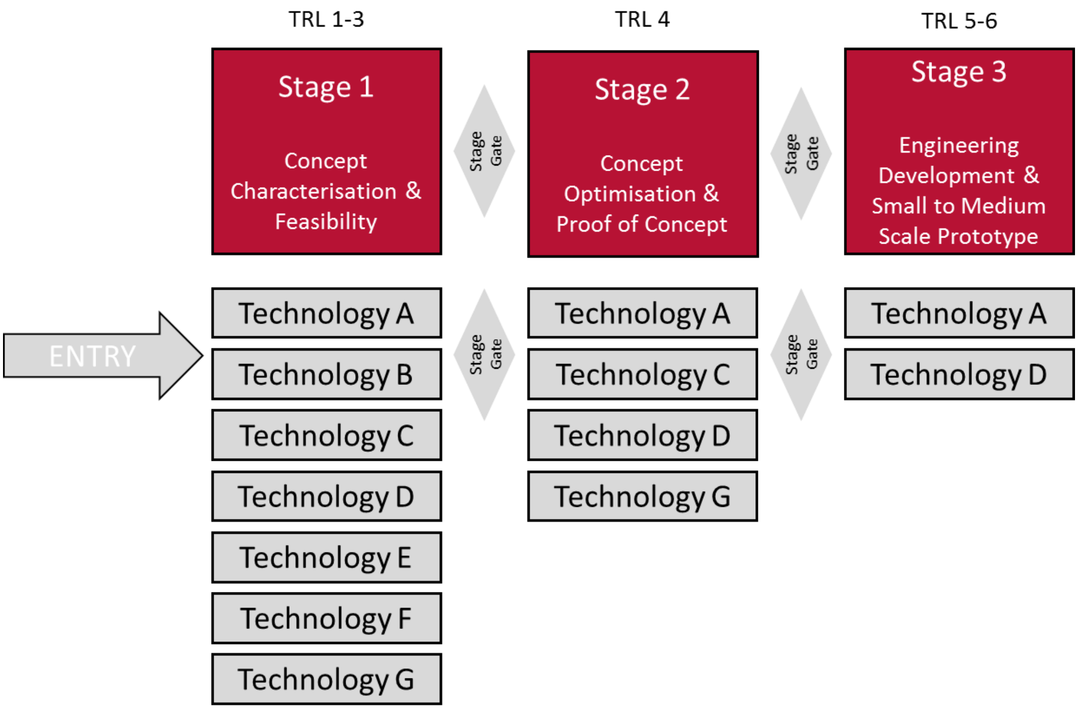
- **Improving power density:** Improved power density would reduce issues with cost and device size. Further work could be undertaken through academic research to identify alternative materials.
- **Reducing material cost:** Material cost could be reduced either through reducing the amount of material needed (through improved power density) or identifying new materials that are cheaper. Further work could be undertaken through academic research to identify alternative materials.
- **Improving confidence in loading:** Due to device immaturity it is uncertain if the identified technologies would survive in a wave energy environment. Further work could be undertaken through academic research to test materials and then move through tank testing, nursery site/test site deployments up to deployment at the sites of interest.
- **Developing an enabling subsystem/WEC architecture:** The technologies identified operate differently to conventional generators therefore there is scope to reconsider the overall device architecture. New Conversion Subsystem designs could also be considered. Further work could be performed through concept design and feasibility assessments.

Wave Energy Scotland Stage Gate Process

To date, WES have launched four technology development programmes:

- Power Take Off Systems (2015)
- Novel Wave Energy Converters (2015)
- Structural Materials and Manufacturing Processes (2016)
- Control Systems (2017)

Each of these follow a Stage Gate process, where the number of projects is reduced following assessment of the technology performance and future development prospects at each gate. A sample of the Stages Gate and progression is given below.



Throughout this report, references are made to projects which are or have been supported by WES through one of the programme streams listed above. The most up to date information on the projects can be found on the Wave Energy Scotland website.

Technology	Power Conversion Chain	Amount of material required for 1MW device		Efficiency		CAPEX Per MW		WEC Installation indicative future through life cost, relative to baseline
		Current	Future*	Current	Future*	Current	Future*	
Rotary Generator (Baseline)	*Rotary mechanical input load converted into electricity*	*- †*	*- ‡*	*95%*	*- ‡*	*£200k*	*- ‡*	*100%*
Magnetostriction	Applying mechanical load changes the magnetic field of the material.	6 m^3 55.5 tonnes	5 m^3 46.3 tonnes	35%	47.5%	£1.6mil	£460k	198%
Triboelectrics	Applying relative motion to touching or separated electrodes builds charge in the electrodes.	53 m^3 15.9 tonnes	5.3 m^3 1.6 tonnes	70%	90%	£6.1mil	£600k	118%
Dielectric Elastomer Generators	Applying load causes material deformation, allowing direct electricity generation.	5.9 m^3 5.9 tonnes	4.7 m^3 4.7 tonnes	60%	90%	£950k	£24k	96%**
Piezoelectrics	Applying mechanical loading in a material directly creating an electric charge	12.0 m^3 92.4 tonnes	2.4 m^3 18 tonnes	50%	75%	£2.8mil	£280k	127%

* Future predictions are based on technology development activities achieving the assumed improvements for each technology as described in Section 7.6.

† The baseline considers a complete rotary generator, rather than just the key generation material (used to cost alternative technologies).

‡ The future development of the baseline generator has not been considered. It has also been assumed that future development of conventional generation will be not be led by the wave energy industry.

** This value considers DEG used as a replacement for the baseline Electrical Generation Subsystem. Further considerations around DEG OPEX are highlighted in 7.6.3.

Recommendations

The recommendations from this landscaping study are to:

- Investigate the technical feasibility of using DEG in an architecture that allows for the removal of some or all of the Conversion Subsystem and Structure (such as a bulge wave or similar configuration). In addition to considering the power generating potential of such a device, this should consider the survivability of a full scale DEG device in the ocean environment and the consequent OPEX costs.
- Conduct further investigation to increase the certainty in the results of this study. Small research projects could focus on testing the assumptions made regarding the cost and performance of each technology.
- Carry out a more detailed study into the design refinements possible for rotary/linear electrical generators.

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Romax Technology

Scuola Superiore Sant'Anna

SBM Offshore

Tecnalia

University of Edinburgh

CONTENTS

1. INTRODUCTION

It is well understood that there is an abundance of clean, renewable energy available from ocean waves. However after many years of research, development and trials, there is not an economically competitive solution to capture this energy and convert it into electricity on a large scale.

Over the past few decades other forms of renewable energy such as wind and solar have seen significant advancements in capability and installed capacity all over the world, which has led to large reductions in the cost of energy. Recent figures published by the International Renewable Energy Agency show that between 2010 and 2016, the Levelised Cost of Energy (LCOE) from solar photovoltaics decreased by 69%, and onshore wind decreased by 18% [1].

This improvement was in large part due to significant private and public investment in the technologies, and large scale installations globally allowing rapid deployment for testing and evaluation of technologies. In this same time period, the amount of deployed wave energy generation capacity was comparatively very low, with less investment in the industry.

Wave Energy Scotland (WES) has commissioned this landscaping study with the aim of identifying and analysing potential alternative generation technologies which may provide opportunities for use in wave energy generation and provide a step change reduction in the LCOE.

The key objectives of this landscaping study are to:

- Identify alternative generation technologies which have potential to produce electricity in a wave energy generation environment,
- Assess key physical and functional characteristics, to assess the capabilities, limitations, applications, and potential opportunities offered by each alternative generation technology,
- Identify which technologies may present an opportunity to deliver a step change reduction in the LCOE,
- Identify the development challenges which would have to be overcome to realise the potential for each technology.

1.1 TERMINOLOGY AND WAVE ENERGY SYSTEM ARCHITECTURE

A system architecture diagram representing a generic Wave Energy Converter (WEC) is shown in Figure 2.

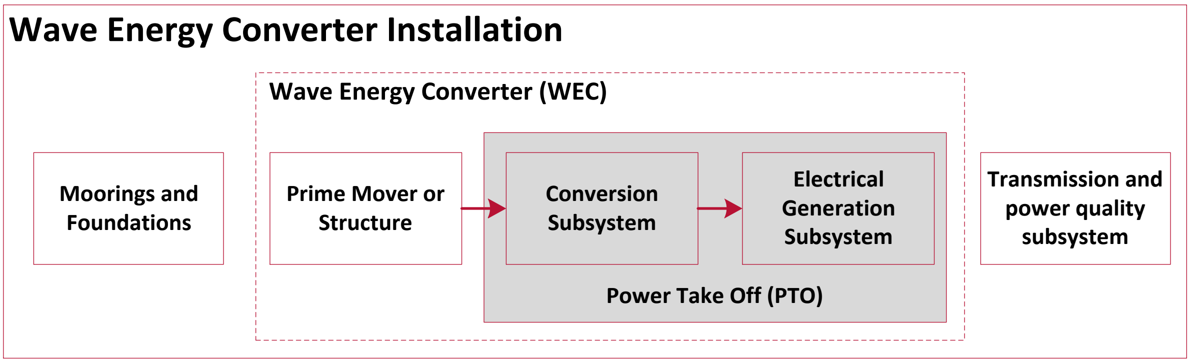

Figure 2 – System Architecture of a Wave Energy Converter Installation

To ensure clarity of communication, this report uses the definitions below:

- **Wave energy Converter Installation**: This is considered to be the whole system which is required to keep a Wave Energy Converter (WEC) on site and connect it back to shore. A typical WEC will require moorings and foundations of some description to remain on station, and an electrical connection to shore or an intermediate hub. Some WEC types have been developed which pump water to shore rather than using an electrical connection.
- **Wave Energy Converter (WEC):** A integrated device comprising the prime mover and the required sub-systems to capture energy from the wave, convert it to mechanical energy and then to electrical output.
- **Prime Mover**: In some device architectures, this is a structure or mechanism that first converts wave energy to another form of energy. Typically it converts wave energy to rigid body kinetic energy.
- **Conversion subsystem**: A system which manages frequency/loading to convert the mechanical output from the prime mover into a more appropriate input to the electrical generation subsystem.
- **Electrical generation subsystem**: The complete system for converting an energy input from the prime mover or conversion subsystem into electricity.
- **Power-Take Off (PTO)**: The subsystem(s) which is used to convert the output from the prime mover into electricity. Typically converts a form of rigid body kinetic energy to a form of AC electricity. In Figure 2, the PTO is comprised of the Conversion and Electrical Generation Subsystems.
- **Generation technology:** A technology that outputs electricity, as a part of the Electrical Generation Subsystem in Figure 2.

1.2 METHODOLOGY

A structured approach was developed for this landscaping study to ensure all potential technologies were identified and to assess them against a common baseline.

The methodology was defined in detail in the internal Alternative Generation Technologies Detailed Study Plan document [2], and is summarised below for convenience.

Assessment Criteria Development

The initial effort was focused on developing a clear understanding of how the technologies under consideration should be assessed and scored, to ensure a robust framework was in place for the study.

To assess the technologies, a set of 10 high-level requirements were identified. Scoring criteria were defined for each requirement to ensure a consistent analysis between technologies, and enable fair comparisons to be made.

One of the key aims of the technology assessment was to consider the technical feasibility and economic opportunity of the technologies, to highlight “opportunities for innovation” for the WES programme.

In order to provide a measure of the technical maturity of the technologies under consideration two Technology Readiness Levels (TRL) scores were developed. The first score is a generic score for the technology as used in its most mature application, whether that is in marine power generation or any other application. The second TRL score has been tailored for this specific wave energy application.

Fundamental Energy Interactions

To maximise the number of innovative alternative generation technologies which could be identified and considered, a fundamental energy interactions matrix was developed. This considered the conversions between forms of energy from first principles and aimed to highlight technical concepts, or illustrative technologies, through which the conversions could occur.

Technology Research and Assessment

In order to develop a baseline to compare the alternative technologies against, a series of conventional technologies were identified and characterised using open public, industry and academic sources. This included feedback from a questionnaire submitted to wave energy stakeholders. The aim was to consider current wave energy conversion devices covering a range of technologies, operational use cases and capabilities. The baseline research included considerations of energy conversion routes, indicative capital (CAPEX) and operating (OPEX) cost characteristics, reliability, and efficiency of operation. Prime Movers and Conversion Subsystems were considered as well as conventional generation technologies.

A broad range of alternative generation technologies were identified using the fundamental energy interactions matrix, expert and stakeholder input, and open research. Technologies were considered regardless of their current application. These were investigated and assessed against the developed criteria, and information about the current and potential future development opportunity was collected.

Following the research and characterisation phases, the alternative technologies were downselected to identify which were most likely to be technically feasible and able to achieve a step change reduction in the LCOE.

Concept Development

The study was performed in such a way as to be architecture independent. However, in order to better understand the economic and technical feasibility of the downselected technologies some potential WEC concepts were developed utilising the alternative generation technologies. These were illustrated through artist's impressions and were used to understand technical feasibility, costing and opportunity arguments.

Economic Analysis

The key opportunity sought in new alternative generation technologies is a step change reduction in the LCOE. LCOE is typically calculated as part of a whole project, however, in order to focus on the results of greatest interest the study focused on how the alternative technology influences LCOE compared to conventional technologies. This also supports the approach of the study to be WEC architecture independent.

The downselected alternative generation technologies were analysed for their influence on cost by:

- Generating engineering claims and arguments as to how the technology as currently available will change the CAPEX, OPEX and efficiency of a device,
- Supporting these arguments with evidence gathered in the research and characterisation where available,
- Developing high-level arguments as to how this might change in the future based on past development,
- Presenting the assumptions that these values are based on, and the uncertainty around the values.

Technology Development Routes

For each downselected alternative technology the potential future technical capabilities were considered, and the research and development challenges which would need to be overcome to realise this potential were identified. The development activities can be grouped into two main categories – activities to advance a technology capability and activities to reduce uncertainty/technical risk.

Activities to advance a technology capability aim to improve performance specifically in the wave energy generation environment, and could involve development which aims to improve power density, reduce build, deployment or development costs, improve resistance to loading and biofouling, or increase efficiency.

Reducing uncertainty/technical risk is a key development activity to ensure that investment is appropriately targeted and has broadly achievable goals. Current LCOE values have high uncertainty and incremental activities could help to reduce this.

The technology development recommendations were considered in line with WES ambitions of achieving utility scale generation in 25 years. The claims and arguments considered a 100MW farm with a 20 year lifespan after 1GW of wave energy was installed globally.

1.3 STRUCTURE OF THIS REPORT

The structure of this report is as follows:

- Section 2 describes the development of the assessment criteria and TRL scales,
- Section 3 describes the Fundamental Energy Interactions,
- Section 4 presents an overview of the conventional technology baseline, as well as exploring supporting technologies,
- Section 5 presents an overview of the alternative generation technologies, and presents the arguments for downselection,
- Section 6 presents the downselected alternative technologies along with discussions around an appropriate prime mover, in a WEC concept device,
- Section 7 presents the economic assessment of each downselected technology,
- Section 8 discusses potential development routes for all included alternative technologies,
- Section 9 presents the conclusions and recommendations from this landscaping study,
- Section 10 contains a list of abbreviations used in the report,
- Section 11 contains key references used in the report. A complete bibliography of all source data used is included in each Technology Capture Sheet in Annex B,
- Section 12 contains calculations for extrapolated or estimated figures presented in the report which were not sourced from open source literature. These calculations have been referenced throughout the body of the report at point of first use.

2. DEFINING THE ASSESSMENT CRITERIA

2.1 REQUIREMENTS DEVELOPMENT

Good system design needs a clear understanding of the requirements. As requirements mature the measures of performance against them become more tightly defined. At this early stage of conceptual design it is appropriate for requirements to be at a high level.

For this wave energy technology assessment a set of high-level requirements were identified and developed by the project team. These initial requirements were then tested in an internal workshop with marine, renewable energy, and electrical experts, considering the applicability towards WEC and PTO devices and technologies. These were also shared with wave energy stakeholders to seek agreement.

The discussions and insights from the workshop were then used to develop the final set of assessment criteria, which are shown in Table 1 below. High, medium and low suitability justification statements have also been developed for each criteria, in order to test and bound the assessment of each technology.

Table 1 – High level assessment criteria which were used for technology evaluations

Criteria ID	Criteria Description	Scoring		
		Low	Medium	High
1	Operate at a combined scale of approximately 500kW or greater.	Unlikely to convert power at many kW to MW scale.	Quite likely to convert power at many kW up to MW scale.	Likely to convert power at MW scale.
2	Operate across irregular wave states that vary in amplitude, period and direction.	Unlikely to be suitable for power conversion with varying input, without onerous power conditioning.	Quite likely to be suitable for power conversion with varying input, only needs typical level of power conditioning.	Likely to be suitable for power conversion with varying input, with negligible or reduced power conditioning.
3	Operate in a surface/ submerged ocean environment for a design life of multiple years. Withstand and manage the influence of biofouling, corrosion and erosion.	Unlikely that the technology will be able to generate power in seawater conditions for many months/years, or will require substantial environmental protection.	Quite likely that the technology will be able to generate power in seawater conditions for many months/years, particularly with some environmental protection.	Likely that the technology will be able to generate power in seawater conditions for many months/years with negligible/modest environmental protection.

Criteria ID	Criteria Description	Scoring		
		Low	Medium	High
4	Maintain operation under sustained fatigue loading, and following extreme loading events, over a design life of multiple years.	Unlikely to survive fatigue/extreme loading and maintain power generation, without substantial additional loading protection.	Quite likely to survive fatigue/extreme loading and maintain power generation, particularly with some additional loading protection.	Likely to survive fatigue/extreme loading and maintain power generation, with negligible/modest additional loading protection.
5	Be controllable, varying the loading experienced and power generated by the system.	Power generated by technology, and reacted loading are unlikely to be controllable.	Power generated by technology, and reacted loading are quite likely to be controllable, or controllable but with significant effort.	Power generated by technology, and reacted loading are likely to be controllable in a relatively straightforward manner.
6	Capital cost	Likely to be significantly higher capital cost than conventional technology.	Likely to be similar capital cost to a conventional technology.	Likely to be significantly lower capital cost than conventional technology.
7	Operating cost	Likely to require significant maintenance in terms of frequency and effort.	Likely to require average maintenance in terms of frequency and effort.	Likely to require significantly less maintenance, in terms of frequency and effort.
8	Energy conversion efficiency	Likely to have a significantly lower conversion efficiency than conventional technology.	Likely to have a similar conversion efficiency to conventional technology.	Likely to have a higher conversion efficiency than conventional technology.
9	Maturity risk	Significant development is required and there is no evidence that this is planned in industry or would be possible within the pace of development that	Requires development work to be feasible in a full-scale WEC within around 5 years. Feasible if a moderate pace of development is	Ready for integration into a WEC now, or with a pace of development that is considered easily achievable within around 5 years.

Criteria ID	Criteria Description	Scoring		
		Low	Medium	High
		WES can achieve.	set in action shortly.	
10	Power density	A MW scale device would likely have notably larger physical dimensions when compared with current WECs.	A MW scale device would likely be of comparable external dimensions to current WECs.	A MW scale device would likely have notably smaller physical dimensions when compared with current WECs.

2.2 TECHNOLOGY READINESS LEVEL SCALES

In order to provide a measure of the technical maturity of the technologies under consideration, two TRL scores have been provided for each technology.

The first score is a generic score for the technology as used in its most mature application, whether that is in marine power generation or any other application. The second TRL score has been tailored for this specific wave energy application. This dual score provides a valuable and realistic assessment of the maturity of a technology, and aims to provide an indication of the effort that may be required to develop the technology for use in the wave energy environment.

Additionally, the Technology Readiness Levels have been defined to help assist the assessment of technical risk present, in particular supporting assessment against criteria 9, Maturity Risk.

The Technology Readiness Levels are shown in Table 2 below. The Generic Definition is used to assess the technology in its main industry, and the Wave Energy Definition is used for the specific wave energy application scores.

Table 2 – Technology Readiness Level definitions

TRL	Generic Definition	Wave Energy Definition
9	Actual technology system qualified through successful mission operations	Full scale wave energy conversion system fully operated at full capacity at sea (i.e. intended deployed environment, sea water and energetic wave climate) for an extended period of time. Proven over that period providing performance information.
8	Actual technology system completed and qualified through test and demonstration	Full scale wave energy technology proven through comprehensive trials at sea (i.e. intended deployed environment, sea water and energetic wave climate) to ensure all specifications and likely requirements are met and any wider system issues are addressed.
7	Technology prototype demonstration in an operational environment	Prototype wave energy system (potentially scaled) demonstrated at sea (i.e. intended deployed environment, sea water and energetic wave climate).

TRL	Generic Definition	Wave Energy Definition
		Evidence shows that it can meet its operating requirements.
6	Technology system/ subsystem model or prototype demonstration in a relevant environment	Prototype wave energy conversion systems or sub-assembly tested in a relevant environment (i.e. sea water with low/no energy wave climate) or simulated operational environment (i.e. wave tank). This could be intermediate-scale models in a wave tank.
5	Technology component and/or basic technology subsystem validation in relevant environment	The basic technological components are integrated with realistic supporting elements and tested under a high-fidelity simulated operational environment, such as a wave tank.
4	Technology component and/or basic technology subsystem validation in laboratory environment	Basic technology components of the wave energy conversion system are integrated to establish that they will work together under a low fidelity laboratory test.
3	Analytical and experimental critical function and/or characteristic proof-of concept	Wave energy conversion has been demonstrated to be viable through validated analysis and/or laboratory experiment on individual elements of the technology.
2	Technology concept and/or application formulated	Speculative practical applications for the deployable energy conversion technology are proposed but there is no proof or detailed analysis to support the assumptions.
1	Basic Principles observed and reported	Studies and research papers in existence identifying and evaluating the basic properties of energy conversion technology.

The TRL score of a technology is also used to define a technology as ‘Alternative’ or ‘Conventional’. For this study, we have defined a wave energy device as conventional if it has a Wave Energy Specific TRL of 7 or higher. The key differentiator between a TRL greater or less than 7 is whether the technology demonstration and testing has taken place in a simulated environment, or if it was demonstrated in its intended environment. This is summarised in Table 3 below:

Table 3 – Conventional or Alternative TRL definitions

Classification	Wave Energy specific TRL	Minimum Description
Conventional	**7 – 9**	The technology has at least been demonstrated as a prototype (all systems elements integrated, albeit at scale) at sea (i.e. intended deployed environment, sea water and energetic wave climate). The evidence from the trials shows that it can meet its operating requirements.
Alternative	**1 – 6**	The technology is still in the initial development phases, and has not successfully progressed beyond scale models in a simulated or relevant environment. Full scale components may have been tested, but not the complete full scale solution.

3. FUNDAMENTAL ENERGY INTERACTIONS

To allow the widest range of alternative technologies to be identified and assessed, a matrix of potentially useful energy interactions which may occur was created. This matrix considered the conversions between major forms of energy, presenting scientific concepts and in some cases providing technologies through which the conversion can occur.

The matrix aimed to capture all physically possible energy conversion processes (i.e. it was not limited to only consider current wave energy use cases) to ensure the study was WEC architecture independent. This allowed novel energy conversion processes to be considered and properly evaluated against the assessment criteria.

The interactions matrix was populated using a combination of internal engineering expertise, academic and open source research. It remained a live document throughout the early phases of the study in order to capture any concepts arising through technology research.

The basic forms of energy considered are summarised below. Some of the forms considered are not strictly fundamental energies, such as mechanical waves, however they were included early on in the matrix development process as they allowed more useful concepts to be categorised and captured.

Energy	Description
Mechanical	Fluid and rigid body kinetic energy.
Elastic	Potential energy stored in a deformed material.
Thermal	Potential energy due to the kinetic motion of an object’s constituent atoms or molecules.
Magnetic	Potential energy stored in a magnetic field.
Gravitational	Potential energy stored due to an object’s position in a gravitational field.
Mechanical wave	Propagation of kinetic energy through an elastic material.
Sound wave	A form of audible mechanical wave, propagating mechanical kinetic energy through a fluid.
Chemical	Energy available through chemical bonds.
Radiant	Energy available through propagated electromagnetic radiation.
Nuclear	Binding energy between nucleons to form the atomic nucleus.
Chromodynamic	The subatomic binding energy between quarks to form hadrons.
Rest	The relativistic energy available from an object's rest mass.

Some of the forms of energy (and related conversions) were eliminated from further consideration at an early stage due to their clear shortfall against the assessment criteria compared to other options. These eliminated energies and the justification for doing so are shown below.

Energy	Reason for elimination
Sound wave	The energy density of audible sound wave propagation is too low to be to be useful for conversion at scale. Other forms of mechanical wave transmission are more suitable for the high power required.
Radiant	Eliminated due to low energy recovery efficiency. Energy conversion chains would likely encounter significant losses during both the radiant energy conversion and recovery processes compared to alternatives.
Nuclear	Eliminated as atomic energy interactions would likely require an external reagent to be continuously supplied, reducing the credibility as a renewable energy technology.
Chromodynamic	Eliminated as no clear interactions could be identified practicably linking wave energy to electrical energy.
Rest	Eliminated due to the inaccessibility of exploitable rest energy, and no interactions could be identified practicably linking wave energy to electrical energy (via direct mass to energy conversion).

The completed Fundamental Interactions Matrix is included in Annex A.

4. CONVENTIONAL TECHNOLOGY BASELINE

This section presents a summary and brief introduction to the conventional technologies considered in this landscaping study. These have been considered to provide context for the alternative generation technologies.

In order to develop a baseline to compare the alternative generation technologies against, a range of conventional technologies were identified and characterised. The aim was to consider current wave energy conversion devices covering a range of technologies, methods of use and capabilities.

The two conventional generation technologies identified were rotary electrical generators and linear electrical generators. The technology baseline investigation also considered prime mover and conversion subsystem technologies. Assessment was performed against the assessment criteria including likely CAPEX, OPEX, reliability and efficiency.

The research and data for this task was collected from open public, industry and academic sources and an engagement questionnaire that was distributed to selected wave energy industry stakeholders for their input.

The technologies included in the baseline conventional wave energy generation assessment are shown below.

Technology	WEC Subsystem	Document Chapter
Rotary electrical generator	Generation	4.1.1
Linear electrical generator	Generation	4.1.2
Wells turbine	Conversion	4.2.1
Bi-radial Turbine	Conversion	4.2.2
Hydraulic	Conversion	4.2.3
Magnetic gear	Conversion	4.2.4
Attenuator	Prime Mover	4.3.1
Point absorber	Prime Mover	4.3.2
Oscillating wave surge converter	Prime Mover	4.3.3
Oscillating water column	Prime Mover	4.3.4
Overtopping device	Prime Mover	4.3.5
Salter's duck style terminator	Prime Mover	4.3.6
Submerged pressure differential	Prime Mover	4.3.7
Rotating mass	Prime Mover	4.3.8
Bulge wave	Prime Mover	4.3.9

The full outputs from this task are presented in the Technology Capture Sheets in Annex B.

4.1 CONVENTIONAL ELECTRICAL GENERATION SUBSYSTEM

4.1.1 Rotary Electrical Generator

Rotary Electrical Generator	
Energy conversion	Mechanical (rotary) > Electric
Existing TRL	9
Wave energy TRL	9

Technology Overview

Rotary generators are devices which can convert rotary shaft motion into electricity. They are currently used in many forms of conventional power generation, and have been widely used in wave energy power generation in multiple device types such as Oscillating Water Columns (in combination with a Wells Turbine), or in Oscillating Wave Surge Converters, like the Aquamarine Oyster which used a high pressure working fluid through a turbine.

This is a highly mature technology in wave energy use as well as in other industries, and current devices can deliver peak conversion efficiencies exceeding 95% [3].

4.1.2 Linear Electrical Generator

Linear Electrical Generator	
Energy conversion	Mechanical (linear) > Electric
Existing TRL	8
Wave energy TRL	8

Technology Overview

Linear generators are devices which convert linear motion directly into electrical energy. They are a fairly mature technology within wave energy, with a 1MW farm (30kW linear generator based PTOs with point absorber WECs) installed off Sweden by Seabased [4]. WES currently have multiple PTO projects, completed or underway at the time of writing, that are developing linear electrical generator units. The companies leading these projects are University of Edinburgh, Trident Energy and Umbra Group

The applications of linear electrical generators can be limited due to the stroke length, force, velocity, and air gap of available generators. Mechanical linkages may be required to convert the motion from the prime mover to an appropriate scale to use a linear generator.

4.2 SUPPORTING TECHNOLOGIES: CONVERSION SUBSYSTEM

4.2.1 Wells Turbine

Wells Turbine	
Energy conversion	Mechanical (air flow) > Mechanical (rotary)
Existing TRL	9
Wave energy TRL	9

Technology Overview

A Wells Turbine is a low pressure air turbine which rotates in a single direction independent of the direction of air flow. Wells turbines are most commonly mounted in Oscillating Water Columns. The 296kW Mutriku oscillating water column (OWC) plant has been in operation since 2011 and consists of 16 Wells turbines.

Wells turbines can achieve peak efficiencies between 60-65% [5], however the WEC air compression losses are typically more significant resulting in current OWC devices achieving total efficiencies of around 25% [6].

4.2.2 Bi-radial Turbine

Bi-radial turbine	
Energy conversion	Mechanical (fluid flow) > Mechanical (rotary)
Existing TRL	4
Wave energy TRL	4

Technology Overview

The Bi-Radial turbine is being developed by Kymaner through the OPERA programme to be a high performance air turbine for use in OWC devices. Current OWC installations use a Wells turbine Conversion Subsystem, however laboratory test results from the bi-radial development programme indicate the bi-radial design may offer a 50% improvement in efficiencies over current air turbines. A prototype bi-radial design has been tested at 1:16 scale in sea water, and a 30kW turbine will be deployed at the Bimep wave energy test site in summer 2018.

Although this technology does not meet the conventional classification criteria of TRL 6, it has not been considered further as generation technologies are the focus of the study.

4.2.3 Hydraulic

Hydraulic	
Energy conversion	Mechanical > Mechanical
Existing TRL	9
Wave energy TRL	9

Technology Overview

Hydraulics have been used in multiple wave energy converters to transfer mechanical energy from the Prime Mover to the Electrical Generation Subsystem using pressurised fluid, and also as the working fluid in a hydraulic motor. Devices which have used hydraulics include the 750kW Pelamis attenuator, the Aquamarine Oyster and AW Energy Waveroller Oscillating Wave Surge Converters (OSWC).

At the time of writing, WES are currently funding the Artemis Intelligent Power's 'Quantor' project in the Stage 3 PTO programme. The Quantor PTO aims to provide continuously variable control of the hydraulic loads, improving efficiency and the productivity range of the hydraulic PTO.

A novel hydraulic pump which requires no seals and can achieve higher pressures than conventional hydraulic pumps with improved survivability featured in a Stage 2 PTO project lead by Exceedence Ltd along with Technology from Ideas Ltd.

4.2.4 Magnetic Gear

Magnetic Gearing	
Energy conversion	Mechanical > Mechanical
Existing TRL	8
Wave energy TRL	5

Technology Overview

A magnetic gearing system is similar in concept to a traditional gearing system, however instead of transmitting force through gear teeth contact, the force is transmitted through interacting magnetic fields. This allows efficient transmission of high mechanical torques, without contact between the input and output shafts. This minimises wear, potential for damage and can reduce mechanical losses in the system. The technology allows for slippage if forces exceed rated values without causing harm to the mechanism.

Magnetic gearing technologies can convert rotary to rotary motion or between linear and rotary motion. Rotary to rotary gearing can have high ratios up to 200:1, which is suited for the low frequency input from wave loading and can step up to higher speeds more appropriate for a rotary generator. Linear to rotary gearing allows conversion from low speed, high force linear motion into low torque, high speed rotor speed.

In most wave energy generations proposals, the magnetic gearing system is combined with a conventional generator, to convert mechanical input into electric output in a single unit. Current prototype systems which have published results of development and testing have been rated up to 10kW [12].

Under the WES PTO programme, Ecosse Subsea Systems[1] are developing the Power Electronic Controlled Magnet Gear (PECMAG) system, which is an integrated magnetic gear unit and PTO. The PECMAG project is aiming to develop and test of systems capable of producing 100kW to 1MW of electricity [13].

[1] Ecosse Subsea Systems was acquired by Oceaneering International in March 2018

4.3 SUPPORTING TECHNOLOGIES: PRIME MOVER

Further information on the device types, along with informative graphics, can be found at the Aquatic Renewable Energy Technologies (Aqua-RET) e-learning website www.aquaret.com.

4.3.1 Attenuator

Attenuator	
Energy conversion	Wave > Kinetic
Existing TRL	7
Wave energy TRL	7

Technology Overview

Attenuator are aligned with the direction of wave travel and capture energy from the waves as they move along the length of the device. Attenuator devices have been demonstrated at full scale (such as the Pelamis machine), over extended deployment periods, however they have not been proven to operate reliably/cost-effectively.

4.3.2 Point Absorber

Point Absorber	
Energy conversion	Wave > Mechanical
Existing TRL	7
Wave energy TRL	7

Technology Overview

Point absorbers typically consist of a single buoyant body (that is small compared to the wavelength) which is tethered to the sea bed or to a heave plate. Energy can be captured from waves moving in any direction, through heave, surge, pitch or sway motion, turning wave energy to kinetic energy. The motion of the body relative to a heave plate or the rigid mooring is captured by the PTO system.

Point absorbers have been tested with many different PTO technologies, including linear electrical generators, hydraulic systems and magnetostrictive elements.

Point absorbers have been developed by many companies including the Carnegie CETO, the CorPower WEC and the Ocean Power Technologies (OPT) PowerBuoy.

4.3.3 Oscillating Wave Surge Converter

Oscillating Wave Surge Converter	
Energy conversion	Wave > Mechanical (rigid body motion)
Existing TRL	7
Wave energy TRL	7

Technology Overview

Oscillating Wave Surge Converters (OWSC) capture the horizontal component of wave motion, typically using a buoyant flap hinged off a structure mounted on the seabed in shallow water to exploit elliptical water particle motion. Examples of deployed OWSC devices include the 800kW Aquamarine Oyster, and the 100kW AW Energy Waveroller. Aquamarine ceased trading in 2015 and the intellectual property for the Oyster devices is currently owned by WES.

Many OSWC devices have used hydraulic Conversion Subsystems, with some devices housing the conversion equipment underwater on the base of the device, and others pumping fluid to a shore based PTO unit. A team comprised of ABB, Resolute Marine Energy and Texas A&M University started development towards a magnetic gearing Conversion Subsystem specifically for OWSC devices, however the current status of the project is unclear.

4.3.4 Oscillating Water Column

Oscillating Water Column	
Energy conversion	Wave energy > Mechanical (air pressure differential)
Existing TRL	9
Wave energy TRL	9

Technology Overview

Oscillating Water Columns consist of an air chamber which is open to the sea at its base. The cyclic action of the waves at the base of the chamber forces air in and out of the top of the chamber, which creates an oscillating airflow. This is typically channelled through a Conversion Subsystem consisting of a bidirectional turbine, such as a Wells turbine.

One of the most mature deployed wave energy devices is the 296kW Mutriku OWC plant in Spain. This plant is integrated into a breakwater, and has been continually operating since 2011, using 16 Wells turbines.

Oscillating water column systems can also be mounted on floating platforms for offshore installation. These have been trialled, but are not as mature as shore based solutions.

A limitation of OWCs is the use of air as the working fluid. The conversion of wave surge to pneumatic pressure is an inefficient process, which reduces the capture and conversion capacity of the system. The requirement for large air chambers can lead to a high CAPEX.

The WaveTrain novel oscillating water column device has been developed by Joules Energy Efficiency Services under the WES Stage 1 Novel Wave Energy Converter programme. This is a novel angled floating OWC design, which uses linked buoys, and aims to achieve high hydrodynamic efficiencies, with a low cost of energy.

4.3.5 Overtopping Device

Overtopping Device	
Energy conversion	Wave > Gravitational potential > Mechanical (fluid flow)
Existing TRL	7
Wave energy TRL	7

Technology Overview

Overtopping devices capture the kinetic energy of waves by directing the wave fluid up into a reservoir at a greater height than the sea. This is then released through the bottom of the reservoir, (typically through a low head turbine), converting the gravitational potential energy into mechanical energy.

Overtopping devices can be shore mounted, or tethered offshore as a floating unit. A floating unit was trialled between 2003 and 2010 by Wave Dragon, however there is limited published information regarding the results of this trial.

The capture width of overtopping devices can be significant, by using structures to funnel and concentrate the waves into the reservoir. This additional structure can add significant cost and complexity to the design, may alter the ability of structure to survive high energy loading, and could also make the device more sensitive to the incoming direction of waves.

4.3.6 Salter's Duck Style Terminator

Salter's Duck Style Terminator	
Energy conversion	Wave energy > Mechanical rotational
Existing TRL	7
Wave energy TRL	7

Technology Overview

Terminators are devices which are oriented perpendicular to the direction of wave travel, as opposed to an attenuator which is aligned with the direction of wave travel. Salter’s Duck is a subtype that incorporated an oval shaped body that “nodded” with the motion of the waves.

The Salter’s Duck terminator was a highly efficient wave energy converter, with capture efficiency estimates ranging from 50% to 90% of the wave energy [7]. This device was originally developed in the 1970s, however this initial development produced a device which contained many subsystems and was impractical and uneconomic to build.

More recently in 2009, a Salter’s Duck style terminator was deployed to test a 10kW hydraulic PTO design [7]. These trials demonstrated the high capture efficiency of the design, however the published results were limited regarding the success of the trials and power generation capability.

By design, terminators can experience very high loads during operation compared to other devices as the entire device is impacted by the wave load at one time. The capture capability of terminator devices can also be sensitive to the incoming wave direction.

4.3.7 Submerged Pressure Differential

Submerged Pressure Differential	
Energy conversion	Wave > Mechanical (pressure)
Existing TRL	5
Wave energy TRL	5

Technology Overview

A Submerged Pressure Differential (SPD) device exploits the hydrostatic pressure variation created as the sea level rises and falls as waves pass over the device. They are typically located near shore and attached to the seabed. The device captures the external cyclic pressure differential to pump a working fluid around a conversion subsystem. Submerged pressure differential devices often use air as the working fluid, which drives a conventional turbine connected to a rotary generator as the PTO.

An example of a SPD device is the AWS Archimedes Waveswing submerged wave power buoy. In 2016, this project received funding through the WES Stage 2 Novel Wave Energy Converter programme.

A different form of SPD device is the Bombora mWave device, which claims a wave energy capture efficiency of 41% [9]. This is a large concrete structure on the seabed, with a series of flexible membranes to convert the cyclic pressure differential into airflow. This system uses an air turbine PTO, which is housed subsea in the main structure. In 2017, Bombora announced development of a 1.5MW mWave unit.

Submerged devices are less exposed to slamming forces than surface equivalents however, depending on design, can be sensitive to the direction of wave travel. The design of the AWS Waveswing eliminates this directional sensitivity.

4.3.8 Rotating Mass

Rotating Mass	
Energy conversion	Wave > Mechanical (rotary)
Existing TRL	8
Wave energy TRL	8

Technology Overview

Rotating mass devices are floating bodies which house a large eccentric mass which is free to rotate. The movement of the floating body with the waves causes pitch and roll that rotates the mass on a shaft, which is typically connected to a standard rotary generator PTO.

The 500kW Wello Oy Penguin device is an example of a rotating mass device which has been deployed and grid connected since early 2017, although the delivered energy generation capability of this system is unknown. Also in 2017, Wello Oy announced development of a 10MW rotating mass farm in Bali.

Kobe University has demonstrated multiple devices rated up to 45kW which use a gyroscope instead of an eccentric mass, with a demonstrated wave to wire efficiency of 68% [10].

4.3.9 Bulge Wave

Rotating Mass	
Energy conversion	Wave > Mechanical (pressure)
Existing TRL	4
Wave energy TRL	4

Technology Overview

Bulge wave devices are a technology consisting of a long, fluid filled flexible tube which is sealed at both ends. A bulge wave is formed within the tube due to the impulse of an oncoming wave interacting with the nose of the device. This wave travels down the device in front of the sea wave, gaining energy and growing in amplitude as it travels along the tube, with the energy in the device eventually removed by a PTO.

Although this technology does not meet the conventional classification criteria of TRL 6, it is considered here as it is a prime mover supporting a conventional or alternative PTO subsystem.

The ANACONDA device, being developed by Checkmate Seaenergy, aims to direct the internal bulge wave between high and low pressure reservoirs at the tail end of the tube, through a conventional turbine PTO. SBM is developing a bulge wave device called the S3. In this concept, the walls of the bulge wave tube are made of a dielectric elastomer material which generates power as it expands and contracts when the internal bulge wave passes by. The full size S3 device has a proposed diameter of 4m, a length of 400m and a generation capability of 2MW [11].

Bulge wave devices can be simply moored and self orient to face the oncoming waves, and has a wave energy capture efficiency which is claimed to be comparable to other wave energy devices.

5. ALTERNATIVE GENERATION TECHNOLOGIES

This section presents a summary and brief introduction to the alternative generation technologies that have been identified and assessed in this landscaping study. The technologies are downselected in Section 5.9 for further economic and technical consideration in Sections 6, 7 and 8.

The initial identification of alternative power conversion technologies was undertaken using the Fundamental Energy Interactions Matrix, expert and stakeholder input, and open research into commercial technology and scientific development programmes.

Technologies were only considered that seemed potentially likely to meet the fundamental requirement of the system, those being technologies which form part of a system which converts a wave energy input to electricity at commercial scale. Additionally, the technology must not use consumable reagents. For example a device that required consumable chemical inputs in the electricity generation process would be unacceptable for this use case.

The list of alternative generation technologies researched is shown below. Detailed research findings for each technology are contained in the Technology Capture Sheets in Annex B, with a high level summary and key figures included in this section below.

All references supporting the discussion in this section can be found in the relevant Technology Capture Sheet.

Technology	Document Chapter
Magnetostriction	5.1
Triboelectric Generation	5.2
Dielectric Elastomers	5.3
Piezoelectrics	5.4
Magnetohydrodynamics	5.5
Thermoelectrics	5.6
Electrokinetics	5.7
Electrohydrodynamics	0

5.1 MAGNETOSTRICTION

Magnetostriction	
Energy conversion	Mechanical (strain) > Magnetic > Electric
Existing TRL	5
Wave energy TRL	4

Technology Overview

Magnetostriction is a property of some ferromagnetic materials, where its magnetic properties change in response to a mechanical strain on the material. By enclosing a magnetostrictive material in coils of wire the changing magnetic field can be exploited, effectively allowing direct conversion of mechanical strain to electric energy.

Magnetostrictive materials can be loaded in multiple ways to change the magnetic field. They can be loaded axially (which stretch or compress the material) or loaded through bending. The magnitude of change in magnetic field strength is a material property and the magnitude of change in the field will be generally proportional to the power output from the generation device.

Oscilla Power Inc. has experimented with a magnetostrictive generator specifically for use in wave energy generation with full scale testing planned for 2018, however results of testing to date were unavailable. As an aside, separately to the development of the magnetostrictive system, Oscilla Power are involved in the WES Stage 2 PTO programme to optimise and demonstrate their linear drivetrain concept, which combines a linear hydraulic “gearbox” with a linear generator.

Toshiyuki Ueno from Kanazawa University has demonstrated a small scale magnetostrictive energy harvesting device. This device used Galfenol as the magnetostrictive material and generated 2W at a power density of 22mW/cm^3 [14]. A linear extrapolation of this figure indicates that to generate 1MW, approximately 45m^3 of material would be required just for the Electrical Generation Subsystem [Calc 1].

Other materials have stronger magnetostrictive properties under loading than Galfenol, such as Terfenol-D, which offers the highest known room-temperature magnetostrictive properties. Data from ETREMA, a leading supplier of both Galfenol and Terfenol-D, shows that under the same loading stress and strain, Terfenol-D has a magnetic field intensity over 4 times greater than Galfenol [15][16][17]. Using this higher output material would lower the material requirement to generate 1MW to be closer to 10m^3 (equal to 92.5 tons of material at a material density of 9.25g/cm^3 [36]). Using the highest power density from [35] suggests a volume of 6m^3, or 55.5 tonnes, for the Electrical Generation Subsystem alone.

5.2 TRIBOELECTRIC GENERATON

Triboelectric	
Energy conversion	Mechanical > Electric
Existing TRL	4
Wave energy TRL	3

Technology Overview

The triboelectric effect generates energy directly from the mechanical energy moving electrodes relative to each other. This can be electrode materials in contact with each other, or with a separation gap between them.

This effect can be embodied in two key forms:

- A “normal” triboelectric generator, where each generator is of the same order of magnitude in size/power as conventional generators,
- Triboelectric nanongenerators (TENG) which are much smaller and produce much less power than conventional generators but have had more recent developments.

Due to the very small charges involved, the power density of TENG is very low. Spherical TENG have been demonstrated with a diameter of 7cm, which each produce approximately 1mW in a small-scale laboratory wave tank. Closely packed, this roughly equates to 1W/m^3 [19].

Alternative designs of triboelectric nanogenerators have demonstrated significantly higher power densities, with 3.5W/m^3 being achieved from a sea snake style device [20]. A 1MW generator would have a volume of 285,000m^3 or dimensions of approximately 65 x 65 x 65m [Calc 3].

The main research into wave energy TENG is currently being performed at the Nanoscience Research Group at the Georgia Institute of Technology, with further independent and collaborative research being published by Beijing Institute of Nanoenergy and Nanosystems. Research is focusing on many aspects of this technology, including material selection, power density, array layout and control.

Using discs to generate the triboelectric effect allows for a much higher power density, leading to a volume of around 55m^3 for 1MW [Calc 11]. Therefore normal triboelectric generators are likely to be more cost effective.

5.3 DIELECTRIC ELASTOMERS

Dielectric Elastomer Generators	
Energy conversion	Mechanical > Electric
Existing TRL	9
Wave energy TRL	5

Technology Overview

Dielectric Elastomers are materials which can convert an applied mechanical force directly into an electrical output. They have been investigated in a wave energy context by a number of organisations, including the WES funded Scuola Superiore Sant'Anna Dielectric Elastomer Generator (DEG) project in the Stage 2 PTO programme. The objective of this funding is to develop and test a 1:15 to 1:25 scale DEG-PTO prototype.

Current commercially available DEG materials offer specific power of 170 W/kg, with a material density close to 1000kg/m^3 [23]. Scaling this into a 1.5mm thick sheet generator (as proposed in [23]), the power density of this generator would be 255W/m^2. Scaling this value indicates that a 1MW generator requires a DEG sheet area of approximately 4000m^2 [Calc 4].

SBM S3 has proposed, and is developing, a DEG bulge wave device. The full scale device will have a diameter of 4m and length of 400m, with a target power output of 2.5MW per device. This power output would require approximately double the power generation capability per area that current DEG technologies offer [22].

An issue with DEG technology in its current form is the limited Mean Cycle Time to Failure (MCTF). Current materials have a MCTF value around 10 million, which with a loading frequency of 15 seconds, corresponds to a mean lifetime under 5 years. Recent studies have claimed that MCTF values can be improved to 15-22 million [23], which would increase the mean lifespan to 7-10 years, however this would still fall short of the target 20-25 years for a large scale generation system [Calc 6].

5.4 PIEZOELECTRICS

Piezoelectric Generators	
Energy conversion	Mechanical > Electric
Existing TRL	9
Wave energy TRL	5

Technology Overview

Piezoelectric materials convert mechanical stress in a material into electrical charge under loading. These materials can be used as the main component in a generation system, in which appropriate loading is applied to the material to generate electricity. Many materials exhibit piezoelectric properties, from natural crystals, composites, nanomaterials, biological materials such as bone or some proteins, synthetic ceramics, and some polymers. Some flexible materials exhibit piezoelectric properties, including some polymer and biological materials [21].

Piezoelectrics are commonly used in sensors such as strain gauges or in power monitoring equipment, however energy harvesting methods have proposed using large scale piezoelectric arrays to generate power. There are currently no piezoelectric wave energy systems, however the studies below have considered their application:

- Arrayed crystalline piezoelectric elements were calculated to have a power density in the order of 10W/m^2 [24],
- Flexible piezoelectric surface sheets have a predicted power density of 20mW/m^2 [24].

Wave energy generators using a PTO based on a flexible piezoelectric technology may not require a conversion subsystem to transfer the wave energy in an appropriate form to the PTO and could allow some components in the conventional WEC architecture to be removed. This is unlikely to be possible when using non-flexible or crystalline piezoelectric technologies as the frequency of direct loading from wave energy is unlikely to be at the optimum frequency for the PTO, therefore requiring a conversion subsystem to operate effectively.

One study [25] has tested a wave energy device using a point absorber and a wave excited pendulum to strike the piezoelectric element. A separate study [26] mounted multiple piezoelectric elements between thin panels mounted on a harbour wall, with the energy of wave impact on the outside panel being transferred through the piezoelectric elements to generate power.

Piezoelectric materials only produce power when being loaded or unloaded, and most piezoelectric materials can generate electricity under loading of any frequency. When used in a generation system, each piezoelectric material will have a loading frequency or range of frequencies which will create the highest electrical output. Although the frequency is different for each material, generally the optimum generation frequency is significantly higher than the natural frequency of ocean waves (which is typically in the order of magnitude of 0.1Hz). It is therefore likely that optimum power output from a piezoelectric generator is achieved by combining a piezoelectric electrical generator subsystem with a WEC or conversion subsystem which is capable of exciting the piezoelectric material at the most appropriate frequency.

Given the significantly (i.e. 500 times [24]) higher power density of crystalline piezoelectric elements than the flexible piezoelectric surface sheets, it is likely that a MW scale wave energy generation system will use the crystalline form in the electrical generation subsystem.

5.5 MAGNETOHYDRODYNAMICS

Magnetohydrodynamics	
Energy conversion	Mechanical > Electric
Existing TRL	7
Wave energy TRL	2

Technology Overview

Magnetohydrodynamics (MHD) refers to the physical interaction effects between magnetic fields and the motion of electrically conducting fluids. In the context of energy generation, this takes the form of capturing energy from a conducting fluid moving through a strong magnetic field.

In wave energy, magnetohydrodynamic power generation systems are very immature, with historical development aimed at power harvesting systems with a magnitude lower than 10W. Based on reasonable assumptions, a hypothetical MHD system has been estimated to have a power density of 280W/m^3 [Calc 7]. However, this relies on the use of electromagnets to generate the field. The power consumption of a device using this technology is also likely to be high, which further reduces the potential power output from a wave energy generation system which operates using magnetohydrodynamics (potentially consuming power instead of generating it).

Permanent magnets typically have a flux density less than 1T, which leads to an illustrative power density less than 60W/m^3 [Calc 8]. This is a significantly lower power density than conventional technologies such as a Wells turbine (which an MHD generator could theoretically replace) which can achieve a peak power density exceeding 5000W/m^3, indicating that for a comparable output wave energy system, the physical dimensions of a MHD system may be significantly larger. Note that the 5000W/m^3 figure is calculated based on the approximate power and dimensions of the turbine of the Limpet device. A MHD generator requires a flow through it therefore it can be considered to be analogous to a turbine, in that it would work best in a duct.

5.6 THERMOELECTRICS

Thermoelectric Generators	
Energy conversion	Heat > Electric
Existing TRL	9
Wave energy TRL	2

Technology Overview

Thermoelectric generators are solid state energy conversion devices, which use the Seebeck effect to convert a temperature gradient across the device into electrical energy. This typically uses a junction between semiconductors. A thermoelectric generator can produce trace amounts of energy from small temperature differences, however to work effectively, a large temperature gradient (>400°C) is required during operation. The efficiency of the system depends on the temperature difference between the plates, a higher difference in temperature will give a higher efficiency.

Thermoelectric generation has not yet been used in a wave energy generation demonstrator. Currently, the main application is for low power energy harvesting in harsh environments such as on satellites. Other applications are being explored such as the Alphabet Energy PowerCard-γ device, which aims to recover energy otherwise lost from the high temperature exhaust gases of conventional fossil fuel generators. Each 4x5cm PowerCard-γ unit can generate 9W at a claimed efficiency of 5% when operating over a 400°C temperature gradient in air [25].

With a high temperature gradient, heat to electrical conversion efficiencies are in the order of 5-10% with current technology capabilities [25] [28]. Typically wave energy devices would not produce a temperature gradient in the optimum range for a thermoelectric generator, and even then the majority of this heat energy would not be converted into electricity, but wasted as uncollected heat.

5.7 ELECTROKINETICS

Electrokinetic Generators	
Energy conversion	Wave > Electric
Existing TRL	3
Wave energy TRL	3

Technology Overview

Wave energy electrokinetic generators exploit the charged ions within seawater, rather than the physical force of the waves themselves to allow a direct conversion from wave energy to electric potential through solid state components.

Investigations into wave energy electrokinetics are very immature, with few published studies. One study demonstrated proof of concept film generators from graphene and carbon black powders, with an area of 15cm^2, and tested them in a laboratory wave tank using collected sea water. The film generators in this study had a peak power output of 297(±263) μW/m^2, with the high uncertainly due to the immaturity of the technology [29]. Scaled linearly, for a generator system with a power output of 1MW, this peak power density corresponds to a film generator area exceeding 3000km^2 to generate a peak output of 1MW [Calc 9].

The study succeeded in demonstrating the technical concept of generating power from sea waves using electrokinetics. However, it is a very early stage study so there are significant technical challenges in maturing this technology. Due to this immaturity, it is likely that improvements to the technology capability can be made through further research and development. However, it is not thought likely that the many orders-of-magnitude improvement that would be required for viable generation on the scale of interest, will be realised.

5.8 ELECTROHYDRODYNAMICS

Electrohydrodynamics	
Energy conversion	Mechanical (fluid flow) > Electric
Existing TRL	5
Wave energy TRL	5

Technology Overview

Electrohydrodynamics (EHD or charge separation) is a technology which uses airflow to move a positively charged sea water mist away from a negatively charged source panel. The increasing separation created as the positive mist is blown from the source panel builds up a large electric potential, which can be exploited as high voltage, direct current electricity.

This technology had been proposed primarily as a wind power technology replacement for offshore wind turbines, with a small input of wave energy to pump sea water. For use in wave energy, this technology could be used alongside a prime mover and/or conversion subsystem which can generate an airflow, such as an OWC, or SPD device (such as the Bombora concept).

A company called Accio Energy was recently developing the technology using US Department of Energy and angel investor funding, however they are no longer in operation as of 2018. Accio had predicted that a device with a 15.5m^2 source panel could produce 2.5 to 3kW of rated power [30].

As a comparison with an existing technology, the 296kW Mutriku OWC plant uses 16 Wells turbines which each have a diameter of 3m. At peak generation, this means the Mutriku plant achieves a power density of 2.6kW/m^2, significantly more than the above electrohydrodynamic peak estimate of 0.2kW/m^2 [31]. In order to match this, a factor of 10 improvement is required in through future development, which is a significant challenge.

Extrapolating this current capability for the 1MW+ generation capacity of interest for this study, the electrohydrodynamic generator would require an airflow channel area exceeding 5000m^2 [Calc 10].

Although the specific details behind the 2.5 to 3kW rated power claim are unknown, it is possible that a wave energy system using electrohydrodynamics could exceed the performance of a wind powered system as the wave energy device could manage and condition the airflow past the source panel to be optimise performance, although this would require additional valve and airflow control systems.

5.9 ALTERNATIVE TECHNOLOGY DOWNSELECTION

This section discusses which alternative generation technologies were considered most likely to be technically feasible and provide a step-change reduction in the LCOE, as agreed between Frazer-Nash and WES.

From the alternative technologies identified, magnetohydrodynamics, thermoelectrics, electrokinetics, and electrohydrodynamics were evaluated to be unsuitable for further inclusion in this study. These technologies were less likely to be able to deliver the desired step change reduction in LCOE compared to the others identified. The justifications for removing them from further consideration are detailed below.

It should be noted that the removal from further consideration in this study is not a conclusion that they are unsuitable for wave energy generation purposes. Each of these technologies could show promise, with significant research and development investment, and technical breakthroughs, however they have been evaluated to not show sufficient promise within the time and scales of interest in this study to warrant more detailed technical or economic assessment.

Magnetohydrodynamics

Magnetohydrodynamic power generation systems are very immature, with development to date aimed at power harvesting systems with a magnitude lower than 10W. Based on reasonable assumptions, calculations provide illustrative power density figures that are significantly lower than current conventional technology [Calc 7][Calc 8]. Power density of MHD could improve through development of the technology, however there is no clear reason for why it would improve, particularly compared to other technologies.

The power consumption of a device using electromagnet based MHD technology is also likely to be high which further reduces the potential power output density below that presented above. The device could consume power instead of generating.

Thermoelectrics

Thermoelectric generation has not yet been used in a wave energy generation demonstrator, but has been shown to be technically feasible in an ocean thermal energy conversion system. The technology requires a high temperature gradient (>400°C) to work efficiently. Current WEC concepts will produce heat, however will not generate the temperature gradient required. To generate a large thermal differential would require an electric heating element (which would already have electricity generated) or use a friction brake to dissipate power (which would have significant fatigue issues).

Even if this high thermal gradient could be achieved, heat to electrical conversion efficiencies are of the order of 5-10% (see the Technology Capture Sheet). This indicates that a thermoelectric technology would be inappropriate to use as the primary PTO.

Electrokinetics

As with magnetohydrodynamics, electrokinetic power generation systems are very immature, with laboratory demonstrated proof of concept systems which produced between 34 to 560 $\mu W/m^2$ (see the Technology Capture Sheet). Based on a linear scaling of the current power generation capabilities, a system with a 1MW generation capacity would need a generator film capture area exceeding $3000km^2$ [Calc 9]. It is highly likely that this area requirement would drop significantly with further development and trials using other materials. However the technical immaturity of this technology, uncertainty around ability to operate in the environment or survive loading, and the need to increase power density by around 4 orders of magnitude eliminate this from further investigation in this study.

Electrohydrodynamics

Based on the available data, electrohydrodynamic generators are predicted to currently have a power density around in the region of $0.2kW/m^2$, approximately 10 times less than the peak power density of conventional technologies (see the Technology Capture Sheet). Even with a 10 fold increase in power density beyond that predicted, it seems unlikely that EHD technologies would be economically favourable once developed compared to a conventional technologies. Furthermore it would require generation of a mist to operate, meaning that OPEX is likely to be comparable or worse than conventional generators.

5.10 SUMMARY

8 alternative generation technologies have been identified that have a TRL of 6 or less for use in wave energy. This is in contrast to their most mature applications where some technologies have a TRL of 9. A summary of the TRL assessments for the alternative technologies is shown below in Table 4. Although identified as alternative, most of the technologies have already been considered in wave energy to some degree already, just not to the same level as conventional technologies.

Those technologies that are of most interest to WES for further consideration are:

- Magnetostriction,
- Triboelectrics,
- Dielectric Elastomers, and
- Piezoelectrics.

Other technologies have been removed due to their poor efficiency or power density compared to the above. The potential future performance of technologies is considered in detail in Section 7, however these technologies currently have a poorer performance and do not seem likely to improve at a rate that would make them superior. Therefore it is considered that they would also be poorer when considering future performance.

Table 4 – Summary of Alternative Technology TRL scores

Technology	Existing TRL	Wave Energy TRL	Downselected
Magnetostriction	5	4	Yes
Triboelectric Generation	4	3	Yes
Dielectric Elastomers	9	5	Yes
Piezoelectrics	9	5	Yes
Magnetohydrodynamics	7	2	No
Thermoelectrics	9	2	No
Electrokinetics	3	3	No
Electrohydrodynamics	5	5	No

6. ALTERNATIVE TECHNOLOGY CONCEPTS

From the alternative technologies, triboelectric, piezoelectric, dielectric elastomers, and magnetostrictive generators were downselected as the most suitable to take forward for economic analysis.

In this section a concept for the use of each technology has been presented with a potential prime mover, to highlight and visualise how the technology could be implemented and arranged with other subsystems. This has been presented in the form of simple artistic impressions of each proposed device, alongside brief discussions highlighting key design considerations and challenges. These discussions help describe the potential applications of the technology, while also providing an indication as to the level of engineering effort required to integrate the technology into a WEC architecture.

Although these proposed wave energy concepts are intended to suitably combine the alternative technology with a prime mover, these concepts are intended to initiate discussions about the appropriate use of the technology, rather than be a complete, viable and optimal device proposal. They are also intended to promote ideas on how wave energy architectures could be innovated. The alternative technology and wave energy prime mover combinations are shown below in Table 5.

The future technology performance has been analysed separately in Section 7.

Table 5 – Alternative Electrical Generation Technology and WEC Concepts

Concept	Alternative Generation Technology	Concept WEC
1	Magnetostriction	Submerged Pressure Differential
2	Triboelectric Generation	Wave Net
3	Dielectric Elastomer Generator	Bulge Wave
4	Piezoelectric Generators	Floating Impact Generator

6.1 MAGNETOSTRICTIVE GENERATION

6.1.1 Utilisation of Magnetostrictive Materials

Magnetostrictive materials (Section 5.1) can be loaded in multiple ways to exploit the material properties for energy generation, including:

- Bending,
- Vibration,
- Or axial loading.

Due to the high stiffness of the materials they are well suited to architectures using high stress, low strain applications. This is explored in the submerged pressure differential concept below.

6.1.2 Submerged Pressure Differential Concept

Loading a magnetostrictive beam through bending, either cantilever, fixed or simply supported, may be suitable for high magnitude, small displacement applications, however many magnetostrictive materials are brittle, which could limit this loading case. The material properties vary depending on the specific material used, and most current development of magnetostrictive materials focuses on development of materials with more favourable mechanical performance, such as the development of Galfenol [17].

Axially loading a magnetostrictive generator could reduce the risk of mechanical failure, and allow the more brittle, higher output materials to be used. A wave energy device most suitable to exploit this technology would be able to capture large magnitude forces from the wave motion, and transfer them to the low displacement generator.

A submerged pressure differential point absorber concept has been considered, which can be deployed in dense arrays to scale the farm power generation potential. An artistic impression of this wave generation concept is shown below in Figure 3 A.

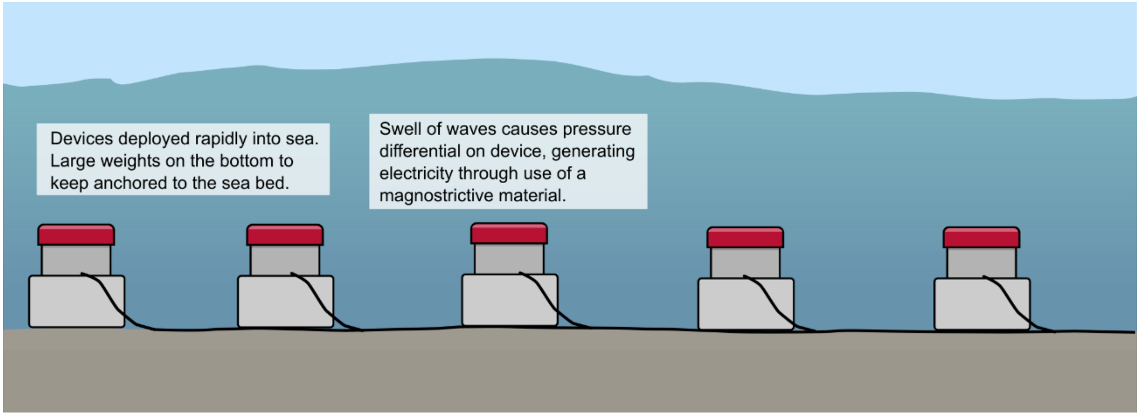

Figure 3 A – Artistic impression of a magnetostrictive PTO SPD device

In this concept, the submerged pressure differential devices are deployed in a large array on the ocean floor, with a top surface having a large collection area. The force captured from the pressure differential device is focused to 'amplify' the pressure onto a smaller magnetostrictive PTO unit. In this artistic impression, this is shown in Figure 3 B as an axially loaded PTO, however a bending form could also be used.

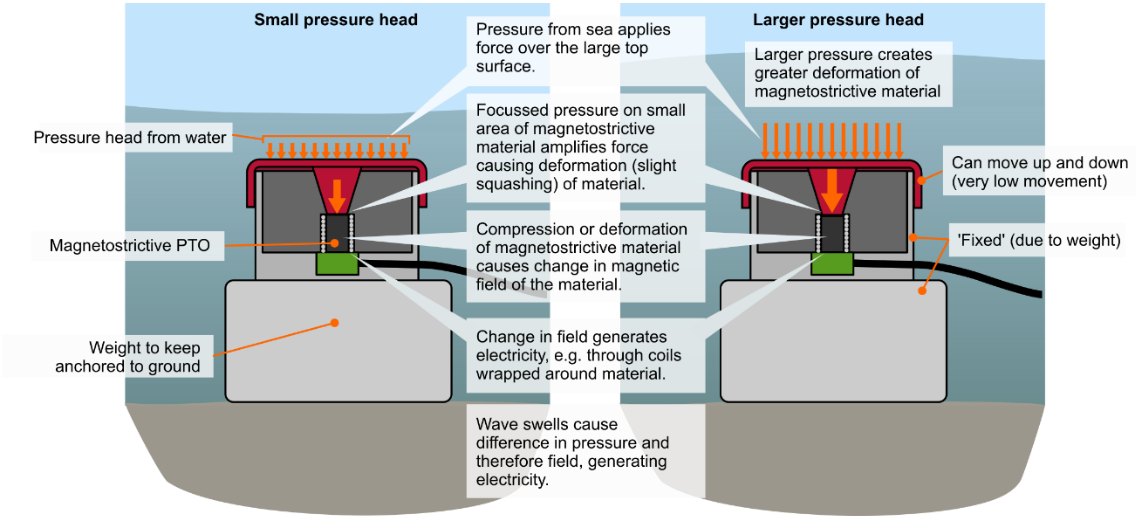

Figure 3 B – Cross section view of the magnetostrictive PTO SPD concept

The device is proposed to be secured to the ocean bed using self weight, and the electric output combined with the output from many other devices before transmission to shore. This simple connection and deployment concept aims to minimise installation costs, while the low amplitude movement of the device aims to minimise maintenance and other OPEX costs. This concept is intended to be deployed in array form, as shown in Figure 3 C

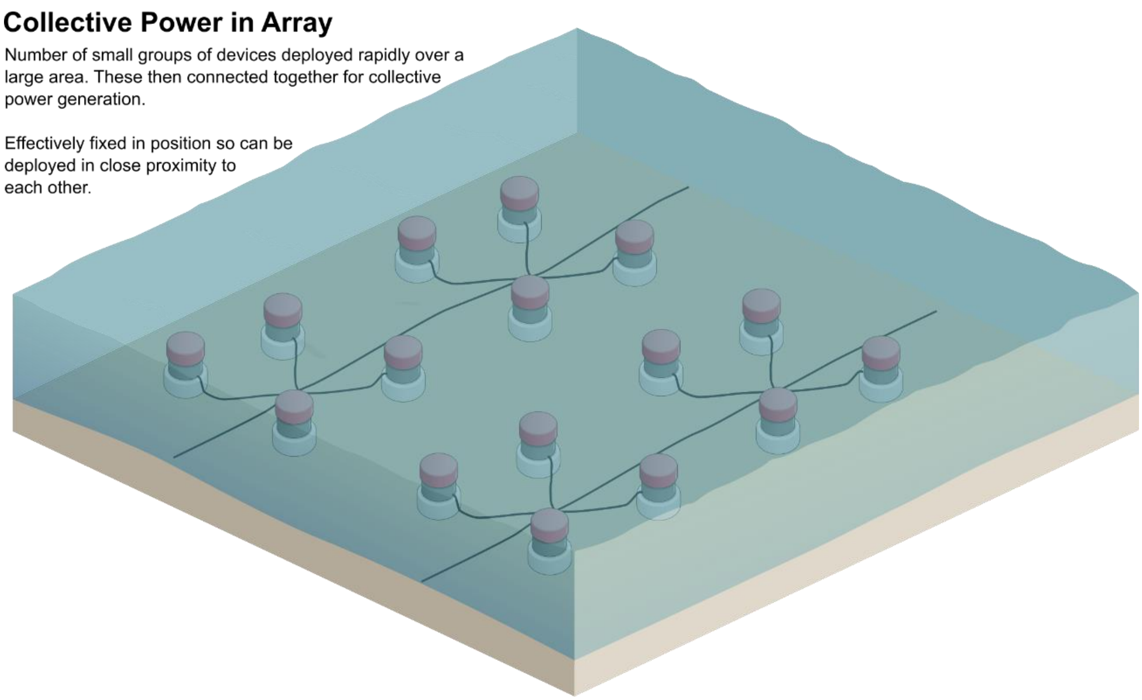

Figure 3 C – Array view of the magnetostrictive PTO SPD concept

6.2 TRIBOELECTRIC NANOGENERATOR

6.2.1 Utilisation of Triboelectrics

Triboelectric generators (Section 5.2) directly generate electricity from the mechanical energy moving electrodes relative to each other. There are four modes of operation for triboelectric generators [31]:

- Vertical contact separation – two oppositely charged dissimilar dielectric materials cycling in and out of contact causes a cyclic potential difference which can be exploited as AC current.
- Lateral sliding – similar to the vertical contact separation mode, oppositely charged dissimilar dielectric materials slide over each other. Charge builds up where the electrodes are not in contact, creating a potential difference which can again be exploited as AC current. This sliding can be linear or rotational, or changing contact such as rotating cylinders or spheres on a surface.
- Single electrode – uses one electrode which is grounded, and one which is mobile but not allowed to come into contact with the grounded electrode. The relative motion between the mobile and grounded electrodes changes the electrical field distribution, which forces an exchange of electrons between the bottom electrode and the ground.
- Freestanding triboelectric layer – exploits the natural charge on common items. When a charged object approaches one of two identical and connected electrodes mounted in a surface its potential will change, there will be a flow of electrons between the connected electrodes to balance the uneven charge. This cyclic charge between the two connected electrodes can be exploited as AC current.

An example of the lateral sliding mode is explored below in the “wave net” concept, using a pair of concentric spheres made from dissimilar materials as the electrodes as a triboelectric nanogenerator.

6.2.2 Wave Net Concept

As discussed in section 5.2 above, the power density of triboelectric nanogenerators is very low compared to conventional WEC technologies. This means that this technology would require a very large number of units to be deployed to generate power at the scale of interest. Although nanogenerators require much more material than other forms of triboelectricity, this concept has been explored as it is very different to conventional architectures.

The concept presented here is a modular floating design, which can be deployed as a single unit or in groups to form a large generation array. This concept is similar to that proposed by the Georgia Institute of Technology research team at scale, with a large connected array of spherical generators (one sphere moving inside another). An artistic impression of the proposed triboelectric net array device is shown below in Figure 4.

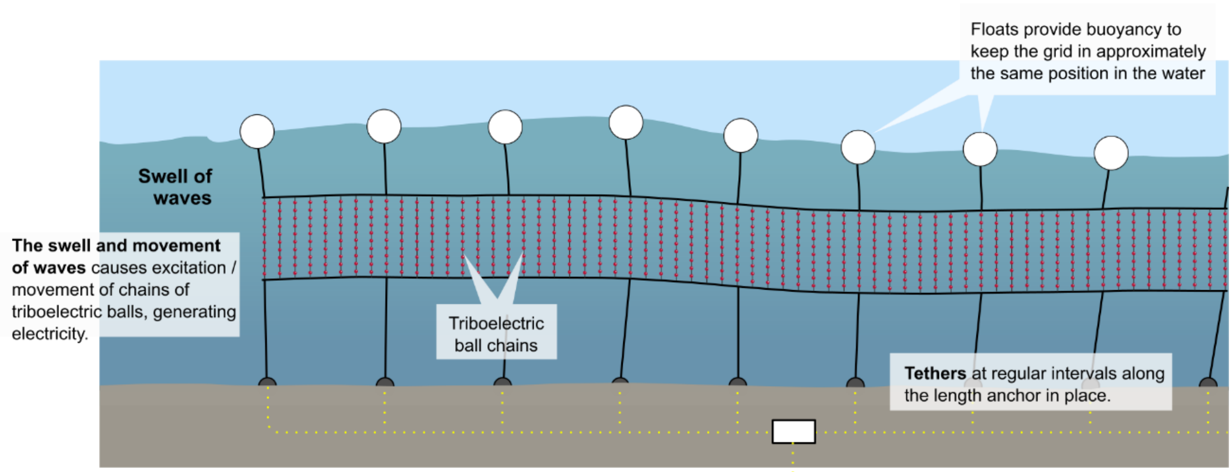

Figure 4 A – Side view artistic impression of the triboelectric nanogenerator wave net

As shown in Figure 4 B, long vertically oriented strings of triboelectric nanogenerators are tethered between a pair of strong, flexible grid structures, such as a coarse steel wire net. The power generated from each generator is transmitted through its individual string, and combined with the output of other strings on one of the grid structures. The entire structure is imagined to be buoyant, and tethered or weighted down to the ocean floor at regular intervals. The generated energy from a single large unit can be transmitted through subsea cables, and combined before transmission multiple units are deployed in an array.

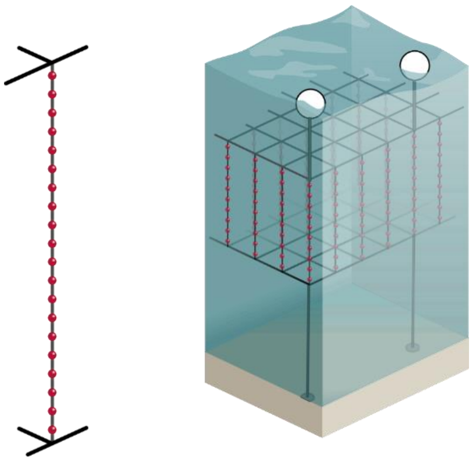

Figure 4 B – Detail view of the triboelectric wave net concept

The low power density of this technology requires a very large collection area and exclusion zone for other marine activity such as shipping, which could be much greater than any offshore wind, tidal or wave energy generation farm of comparable output.

This would not prevent very close deployment of multiple generation modules as shown in Figure 4 C, however the impacts on collection efficiency of deploying modules close together must be understood. Modelling the inter-array interactions in this concept is complicated as well as ensuring that the system is hydrodynamically tuned for optimum generation considering interactions between spheres.

The extremely large scale of the full array would require significant consideration to assess and mitigate the environmental impacts of deployment. The closely packed nanogenerators could potentially affect marine life or damage ecosystems around the deployment area (as it is a large net). Furthermore such a structure is likely to attract significant biofouling through plant growth, clogging up the net in time.

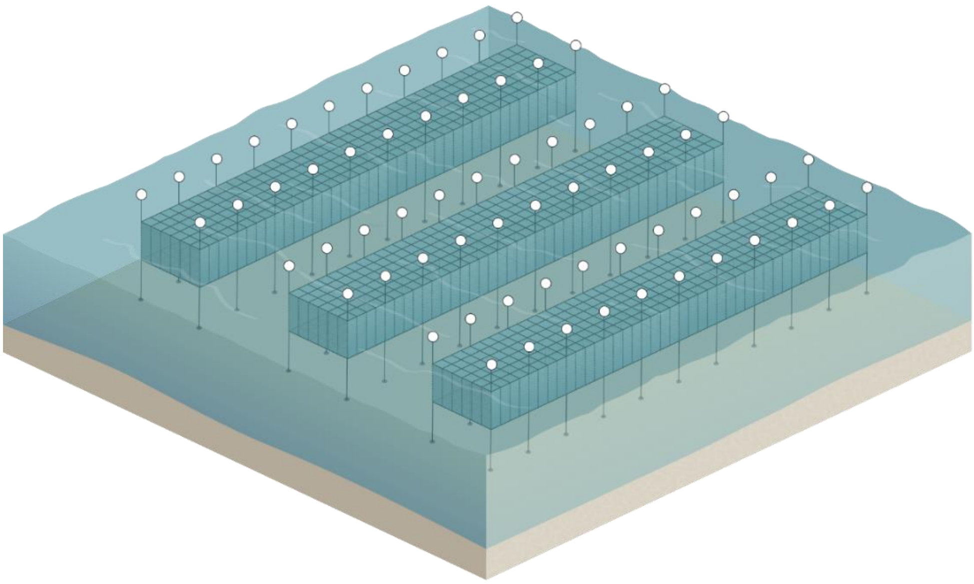

Figure 4 C – Array view of the triboelectric wave net concept

6.3 DIELECTRIC ELASTOMER GENERATOR

6.3.1 Utilisation of Dielectric Elastomers

DEGs generate electricity when they are deformed, changing the separation gap between charged electrodes. Therefore any wave energy architecture capable of providing a local bending moment is appropriate. DEGs can be used as the PTO alongside many current WEC concepts. This is discussed in more detail in section 1.5 of the WES Stage 1 PTO report from Scuola Superiore Sant'Anna. An example is the bulge wave concept, which is explored further below.

6.3.2 Bulge Wave Concept

As discussed in Section 5.3 above, when layered current DEGs can achieve a specific power of 170 W/kg [23], which corresponds to a 4000m^2, 1.5mm thick generator area for a 1MW output [Calc 4]. A bulge wave device is highly suited to this very large area requirement for a large capacity device. In this format, the bulge wave DEG device acts as the entire energy conversion from wave energy to electricity. This concept of a DEG PTO used in bulge wave energy converter has also already been considered and is under development in the SBM S3 device.

An artistic impression of the proposed bulge wave DEG is shown below in Figure 5 A.

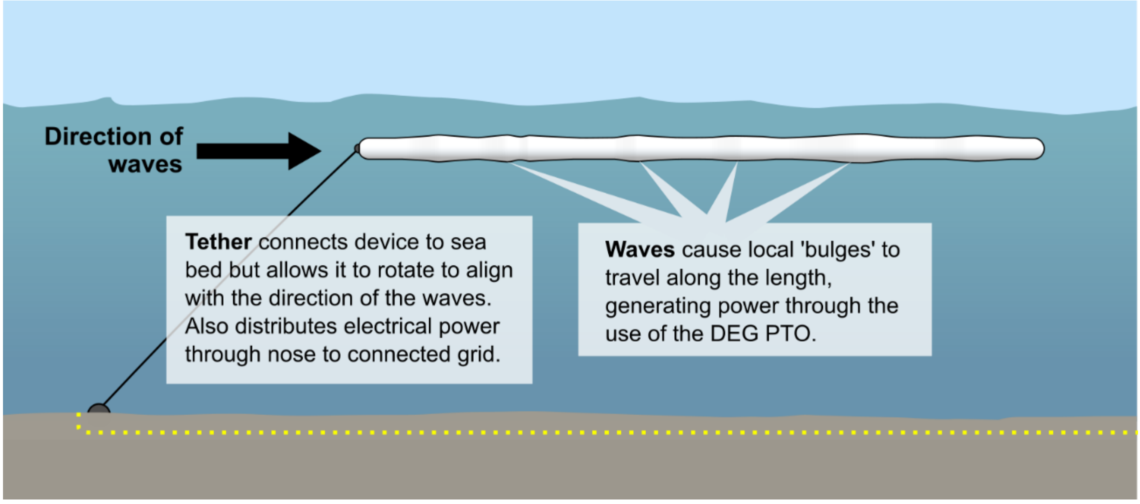

Figure 5 A - Side view artistic impression of the bulge wave DEG concept

A major design challenge for the DEG bulge wave is the actual structure of the tube. The thin DEG sheets are unlikely to be able to withstand the peak forces which the device will experience over its deployment lifetime (slap, slam, and repeated off-axis loading), so additional structural support will be required.

This concept consists of layered sheets formed of layered DEGs, however the layered sheets demonstrated to date are still thin and may lack the required mechanical strength. The DEG materials can be layered to provide suitable mechanical strength, however the power output of a material with sufficient layers for mechanical strength is unknown. There will be a trade-off to be considered during the layered DEG design process, between mechanical strength and power output. It is believed that there will be diminishing returns in the sheet power output from increasing the number of DEG layers. For this concept, this has been addressed by proposing additional rubber layers in the structure, sandwiched between the DEG layers. This is highlighted in Figure 5 B.

The device is expected to move freely about the mooring position in order to orient to the most energetic waves, which indicates that the entire device would have to be tethered and have its power transmitted through a point likely in the nose of the device. This indicates that a single point connection is the most appropriate solution, with the connection allowing mechanical load and power transmission (although the connection may have distinct structural and electrical sub-elements).

As the power is generated through the entire skin of the device, internal power transmission will be required to allow the power removal through the tether point. This has been addressed in the cutaway view in Figure 5 B, demonstrating a flexible busbar style electricity transfer system. The structure should deform by a similar amount around its circumference, therefore placement is relatively arbitrary. If it is at the bottom of the device then it will not cause a mass imbalance leading to a rolling moment.

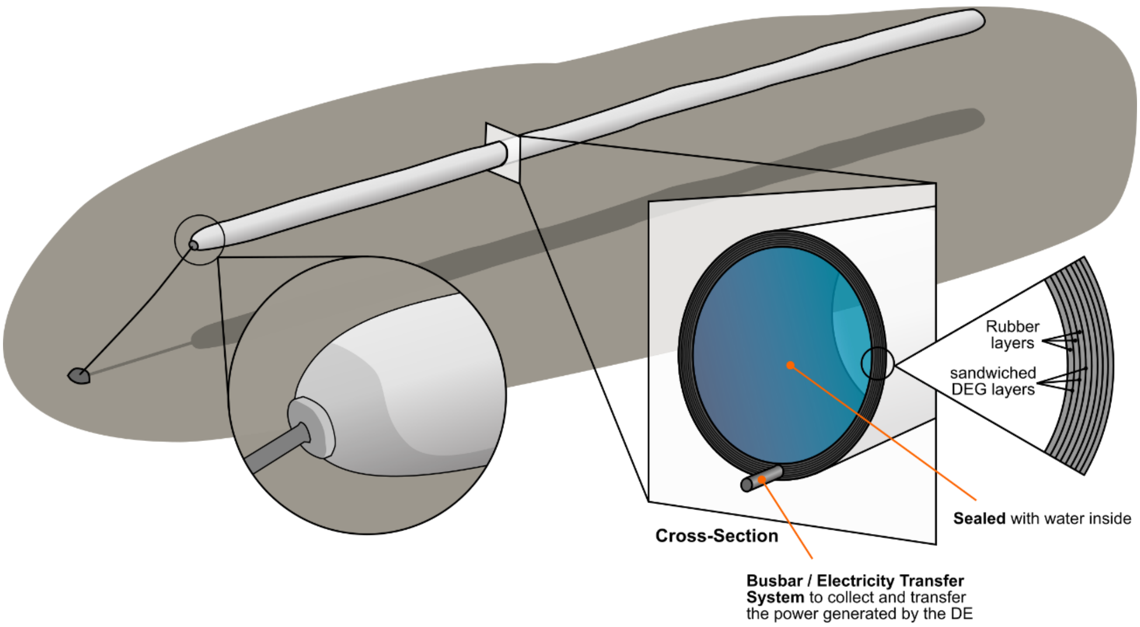

Figure 5 B – Cross section view of the bulge wave DEG concept

Due to the moderate power generation capacity of a single device, a large array (in terms of seabed area) is required to achieve the 100MW generation target. An array of devices would have to have suitable separation to ensure that no devices could come into contact and interfere with each other when considering wave motion or failures. This is in shown in Figure 5 C below.

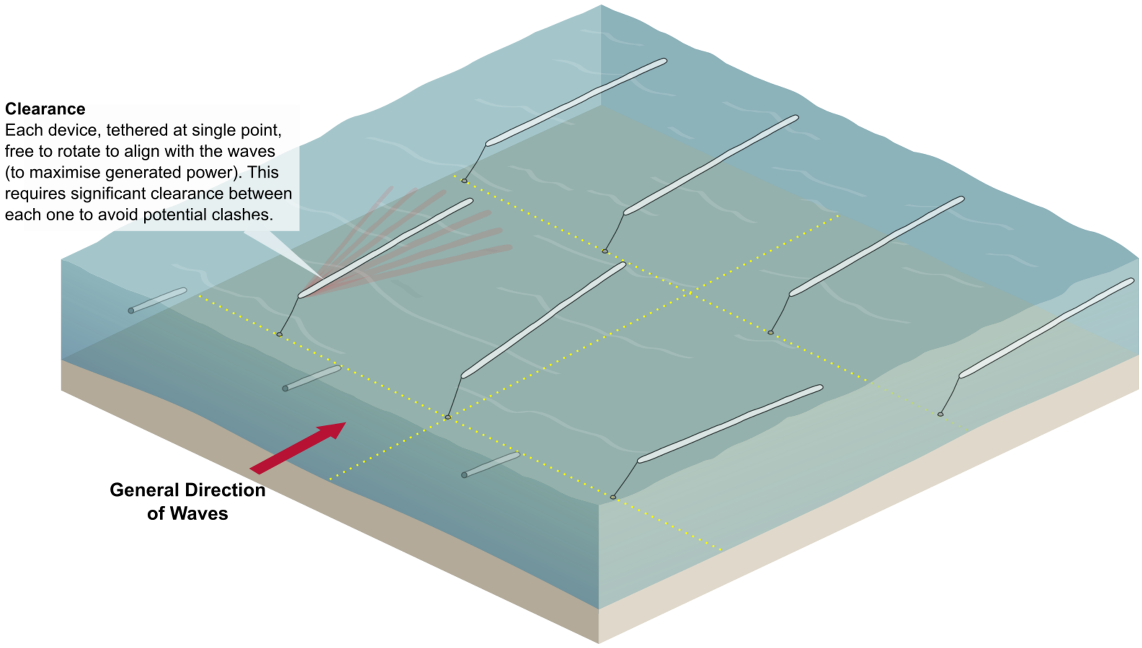

Figure 5 C – Array view of the bulge wave DEG concept

6.4 PIEZOELECTRIC GENERATION

6.4.1 Utilisation of Piezoelectric Materials

Piezoelectric materials can be loaded in multiple ways to exploit the material properties for energy generation, including:

- Bending,
- Vibration, or
- Axial loading.

The first mode is explored in the floating generator concept below.

6.4.2 Floating Impact Generator

As with triboelectricity, a key limitation of piezoelectricity is the low power output per unit, requiring a large number of units to be deployed to generate power at the scale of interest.

Another key limitation is the optimum operating frequencies of piezoelectric materials tends to be multiple orders of magnitude higher than the natural frequency of wave loading. Therefore an appropriate WEC design should increase this operating frequency while minimising energy losses.

The wave capture mechanism proposed for this conceptual piezoelectric device is in essence a wave surge converter, absorbing energy from each ocean waves as it impacts on the device. The artistic impression of this wave generation concept is shown below in Figure 6 A.

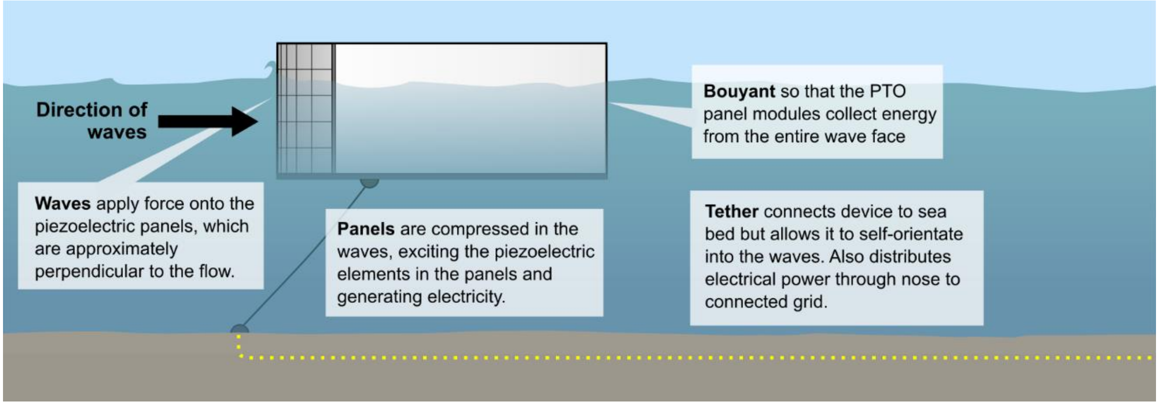

Figure 6 A – Artistic impression of the floating piezoelectric PTO concept

This device consists of a large floating structure, which is simply tethered and self-orienting into the waves. The device floats on the surface, with the front surface acting as the wave capture area. This front surface area is proposed to be 500m^2, which is covered in many identical piezoelectric PTO modules (conversion plus generation), as shown in Figure 6 B. The physical device size proposed here is not driven by any inherent limitations of the piezoelectric technology, but is an example size for a device which could be easily and cheaply deployed using current methods.

Each PTO module takes the form of a piston device, which is compressed by the impulse of the wave, and returned to its original position by internal springs. The interior of the piston device consists of thousands of piezoelectric elements, arranged so they are physically excited by the travel of the piston. Each piezoelectric element is excited many times during each stroke (or each wave cycle), effectively increasing input frequency from wave loading.

The transmission for such a device would be comparable to a point absorber, or other floating surface device, with a cable either separate to or combined with the physical mooring.

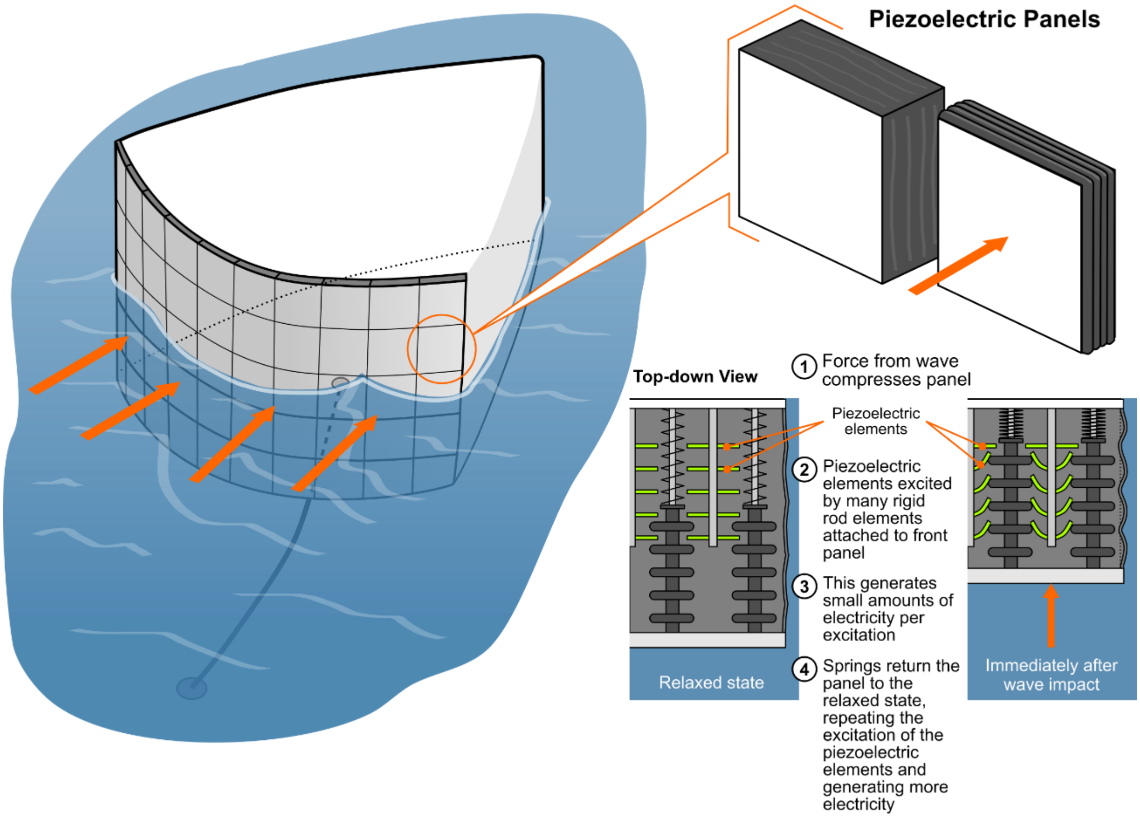

Figure 6 B – Detail view of the piezoelectric PTO module operation

The low power density of piezoelectric based devices will require a large array deployment area (compared to installations such as offshore wind) to generate power on the scale of interest. This would require almost exclusive use of a large area of the ocean, excluding other seafaring activity from taking place. An array of devices, as shown in Figure 6 C, would require suitable separation to ensure that no devices contact each other during operation to prevent damage and array interference effects, and to ensure there is sufficient space for safe ship access for installation and maintenance.

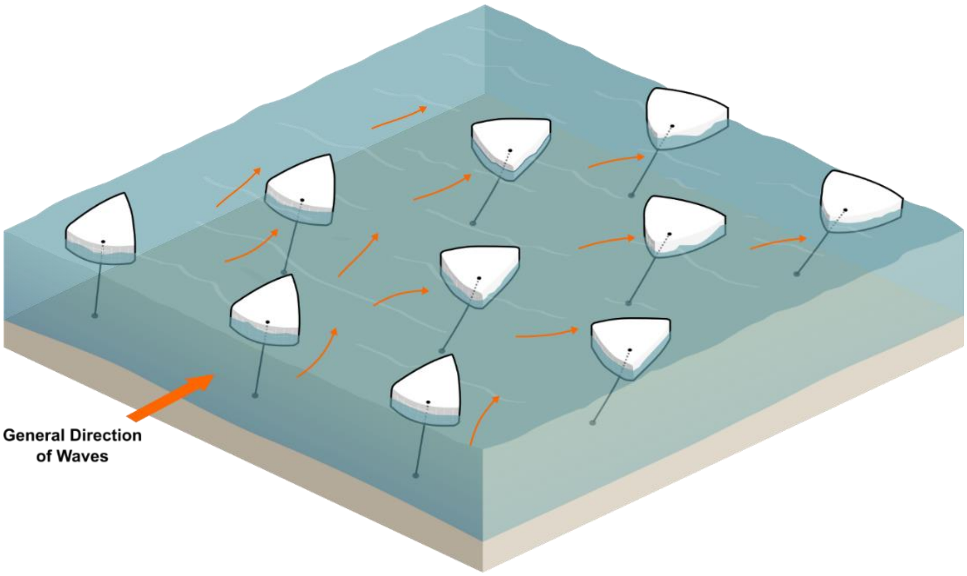

Figure 6 C – Array view of the floating piezoelectric PTO concept

7. ECONOMIC ANALYSIS

This section describes analysis undertaken to better understand the economic opportunity arising from the use of alternative generation technologies. It discusses:

- The approach,
- Assumptions,
- Justification of the approach,
- Conventional technology baseline,
- Results for alternative technologies,
- Summary.

7.1 APPROACH

The approach taken has been:

- Developed conventional baseline CAPEX, OPEX and efficiency for the Electrical Generation Subsystem from the public data research and industry stakeholder engagement activity,
- Developed claims and engineering arguments as to how alternative generation technology CAPEX, OPEX and efficiency currently compare to the conventional baseline,
- Used evidence from the public data research and industry stakeholder engagement activity to support these arguments where possible,
- Reviewed the trend in technology development to suggest how the alternative CAPEX, OPEX and efficiency of these technologies will change in the next 25 years (see individual technology assumptions).
- Calculated the LCOE for a device using the suggested future performance of the alternative technology.
- Allocated a high/medium/low uncertainty to the results.

7.2 WAVE ENERGY ARCHITECTURE CONSIDERATIONS

When considering the four downselected technologies, three (magnetostriction, triboelectrics and piezoelectrics) still need a form of Conversion Subsystem to manage frequency or loading input to the generator, regardless of architecture, as shown in Figure 7 below. This subsystem could be hydraulics in many cases, therefore we have assumed comparable costs across the different architectures.

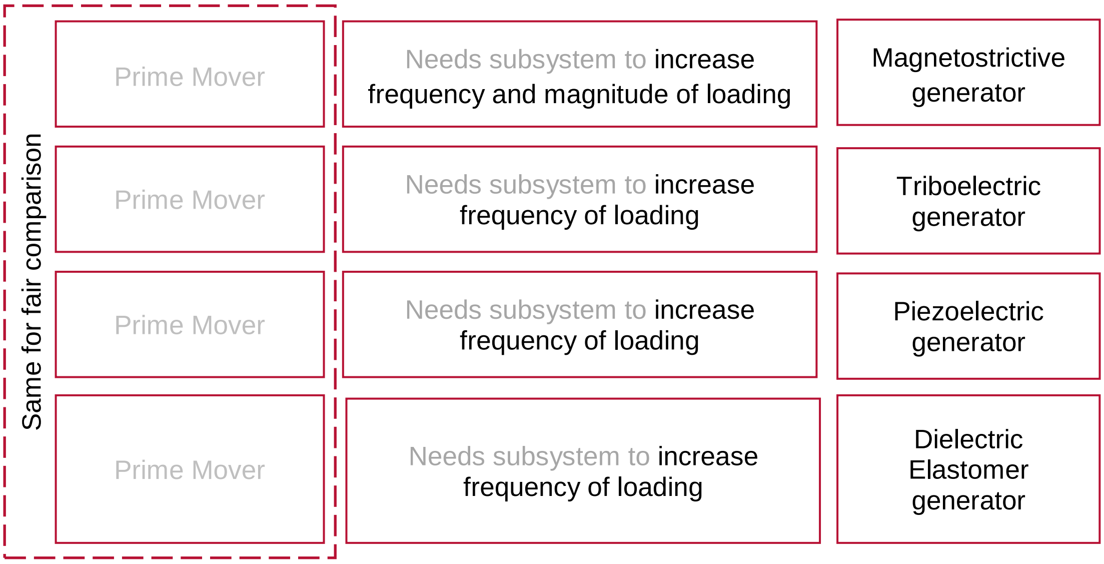

Figure 7 – Alternative Technology WECs considered

The Moorings and Foundations, Structure, and Transmission and Power Quality Subsystems detailed in Figure 2 will still be required for wave energy devices using a magnetostrictive, triboelectric, piezoelectric, or conventional Electrical Generation technology.

For a fair comparison of the economic impact of each alternative generation technology, the same assumed performance and cost of these supporting subsystems should be used. There has been no justification found that using the alternative technologies would require significant changes to these subsystems. Therefore, the impact of the other subsystems on the overall costs would be the same and it is fair to compare the alternative Wave Energy Conversion subsystems directly with the conventional electrical generators.

For this reason, the economic assessments presented below only considers the cost, volume and mass of the key generation material. That is, the indicative costs do not include any subsystems other than the Electrical Generation Subsystem.

Special Considerations for Dielectric Elastomer Generators

In some specific architectures, such as a bulge wave, Dielectric Elastomer Generators may not require a Conversion Subsystem. It may also be possible to remove some, possibly all, of the device structure (this does not include removal of mooring, foundation, transmission and power quality subsystems). In other architectures, such as OWC or SPD devices, there would still be a requirement for a significant amount of structure. An analysis of the removal of elements of the device structure has not been done in this study.

7.3 ASSUMPTIONS

Assumptions are needed for economic analysis of immature technology as there is a large amount of uncertainty. At this early stage approximations provide sufficient indication of the likely influence on LCOE. The following key assumptions have been made:

Power and Efficiency

- Assessment is for a 100MW farm with a 20 year lifespan after 1GW of wave energy has been installed globally (in 25 years' time). The number of WECs in the farm is determined by the technology power output, e.g 100 x 1MW. This has been used to inform relative OPEX costs when systems require replacement after a given number of years.
- The efficiency of the Prime Mover and Conversion Subsystem is assumed constant between technologies.
- The wave energy resource is assumed constant between technologies.
- As the device output (capacity factor) and resource are assumed to be constant, the amount of energy produced, and the capacity factor, is assumed constant across technologies. For example, devices using different generation technologies have been assumed to produce equal energy given the same input from the wave resource. LCOE is through life cost divided by energy produced. As the energy produced is the same, the difference in LCOE is assessed through the difference in through life cost as the devices may have different CAPEX and OPEX values.
- The conventional baseline efficiency and cost is assumed to be constant due to the high technology maturity. The conventional baseline CAPEX, OPEX, efficiency and through life cost are presented in section 7.5.
- For alternative generation technologies, a range of efficiencies based on generator input is not available from literature so figures are assumed to be peak.
- Where a range of parameters is available, typically the most optimistic value has been used. In selected cases, where there is a range of values available which is too broad to be meaningfully interpreted, a suitable mid-range value has been taken (for example academic studies gave figures for the mechanical to electrical efficiency of piezoelectric generators from 1% to 90%).
- Power for alternative generation technologies scales linearly with material quantity.
- Variation in efficiency across different sea states, or generator input conditions is not included, using instead the peak efficiency figures for conventional and alternative generation technologies.

Cost

- Only the cost, volume and mass of the key generation material has been considered in the alternative generation technology CAPEX, i.e. lower level subsystems of the generation technology itself are not considered. This will provide a lower cost than an assembled generator, so the results should be viewed as indicative but optimistic. If this approach were taken for the baseline conventional generator only the permanent magnets and wire coils would be considered, not the fully manufactured and assembled generator (as has actually been used for the baseline).
- Conversion Subsystems are assumed to be of comparable cost, as per Section 7.2. As these are comparable across technologies they have not been modelled explicitly as they would have the same economic/performance impact on through life cost.
- The OPEX costs only include the used lubricant/components. The cost of WEC recovery is excluded as it will be highly dependent on the size and architecture of the WEC. The cost of labour is excluded as it will be highly dependent on the architecture and design of

the WEC. It is considered that these costs are comparable between conventional and alternative generation technologies and are omitted.

- All costs have been taken at today's prices and no economic treatments (e.g. inflation) have been applied.
- The PTO costs are assumed to be split equally between Conversion Subsystem and the Electrical Generation Subsystem. The PTO contributes approximately 20% of the overall cost of energy according to [8]. Therefore, the Electrical Generation Subsystem is assumed to contribute 10% of the overall cost of the cost of energy.
- OPEX is assumed to contribute approximately 25% of the LCOE as per [8].
- The cost of the Balance of Plant (i.e. all subsystems other than the Electrical Generation System) scales linearly with power output.

7.4 APPROACH JUSTIFICATION

7.4.1 Comparison Against Conventional CAPEX, OPEX and Efficiency

This study has been undertaken in such a way as to remain architecture agnostic. This aims to provide opportunities for innovation inspired by alternative generation technologies, without being constrained by conventional designs.

As mentioned previously, generation technologies are only those that produce electrical power at their output. They therefore sit as one subsystem of the wider WEC. WECs also commonly exist within an array which itself can be considered as a system (or a system-of-systems) which has inter-array interactions, interacts with the local environment and wave resource and must have supporting/enabling subsystems while interfacing with the local grid infrastructure. The costs and design of an alternative generation system can be influenced by requirements or constraints arising from other subsystems or environments.

It is difficult to provide high-confidence, high-accuracy costs for the alternative generation technologies as they range in maturity from TRL 2 to 6, therefore there is uncertainty as to whether they can actually be applied in a commercial wave array. TRLs do not always increase for a technology – they can stagnate when a technical barrier is met or even decrease if the requirements change.

Initial, high level estimates of cost can be interfered by identifying how new technologies may influence CAPEX, OPEX and device efficiency. It is then possible to consider whether these influences provide sufficient promise within WES's risk and investment appetite to invest relatively small amounts to reduce uncertainty/increment TRL, or more substantial amounts to substantially mature the technologies.

We have focused on understanding the CAPEX, OPEX and efficiency of generation technologies compared to a conventional baseline. This means that the economic impact and uncertainty is focused on alternative generation technologies and not concealed behind the influence of other subsystems and the array environment.

Conventional generators are typically used with another system as part of the drivetrain, such as hydraulics or a gearbox. The requirement for these systems increases the CAPEX and OPEX but increases the power density/efficiency of the device. The influence of these supporting PTO systems is discussed in the alternative technologies where appropriate.

7.4.2 Calculating Through Life Cost

As noted in Section 7.3 as the device output (capacity factor) and resource are assumed to be constant, the amount of energy produced is assumed constant across technologies. The difference in LCOE is assessed through the difference in through life cost.

The overall WEC Installation through life cost is decomposed into four cost centres of interest:

- Electrical Generation Subsystem CAPEX
- Electrical Generation Subsystem OPEX
- Balance of Plant CAPEX
- Balance of Plant OPEX

Through the assumptions and baseline definition (Section 7.5) the relative contributions of each cost centre to the through life cost can be calculated, relative to the baseline through life cost.

The difference in Electrical Generation Subsystem CAPEX, OPEX and efficiency is justified through the claims, argument and evidence provided in the economic analysis (Section 7.6).

If the efficiency of the Electrical Generation Subsystem is lower than the baseline then the Balance of Plant needs to grow larger to provide more power to the Electrical Generation Subsystem. In turn this means attracting more load, so the foundations, moorings and structure have to get larger.

Presenting this mathematically:

- The balance of plant required to achieve an input power to the Electrical Generation Subsystem of P_{in} is BOP_{cost}.
- The BOP_{cost} scales linearly with P_{in}, i.e. that the larger the input power to the generator, the larger the Prime Mover and Conversion Systems have to be. As these subsystems have had to increase, the loads have increased, and the Moorings & Foundation and Transmission subsystems have also had to increase in size/cost.
- The current efficiency of the generator is μ_{Base}.
- Therefore the amount of energy generated can be represented as P_{in} x μ_{Base} x time for a given wave climate and length of time.
- If the same amount of energy is produced then the Balance of Plant required to produce it is altered.
- If the amount of energy produced (E_{Base}) is held constant, then the generator efficiency changes from μ_{Base} to μ_{Alt}, then the Pin must change to be:

$$\text{New } P_{in} = \frac{\mu_{Base}}{\mu_{Alt}} P_{in}$$

- Then the change in the BOP_{cost} must be:

$$\text{New } BOP_{cost} = \frac{\mu_{Base}}{\mu_{Alt}} BOP_{cost}$$

This relationship is used to scale Balance of Plant costs from the baseline.

7.4.3 Worked Example

To clarify the approach and treatment of efficiencies, this section contains a worked example showing how the final figures were reached. This example uses the baseline values in Section 7.5 and figures for magnetostriction, which are detailed in Section 7.6.1. Calculations for other technologies can be found in Section 12.

$CAPEXGenerator_{Base}$:	£200k	(Discussed in section 7.5.1)
$OPEXGenerator_{Base}$:	£280k	(Discussed in section 7.5.2)
$Efficiency_{Base}$:	95%	(Discussed in section 7.5.3)

The predicted future values for a 1MW magnetostrictive generator are:

$CAPEXGenerator_{Alt}$:	£460k	(230% of the baseline, $CAPEXGenerator_{Base}$)
$OPEXGenerator_{Alt}$:	£126k	(45% of the baseline, $OPEXGenerator_{Base}$)
$Efficiency_{Alt}$:	47.5%	(50% of the baseline, $Efficiency_{Base}$)

As detailed in Section 7.3, it has been assumed that total CAPEX contributes 75% of the baseline through life cost while total OPEX contributes 25% [8]. This is illustrated below in Figure 8.

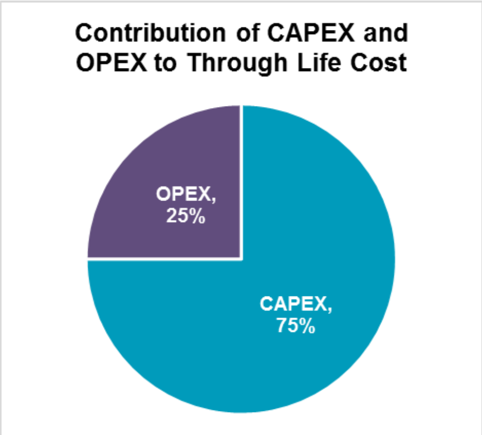

Figure 8 – Pie chart showing the contribution of CAPEX and OPEX to the total LCOE

Also as detailed in Section 7.3, the contribution of the generation subsystem is 10% of total baseline cost, therefore it is assumed to contribute 10% of CAPEX and 10% of OPEX. This is illustrated below in Figure 9.

The contributions of the Generation Subsystem and Balance of Plant can be scaled to show how the sum of contributions changes compared to the baseline through life cost. For the baseline the sum of contributions (CAPEX and OPEX of the Generation Subsystem and Balance of Plant) is 100%.

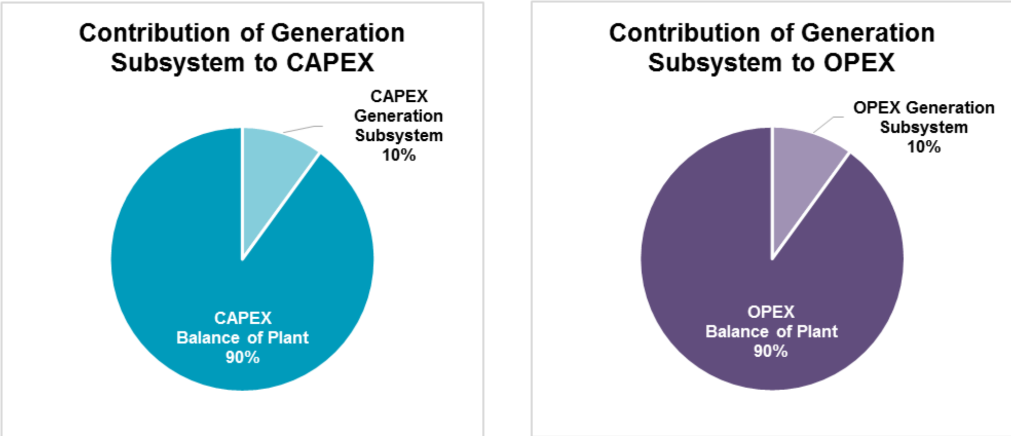

Figure 9 – Pie charts showing the contribution of the Generation Subsystem to CAPEX and OPEX

The initial calculation step is to determine the impact of the generation subsystem on the CAPEX and OPEX, relative to the baseline total device cost.

Generation Subsystem CAPEX:

$$\text{GeneratorContributionToCAPEX} \times \text{CAPEXContributionToLCOE} \times \frac{\text{CAPEXGenerator}_{\text{Alt}}}{\text{CAPEXGenerator}_{\text{Base}}}$$

$$10\% \times 75\% \times \frac{£460k}{£200k} = 17.3\%$$

The alternative generator CAPEX is equivalent to 17.3% of the baseline total through life device cost.

Generation Subsystem OPEX:

$$\text{GeneratorContributionToOPEX} \times \text{OPEXContributionToLCOE} \times \frac{\text{OPEXGenerator}_{\text{Alt}}}{\text{OPEXGenerator}_{\text{Base}}}$$

$$10\% \times 25\% \times \frac{£126k}{£280k} = 1.1\%$$

The alternative generator OPEX is equivalent to 1.1% of the baseline total through life device cost.

The impact of the generation system efficiency on the Balance of Plant (BOP) must also be considered.

The efficiency of the magnetostrictive generator is 47.5%, meaning that the BOP needs to scale up to provide the generator with a greater input power. If the efficiency of the alternative technology generation subsystem was higher than the baseline efficiency (95%), the BOP would scale down to provide the generator with the appropriate input power. The BOP contributes 90% of the baseline through life cost.

Balance Of Plant CAPEX:

$$\text{BOPContributionToCAPEX} \times \text{CAPEXContributionToLCOE} \times \frac{\text{Efficiency}_{\text{Base}}}{\text{Efficiency}_{\text{Alt}}}$$

$$90\% \times 75\% \times \frac{95\%}{47.5\%} = 135.0\%$$

The BOP CAPEX is 135.0% of the baseline total through life device cost.

Balance Of Plant OPEX:

$$\text{BOPContributionToOPEX} \times \text{OPEXContributionToLCOE} \times \frac{\text{Efficiency}_{\text{Base}}}{\text{Efficiency}_{\text{Alt}}}$$

$$90\% \times 25\% \times \frac{95\%}{47.5\%} = 45.0\%$$

The BOP OPEX is 45.0% of the baseline total through life device cost.

TOTAL

These four cost centres can be combined to show how the total device through life cost compares to the baseline.

Generator CAPEX + Generator OPEX + BOP CAPEX + BOP OPEX = Total through life cost

17.3% + 1.1% + 135.0% + 45.0% = 198.4%

So a WEC Installation using a magnetostrictive generator with the same lifetime output energy as the baseline would have a through life cost around 198% of the baseline through life cost, i.e. around 98% higher.

7.5 CONVENTIONAL TECHNOLOGY BASELINE

The most representative conventional generation technology was agreed to be rotary electrical generators, therefore this was used to form the conventional baseline for comparison.

Note that hydraulics are also often used as part of a PTO in wave energy devices, however they are not a generation system as they do not generate electricity, unless the hydraulic motor is connected to a rotary generator. Similarly gearboxes can be used to increase comparatively low frequency motion into the high frequency which is more appropriate for rotary electrical generators. Both of these are examples of additional conversion subsystems that are required to convert wave power to an input appropriate for a generator.

7.5.1 Baseline CAPEX

The baseline CAPEX for the electrical generator has been taken as approximately £200k, for a generator suitable for use in a wave energy system which generates 1MW. This is based on:

- Frazer-Nash Subject Matter Expert (SME) experience suggests that a typical 1MW generator would cost in the region of £50k to £80k. A marinised generator suitable for variable input loading would cost a factor more than this.
- Bombora have published a cost report for a 60MW array off of Portugal which allocates £287k to the PTO [9]. The device uses flexible membranes to circulate pressurised air around a circuit to drive a turbine which drives a generator. It seems reasonable that around 2/3 of this cost would be the generator, providing values of around £200k.
- This cost is only for the mechanical to electrical generator unit, which acts as the Electrical Generation subsystem in Figure 2. This does not consider any equipment such

as a gearbox or hydraulic system which would be considered part of the Conversion Subsystem. The justification for this is detailed in section 7.2.

7.5.2 Baseline OPEX

The baseline OPEX for the 1MW generator is approximately £280k over its life, or around £14k per MW per year. This is based on the argument below.

For some of the latest tidal devices deployed in the MeyGen array it is intended that the devices are only maintained under planned maintenance every 5 years [33]. It is likely that in this period the generation system would also be maintained, and that this would also be the targeted schedule for a commercial WEC.

Maintenance of generators in wind turbines covers a number of typical activities including:

- Bearing changes and brush replacement/realignment to address wear and misalignment.
- Cleaning, degreasing and lubricant refill.
- In some cases generators could be replaced.

For this study we will assume that 25% of the cost of the generator is incurred in parts/replenishment at each planned maintenance interval (without full generator replacement), with a further 10% of the cost in labour. OPEX is therefore considered to be, in total, approximately equal to 140% of the CAPEX of the generator over its life, leading to a value of approximately £280k/MW, or £14k/MW/year.

While the ratio of OPEX:CAPEX for the Electrical Generation Subsystem differs from the 25%:75% used in the assumptions, this result seems reasonable as this subsystem seems more likely to need maintenance compared to the moorings etc.

7.5.3 Baseline Efficiency

Efficiency can be defined both as the peak efficiency of a generator (i.e. the greatest achieved during a cycle of generation, under specific conditions) or average efficiency.

Peak efficiency for a rotary electrical generator is taken as around 95% for this comparison. This is based on:

- The output of the Conversion Subsystem to the device output.
- Public data suggesting that peak efficiency is 95% or greater [1].
- The Bombora cost of energy report claimed “Turbine-Generator” losses of 7% [9].
- Frazer-Nash SME experience for values of approximately 95%.

However, average efficiency will be lower as the generator will be under variable loads. Based on Frazer-Nash SME experience from wind energy, under low power conditions conventional generators can drop to around 60% efficiency (from the Conversion Subsystem, i.e. gearbox, output to electrical power).

7.5.4 Baseline Through life Cost

Knowing the CAPEX, OPEX and lifetime of an intended deployment means that the through life cost can be calculated. As the level of energy output is fixed across technologies (i.e. a 20 year lifespan generating 100MW with a constant capacity factor), this also means that the impact of the generation systems’ contribution to LCOE can be identified. For clarity, it is not the impact to the overall LCOE, just that which is associated with the Electrical Generation Subsystem. As discussed in Section 7.2 this is a fair comparison for the alternative generation technologies, with the exception of DEG that can be treated differently.

Using the baseline CAPEX, OPEX and 20 year lifetime leads to a baseline total through life cost of around £480k.

7.6 ALTERNATIVE TECHNOLOGY ECONOMICS

7.6.1 Magnetostriction

The economic results provided in this section consider the use of magnetostriction.

Power densities and efficiencies for magnetostriction are claimed for frequencies of the order of 100Hz, which is approximately 1000 times that of input wave frequency. Therefore it is necessary for magnetostriction to be used with an additional system to increase the frequency of loading applied to it, similar to a conventional generator. This will add an additional CAPEX and OPEX for the additional subsystem that is not incorporated below.

As an addition to the above, this system is also likely to be required as wave motion is large compared to the small strains used to drive magnetostrictive materials.

Key Assumptions

The following assumptions have been made in this analysis:

- Significant magnetostrictive materials, and their decades of discovery, are Alfenol (~1940s), Terfenol-D and Metglas (~1970s) and Galfenol (late 1990s). It has been 20 years since the last material discovery with an apparent improvement in the material magnetostrictive property, suggesting that it is unlikely that there will be significant further improvement within the timeframe of interest. However, to be optimistic, an increase in material performance beyond current performance has been assumed in developing the “Future Potential” of this technology. Commercial scale magnetostrictive generators only seem to be of interest to wave energy therefore development appears to be limited in this area, however Oscilla Power have been developing a wave energy PTO based on magnetostrictive materials [34].
- It is assumed that the characteristically brittle magnetostrictive generators (or the supporting system) would be able to withstand the load without significant mechanical protection or engineering for robustness. We have not increased the costs to allow for additional steel structure or mechanisms to protect the generator.
- It is assumed that sufficient material is available. Some sources limit the amount of Terfenol-D that can be supplied to around 100kg/month [37]. As detailed in Section 5.1, an optimistic estimate of the volume of Terfenol-D required to generate 1MW was 6m^3, or 55.5 tons of material, which indicates that there may be a significant supply chain challenge in sourcing enough material for a 100MW deployment.

Arguments and justification for current and future performance

	Current		Future
	Capability: Claims and Arguments	**Justification**	**Potential (25 years)**
Efficiency	It is expected that a magnetostrictive generator will have an efficiency of around 35% of that of a conventional generator when applied in practice (Conversion System output to electrical output).	The Georgia Institute of Technology review of magnetostrictive harvesters shows an (apparently peak) efficiency of 35% obtained in one laboratory experiment under a frequency of ~200Hz [35]. A number of sources suggest "high efficiency" magnetostrictive generators, but give no efficiency value.	**Given the 25 year time available, one more significant advance in materials has been allowed for. Allowing for a 50% increase on current efficiency would allow magnetostriction to reach an efficiency around 50% of conventional generators.**
CAPEX Influence (Technology cost)	It is expected that, per kg of material, magnetostrictive generators are about half the cost of conventional generators. This is because there are no moving parts, reducing the engineering effort. However given the potentially low amount of power per m^3 it is necessary to gain a large volume. Therefore the cost of a magnetostrictive generator is thought to be about 8 times than that of a conventional generator.	A review of commercial suppliers of magnetostrictive materials suggests values of around £10/kg for material cost [37]. Academic studies suggest power densities over a range of 3 orders of magnitude. Using the highest performing value (Section 5.1) suggests a power density output of $6m^3$ of material. With a density of $9.25g/cm^3$ [36], this suggests a cost of around £550k for a 1MW power output.	**The power density is likely to somewhat increase when an improved material is found, expected to be of the order of 20% power density. It is unlikely that the cost of the raw material itself will change significantly.** **This would lead to a generator cost of around £460k for a 1MW output.** **This is 230% of the baseline generator CAPEX.**
OPEX Influence (Technology reliability)	It is expected that magnetostrictive generators will be more reliable than conventional generators as there is very little movement involved – therefore no bearings would need replacing. It is expected that they would be around twice as reliable, and not use any	No publicly available evidence has been found to support or contradict this argument. Note that this value is for the generator itself, not the supporting system to step-up frequency.	**There is no foreseen reason as to why the reliability would increase, other than incremental change through improved design. It is expected this would increase reliability by 10%.**

	Current		Future
	Capability: Claims and Arguments	**Justification**	**Potential (25 years)**
	consumables (lubricant) halving the associated OPEX cost to just that of disassembly, inspection and cleaning. Considering the current efficiency however leads to an OPEX that is about 50% higher than conventional generators.	Considering the cleaning cost to be the same as for a conventional generator, half of the baseline cost is £7k/MW/year.	**This results in an OPEX which is about 45% of current generators, or about £6.3k/MW/year.**
Uncertainty	Medium – some evidence is available to justify, but this is limited. There are large ranges of estimates produced for power density in particular, all of which require high frequency input.		**High – some evidence is available to justify, but this is limited. Future development is entirely speculative, based on Frazer-Nash judgement, and assumes funding/incentive to install 1GW plus optimism based on prior advances.**

Summary of results

The summary of future predicted results for magnetostrictive generators, compared to a conventional baseline, is presented in the table below.

Technology	**Future CAPEX** (relative to baseline)	**Future OPEX** (relative to baseline)	**Future Efficiency** (relative to baseline)	**Future Through life Cost** (relative to baseline)	Uncertainty	Comments
Magnetostriction	230%	45%	50%	198% [2]	High	Requires a Conversion Subsystem. Assumes no mechanical system to help generator withstand loads.

[2] This calculation has been included as the worked example in 7.4.3

7.6.2 Triboelectrics

As discussed in Section 5.2, the triboelectric effect at comparable scale to current generation has been used instead of TENG.

Disc style generators have been tested (although at much higher frequencies than waves of 3000rpm, or 50Hz). Therefore it seems much more effective to use a Conversion Subsystem to scale the results from disc-shaped generators, similar to a conventional generator requiring a gearbox.

The material assumed was PTFE, a low cost, synthetic polymer which also has a very high tendency to gain electrons, a very positive trait for a material used in a triboelectric generator [40].

Key Assumptions

The following assumptions have been made in this analysis:

- The triboelectric effect has been known since ancient Greece however an effective generator was only demonstrated in 2011. Since then there has been interest in biomedical applications, and experiments in generating power from human motion, vibration, rotating tires as well as wind and ocean energy. Given that it has been considered for a relatively short period of time it is difficult to suggest how much progression will be made, particularly as the triboelectric effect of materials is quite well understood (particularly for static discharge management). However, to provide an optimistic view of the use of the material, significant improvements have been assumed in future development.
- Costs were provided to Frazer-Nash from researchers at Georgia Institute of Technology using PTFE as a base material. A device was assumed to be two rotating discs, contained in a disc enclosure of the same material. A 1MW device has been considered by scaling the performance from the 10cm disc units each producing 1.5W, which corresponds to a power density of 19 mW/cm^2 at a rotation speed of 3,000 rpm [38] [39] . The 10cm diameter was selected to mimic a device tested during academic research [39], however is not a material or device design limitation.
- The cost of power electronics and a system for increasing frequency input is not included.

Arguments and justification for current and future performance

	Current		Future
	Capability: Claims and Arguments	Justification Supporting	Potential (25 years)
Efficiency	It is expected that triboelectric generators will be less efficient than conventional generators due to the energy potentially lost through contact/friction. A value of 70% is considered correct at present.	A 2015 paper from the Georgia Institute of Technology shows an "instantaneous conversion efficiency" of 85% and claims an "average" efficiency of 70% [41].	**Given the 25 year time available, the relatively low TRL and alterations to materials in that time, it would be expected for the efficiency to increase to around 90%. An amount of loss is still expected due to the requirement for contact/friction.** **<u>This is 95% of the baseline generator efficiency.</u>**
CAPEX Influence (Technology cost)	It is expected that the cost of the triboelectric will be many orders of magnitude more expensive than normal generation due to the very low power density of such systems. While the material has a much lower cost per kg compared to steel the low power density means it is necessary to use a large area/volume. The cost of a triboelectric generator is expected to be around 43 times greater than a conventional generator due to the low power density needing more material.	Using performance values from disc generators with PTFE suggests a power density of $19mW/cm^2$ of disc area [41] or a power density of $19kW/m^3$ (considering matched discs of 5mm thickness). This leads to around $53m^3$ per MW, which is equal to 5.9 tonnes of key generation material [Calc 5] using a material density of $1000kg/m^3$ [43]. Using PTFE material prices provided to Frazer-Nash suggests a cost of £6.1mil per MW.	**It seems that new materials/forms may become available, potentially increasing power density by a factor of 10. However, it is unlikely that the new materials will be cheaper per kg than polymers that are currently widely available.** **This would reduce the cost to £600k/MW.** **<u>This is 300% of the baseline generator CAPEX.</u>**
OPEX Influence (Technology reliability)	Triboelectric generation can use contact therefore there may be wear on devices using polymers over long periods of oscillation. However, assuming that this can be accounted for in design then the	No publicly available evidence has been found to support or contradict this argument. The cost of replacing the generator once over the life of the farm means a cost of £6.1mil/MW or ~£300k per year.	**The innovation and development of new materials could lead to more resistant surfaces/designs that would not need replacing for the life of the array. It could be possible that this would lead to a device that does not**

	Current		Future
	Capability: Claims and Arguments	**Justification Supporting**	**Potential (25 years)**
	OPEX cost of the units would be minimal if not zero. If a change of the friction surfaces was required it would be a costly exercise over the many units. It is likely to be more cost effective to decommission and recommission a whole generation system. It is therefore expected to be replaced at least once in a farm's life. Therefore it is expected that the OPEX cost for these generators at current maturity levels would be around 90 times that of current technologies, as units wear out and need replacing.		**require any remedial maintenance, reducing the generation OPEX to nothing.** **<u>This is 0% of the baseline generator OPEX.</u>**
Uncertainty	Medium – some evidence is available to justify but this is still relatively limited in scope and in a laboratory setting.		**High – some evidence is available to justify, but this is limited and the technology has only been available for a relatively short time. Future development is entirely speculative, based on Frazer-Nash judgement, and assumes funding/incentive to install 1GW.**

Summary of results

The summary of future predicted results for triboelectric generators, compared to a conventional baseline, is presented in the table below

.Technology	Future CAPEX (relative to baseline)	Future OPEX (relative to baseline)	Future Efficiency (relative to baseline)	Future Through life Cost (relative to baseline)	Uncertainty	Comments
Triboelectrics	300%	0%	95%	118% [Calc 18]	High	Assumes it is possible to engineer a triboelectric generator that does not need maintenance.

7.6.3 Dielectric Elastomer Generators

The economic results provided in this section consider the use of DEGs. It is expected that the DE might be bonded to another elastomer to withstand the loads placed upon it, as per the bulge wave concept. The cost of this additional elastomer is not included in the generation estimate. The cost of comparable rubber fenders (which could act as the supporting material) has been explored in other WES reports [41].

Although structural support is required it is possible that no intermediate Conversion System is required, thus removing a subsystem CAPEX and OPEX cost from the WEC. This is not considered in the analysis below.

Key Assumptions

The following assumptions have been made in this analysis:

- It is assumed that the quantities required for a WEC fall into the definition of "large quantities" as defined in the Scuola Superiore Sant'Anna WES reports [23].
- This study has been performed to be WEC agnostic however, due to the low power density per unit of area, it seems likely that this technology aligns well with use in bulge wave systems. Increasing the thickness/using multiple layers could help to mitigate some of the concern around loading, however the increasing stiffness could also reduce generation. The amount of layering considered in this study is aligned with work from Scuola Superiore Sant'Anna.
- The analysis in the table below considers the economic impact if DEGs are used to only replace the Electrical Generation subsystem. As noted in Section 7.2 DEGs could also potentially be used in architectures without the Conversion Subsystem and with a reduced amount of Structure. This would make the CAPEX costs significantly lower than the table below represents. However, the total OPEX (i.e. including WEC recovery) is uncertain and may be dominated by vessel hire and labour costs. This could result in higher total OPEX costs than indicated in the table below.
- Although theorised in the 19th century, demonstration of DE grew particularly in the early 1990s and into the 2000s. Within around 15 years there has been significant growth in the understanding and application of DE. The area is being strongly pursued in so-called "soft robotics" therefore there is likely to be growth without investment from wave energy, although this is likely to target lower power applications, curbing the growth that is relevant to wave energy. Dielectric polymers have been considered in other wave energy projects such as the FP7 PolyWEC, however there is no more news of the concept. Therefore it is assumed that there will be development in the technology, but not as fast as in other applications.
- As the DEG consists of only one membrane component, it is assumed that once the Mean Cycles To Failure (MCTF)/maintenance interval has elapsed, the whole DEG component will have to be replaced.

Arguments and justification for current and future performance

	Current		Future
	Capability: Claims and Arguments	**Justification Supporting**	**Potential (25 years)**
Technology efficiency	It is expected that the DEG will have an efficiency of just over half that of a conventional generator, as it is a less developed technology. Therefore the current efficiency is considered to be around 60%.	The Scuola Superiore Sant'Anna WES report suggests an electro-mechanical efficiency in the range of 50 – 90%. At this relatively early stage a lower estimate of 60% is assumed [43].	**Given the 25 year time available and moderate development in wave energy and other industries, it is expected that the efficiency will reach its maximum potential of 90%. This would make efficiency close to that of current generators.** **<u>This is 95% of the baseline generator efficiency.</u>**
CAPEX Influence (Technology cost)	It is expected that the cost of the DEG alone will be significantly higher than current generators, of the order of 6 times the price as they are solid state devices that are reasonably cheap per kg, but quite low power density and efficiency. Given the low amount of power per m^2 it is necessary to use a large area of the material.	Information from Scuola Superiore Sant'Anna suggests current values of £360k-£900k/MW. A middling value of £600k/MW is considered [23] [Calc 12].	**Given the assumed development, it is expected that the capital cost per kg of material will reach its predicted minimum of around £5/kg, and the specific power will increase by around 25% (i.e. from 170W/kg [23] to around 210W/kg).** **This would result in a cost of around £24k/MW [Calc 16].** **<u>This is 12% of the baseline generator CAPEX,</u> only considering a direct replacement of the conventional electrical generation subsystem.**
OPEX Influence (Technology reliability)	It is expected that DEGs will fail less often than conventional generation due to their solid state nature. However their limited life span means the whole system will need to be replaced 3 times over a project using current reliability estimates.	Engagement with industry experts suggests that the number of cycles that a DEG can survive is 10 million cycles, corresponding to 4-5 years. Using current CAPEX estimates would result in a lifetime OPEX of £2.9mil/MW	**Engagement with industry experts suggests that with development the life of a device could be increased to 7-10 years. This would mean that the DEG would only need to be replaced once in a farm lifetime.**

	Current		Future
	Capability: Claims and Arguments	**Justification Supporting**	**Potential (25 years)**
	This will require approximately 10 times the OPEX of conventional generators.	(from 3 x £600k/MW) or around £88k/MW/year. This is supported by the estimates that suggests an OPEX of £80-180k/MW/year, approximately 6-13 times the conventional baseline.	**As a result, the lifetime OPEX of the farm would be equivalent to the CAPEX (as one system is replaced) leading to a lifetime cost of around £24k/MW.** **This would therefore reduce the OPEX to around £1.2k/MW/year.** **<u>This is 9% of the baseline generator OPEX.</u>**
Uncertainty	Medium – some evidence is available to justify, but there is limited information in the public domain. However, the values that have been presented here are based on work done under the WES programme. Other projects (such as PolyWEC) do not appear to have been successful in justifying further development.		**High – some evidence is available to justify, but this is limited. Future development is entirely speculative, based on Frazer-Nash judgement. This assumes funding/incentives to install 1GW in wave energy using this technology, as well as continual investment in other applications.**

Summary of results

The summary of future predicted results for DEG, compared to a conventional baseline, is presented in the table below.

Technology	**Future CAPEX** (relative to baseline)	**Future OPEX** (relative to baseline)	**Future Efficiency** (relative to baseline)	**Future Through life Cost** (relative to baseline)	**Uncertainty**	**Comments**
Dielectric Elastomer Generators	12%	9%	95%	96% [Calc 19]	High	These values only consider the DEG as direct replacement for the Electrical Generator subsystem. Removing the Conversion Subsystem or some of the Structure would also reduce the comparative CAPEX costs.

7.6.4 Piezoelectric Generators

This section considers the economic impact of piezoelectric generation.

As recognised in existing studies into piezoelectric wave energy generation, one of the key challenges in using piezoelectrics is managing the disparity between the frequency of ocean waves (of the order of 0.1Hz) and the natural frequency of common piezo crystals (of the order of 1kHz).

Therefore it is necessary for piezoelectrics to be used with an additional system to increase the frequency of oscillations applied to it, similar to a conventional generator. This will add an additional CAPEX and OPEX for the additional subsystem that is not incorporated below.

Key Assumptions

The following assumptions have been made in this analysis:

- Piezoelectricity was discovered in the 1880s using crystals such as quartz. However a key practical application was its use in sonar in the mid-1910s in the First World War, still using quartz as the primary material. Piezoelectrics are used in many industries such as medicine, automotive and sensing, therefore it seems likely that there will be continual development of the technology, regardless of its use in wave energy. This is supported by statistics that show there are more than 450 publications each year on lead-free piezoceramic materials alone. Therefore it has been assumed that there will be continuous research and improvement in piezoelectric materials, even if this is incremental (as they have been used for around 100 years, and are therefore quite mature).

Arguments and justification for current and future performance

	Current		Future
	Capability: Claims and Arguments	**Justification Supporting**	**Potential (25 years)**
Efficiency	It is expected that piezoelectric generation will be less efficient than conventional generators, primarily due to the dissipation of energy into other directions/vibrations.	Depending on material selection and application, there is a very broad range of values for the exploitable mechanical to electrical efficiency from 1% to 90% [44]. For this study, we have considered a mid-range efficiency of 50%.	**Given the 25 year time available, there is potential that continuous incremental or breakthrough development of new materials could improve the efficiency by 50% over current capabilities, i.e. an efficiency approaching 75%. <u>This is 79% of the baseline generator efficiency.</u>**
CAPEX Influence (Technology cost)	An optimistic assessment shows that the expected cost of the raw material exceeds £1.5m per MW. This is not including any considerations towards manufacture of the piezoelectric PTO system, indicating that the completed system would be significantly more expensive than a conventional generation PTO. A more pessimistic cost assessment estimates that this raw material cost may be over 250 times greater than this optimistic assessment, indicating the levels of uncertainty in the estimate. The additional manufacturing costs are highly sensitive to the design of the PTO and wave energy prime mover. Just considering the raw material costs, the cost of a piezoelectric generator is expected to be at least 15 times greater than a conventional generator due to the low power density and efficiency.	There is a very broad range of values for the power density of piezoelectric materials, which vary depending on the specific materials and applications under consideration. A low estimate for the power density of piezoelectric materials is 300W/m^3, from a study into vibration energy scavenging, and a high estimate provides a figure 83,000W/m^3, from a study into ultra-high power density piezoelectric energy harvesters [45]. The assumed cost of piezoelectric materials is £119k per cubic metre, which has been scaled from an assessment of piezoelectric materials for energy harvesting on roads [46][Calc 14][Calc 15]. Taking the optimistic figure for power density, the cost of raw material required to generate 1MW is £1.4 million, while	**It seems that new materials/forms may become available, potentially increasing power density by a factor of 5. However, it is unlikely that the new materials will be cheaper per cubic metre than materials that are currently used. Based on the most optimistic cost estimate, this would reduce the cost of the raw material to £280k per MW.** **<u>This is 140% of the baseline generator CAPEX.</u>**

	Current		Future
	Capability: Claims and Arguments	Justification Supporting	Potential (25 years)
		the lower density figure gives a cost approaching £400 million.	
OPEX Influence (Technology reliability)	It is expected that piezoelectric generators will be more reliable than conventional generators as there is little wear involved, however this is dependent on the specific PTO design. It is expected that they would not use any consumables (lubricant), reducing the associated OPEX cost to just that of disassembly, inspection and cleaning halving the associated OPEX. Considering the current efficiency however leads to an OPEX that is about the same as conventional generators.	No publicly available evidence has been found to support or contradict this argument.	**The development of new or higher efficiency materials is unlikely to have a large impact on the OPEX of a piezoelectric PTO system, with any major improvements likely to come through the design of secondary enabling systems to the main PTO.** **It is expected this would increase reliability by around 10%, decreasing the OPEX to about £252k/MW.** **<u>This is 90% of the baseline generator OPEX.</u>**
Uncertainty	High – significant work has been invested into power generation using piezoelectric materials, however the majority of research effort to date has not been at the scale of interest for this study. The highest area of uncertainty surrounds the cost information estimates for the CAPEX and OPEX. The wide range of cost information available is often contradictory, and would require more dedicated wave energy specific study, potentially considering a more defined piezoelectric PTO design, to develop more accurate estimates.		**High – some evidence is available to justify, but this is limited and often contrasting. Future development is entirely speculative and assumes funding/incentive to install 1GW.**

Summary of results

The summary of future predicted results for piezoelectric generators, compared to a conventional baseline, is presented in the table below.

Technology	Future CAPEX (relative to baseline)	Future OPEX (relative to baseline)	Future Efficiency (relative to baseline)	Future Through life Cost (relative to baseline)	Uncertainty	Comments
Piezoelectrics	140%	90%	79%	127% [Calc 20]	High	Assumes no mechanical system to help generator withstand loads.

7.7 SUMMARY

The key values arising from the economic assessment are reported in Table 6 below. These have been based on the information gathered from public data and from industry engagement, from which an optimistic view of future technology performance has been developed.

Most of the Electrical Generation Subsystem technologies require an additional Conversion Subsystem for frequency step-up/changing the range of movement. This is similar to the conventional generation requirement for an intermediate system (e.g. gearbox/hydraulics), therefore the economic comparison could be done considering a replacement of the Electrical Generation Subsystem alone.

The results show that:

- The estimated future economic performance for alternative generation technologies (at least over the next 25 years) will not deliver a step change reduction in the LCOE when used as replacement of the Electrical Generation Subsystem alone, with the potential exception of DEG.
- DEGs do not necessarily need a Conversion Subsystem and it is possible that there are architectures using DEG that could reduce the amount of WEC structure required. This would make the CAPEX costs significantly lower than the table below represents. However, the total OPEX costs (i.e. including WEC recovery) are uncertain and may be dominated by vessel hire and labour costs. This could result in higher total OPEX costs than indicated in the table below. Therefore while DEGs can be considered as replacements for conventional generators, they show more economic promise as a technology because they allow for the removal of other subsystems.
- There are high values of uncertainty due to current data immaturity and the amount of time to elapse before the target case (i.e. 25 years). This means that future performance could be significantly higher or lower than that predicted here.
- The key driver of poor economic performance is poor power density compared to conventional generators. Lower power density requires a larger amount of generation material, increasing the cost. Technology development programmes may improve the power density of the materials considered.

Table 6 – Summary of Economic Analysis for a WEC Installation

Technology	Future CAPEX (relative to baseline)	Future OPEX (relative to baseline)	Future Efficiency (relative to baseline)	Indicative Future Through Life Cost (relative to baseline)
Magnetostrictive	230%	45%	50%	198%
Triboelectric	300%	0%	95%	118%
DEG*	12%	9%	95%	96%
Piezoelectric	140%	90%	79%	127%

* These results for DEG consider it as a direct replacement of the Electrical Generation subsystem, in the same way as the other technologies here have been treated

8. TECHNOLOGY DEVELOPMENT ROUTES

This section contains a high level discussion of the development challenges which would have to be overcome to realise the potential for each technology and for them to be used in a commercial scale wave farm. In this context, utility scale generation is considered to be a 100MW farm with a 20 year lifespan after 1GW of wave energy was installed globally.

The economic analysis in Section 7 assumes that the technology performance and cost improvements discussed below will be achieved. Using these improved values still suggests that the technologies will not improve LCOE if used as direct replacement for the Electrical Generation subsystem.

The development activities can be grouped into two main categories. The first is an activity which matures or advances the capability of a technology, for example improving performance, power density, efficiency, resistance to loading and biofouling, or reducing the costs of development, construction or installation.

The second set of activities are not focused on maturing a component of a technology, but undertaking activities or trials to minimise uncertainty, to provide a greater confidence as to whether a technology is promising or not, and to ensure that investment is appropriately targeted and has broadly achievable goals.

Note that all of the technologies considered are still relatively immature, therefore in addition to the specific activities identified below it would be recommended to:

- Test the technology in a bench-top laboratory experiment.
- Develop numerical models.
- Perform laboratory experiments in simulated wave devices and climates.
- Build a WEC/PTO prototype in a wave tank.
- Perform scale WEC demonstration in a nursery test site.
- Full scale WEC demonstration in a test site.

8.1 MAGNETOSTRICTION

Key performance issues relating to the application of magnetostriction, are discussed further below. These are also the issues with highest uncertainty.

- **Power density:** The power density of magnetostrictive materials is currently an issue affecting cost and materials availability (discussed below). This could be improved by:
  - Performing academic research to identify new materials that have higher power density. Note that Galfenol was developed in 1998 through research in this form. There is significant technical risk in this process, and no material with higher room temperature magnetostrictive properties than Terfenol-D has been identified since its development in the 1970s.
- **Material availability in volume:** In mature industrial use, the amount of magnetostrictive material used is relatively small compared to the amount required per wave energy device. While some magnetostrictive materials are quite abundant, the highest performing materials may have limited availability (with one supplier limited to 100kg per month, or about $0.01m^3$). This could be improved by:

- Performing a study to identify if there is sufficient supply chain to provide the volume of high performing materials required.
- Performing academic research to identify new materials that have higher power density, reducing the amount of material required per device. Confirm that the availability of these materials is higher.

- **Manufacture at volume:** Most commercially available magnetostrictive materials are manufactured in rod or bar form, with the largest dimensions of Terfenol-D found being a rod of 50mm diameter, and length of 200mm [37]. This could be improved by:
  - Performing design studies on the appropriate dimensions of magnetostrictive material for the generator design, and considering the manufacturing requirement. It is possible to manufacture and machine Galfenol in sheets, however the effects of laminating sheets is unknown.
- **Material cost:** Magnetostrictive materials have a high cost compared to other technologies such as piezoelectricity. The 6m^3 material requirement for a 1MW device would require 55,500kg of material. This could be improved by:
  - Performing academic research to identify new materials that have higher power density, or are cheaper per unit volume.
- **Development of an enabling Conversion Subsystem/WEC architecture:** Current magnetostrictive materials are most suited to high stress, low strain applications. Wave motion is comparatively large therefore the force needs to be concentrated, the frequency of oscillation increased and the range of motion greatly decreased. This could be performed by:
  - Developing new WEC architectures or Conversion Subsystem designs that are appropriate for use with magnetostriction. Note that some magnetostrictive materials such as Terfenol-D are brittle, so the energy transfer mechanism from the prime mover must consider this. More modern materials like Galfenol are less brittle, however have lower power density.

8.2 TRIBOELECTRIC GENERATION

Key performance issues relating to the application of triboelectrics are discussed further below. These are also the issues with highest uncertainty.

- **Power density:** As discussed above, the power density of a triboelectric generator is low, leading to large material costs. This could be improved by:
  - Performing academic research to identify new materials, or new generation modes that have higher power density. It is likely that improvements could be made, as this is a very immature technology, however the level of uncertainty means it is not possible to quantify on what scale the improvements would be.
- **Reliability:** Triboelectric generation requires materials to move in close proximity to one another and potentially move while in contact. This could lead to significant maintenance requirements. This could be improved by:
  - Performing academic research to identify harder-wearing materials, or to improve the efficiency of devices that do not utilise contact.

8.3 DIELECTRIC ELASTOMERS

Key performance issues relating to the application of dielectric elastomers are discussed further below. These are also the issues with highest uncertainty.

- **Development of an enabling WEC architecture:** DEGs are the most likely material to provide a step-change reduction in the LCOE if it can be shown that they can be used in architectures that do not need Conversion Subsystems or can reduce the amount of structure required. This could be explored by:
  - Undertaking design studies to develop alternative architectures followed by feasibility studies of the identified designs. This should build on the work already performed in the PolyWEC project that explored this idea.
- **Power density**: Significant increases on current power density have been assumed in the economic analysis. This is key to reducing the amount of material required and therefore the overall cost. This might be addressed by:
  - Performing academic research to identify new materials that have higher power density. However, there have been multiple studies into increasing the power density of DEG materials, within the wave energy sector and in wider academic and industry organisations, with most focusing on the use of alternative materials or methods of layering DEG sheets. This reduces the likelihood of a small project having an impact.
  - Undertaking a design study to develop alternatives and consider which WEC architecture will be most appropriate.
- **Fatigue life:** As highlighted by the Scuola Superiore Sant'Anna WES reports, DEG materials to have a limited lifespan, as defined by the mean cycle time to failure. Development programmes could:
  - Test the use of novel materials or supporting structures to increase the lifespan, however economic assessments should consider the limited lifespan when considering a requirement for generation solutions expected to last in the region of 20 years.
- **Material cost:** Due to the large amount of material required, and the cost of the material, DEGs based on existing materials are predicted to be more expensive than conventional generators when used as a replacement for the Electrical Generation Subsystem. To meet the assumptions in the economic analysis the material cost per kW could be improved by:
  - Performing academic research to identify new materials that have higher power density, or are cheaper per unit volume. However, as noted under “power density” it would likely require significant effort/innovation to find a breakthrough material.
- **Yield strength:** Current DEG materials exist as a thin sheet, which can be layered into sheets of millimetre to centimetre scale thickness. With the high loads which may be experienced by wave device (and particularly in the bulge wave concept), it is likely that DEG material would not be suitable on its own, and a stronger supporting system would be required. Further studies could:
  - Investigate suitability of different WEC architectures, incorporating rigid structures, flexible supporting structures such as stiffer rubber ‘skeleton’, or a flexible, easily deployable system, which becomes rigid under pressure or loading.

    - Incorporation of a support system such as the rubber skeleton could be a suitable solution to increase the MCTF of the DEG material, increasing the useful life of a DEG based device and improving the economic opportunity it may present. Further investigation could consider the potential increase in DEG MCTF which could be achievable.

- **Manufacturability:** Current DEG manufacturers can produce sheets of hundreds of meters in length, and 1.4m in width. This may limit the cost-effectiveness of the manufacturability. Further research should:
    - Investigate the details of manufacturing methods, and identify whether it is possible to increase the dimensions of the manufactured sheets via a manufacturing study.
    - It is also important to consider the possibilities and limitations around joining sheets, whether that is a layered construction of multiple sheets to increase thickness, or combining sheets along the edges to create a wider sheet. This would be addressed through a design option study.

8.4 PIEZOELECTRICS

Key areas that are necessary for performance improvement are:

- **Power density:** The power density of piezoelectric materials is currently an issue affecting system cost. This could be improved by:
    - Performing academic research to identify new piezoelectric materials that have higher power density.
- **Develop suitable Conversion Subsystem:** Piezoelectric elements typically require higher frequency loading for optimum operation than the natural frequency of ocean waves. For power generation, the most suitable loading for crystalline piezoelectric elements would be vibration which is close to the natural resonant frequency of the element. This could be addressed by:
    - Investigating and defining the forms of loading achievable by conventional WEC prime movers, and identifying specific materials or families of materials which could effectively operate with this form of loading.
    - Designing new Conversion Subsystems to convert input from a Prime Mover into the piezoelectric generator.
- **WEC architecture/design:** As a piezoelectric generator may require unique forms or frequencies of loading, existing WEC designs may not be suitable. This could be addressed by:
    - Assessing existing WEC designs for suitability of use with a piezoelectric generator.
    - Investigating potential new WEC designs, or supporting systems to allow existing prime movers to transfer wave energy to mechanical energy at an appropriate frequency for the piezoelectric generator.
    - Considering the potential use of adaptive tuning mechanisms to maximise the range of wave loading conditions which allow the piezoelectric generator to operate at its highest efficiency or output.

8.5 SUMMARY

The key areas which further development to realise the potential for each technology, and enable them to be used in a commercial scale wave farm, are listed in 7 below.

Table 7 – Summary of Development Areas

Technology	Development Area
Magnetostriction	Power density
	Material availability
	Manufacture at volume
	Material cost
	Develop enabling Conversion subsystem/WEC architecture
Triboelectric	Power density
	Improving reliability
DEG	Develop enabling subsystems/WEC architecture
	Fatigue life
	Material cost
	Yield strength
	Manufacturability
	Power density
Piezoelectrics	Power density
	Develop enabling Conversion subsystems
	Develop WEC architecture

The key technology development challenges can be summarised as:

- Improving power density: Improved power density would reduce issues with cost and device size. Further work could be undertaken through academic research to identify alternative materials.
- Reducing material cost: Material cost could be reduced either through reducing the amount of material needed (through improved power density) or identifying new materials that are cheaper. Further work could be undertaken through academic research to identify alternative materials.
- Improving confidence in loading: Due to device immaturity it is uncertain if the identified technologies would survive in a wave energy environment. Further work could be undertaken through academic research to test materials and then move through tank testing, nursery site/test site deployments up to deployment at the sites of interest.
- Developing an enabling subsystem/WEC architecture: The technologies identified operate differently to conventional generators therefore there is scope to reconsider the overall device architecture. New Conversion Subsystem designs could also be considered. Further work could be performed through concept design and feasibility assessments.

9. CONCLUSIONS & RECOMMENDATIONS

9.1 CONCLUSIONS

Baseline Technology

A broad range of technologies have been developed to quite high technology maturities in a wave energy context, however many of these are Prime Movers or Conversion Subsystems. Investigation into Electrical Generation Subsystems has not advanced as far, with rotary and linear generators being the only technologies currently used in mature wave energy devices.

The conventional baseline to assess the alternative generation technologies against was developed from rotary induction generators. The baseline developed during this study was a CAPEX of £200k/MW, OPEX of £14k/MW/year and peak generator efficiency (rotational input to electrical output) of 95% (Section 7.1).

Alternative Technology

The assumptions used to project future cost or performance improvements for the alternative generation technologies are gathered from public sources, such as academic papers or funded project details. These assumptions account for a level of future development, however this could be greater if there is additional R&D effort or funding of these technologies due to interest from other industries. Their attractiveness to the wave energy sector can be strongly influenced by their applicability to other industries, especially if they are considered game-changing or enabling technologies. While projections in this report are optimistic, collaboration with other organisations will likely be required to ensure the most promising are kept in consideration for their marine energy potential.

This report helps to identify the nascent technologies which show promise for the wave energy sector and opportunities for future development considered.

8 alternative generation technologies were identified that have a wave energy TRL of 6 or lower. This is in contrast to applications outside their use in a wave energy environment where some alternative technologies have a TRL of 9.

Although identified as “alternative”, most of the technologies have been considered in wave energy to some degree already, but not to the same level as wave devices using conventional rotary electrical generators. This suggests that:

- Either the wave energy industry has been good at trying to innovate around the technology over the decades it has been considered, and/or
- Many novel technology developers recognise that wave energy is an industry that is looking for new ideas.

The alternative technologies that were downselected as those most likely to be feasible and to provide economic opportunity for the timescale of interest were triboelectrics, piezoelectrics, dielectric elastomers (DEGs) and magnetostrictive generators (Section 5).

These technologies form the Electrical Generation Subsystem. A generic WEC’s PTO consists of a Conversion Subsystem (possibly a gearbox or hydraulic accumulators) and an Electrical Generation Subsystem. Due to the requirement for a frequency input that is orders-of-magnitude greater than provided by waves for efficient generation, it is considered necessary to include a Conversion Subsystem for triboelectrics, piezoelectrics and magnetostrictive generators. These technologies are also unlikely to remove the need for other WEC subsystems, therefore they can be considered as direct replacements for the conventional Electrical Generation Subsystem.

DEGs do not necessarily need a Conversion Subsystem and it is possible that there are architectures using DEG that could reduce the amount of structure required. Therefore while DEGs can be considered as replacements for conventional generators, they show more economic promise as a technology because they allow for the removal of other subsystems.

Alternative technologies that were not considered further at this time included thermoelectric, magnetohydrodynamic, electrokinetic and electrohydrodynamic generators, primarily due to their poor efficiency or low power density when compared with other alternatives. These technologies may be viable for use in a wave energy system, following a successful development programme, however they were assessed to be less viable (both now and in the future) than the 4 downselected technologies.

Economic Analysis and Technical Feasibility Evaluation

The technical and economic aspects of the assessment have been developed based on the information gathered from public data and from industry engagement.

The economic analysis shows that:

- Alternative generation technologies (at least over the next 25 years) will not deliver a step change reduction in the cost of energy when used as a direct replacement of the Electrical Generation Subsystem alone, with the potential exception of DEG.
- If an alternative technology could remove or replace other subsystems such as the Conversion Subsystem or Structure, there is potential for a reduction in the LCOE.
- DEG could eliminate the Conversion Subsystem and remove the need for some amount of Structure, however this would be dependent on the architecture. A bulge wave is one example of such an architecture.
- There are high values of uncertainty in the predicted future costs due to current data immaturity and the amount of time to elapse before the target case (i.e. 25 years). This means that future performance could be significantly higher or lower than that predicted.
- The key driver of poor economic performance is poor power density compared to conventional generators. Lower power density requires a larger amount of generation material. For a given generation material this means more is required, increasing the cost.

The technical feasibility results show that:

- None of the technologies appear highly likely to be technically feasible to generate power at the commercial scale of interest to WES in the development window in question.
- Magnetostriction has been demonstrated to the highest TRL of the alternative technologies.
- Magnetostriction and DEG are the technologies that are most likely to be technically feasible for power generation at scale.
- Low power density is a key issue across technologies, making it more difficult for devices to achieve the absolute level of power output required. Future technology development programmes may improve the power density of the materials considered.

- Other aspects of concern are resistance to loading (fatigue and extreme), environmental impact of large devices (where much larger devices may be required, meaning that more area is obstructed by an array), manufacturability and material cost.

The alternative technology that appears to have the best mix of technical feasibility and economic opportunity, in the target scenario, is DEG (when considered in an architecture where there is potential to remove some subsystems compared to conventional architectures).

The key technical feasibility and economic opportunity results are presented in the table below.

Technology	Power Conversion Chain	Amount of material required for 1MW output device		Efficiency		CAPEX Per MW		Indicative future through life cost, relative to baseline
		Current	Future*	Current	Future*	Current	Future*	
Rotary Generator (Baseline)	*Rotary mechanical input load converted into electricity*	*- †*	*- ‡*	*95%*	*- ‡*	*£200k*	*- ‡*	*100%*
Magnetostriction	Applying mechanical load changes the magnetic field of the material.	6 m^3 55.5 tonnes	5 m^3 46.3 tonnes	35%	47.5%	£1.6mil	£460k	198%
Triboelectrics	Applying relative motion to touching or separated electrodes builds charge in the electrodes.	53 m^3 15.9 tonnes	5.3 m^3 1.6 tonnes	70%	90%	£8.7mil	£600k	118%
Dielectric Elastomer Generators	Applying load causes material deformation, allowing direct electricity generation.	5.9 m^3 5.9 tonnes	4.7 m^3 4.7 tonnes	60%	90%	£950k	£24k	96%**
Piezoelectrics	Applying mechanical loading in a material directly creating an electric charge	12.0 m^3 92.4 tonnes	2.4 m^3 18 tonnes	50%	75%	£2.8mil	£280k	127%

* Future predictions are based on technology development activities achieving the assumed improvements for each technology as described in Section 7.6.
† The baseline considers a complete rotary generator, rather than just the key generation material (used to cost alternative technologies).
‡ The future development of the baseline generator has not been considered. It has also been assumed that future development of conventional generation will be not be led by the wave energy industry.
** This value considers DEG used as a replacement for the baseline Electrical Generation Subsystem

9.2 RECOMMENDATIONS

The recommendations from this landscaping study are to:

- Investigate the technical feasibility of using DEG in an architecture that allows for the removal of some or all of the Conversion Subsystem and Structure (such as a bulge wave or similar configuration). In addition to considering the power generating potential of such a device, this should consider the survivability of a full scale DEG device in the ocean environment and the consequent OPEX costs.
- Conduct further investigation to increase the certainty in the results of this study. Small research projects could focus on testing the assumptions made regarding the cost and performance of each technology.
- Carry out a more detailed study into the design refinements possible for rotary/linear electrical generators.

10. ABBREVIATIONS AND ACRONYMS

Abbreviation	Description
CAPEX	Capital Expenditure
DEG	Dielectric Elastomer Generator
EHD	Electrohydrodynamics
kW	Kilowatt
LCOE	Levelised Cost of Energy
MHD	Magnetohydrodynamics
MW	Megawatt
MWh	Megawatt hour
GW	Gigawatt
MCTF	Mean Cycle Time To Failure
MHD	Magnetohydrodynamics
MRL	Manufacturing Readiness Level
OPEX	Operational Expenditure
OWC	Oscillating Water Column
OWSC	Oscillating Wave Surge Converter
PTO	Power Take Off
SPD	Submerged Pressure Differential
TRL	Technology Readiness Level
W	Watt
WEC	Wave Energy Converter
WES	Wave Energy Scotland

11. REFERENCES

The following references support the numbers or arguments presented in the main body of this report. A complete bibliography of all source data used is included in each Technology Capture Sheet in Annex B.

All references were accessed between March and June 2018.

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12. CALCULATIONS

The following calculations are extrapolations based on source data to support or contextualise the numbers or arguments presented in the main body of this report.

[Calc 1] Measured power density of Galfenol = 22 mW/cm^3 = 22,000W/m^3 [14]

Considering a 1MW system:

Required power / Power density = Required volume

$1x10^6$ W / 22,000 W/m^3 = 45.4m^3

[Calc 2] Peak power density = 171 mW/cm^3 = 171,000W/m^3

Considering a 1MW system:

Required power / Power density = Required volume

$1x10^6$ W / 171,000W/m^3 = 5.8m^3

[Calc 3] Power Density = 3.5W/m^3 [20]

Required power / Power density = Required volume

1MW / 3.5W/m^3 = 285,000m^3

Side length can be approximated by cube root of the volume:

$285{,}000^{1/3}$ = 65.8m

[Calc 4] Predicted area power density of 1.5mm DEG sheets = 255 W/m^2 [23]

Considering a 1MW system: Required power / Power per area = Required area

$1x10^6$ W / 255 W/m^2 = 3922m^2

[Calc 5] Assuming linear scaling of power density of DEG sheets with increasing sheet thickness, a 1m thick DEG material will consist of 667 layered 1.5mm sheets (each with an area power density of 255 W/m^2).

Number of sheets in 1m^3 x Sheet power density = Power density

667 sheets x 255 W/m^2 = 170 kW/m^3

Volume required = Power required / Power density

Volume required = $1x10^6$ W / 170,000 W/m^3 = 5.88 m^3

Material density is around 1000kg/m^3 [43], therefore 5.88 tonnes

[Calc 6] Assuming a 15 second loading period = 1/15 Hz = 0.06667 Hz

Number of excitations per year = Excitation frequency x number of seconds per year

Number of excitations per year = 0.06667 Hz x 31536000 ≈ $2.1*10^6$

Estimated lifespan = Mean cycles before failure / excitations per year

15 million cycles: $15x10^6$ / $2.1x10^6$ = 7.1 years

22 million cycles: $22x10^6$ / $2.1x10^6$ = 10.5 years

[Calc 7] Maximum power from an MHD device per m^3, W_{max} is given by

$$W_{max} = \frac{u^2 B^2 \sigma}{4}$$

U = flow speed, taken as 10m/s (assumed)

B = Magnetic field, taken as 1.5 Tesla for an MRI [49]

σ = Conductivity mho/m, taken as 5 for water [50]

Wmax = 10^2 x 1.5^2 x 5 / 4 = 281 W/m^3

[Calc 8] Maximum power from an MHD device per m^3, W_{max} is given by

$$W_{max} = \frac{u^2 B^2 \sigma}{4}$$

U = flow speed, taken as 10m/s (assumed)

B = Magnetic field, taken as 0.7 Tesla for neodymium [51]

σ = Conductivity mho/m, taken as 5 for water [50]

Wmax = 10^2 x 0.7^2 x 5 / 4 = 60W/m^3

[Calc 9] Peak power density = 297(±263) μW/m^2 [29]

Considering a 1MW system: Required power / Area power density = Required Area

10^6 W / 297*10^{-6} W/m^2 = 3.367*10^9 m^2 =3367 km^2

Considering peak power density with optimistic error margin:

10^6 W /(297+263)*10^{-6} W/m^2 = 1786 km^2

[Calc 10] Current system produces 3kW for a 15.5m^2 panel area [30].

Power output / Area used = Area power density

3000 W / 15.5 m^2 = 193.5 W/m^2

Considering a 1MW system: Required power / Area power density = Required Area

10^6 W / 193.5 W/m^2 = 5167 m^2

[Calc 11] [38] uses two discs of 10cm diameter, 5mm thickness.

Volume = 2 x π x radius^2 x thickness

Volume = 2 x π x 0.05^2 x 0.005 = 7.85 x 10^{-5} m^3

This volume generates 1.5W therefore the power density is:

Power Density = Power / volume of material used

Power Density = 1.5 W / 7.85 x 10^{-5} m^3 = 19,100W/m^3

To generate 1 MW: Required volume = Required power / Power density

Volume = 1x10^6 W / 19,100 W/m^3

Volume = 52.4m^3

[Calc 12] Suggested CAPEX for DEG PTO is £0.6 - 1.5M/MW [23] which is broken into 60% for the elastomeric Energy Conversion Unit and 40% for the power electronics.

60% of the CAPEX (£0.6-1.5mil/MW) = £0.36 – 0.9M/MW

[Calc 13] Suggested future CAPEX for DEG PTO is £0.4 to 0.6M/MW.

Using the same composition of equipment as above leads to:

60% of the CAPEX (£0.4 – 0.6M/MW) = £0.24 to 0.36M/MW

[Calc 14] [45] states one system has a weight of 34 grams and an electrical power of 366mW

Specific power = 366mW / 34g = 10.76mW/g = 10.76W/kg

Material density of 7.7g/cm^3 = 7700kg/m^3 from [47]

Power density of 7700kg/m^3 x 10.76 mW/g = 82,852W/m^3

[Calc 15] Reference [46] gives costs of \$0.155/cm^3 and power density from above equal to \$155,000 per m^3. Considering a USD:GBP ratio of 0.11 results in £119,350 per m^3

Volume = Power / Power density = 1000000 W / 82,852 W/m^3 = 12m^3

Cost = Volume x Volumetric price

Cost = 12 x £119,350 = £1.4 mil

[Calc 16] For a specific power of 210 W/kg

Amount of material = Power required / specific power

Amount of material = 1x10^6 W / 210 W/kg = 4760kg

For a price per kg of £5/kg

Total Price = Amount of material x price per kg

Total Price = 4760 x 5 = £23,800

[Calc 17] The tables below show the inputs and calculation steps used to calculate the CAPEX, OPEX and future through life cost of the alternative generation technologies, relative to the conventional baseline. These calculations are also shown in expanded form in the worked example in section 7.4.3, and in [Calc 18], [Calc 19] and [Calc 20] below.

					Magnetostriction			Triboelectric		
Value		**Baseline CAPEX/OPEX Ratio**	**Subsystem Contribution**	**Baseline values (£k)**	Input values (£k)	Relative to baseline (%)	Contribution to through life cost (% baseline)	Input values (£k)	Relative to baseline (%)	Contribution to through life cost (% baseline)
Generator	CAPEX	0.75	0.1	200	460	230%	17%	600	300%	23%
Generator	OPEX	0.25	0.1	280	126	45%	1%	0	0%	0%
Efficiency				95%	48%	50%		90%	95%	
Balance of Plant	CAPEX	0.75	0.9			200%	135%		106%	71%
Balance of Plant	OPEX	0.25	0.9			200%	45%		106%	24%
						TOTAL	198%		TOTAL	118%

					DEG			Piezoelectric		
Value		**Baseline CAPEX/OPEX Ratio**	**Subsystem Contribution**	**Baseline values (£k)**	Input values (£k)	Relative to baseline (%)	Contribution to through life cost (% baseline)	Input values (£k)	Relative to baseline (%)	Contribution to through life cost (% baseline)
Generator	CAPEX	0.75	0.1	200	24	12%	1%	280	140%	11%
Generator	OPEX	0.25	0.1	280	24	9%	0%	252	90%	2%
Efficiency				95%	90%	95%		75%	79%	
Balance of Plant	CAPEX	0.75	0.9			106%	71%		127%	86%
Balance of Plant	OPEX	0.25	0.9			106%	24%		127%	29%
						TOTAL	96%		TOTAL	127%

[Calc 18] **Triboelectric**

This calculation uses the baseline values in Section 7.5 and figures for triboelectric generation.

$CAPEXGenerator_{Base}$:	£200k	(Discussed in section 7.5.1)
$OPEXGenerator_{Base}$:	£280k	(Discussed in section 7.5.2)
$Efficiency_{Base}$:	95%	(Discussed in section 7.5.3)

The predicted future values for a 1MW triboelectric generator are discussed in Section 7.6.2, and are:

$CAPEXGenerator_{Alt}$:	£600k	(300% of the baseline, $CAPEXGenerator_{Base}$)
$OPEXGenerator_{Alt}$:	£0k	(0% of the baseline, $OPEXGenerator_{Base}$)
$Efficiency_{Alt}$:	90%	(95% of the baseline, $Efficiency_{Base}$)

As detailed in Section 7.3 it has been assumed that total CAPEX contributes 75% of the baseline through life cost while total OPEX contributes 25%.

The contribution of the generator is 10% of total baseline cost, and it is assumed to contribute 10% of CAPEX and 10% of OPEX. The contributions of the Generator and Balance of Plant can be scaled to show how the sum of contributions changes compared to the baseline through life cost. For the baseline the sum of contributions is 100%.

Generator CAPEX

$$\text{GeneratorContributionToCAPEX} \times \text{CAPEXContributionToLCOE} \times \frac{\text{CAPEXGenerator}_{Alt}}{\text{CAPEXGenerator}_{Base}}$$

$$10\% \times 75\% \times \frac{£600k}{£200k} = 22.5\%$$

The alternative generator CAPEX is equivalent to 22.5% of the baseline total through life device cost.

Generator OPEX

$$\text{GeneratorContributionToOPEX} \times \text{OPEXContributionToLCOE} \times \frac{\text{OPEXGenerator}_{Alt}}{\text{OPEXGenerator}_{Base}}$$

$$10\% \times 25\% \times \frac{£0k}{£280k} = 0.0\%$$

The alternative generator OPEX is equivalent to 0.0% of the baseline total through life device cost.

Furthermore the efficiency of the triboelectric generator is 90%, meaning that the Balance of Plant (BOP) needs to scale up to provide the generator with a greater input power. The BOP Contributes 90% of the baseline through life cost.

BOP CAPEX

$$\text{BOPContributionToCAPEX} \times \text{CAPEXContributionToLCOE} \times \frac{\text{Efficiency}_{Base}}{\text{Efficiency}_{Alt}}$$

$$90\% \times 75\% \times \frac{95\%}{90\%} = 71.3\%$$

The BOP CAPEX is 71.3% of the baseline total through life device cost.

BOP OPEX

$$BOPContributionToOPEX \times OPEXContributionToLCOE \times \frac{Efficiency_{Base}}{Efficiency_{Alt}}$$

$$90\% \times 25\% \times \frac{95\%}{90\%} = 23.8\%$$

The BOP OPEX is 23.8% of the baseline total through life device cost.

TOTAL

These four cost centres can be combined to show how the total device through life cost compares to the baseline.

Generator CAPEX + Generator OPEX + BOP CAPEX + BOP OPEX = Total through life cost

22.5% + 0.0% + 71.3% + 23.8% = 117.6%

So a WEC Installation using a triboelectric generator with the same lifetime output energy as the baseline would have a through life cost around 118% of the baseline through life cost, i.e. around 18% higher.

[Calc 19] **DEG**

This calculation uses the baseline values in Section 7.5 and figures for DEG generation, only when considering a direct replacement of the conventional electrical generation subsystem.

$CAPEXGenerator_{Base}$:	£200k	(Discussed in section 7.5.1)
$OPEXGenerator_{Base}$:	£280k	(Discussed in section 7.5.2)
$Efficiency_{Base}$:	95%	(Discussed in section 7.5.3)

The predicted future values for a 1MW DEG based generator are discussed in Section 7.6.3, and are:

$CAPEXGenerator_{Alt}$:	£24k	(12% of the baseline, $CAPEXGenerator_{Base}$)
$OPEXGenerator_{Alt}$:	£24k	(9% of the baseline, $OPEXGenerator_{Base}$)
$Efficiency_{Alt}$:	90%	(95% of the baseline, $Efficiency_{Base}$)

As detailed in Section 7.3 it has been assumed that total CAPEX contributes 75% of the baseline through life cost while total OPEX contributes 25%.

The contribution of the generator is 10% of total baseline cost, therefore 10% of CAPEX and 10% of OPEX. The contributions of the Generator and Balance of Plant can be scaled to show how the sum of contributions changes compared to the baseline through life cost. For the baseline the sum of contributions is 100%.

Generator CAPEX

$$GeneratorContributionToCAPEX \times CAPEXContributionToLCOE \times \frac{CAPEXGenerator_{Alt}}{CAPEXGenerator_{Base}}$$

$$10\% \times 75\% \times \frac{£24k}{£200k} = 0.9\%$$

The alternative generator CAPEX is equivalent to 0.9% of the baseline total through life device cost.

Generator OPEX

$$\text{GeneratorContributionToOPEX} \times \text{OPEXContributionToLCOE} \times \frac{\text{OPEXGenerator}_{\text{Alt}}}{\text{OPEXGenerator}_{\text{Base}}}$$

$$10\% \times 25\% \times \frac{£24\text{k}}{£280\text{k}} = 0.2\%$$

The alternative generator OPEX is equivalent to 0.2% of the baseline total through life device cost.

Furthermore the efficiency of the DEG is 90%, meaning that the Balance of Plant (BOP) needs to scale up to provide the generator with a greater input power. The BOP Contributes 90% of the baseline through life cost.

BOP CAPEX

$$\text{BOPContributionToCAPEX} \times \text{CAPEXContributionToLCOE} \times \frac{\text{Efficiency}_{\text{Base}}}{\text{Efficiency}_{\text{Alt}}}$$

$$90\% \times 75\% \times \frac{95\%}{90\%} = 71.3\%$$

The BOP CAPEX is 71.3% of the baseline total through life device cost.

BOP OPEX

$$\text{BOPContributionToOPEX} \times \text{OPEXContributionToLCOE} \times \frac{\text{Efficiency}_{\text{Base}}}{\text{Efficiency}_{\text{Alt}}}$$

$$90\% \times 25\% \times \frac{95\%}{90\%} = 23.8\%$$

The BOP OPEX is 23.8% of the baseline total through life device cost.

TOTAL

These four cost centres can be combined to show how the total device through life cost compares to the baseline.

Generator CAPEX + Generator OPEX + BOP CAPEX + BOP OPEX = Total through life cost

0.9% + 0.2% + 71.3% + 23.8% = 96.2%

So a WEC Installation using a DEG with the same lifetime output energy as the baseline would have a through life cost around 96% of the baseline through life cost, i.e. around 4% lower.

[Calc 20] **Piezoelectric**

This calculation uses the baseline values in Section 7.5 and figures for piezoelectric generation.

$CAPEXGenerator_{Base}$:	£200k	(Discussed in section 7.5.1)
$OPEXGenerator_{Base}$:	£280k	(Discussed in section 7.5.2)
$Efficiency_{Base}$:	95%	(Discussed in section 7.5.3)

The predicted future values for a 1MW piezoelectric generator are discussed in Section 7.6.4, and are:

$CAPEXGenerator_{Alt}$:	£280k	(140% of the baseline, $CAPEXGenerator_{Base}$)
$OPEXGenerator_{Alt}$:	£252k	(90% of the baseline, $OPEXGenerator_{Base}$)
$Efficiency_{Alt}$:	75%	(79% of the baseline, $Efficiency_{Base}$)

As detailed in Section 7.3 it has been assumed that total CAPEX contributes 75% of the baseline through life cost while total OPEX contributes 25%.

The contribution of the generator is 10% of total baseline cost, therefore 10% of CAPEX and 10% of OPEX. The contributions of the Generator and Balance of Plant can be scaled to show how the sum of contributions changes compared to the baseline through life cost. For the baseline the sum of contributions is 100%.

Generator CAPEX

$$\text{GeneratorContributionToCAPEX} \times \text{CAPEXContributionToLCOE} \times \frac{\text{CAPEXGenerator}_{\text{Alt}}}{\text{CAPEXGenerator}_{\text{Base}}}$$

$$10\% \times 75\% \times \frac{£280k}{£200k} = 10.5\%$$

The alternative generator CAPEX is equivalent to 10.5% of the baseline total through life device cost.

Generator OPEX

$$\text{GeneratorContributionToOPEX} \times \text{OPEXContributionToLCOE} \times \frac{\text{OPEXGenerator}_{\text{Alt}}}{\text{OPEXGenerator}_{\text{Base}}}$$

$$10\% \times 25\% \times \frac{£252k}{£280k} = 2.3\%$$

The alternative generator OPEX is equivalent to 2.3% of the baseline total through life device cost.

Furthermore the efficiency of the piezoelectric generator is 75%, meaning that the Balance of Plant (BOP) needs to scale up to provide the generator with a greater input power. The BOP Contributes 90% of the baseline through life cost.

BOP CAPEX

$$\text{BOPContributionToCAPEX} \times \text{CAPEXContributionToLCOE} \times \frac{\text{Efficiency}_{\text{Base}}}{\text{Efficiency}_{\text{Alt}}}$$

$$90\% \times 75\% \times \frac{95\%}{75\%} = 85.5\%$$

The BOP CAPEX is 85.5% of the baseline total through life device cost.

BOP OPEX

$$BOPContributionToOPEX \times OPEXContributionToLCOE \times \frac{Efficiency_{Base}}{Efficiency_{Alt}}$$

$$90\% \times 25\% \times \frac{95\%}{75\%} = 28.5\%$$

The BOP OPEX is 28.5% of the baseline total through life device cost.

TOTAL

These four cost centres can be combined to show how the total device through life cost compares to the baseline.

Generator CAPEX + Generator OPEX + BOP CAPEX + BOP OPEX = Total through life cost

10.5% + 2.3% + 85.5% + 28.5% = 126.8%

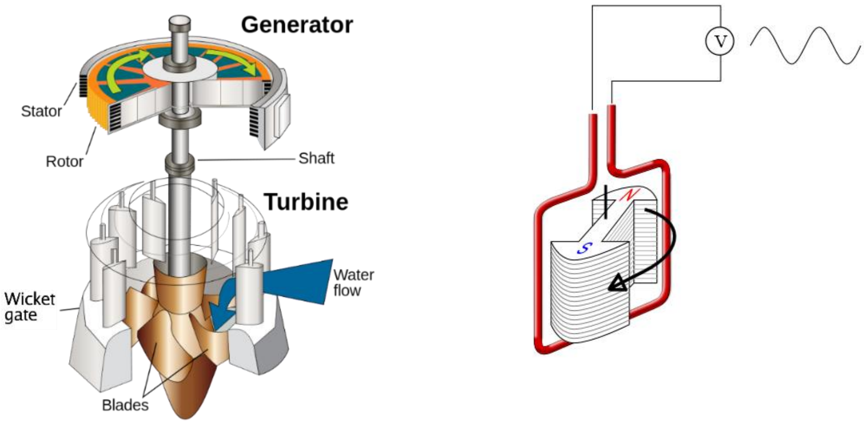
So a WEC Installation using a piezoelectric generator with the same lifetime output energy as the baseline would have a through life cost around 127% of the baseline through life cost, i.e. around 27% higher.

ANNEX A - FUNDAMENTAL ENERGY INTERACTIONS MATRIX

	Electric	Mechanical	Elastic	Thermal	Magnetic	Gravitational	Mechanical wave	Chemical
Mechanical Standard Kinetic and rotational motion, Fluid mass flow, Fluid surface distortion, Sea bed interactions, Pressure differential	Solid state polymer: Dielectric elastomers Piezo electric effect Sea bed interactions: sedimentation potential effect Conventional rotating/linear generator Magnetohydrodynamics – capturing energy of conducting fluid Electrokinetics Electrohydrodynamics Triboelectricity	Flow driven turbine Flow over a material generate vibrations due to vortex shedding Surface deformation creating relative motion on buoyant bodies Cyclic motion of buoyant body Oscillating water column Magnetic Gearing	Deforming a material to store elastic energy Drag loading a membrane or plate in the path of the flow Surface waves deforming a material to store elastic energy Using head pressure difference to load a surface	Resist rigid body motion via friction creating heat Friction with flow boundary Cyclic pressure heating a working fluid	Magnetostriction (Terfenol-D style materials)	Mechanical winch increase head by directing fluid flow into a column Overtopping / terminator device Cyclic vertical motion of a buoyant body Mechanical linkage to a weight	Mechanical energy linked to membrane to create surface wave in material Mechanical linking a body to a whip-like structure	Reversible reactions catalysed by pressure or temperature change Drive fluid flow in a flow battery (redox, requires two consumable liquids)
Elastic	No direct conversion found; elastic energy typically converted to kinetic (mechanical) before electric	Release of elastic potential energy will create kinetic motion	Not a useful conversion	Inefficient release of elastic potential could release thermal energy	No direct conversion found; elastic energy typically converted to kinetic (mechanical) energy before magnetic	Elastic energy could be mechanically linked to transfer energy to a raised weight	Release of elastic potential could be mechanically linked to create a mechanical wave	No direct conversion found
Thermal	Thermoelectric materials Thermally actuated shape memory polymer Seebeck generator	Heat engine (Stirling, steam turbine)	Thermo-elastic materials	Not a useful conversion	Thermomagnetic motor	No direct conversion found	No direct conversion found	Endothermic reactions Reversible reactions which are initiated or catalysed by temperature change
Magnetic	Magnetic fields have to be moved, or fluctuate, to generate electricity. This is covered by mechanical/electrical interactions.	Magnetic field creates kinetic motion. Magnetohydrodynamics Magnetostriction Magnetically activated shape memory alloy	Magnetic field can load a material to store elastic energy	No direct conversion found	Not a useful conversion	Magnetic field can raise ferrous object and create gravitational potential	No direct conversion found	No direct conversion found
Gravitational	No direction conversion found: usually goes through kinetic energy e.g. hydro dam, or wave overtopping device	Release of gravitational potential energy through a falling object/fluid will create kinetic motion	No direct conversion found	Inefficient release of gravitational potential energy to kinetic	No direct conversion found	Not a useful conversion	No direct conversion found	No direct conversion found
Mechanical wave	Piezo electric effect Colloid vibration current	Linkage to connect mechanical wave to a rigid body/fluid	No direct conversion found	No direct conversion found	No direct conversion found	No direct conversion found	Not a useful conversion	No direct conversion found
Chemical	Traditional battery anode/cathode reaction Osmotic power Fuel cell	Usually through combustion, i.e. rocket engine Pressure change through reaction (Internal Combustion engine)	Muscle mimicking	Exothermic reaction (combustion)	No direct conversion found	No direct conversion found	No direct conversion found	Not a useful conversion

ANNEX B - TECHNOLOGY CAPTURE SHEETS

Title	Rotary Generators	ID:	1
Conversion	Rotary mechanical > Electric		



The diagram on the left shows a Water Turbine directly connected to a generator, and the right is a simplified diagram of an electrical generator, with a rotating magnet and static coil.

Principle of operation

Rotary generators are devices which turn rotary motion into electrical energy. This Technology Capture Sheet is focused on alternators - devices which convert the mechanical energy to alternating current, rather than to direct current (a dynamo).

Rotary generators consist of a stator and rotor and either permanent or electromagnets can be used. As the magnet moves relative to the coil a current is created.

Given agreeable input conditions, rotary generators can reliably and efficiently produce electricity. The technology is highly mature in both land and marine environments, and can have long operation periods between maintenance.

Current Use

Rotary generators are used in many forms of conventional power generation. This includes converting the rotating motion of a steam turbine in a nuclear or fossil fuel power plant to collecting the electricity from the rotating shaft in a wind turbine.

In marine power generation, rotary generators are used in a number of ways in different device types.

One typical use is in combination with a Wells turbine (Technology Capture Sheet 3) in an oscillating water column set up. The rotational shaft power output from the turbine can be directly used as the rotational input to the generator.

The same principle or rotational shaft output driving the generator can be found in use in overtopping devices, which use a low head water turbine instead of a Wells turbine. Similar again is the use in devices such as the Aquamarine Oyster, which pumps high pressure fluid to shore which then powers a water turbine.

Point absorbers or rotating mass do not necessarily use fluid turbines, but can use direct mechanical inputs to rotate the input generator shaft.

Maturity Evaluation

Existing TRL	Justification	WEC TRL	Justification
9	Rotary generators are very widely used and proven in many industries,	9	Full scale wave energy conversion systems have been operational at full capacity in the

Title	Rotary Generators	ID:	1
	from small scale generation to multi MW installations.		form of shore mounted Oscillating Water Columns.

Assessment against criteria		
Criteria	**Score**	**Justification**
Operate in environment		Rotary generators are widely in use in wave energy generation, both on shore and at sea. The main environmental operation constraints and issues depend on the mechanical link which transfers force between the waves and the generator device.
Survive loading		Rotary generators are extremely reliable and will continue to provide energy under extreme loading. The overloading can then be dealt with electrically rather than mechanically. The moving parts are stable under large loads, and can last long periods before maintenance and fatigue failure become a likely issue.
Controllable		These devices are very controllable, however without adjustable gearing for the input, the electrical output is highly dependent on the frequency of the waves or the use of an electrical converter.
Convert at scale		Rotary generators easily scale from mW to MW, and can be designed to optimise the electrical output based on the predicted input frequencies. Depending on configurations, they can produce single or multiphase electricity.
Tolerant of irregularity		Rotary generators are extremely tolerant of irregular behaviour, however the electricity output will reflect the irregularity of the input. They can cope with variation of wave heights, directions and frequencies and remain efficient.
Power density		Rotary generators are of a comparable size to many other Electrical Generation Subsystem Technologies. As the most ubiquitous electrical machine they have had significant investment to refine their design, including power density.
Capital cost		The capital cost of rotary generators is low compared to other devices in use in wave energy generation such as linear generators. Rotary devices have been under development for decades to minimise initial cost, maximise efficiency and durability. The capital costs for devices specifically designed for offshore use is likely to be higher than shore based devices due to the requirement for increased water ingress protection.
Operating cost		The operating costs of rotary generators is low, and is likely dominated by potential maintenance costs. By design, they are relatively low maintenance devices due to their simplicity and few moving parts. The designs are highly mature for use in many environments. Planned offshore use would dramatically increase the maintenance costs due to low accessibility compared to onshore installations.
Efficiency		Efficiencies of 95% are realistic with modern rotary generators, as long as adequate heat removal systems are being used.
Maturity risk		This technology is currently widely used in commercial wave energy generation systems.

Title	Rotary Generators	ID:	1
Summary			
Economic opportunity	(red)	Rotary generation is currently the most common form of PTO for a wave energy generation system and given the high level of market penetration provides the least opportunity for improvement.	
Technical feasibility	(green)	Rotary generators are highly mature and feasible for use in many forms of wave energy generation.	
References			

1. Image Credit https://upload.wikimedia.org/wikipedia/commons/0/09/Water_turbine_%28en_2%29.svg
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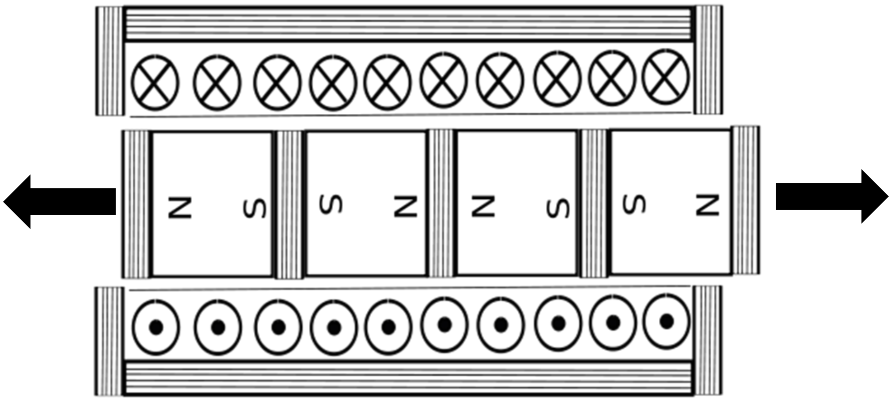
Title	Linear Generators	ID:	2
Conversion	Mechanical > Electric		



A cutaway of a linear generator. In this example, the permanent magnets are the moving component, with the coils being mounted on the static component.

<table>
<tr><th>Principle of operation</th><th>Current Use</th></tr>
<tr><td>Linear generators are devices which turn a linear motion into electrical energy. They work on the same principle as a rotary generator, and use a coil of wire and magnets moving relative to it. Typically, linear generators have a static coil arrangement, and a moving magnet to generate electrical energy, however some solutions use permanent magnets as the stator and use a moving coil of wire.

Linear generators can have higher efficiencies than rotary generators due to fewer potential mechanical losses. However, they are not widely used in industry as rotary generators are usually cheaper. The inverse technology, a linear motor, is more widely used.</td><td>They are used in low power applications such as robotics, and in high power situations such as railway propulsion and applications which require rapid linear acceleration.

Linear generators have been proposed for use in wave energy generation due to their simple operation, and low maintenance requirements. There are numerous academic studies into this use case, and multiple companies are developing commercial products for wave energy generation.

Trident Energy have a modular PTO linear generator design called the PowerPod. The modular design can create units capable of producing outputs from 60 to 360kW.

Seabased have developed a full wave energy generator design, which uses a surface floating point absorber tethered to the sea floor through a linear generator. Seabased use units rated from 10 to 30kW in an array format to create generation farms. They have been sea testing their technology since 2006 and have recently been awarded a contract to build a 100MW farm off the coast of Ghana.</td></tr>
</table>

<table>
<tr><th colspan="4">Maturity Evaluation</th></tr>
<tr><th>Existing TRL</th><th>Justification</th><th>WEC TRL</th><th>Justification</th></tr>
<tr><td>8</td><td>Linear generators have been proven in many different tests and demonstrations, however they are still not widely used for energy generation as rotary solutions are often more suitable.</td><td>8</td><td>The use of linear generators for wave energy generation applications has been proven through long term ocean trials by Seabased, with other commercial companies developing technologies which are approaching readiness for commercial deployment.</td></tr>
</table>

Title	Linear Generators	ID:	2

Assessment against criteria

Criteria	Score	Justification
Operate in environment		Seabased has shown the suitability of linear generation devices in tests demonstrating almost continuous operation over 15 months. This included harsh operating conditions including sea ice.
Survive loading		Linear generators are extremely reliable and will continue to provide energy under loading from high sea states. The generator's ability to cope with extreme loading is highly dependent on the WEC it is used with.
Controllable		Linear generators can be tuned in order to have an optimum operating frequency close to the frequency of loading expected from the waves. Similar to rotary generators, the electrical field can be altered to change the power extracted and mechanical resistance presented by them.
Convert at scale		Commercially available linear generators for wave energy use are rated up to 360kW per unit. Seabased have installed an array of 36 WECs in Sotenas, Sweden, which has a capacity of 3MW and is connected to the Swedish Grid using linear generators. This company is contracted to and is currently developing a 100MW system to be installed in Ghana.
Tolerant of irregularity		Linear generators are tolerant of irregular behaviour. Power will be generated if linear motion is maintained, however the power output will reflect an irregular input. Active damping could be used to manage the WEC's response to wave height variation, direction and frequencies.
Power density		Linear generators are of a comparable size to many other wave generation devices. The size of the overall system is dependent on the WEC used. The overall stroke length of the large 360KW Trident Energy generators is 4.6m.
Capital cost		The 100MW Seabased plant will cost in the region of £140m to complete, which is comparable with current wave energy methods. Until recently, there has been a lack of commercially available linear generators on the scale required for a WEC device. This has necessitated the use of tailored systems when prototyping WEC devices, increasing development cost.
Operating cost		Linear generators are relatively low maintenance devices due to their simplicity and lack of moving parts, however to be most effective they require the use of an electrical converter.
Efficiency		Efficiencies of 80% are realistic and 95% efficiencies are possible with proper damping, however the efficiency of the generator is highly dependent on the stroke speed. There are many designs which have been proposed in academic studies promising improvements in efficiency which will require practical testing to confirm.
Maturity risk		This technology is currently in commercial use in a number of locations, however only a few commercial companies offer a complete WEC/PTO solution.

Summary

Economic opportunity		This is already a relatively mature technology in wave energy use, diminishing the opportunity for further improvements.

Title	Linear Generators		ID:	2
Technical feasibility		Linear generators have been shown to be a feasible solution for generating usable energy from waves. The technology is effective in small scale single unit use, and has been demonstrated in multi-megawatt arrays.		

References

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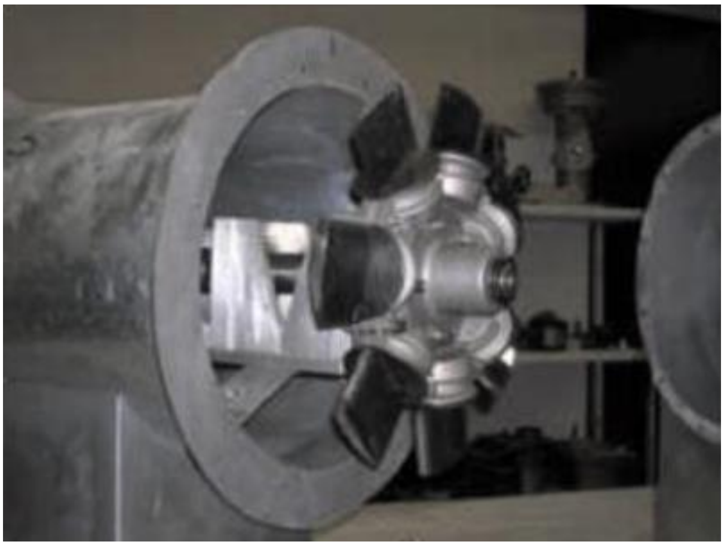
Title	Wells Turbine	ID:	3
Conversion	Mechanical air flow > Mechanical rotary		



A Wells turbine

Principle of operation	Current Use
A Wells turbine is a low pressure air turbine which rotates in a single direction independent of the direction of the flow. The blades of the turbine are symmetrical to work with the bidirectional input flow and therefore offer lower efficiency than other turbines. Due to the relatively low efficiency compared to other turbine designs Wells turbines can produce a high amount of noise during operation. This low efficiency arises from turbine blade profiles being less efficient in each direction to allow for bi-directional operation. Some air turbine designs incorporate systems which can either adjust the pitch of the blades in the turbine, or adjust guide vanes in the turbine inlet. These systems can increase the operating range of the turbine, however often at a small loss of efficiency compared to a static pitch guide vane Wells turbine.	Wells turbines have been used for over 20 years in wave energy generation. They are typically used to extract energy from the air flow output of an Oscillating Water Column (OWC) WEC, where a column of water compresses air and forces it into a chamber, however they have been used in other air-powered concepts such as the AWS III wave absorber. Examples of Wells turbines in extended use in a OWC include the 250 kW LIMPET device operating in Islay since 1991. This is a shore based OWC, which channels the air flow into a horizontally orientated turbine. The 300kW Mutriku plant in Spain has been operational since 2011 and consists of 16 Wells turbines using the OWC method, each with a capacity of 18.5kW. Each 1200kg turbine has a diameter of approximately 3m and a depth of 1.25m. During the first 5 years of operation the Mutriku plant generated over 1GWh of electrical energy.

Maturity Evaluation

Existing TRL	Justification	WEC TRL	Justification
9	Wells turbines have been used in many wave energy devices and have been fully qualified through extended use and analysis.	9	Wells turbines have been used in many wave energy devices and have been fully qualified through extended use and analysis.

Title	Wells Turbine	ID:	3

Assessment against criteria

Criteria	Score	Justification
Operate in environment	Green	Wells turbines have been proven to operate in the environment over many years in multiple different installations. The devices are designed to be driven by air and are not directly in contact with the sea. The Mutriku plant uses automatic water sprays to clear the turbines of salt and debris if necessary.
Survive loading	Green	A number of devices have been in operation over 20 years demonstrating their performance over a wide range of loads. The design of the commonly used OWC WEC limits the effects of extreme loading as much of the force is taken by the WEC itself. Air can be depressurised with valves.
Controllable	Amber	The controllability is dependent on the generator used with the turbine. In an OWC device power is generated both when the air is compressed by the wave and then when it is expanded. Loads on the turbine can be managed by altering the torque demand from the attached generator. The power generated directly depends on the wave height and the tip speed ratio of the turbine. Using variable pitch turbine blades also allows some degree of control although this would increase complexity and maintenance.
Convert at scale	Green	There are a number of existing installations which produce power on the 100kW scale using the OWC method. The Mutriku plant has been in operation for 5 years and has generated over 1GWh.
Tolerant of irregularity	Green	A Wells turbine is capable of coping with irregular flow, however the electricity output from the rotary turbine will be irregular. For peak efficiency the turbine should operate at its design tip-speed ratio, which varies through a compression-expansion cycle.
Power density	Green	The power of a turbine is dependent on the volume flow rate of air and pressure across the turbine, both of which can be optimised by the system design. The efficiency is comparable to other PTOs.
Capital cost	Green	The 296 kW Mutriku plant cost €2.3 million to build, although this plant was integrated into an existing breakwater. Building power generation capacity into costal defences during initial construction of the defences would have a large impact on the capital costs. The relatively simple shape and use of steel (or similar) is likely to result in moderate costs.
Operating cost	Green	As the turbine's working fluid is air it should suffer less corrosion although it will still be subject to a corrosive environment. Automatic cleaning designs can minimise the effects of harsh salt spray environments.
Efficiency	Amber	Wells turbines typically have efficiencies of between 60 – 65% although it is possible to achieve efficiencies of 70% with guide vanes using specific airfoils. However, the air compression losses are typically more significant resulting in current OWC devices achieving total efficiencies of around 25%.
Maturity risk	Green	Wells turbines have been successfully employed in several commercially operating power plants both on the shore and in shallow coastal areas.

Title	Wells Turbine		ID:	3
Summary				
Economic opportunity		Wells turbines are currently, and have in the past been, used in commercial wave power plants. The low efficiency of the Wells turbine (when considering the compression of air losses) needs to be improved to increase the commercial viability of the technology. Some other turbine designs can offer significantly higher efficiencies, however are not as mature a design as a Wells turbine.		
Technical feasibility		The Wells turbine is a relatively simple device and therefore easy and cheap to manufacture. It has been proven in wave energy devices.		
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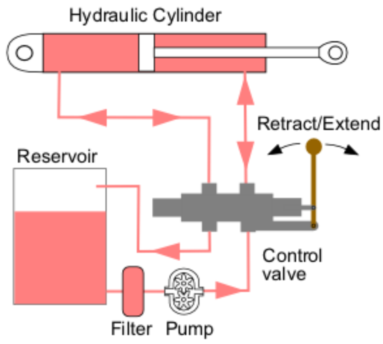
Title	Hydraulics	ID:	4
Conversion	Mechanical > Mechanical		



A schematic of a simple hydraulic system

Principle of operation	Current Use
Mechanical motion is transferred to pressure and flow of hydraulic fluid through a hydraulic cylinder/actuator, creating hydraulic potential energy. This is transported along pipes towards a PTO system. In a hydraulic circuit, losses are most likely due to valves, fittings, pipe geometry and the interior surface. An accumulator may be used to store energy enabling a consistent pressure within the hydraulic circuit and smoothing input to the PTO. Hydraulic pressure is then converted to hydraulic kinetic as it is expanded. The hydraulic kinetic energy is turned to rotary mechanical energy in a hydraulic motor, and then into electricity through a conventional generator. Transferring energy into and out of hydraulic incurs efficiency losses. The conversion from mechanical to hydraulic is very high efficiency, with minor losses due to heat, cushioning, seals and flow losses inside the cylinder. Conversion from hydraulic to mechanical can be as high as 95% in a radial piston motor, and around 80% for gear and orbital motors. The efficiency losses in the pipe between the WEC and PTO is hard to quantify as it is highly sensitive to geometry, material, and length of the piping used for transport. However control systems can manage flow rate to minimise pipe losses. The use of hydraulics can have multiple benefits over a mechanical linkage, and can include easier installation, lower maintenance requirements, more flexible connections between the WEC and PTO, and it can enable multiple WEC hydraulic outputs to be combined into one PTO device input.	Some WECs use hydraulic pressure to transfer mechanical energy from the prime mover to the PTO. The 750kW Pelamis attenuator used the relative motion between its cylindrical segments to pressure hydraulic fluid and generate electricity through a hydraulic motor and a conventional rotary generator. Oscillating wave surge converters such as the Aquamarine Oyster and the AW Energy Waveroller convert reciprocating flap motion into pressurised hydraulic fluid, which is then transferred to a hydraulic motor and conventional PTO arrangement. The Oyster device has an onshore PTO with longer piping to the WEC, whereas the Waveroller concept had a shorter transfer distance and housed a PTO generator next to the base of the WEC. The Artemis Intelligent Power 'Quantor' project is currently in the WES Stage 3 PTO programme. This project aims to develop a PTO device which is able to provide variable control of the hydraulic loads, improving conversion efficiency and increasing the productivity range.

Title	Hydraulics			ID:	4
Maturity Evaluation					
Existing TRL	Justification	WEC TRL	Justification		
9	Hydraulic systems are widely used in many industries for transferring and accumulating mechanical energy.	9	Hydraulics have been used in multiple WECs which have been deployed at sea for extended periods of time.		

Assessment against criteria		
Criteria	Score	Justification
Operate in environment		Hydraulics are highly suited for operation in marine environments. They can be used onboard devices such as in the Pelamis and AW Energy systems, or be used to transfer energy to shore such as in the Oyster devices.
Survive loading		Hydraulic systems can be easily designed to suit the high loads which could be seen in a wave energy device. They are tolerant of variable loading and can be used to combine outputs from multiple WECs into a single PTO.
Controllable		Hydraulic systems can have simple, effective control systems. They can smooth the input into the generator, which can reduce the burden on electrical quality equipment as well as varying the level of force used to resist the prime mover motions.
Convert at scale		High pressure hydraulic systems can transfer large amounts of energy from the WEC to the PTO and have been used on WECs at near-MW scale.
Tolerant of irregularity		Hydraulic systems have shown themselves to be highly tolerant of variable loading, particularly when using accumulators.
Power density		Hydraulic systems can be physically compact as they are very power dense and capable of transferring large amounts of mechanical energy.
Capital cost		Hydraulic systems typically have a low capital cost compared to mechanical linkages, and are widely used in conventional WECs.
Operating cost		Hydraulic systems require maintenance, however this is likely to be comparable to other existing systems used in wave energy generation.
Efficiency		Transferring mechanical energy into a hydraulic system can be achieved at a very high efficiency. Transmission efficiencies are highly dependent on pipe geometry, material, and length. Conversion from hydraulic to mechanical can be as high as 95% in a radial piston motor, and around 80% for gear and orbital motors.
Maturity risk		Hydraulic systems are highly mature in the marine environment and also have completed extended use in WEC prototype devices.
Summary		
Economic opportunity		Hydraulic systems are used extensively throughout wave energy due to their effectiveness at transmitting power and have advantages over mechanical linkages which can be more complex and require more moving parts to achieve the same end result. Hydraulic systems are also used extensively in industry, therefore there is little scope to improve them further.

Title	Hydraulics		ID:	4
Technical feasibility		This is a very mature technology, and systems can be produced very economically from commercial off the shelf components. They are very suitable for use in marine environments, under wave loading and can be effective over a range of generation scales from different sea states.		
References				

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Title	Attenuator	ID:	5
Conversion	Wave > Kinetic		

Pelamis Wave Energy Converter

Principle of operation	Current Use
An attenuator is a device consisting of 2 or more buoyant bodies that each move relative to the surface of sea, rising with wave crests and dropping with troughs. As such the wave energy is turned into kinetic energy. The relative motion between the bodies can be captured in a power take off (PTO) device that resists the motion. This power take off acts at the “hinges” of the attenuator. Attenuators operate parallel to the primary wave direction, effectively "riding" the waves. For this reason it means that they are highly directional and have to orient into the dominant wave direction when it changes.	Attenuators are most commonly found used as wave energy devices and are not prominent in other industries. The most widely recognised attenuator is probably the Pelamis device which captured the motion at the joints from relative side-side motion as well as vertical motion. The buoyant bodies were cylindrical and formed from a marinised steel construction using standard shipyard techniques. The mooring used allowed each Pelamis device to orient into the oncoming wave direction. Full scale Pelamis machines were deployed, including one small array of 3 machines which operated for 2 months. Other attenuators include the Wave Star machine that uses many hemispherical buoyant bodies in a row to generate power.

Maturity Evaluation

Existing TRL	Justification	WEC TRL	Justification
7	Attenuator devices have been demonstrated at full scale, over an extended deployment periods, however have not been proven to operate reliably.	7	Attenuator devices have been demonstrated at full scale, over an extended deployment periods, however have not been proven to operate reliably.

Title	Attenuator	ID:	5
Assessment against criteria			

Criteria	Score	Justification
Operate in environment		Attenuators are relatively straightforward in construction and can be formed from steel structures or other marinised materials. These materials and structures are widely used in the wider marine industry and shown to operate in the ocean environment.
Survive loading		Attenuators are relatively resilient to wave loading assuming that the connections (hinges) between them have been built for the appropriate fatigue and extreme loading. However, attenuators can fail in extreme wave states if it is possible for them to surpass the endstops that limit motion between bodies.
Controllable		Attenuators require a PTO system for them to be controllable, however a PTO would also be required for power generation.
Convert at scale		Attenuators have been used at 750kW, and are a scalable technology.
Tolerant of irregularity		Attenuators can handle variable wave direction if moored in such a way that allows them to orient themselves. Variability in wave period and height can be altered via the use of a suitable PTO.
Power density		The Pelamis device had a power output of 750kW for a volume of 1600m3 and a mass of 700 tonnes, however this includes the PTO and other systems onboard the device.
Capital cost		Attenuators require a significant amount of material to generate at scale, however their construction is relatively straightforward and can use well established manufacturing methods and capability.
Operating cost		Attenuators themselves are relatively simple systems and can be constructed from materials and structures already readily used in the marine environment using conventional maintenance/protection. There are minimal modes of failure that would require unplanned maintenance. The key complexity arises from the PTO used, which is a separate technology.
Efficiency		Depending on the sea state, attenuators can have a maximum capture width of either 0.5λ or 0.73λ which is higher than point absorbers but lower than terminators.
Maturity risk		Attenuators are already being used in the wave energy industry and therefore they are already very mature.
Summary		
Economic opportunity		Attenuators are a conventional technology that have been pursued in mature concepts therefore there is limited opportunity in pursuing them further.
Technical feasibility		Attenuators are a conventional technology that have been shown to be technically feasible.

References

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Title	Attenuator	ID:	5
%20Converters%20%28WECs%29%206.pdf 3. Wave Energy Converters. Marine Biodiversity and Ecosystem Functioning EU Network of Excellence. http://www.marbef.org/wiki/Wave_energy_converters 4. Technological Cost-Reduction Pathways for Point Absorber Wave Energy Converters in the Marine Hydrokinetic Environment. SANDIA National Laboratories, September 2013 http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.648.1152&rep=rep1&type=pdf 5. Image Credit: https://commons.wikimedia.org/wiki/File:Pelamis_at_EMEC.jpg			

Title	Point Absorber	ID:	6
Conversion	**Wave energy > Mechanical**		

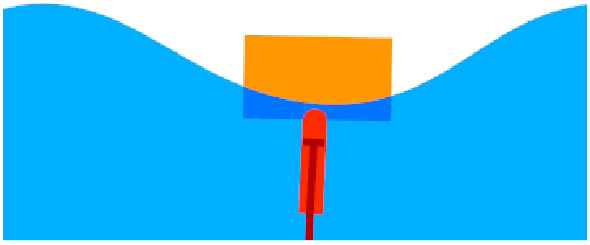

Diagram showing the buoyant body of a point absorber in a wave environment

Principle of operation	Current Use
A point absorber consists of a single buoyant body that moves with the waves. This energy can be generated in heave, surge, pitch or sway motion, turning wave energy to kinetic energy. Point absorbers can be 1, 2 or 3 Degrees of Freedom (DOF). The motion of the buoyant body relative to either a rigid base or a plate (with large drag resistance) is captured in a power take off (PTO) that resists the motion. The PTO itself can be in the buoyant body, the connection, or in the base. Point absorbers capture energy at one point in the wave field, therefore they are not sensitive to wave direction if they are axisymmetric in shape.	Point absorbers are most commonly used as wave energy devices and are not prominent in other industries for power capture, however simple buoyant bodies are used in a wide variety of applications. Examples of point absorbers include the Carnegie CETO, AquaBuoy and the Ocean Power PowerBuoy. Carnegie's CETO device has most recently been tested in 2015 as an 11m diameter, 240kW unit in a live site. A 1MW version is planned, which started development in 2013. AquaBuoy was deployed in 2007 as a 20m tall structure, however sunk after deployment. The PowerBuoy is reported at having a 3kW and 15kW output device that have been deployed at sea.

Maturity Evaluation

Existing TRL	Justification	WEC TRL	Justification
7	Used in conventional wave energy devices that have been deployed, although not at full scale/the scale of interest, have been proven to operate in the marine environment.	7	Used in conventional wave energy devices that have been deployed, although not at full scale/the scale of interest, have been proven to operate in the marine environment.

Assessment against criteria

Criteria	Score	Justification
Operate in environment		Point absorbers are relatively straightforward in construction and can be formed from steel structures or other marinised materials. These materials and structures are widely used in the wider marine industry and proven to operate in the ocean environment.
Survive loading		Point absorbers are relatively resilient to wave loading assuming that the connections between the two moving elements have been built for the

Title	Point Absorber		ID: 6
			appropriate fatigue and extreme loading. However, point absorbers can fail in extreme wave states if it is possible for them to surpass the endstops that limit motion between bodies.
Controllable			Point absorbers require a PTO system for them to be controllable, however a PTO would also be required for power generation.
Convert at scale			Point absorbers have been used at up to 240kW, and are a scalable technology, based on the dimensions of the wave activated bodies.
Tolerant of irregularity			Point absorbers can produce power from all wave directions. Variability in wave period and height can be altered via the use of a suitable PTO.
Power density			Using the 3kW device data provided PowerBuoy suggests a power density of 0.36kW/tonne or 0.12 kW/m3, however this includes the use/mass of the PTO and other systems onboard the buoy.
Capital cost			Point absorbers require a significant amount of material to generate at scale, however their construction is relatively straightforward and can use well established manufacturing methods and capability.
Operating cost			Point absorbers themselves are relatively simple systems and can be constructed from materials and structures already widely used in the marine environment using conventional maintenance/protection. There are minimal modes of failure that would require unplanned maintenance. The key complexity arises from the PTO used, which is a separate technology.
Efficiency			Point absorbers have variable capture widths depending on the DOF they absorb. 1-DOF Heave : 0.16λ 1-DOF Surge or pitch: 0.32λ 2-DOF or 3-DOF: Heave and surge, heave and pitch, heave and surge and pitch, surge and sway and pitch: 0.48λ
Maturity risk			Point absorbers are already being used in the wave energy industry and are already a mature technology.
Summary			
Economic opportunity			Point absorbers are a conventional technology that have been demonstrated in mature concepts, therefore there is limited opportunity in pursuing them further.
Technical feasibility			Point absorbers are a conventional technology that have been shown to be technically feasible.

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Title	Point Absorber	ID:	6

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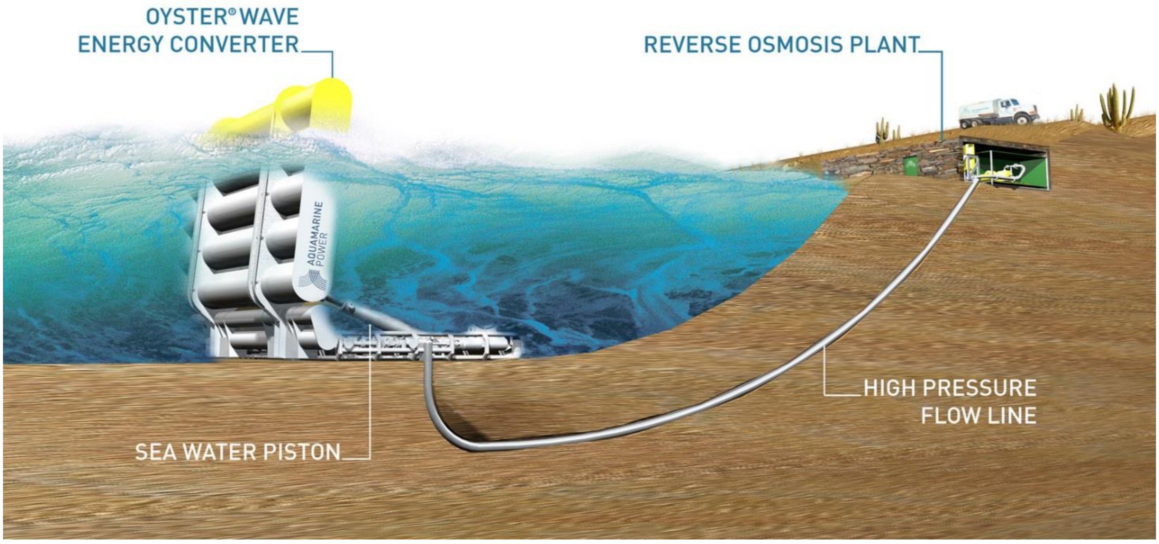
Title	Oscillating Wave Surge Converter	ID:	7
Conversion	Wave > Mechanical (rigid body motion)		



Principle of operation	Current Use
These devices capture the specific horizontal component of wave motion, called surge. They can take the form of a large buoyant flap which is mounted to the seabed that pitches back and forth along a fixed axis that is normal to the expected wave direction. They are mounted in shallow water (typically 10-20m depth) to capture wave energy which is densest near the sea surface. The pitching flap can drive a mechanical linkage to be connected to a PTO.	Oscillating surge conversion is only used in wave energy. The Oyster was an oscillating wave surge converter device which was developed and tested by Aquamarine Power. It consisted of a flap capture device, mounted to the sea bed at a depth of 10m, approximately 0.5km offshore. The WEC fed high pressure water back to a shore based hydraulic turbine which converted the pressurised flow into electricity. Two devices were tested at the EMEC site in Orkney, the first was rated at 315kW, and the second generation device was rated at 800kW and installed in 2012. Aquamarine Power closed in 2015 and there will be no further development on the Oyster concept. Similar systems are under more active development such as the AW Energy Waveroller system, which has a power output rating of up to 1MW. This is conceptually similar to the Oyster device, except the hydraulic conversion takes place in the underwater device. AW Energy are actively developing and pursuing funding for installation of Waveroller devices around the world.

Maturity Evaluation

Title	Oscillating Wave Surge Converter	ID:	7
Existing TRL	**Justification**	**WEC TRL**	**Justification**
7	Prototype full scale oscillating wave surge converters have been deployed in marine environments for long term testing and grid scale energy generation.	7	Prototype full scale oscillating wave surge converters have been deployed in marine environments for long term testing and grid scale energy generation.

Assessment against criteria		
Criteria	**Score**	**Justification**
Operate in environment		Oscillating wave surge converter devices have been shown capable of operation over extended periods of time in the environment.
Survive loading		Oscillating surge converters have been shown to survive loading when designed robustly, and a design feature is that large waves in high sea states can pass over the device, particularly if the flap is lowered.
Controllable		Oscillating wave surge converters can only be controlled by the use of other systems. This is mainly via the use of force feedback from the PTO, which would also be required for generation. Some devices can flood chambers in the flap section to lower or raise them in the water and control the loading.
Convert at scale		Oscillating wave surge converters such as the Oyster have been deployed and demonstrated at 800kW, with different 1MW systems proposed for deployment.
Tolerant of irregularity		Flap style wave energy devices are sensitive to wave direction, however this is mitigated by their location close to shore which can be selected for the predominant direction of the wave climate. In order to operate efficiently in a range of wave states it is necessary for the PTO to be controllable.
Power density		The 315kW Oyster 1 device measured 18m across by 10m high. The proposed design for Oyster 2 was for 3 flaps, each rated at 800kW and measuring 26m. These values suggest that each device can generate significant power.
Capital cost		The 315kW Oyster 1 device cost approximately £2.7 million to install, however this figure fell significantly with development and design iteration. However, this value covers the cost of the whole installation including foundations and not just the WEC.
Operating cost		Submerged devices are less exposed to slamming forces than surface equivalents, and therefore less likely to experience high loading. The devices are located nearshore because they are attached to the seabed, although their attachment to the seabed raises maintenance costs. The costs of maintaining the subsea elements (e.g. the PTO, bearings, or similar) is still likely to be high due to low accessibility.
Efficiency		Analysis of the dynamics of the Oyster device suggest that it is possible for it to surpass the capture width of terminator devices, and therefore to be one of the most efficient of wave capture approaches.
Maturity risk		As demonstrated by multiple full scale operating units, this is a more mature technology than many in use in wave energy generation.
Summary		

Title	Oscillating Wave Surge Converter		ID:	7
Economic opportunity		Oscillating wave surge converters have been developed to a very mature state, limiting the amount of further development opportunity.		
Technical feasibility		As demonstrated, these wave energy conversion devices are technically feasible, however remain costly and difficult to install and maintain. They are well suited for long term use and energy transfer back to shore (in hydraulic or electric form) is a simple and cheap solution compared to wave energy devices which require being installed far offshore to work efficiently.		

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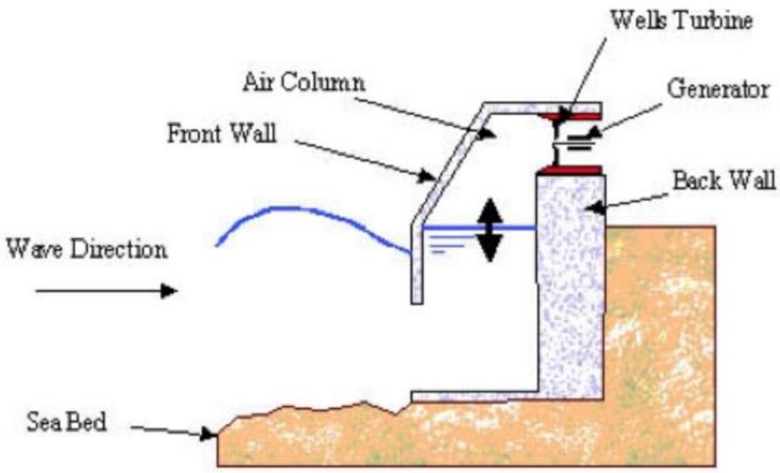
Title	Oscillating Water Column	ID:	8
Conversion	Wave energy > Mechanical (Pressure differential)		



Side view diagram showing the operation of an Oscillating Water Column

Principle of operation	Current Use
Oscillating Water Column (OWC) generators consist of an immersed chamber of air which is open to the action of waves at the bottom. As the water moves up and down (i.e. heaves) the air in the chamber is correspondingly compressed and expanded, varying the pressure. The compression and expansion of air can then be used to drive a power take-off (PTO). Commonly a Wells turbine is used as it can generate power as air flows in and out of the chamber. OWCs can either be made floating or as a fixed structure to either the shore or seabed.	This technology has been successfully used to generate wave power commercially for an extended period of time in many projects. In 1991 the 500kW Islay LIMPET device was opened although it is a shore based device. The 296kW Mutriku plant in Spain uses OWCs and has been running since 2011. During its first 5 years of operation this plant generated over 1GWh of energy. The plant was integrated into a break water. An earlier example of a breakwater OWC is the Sakata plant in Japan with 60kW capacity, installed in 1990. A U-Shaped OWC has also been constructed at the harbour of Civitavecchi near Rome. The Mighty Whale floating OWC consisted of three air chambers producing a power of 110kW and was tested for several years following deployment in 1998. Oceanlinx, an Australian company, successfully tested a grid connected, scale version of their floating OWC in 2010. A 1MW scale device was produced but sank during deployment. The WaveTrain novel OWC device is currently being developed by Joules Energy Efficiency Services under the WES Stage 1 PTO programme. This is a novel angled floating OWC design, which uses linked buoys, and aims to achieve high hydrodynamic efficiencies, with a low cost of energy.

Title	Oscillating Water Column	ID:	8

Maturity Evaluation			
Existing TRL	**Justification**	**WEC TRL**	**Justification**
9	Used in conventional wave energy devices, at full scale, that have been proven to operate over many years.	9	Used in conventional wave energy devices, at full scale, that have been proven to operate over many years.

Assessment against criteria

Criteria	Score	Justification
Operate in environment		OWCs have been commercially operating since 1991. While not all of the devices tested have been successful, it has been shown that the technology can successfully generate power in a marine environment for long periods of time.
Survive loading		Many devices have been successfully operating for an extended period of time. However, some have not withstood deployment or have been destroyed by bad weather, such as the Osprey 1MW OWC generator.
Controllable		OWCs require either a PTO or some control surfaces within the air chamber to be controllable. If a turbine is used the controllability of the turbine is limited as the air in the chamber is open to the effects of the sea.
Convert at scale		There are a number of existing devices which produce power on the 100kW+ scale. Currently there is a 500kW device at Jeju Island South Korea which has been operational since 2016, and the LIMPET device has been operational at 500kW.
Tolerant of irregularity		OWCs can function with flows of different frequencies and direction while still generating power.
Power density		OWC devices tend to be large, shore mounted, bulky structures. The dimensions are comparable to other devices however the mass of OWCs tends to be higher. Many OWCs are built as part of costal defences and therefore are extremely high mass.
Capital cost		The Mutriku plant cost €2.3 million, has a rated power of 296kW and was part of the development of a breakwater. OWCs tend to be close to the shore and therefore do not require long underwater cables or deep water mooring systems. The cost of 10 Osprey devices was estimated at £26.4 million.
Operating cost		The OWC itself (as opposed to the PTO) is a large, static structure that should not require significant repair or cleaning. Further, given that the structures are onshore it is generally easier to access them for maintenance.
Efficiency		The efficiency of the air chamber at capturing the energy of the waves in the Jeju Island instillation has been found to be 52%. The overall efficiency of the plant depends on the PTO. Often a Wells turbine is used for its bidirectional capability however they are relatively inefficient.
Maturity risk		There are several commercially operating OWCs in different countries. Both of the MW scale devices which have been attempted failed. Potentially

Title	Oscillating Water Column		ID:	8
		there are issues with the ability of the technology to be scaled up any further.		
Summary				
Economic opportunity		There are already a number of viable plants generating power commercially; these are primarily onshore. Despite this there may be areas where advancements could be made, specifically around identifying if there are economies of scale for producing larger OWCs, or deploying more in parallel.		
Technical feasibility		OWCs have been shown to be feasible for 100kW+ scale over decades, however none of the MW scale generators have been successfully operated for a long period of time.		

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Title	Overtopping devices	ID:	9
Conversion	Wave > Gravitational potential > Mechanical (fluid flow)		

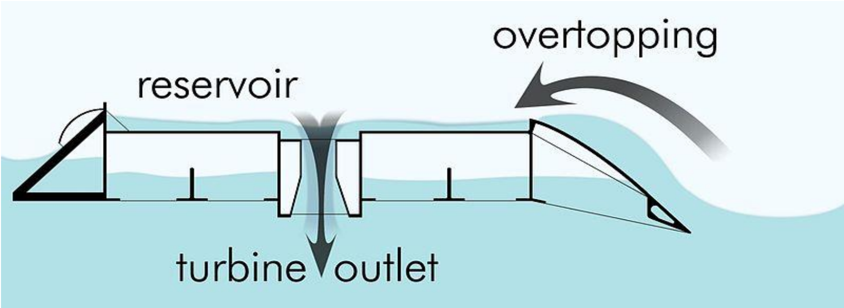

Diagram showing the operation of an Overtopping device

Principle of operation	Current Use
Overtopping captures the kinetic energy in fluid by first redirecting the moving fluid up a slope, converting kinetic to potential energy. This is held in a reservoir and then the fluid is allowed to fall down a hole. This converts the potential energy back into fluid kinetic energy that can be used to drive a Power Take Off, usually a low-head turbine. The energy generated depends on the drop that the fluid experiences.	These devices can either be floating on the surface or moored. This approach has only been used in wave energy devices. Wave Dragon is a floating wave energy generator. Different Wave Dragon prototypes (up to 1/5th scale/20kW) have run for over 20,000 hours since 2003, however there is limited open source information or evidence from these trials. No news has been reported since 2010 after the prototype was scrapped. Another proposed design, the Seawave Slot-cone Generator (SSG), is an overtopping WEC which uses multiple stacked reservoirs. This device would be placed on or near the shore.

Maturity Evaluation

Existing TRL	Justification	WEC TRL	Justification
7	Small scale Wave Dragon overtopping device prototypes have demonstrated extended periods of generation at scale.	7	Small scale Wave Dragon overtopping device prototypes have demonstrated extended periods of generation at scale.

Assessment against criteria

Criteria	Score	Justification
Operate in environment		The Wave Dragon overtopping WECs have been in operation for over 20,000 hours without any reported issues. Biofouling has not been a problem for the device and a 50mm grill has prevented marine debris from reaching the turbine. The testing has also showed that the device is not affected by fish.

Title	Overtopping devices	ID:	9
Survive loading	(amber)	Many overtopping devices are based on or near the shore and take the form of large concrete structures. These are extremely effective at surviving in the marine environment. Early Wave Dragon prototypes had issues surviving wave loading, specifically the connections between the arms and reservoir would break in storm conditions. The early Wave Dragon prototype was designed to last 3 years but survived 7 years in a wave deployment.	
Controllable	(red)	Mechanical control of such a device would vary depending on the design. A shore-mounted concrete structure could incorporate doors or barriers to prevent or limit waves from entering the reservoir. A floating device could use a similar approach but it would be more difficult. In both of these cases control is via an additional system, not via the PTO itself, and would probably have to resist significant loads.	
Convert at scale	(green)	The SSG concept was estimated to have an installed capacity of 163kW. Wave dragon generators were estimated to have a capacity between 1.5MW and 12MW, although this scale was never achieved. Shore based concepts depend on the geography of the location and can be easily integrated into breakwaters and other coastal defences, suggesting that this would be straightforward to make work at scale.	
Tolerant of irregularity	(green)	Depending on the geometry of the ramp around the reservoir, or the mooring system employed overtopping devices should be capable of dealing with waves from different directions and frequencies. The key requirement is having enough energy in the wave to scale the ramp. Shore based devices are more sensitive to wave direction.	
Power density	(amber)	Wave Dragon's proposed 4MW device had an arm length of 150m with the tips of the arms being 230m apart. While this is above average for power density, this design was never built. The shore based devices are relatively compact concrete structures. The advantage of floating devices is that they can be moved to areas of higher wave power density assuming they have sufficient strength.	
Capital cost	(amber)	The 4MW Wave Dragon prototype had a budget of €3.3 million which is comparable to other wave capture technologies, however this cost apparently covers the whole installation, not just the WEC.	
Operating cost	(amber)	The size of Wave Dragon means that repairs and maintenance could be carried out at sea on the platform with relative ease. Shore based concepts have the advantage of easy access and availability throughout the year. The wave capture aspect of these devices are relatively simple, assuming that the reservoir/arms are built robustly.	
Efficiency	(green)	The efficiency of the overall WEC device mainly depends on the power take off system employed. However, considering the wave capture element alone, terminator devices have the highest capture width of all wave WEC types, being equivalent to the wavelength.	
Maturity risk	(amber)	Wave Dragon prototypes have spent an extended period of time in operation and are therefore at a relatively high state of maturity. However, after initial prototypes no development has occurred since 2010, suggesting difficulties in maturation. Designs of shore based devices have also been developed and put forward. Shore mounted devices are more likely to reach maturity due to their simpler design.	

Title	Overtopping devices		ID:	9
Summary				
Economic opportunity	(red)	The Wave Dragon concept has been around since 2003 but has not been developed since 2010. Shore based devices require further development and could provide power at comparable cost to other alternatives, in particular the requirement for a large amount of material to capture waves makes them similar to OWCs. It seems unlikely that such concepts will decrease the LCOE of wave energy.		
Technical feasibility	(green)	Relatively mature designs exist for shore based concepts such as SSG. Wave Dragon has demonstrated that the technology works and is technically possible, however there are issues with survivability to resolve.		
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Title	Terminator: Salter's Duck	ID:	10
Conversion	Wave energy > Mechanical rotational		

No open source image available.

Principle of operation	Current Use
Salter's Duck is a terminator device developed to absorb a high proportion of the wave energy and leave a calm sea behind it. It is tethered to the sea floor and floats on the surface, such that the cam-shaped elements can rotate about a spine perpendicular to the direction of wave travel. The nodding duck element converts the wave energy into rotational mechanical energy. This can be captured by a PTO, which has historically been done by hydraulic pressure, which is then converted to electricity through a conventional hydraulic motor and rotational generator. The Salter's Duck design is highly efficient, with capture efficiency estimates ranging from 50% to 90% of the wave energy.	A 20kW Salter's Duck prototype was installed in 1976, however development ceased in 1987. In 2009 a Chinese team deployed a floating 10kW Duck concept tethered to the sea using a hydraulic power take off. These sea trials demonstrated the high capture efficiency of the duck design, however most of the research publications focused on the tethering system rather than the success and development of the WEC or PTO design.

Maturity Evaluation

Existing TRL	Justification	WEC TRL	Justification
7	The deployed Salters Duck design has demonstrated the operation of	7	The deployed Salters Duck design has demonstrated the operation of the device. A full scale system has not been deployed.

Title	Terminator: Salter's Duck	ID:	10
	the device. A full scale system has not been deployed.		

Assessment against criteria

Criteria	Score	Justification
Operate in environment		The original Salter's Duck and 2009 sea trials of a duck concept terminator demonstrated that the device was capable of generating power in a marine environment. Biofouling is unlikely to cause a problem for the device as it is simply a large rotating mass. Corrosion can be managed as the structure can be formed from standard marine materials.
Survive loading		In extreme weather the tethers holding the device down would undergo high loading. In large sea states there is a risk of the tethers becoming slack and then taut, leading to snap loads. Fatigue failure is possible but there are no major factors that appear to increase the risk of failure. Terminator devices attract the largest extreme loads.
Controllable		The duck itself is not controllable however this could be achieved by the use of a PTO (which is required for generation anyway). For example, an electrical drivetrain could alter the torque demand from the generator, varying the resistance to motion. Mechanical control of the Duck would require a great deal of structure to halt the motion of the Duck, especially in a high sea state as the power is captured at low speed, high force conditions.
Convert at scale		In 1983 a design was proposed for a 2GW instillation consisting of an array of 14m diameter ducks which suggests it is possible to generate at scale. However realised devices have only been built as small scale prototypes, generating up to 10kW.
Tolerant of irregularity		The duck is capable of generating power from waves of a variety of frequencies, however the method of tethering (as a terminator) means that the device is most effective when broadside to the wave field. Therefore the effectiveness decreases as the direction moves away from normal.
Power density		Salter's Duck devices have shown themselves to be very capable of extracting a high percentage of the wave power, suggesting very high power density.
Capital cost		The initial cost estimates in 1983 were £6.3 billion for a 2GW instillation. This equal to £7 million per duck in 1983 prices. In 1991 improvements in the design of the Duck were made and the new cost estimate in the same location was £2.4 Billion. These are old estimates, however it indicates a higher cost than expected for other wave energy conversion approaches.
Operating cost		The operational cost of the 2GW plant was estimated to be in the region of £74 million per year. Most components requiring maintenance are inside the moving duck, which would be inaccessible for maintenance unless the motion of the device could be safely arrested, as per other concepts.
Efficiency		The capture efficiency has been estimated between 50% and 90%, however this is dependent on the wave climate.
Maturity risk		The large scale 2GW proposal was done in some detail although no testing or prototypes were made. More modern, small scale devices have been tested however they are nowhere close to the scale required to generate

Title	Terminator: Salter's Duck		ID:	10
		power commercially. The concept has been pursued for some time with no maturation, suggesting that there is a moderate risk.		
Summary				
Economic opportunity		There are a number of areas which require further research and development specifically around ensuring that the estimated costs of manufacture and maintenance of proposed schemes are realistic.		
Technical feasibility		Carrying out full scale testing on such devices may be expensive, however it appears a feasible option from a technical viewpoint. The key risk arises from off-axis climates and from surviving extreme waves, in addition to evidence that previous devices suffered from complexity requiring a large number of subsystems.		
References				

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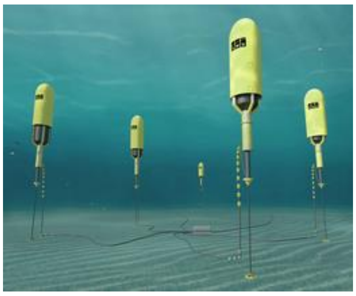
Title	Submerged Pressure Differential	ID:	11
Conversion	Wave > Mechanical (pressure)		

Bombora mWave



AWS Ocean Energy Ltd

Principle of operation	Current Use
As waves travel they lead to a change in the height of the sea surface, leading to a pressure change arising from the elevated water mass. As crests and troughs pass, the pressure beneath the surface fluctuates. Submerged pressure differential devices use this fluctuating pressure to pump a working fluid around a circuit. Compressing a sealed chamber increases the pressure of and drives the working fluid. As the sealed chamber expands again the working fluid is decompressed. The direction of the working fluid is controllable with valves. The fluctuations in working fluid pressure can drive a power take-off (PTO), namely an air or water turbine. The shape of the submerged pressure vessel can either be an ellipsoid (similar to a point absorber) or can be a flexible membrane stretched across a structure that, under wave pressure, compresses an internal working fluid.	While pressure fluctuations to drive motion are used in a wide variety of locations, the use of fluctuating hydrostatic pressure is mainly used within the wave energy industry. The AWS Archimedes Waveswing is an example of a submerged pressure differential device in an ellipsoid shape. It has been reported that a 1/20th scale model has been successfully completed at a wave tank in 2016. The US Department of Energy awarded funding for open water testing to The CalWave Wave Carpet and Waveswing America at the end of 2016. This project has received funding from the WES Novel Wave Energy Converter programme. The Bombora mWave technology is a flexible membrane style device and after a deployment at "mid-scale" in 2015 is working towards a 1.5MW scale device. The construction of this 1.5MW unit was announced in late 2017. The M3 Wave DMP claimed a TRL of 4, however there have been no further reports since 2016.

Maturity Evaluation

Existing TRL	Justification	WEC TRL	Justification
5	There is evidence that submerged pressure differential devices have been tested at small scale in wave tanks and open water.	5	There is evidence that submerged pressure differential devices have been tested at small scale in wave tanks and open water.

Assessment against criteria

Criteria	Score	Justification
Operate in environment		The operation of these devices is relatively simple. The key complexity is the resilience of a submerged membrane or maintaining a mechanical seal, both of which currently exist in marine environment applications.

Title	Submerged Pressure Differential	ID: 11
		The hydrodynamic properties appear to have relatively minor effects, therefore the changing of any surface under the presence of biofouling seems manageable.
Survive loading		Mechanical seals and flexible membranes are widely used in the marine environment, so it seems quite likely that the device would be able to survive fatigue loading. It also seems quite likely that extreme conditions could be withstood by removing all resistance (e.g. via valve/turbine control) to the working fluid.
Controllable		By varying the valves controlling the working fluid, or the torque demanded from the turbine generators, it seems to be quite possible to control these devices.
Convert at scale		These devices appear to be capable of converting at the scale of interest for this study, however there are currently no working examples to prove the concept.
Tolerant of irregularity		Axisymmetric pressure vessels would be insensitive to wave direction, while terminator-style pressure vessels would be more sensitive.
Power density		The Bombora mWave proposed a device of 60m length by 15m width to achieve a power of 1.5MW. This is comparable to existing devices of similar power, if not slightly favourable.
Capital cost		For the Bombora example, the structure makes up almost half of the capital costs and the grid connection approximately 20%. Configuring devices in groups or integrated modules allows economies of scale as well as a reduction in structural material, further reducing cost.
Operating cost		Submerged devices are less exposed to slamming forces than surface equivalents. The devices are located nearshore because they are attached to the seabed, although their attachment to the seabed raises maintenance costs due to limited accessibility. The Bombora mWave 60MW wave farm (made up of 40 converters) has a predicted annual operating cost of $8 million which includes a 30% allowance for unscheduled repair.
Efficiency		There are losses in power transmission from the seabed to shore. There are also power losses returning the device to its initial shape following compression. Bombora reports that of the total annual incident energy, 59% is uncollected wave power, 12% are losses and the remainder is wave to wire energy.
Maturity risk		There are no full scale, submerged pressure differential devices in operation, however some commercial designs are close to deployment at this scale. There is a risk that the designs are not suitable for full size operation, and that the maintenance and repair costs have not been proven in a suitable environment.
Summary		
Economic opportunity		There is opportunity for submerged pressure differential devices to improve the LCOE, as demonstrated by the mWave proposal for a 60MW farm, however this is uncertain and these have not been demonstrated yet.

Title	Submerged Pressure Differential		ID:	11
Technical feasibility		The devices are technically feasible, however technical risks remain including maintenance accessibility of bottom mounted systems, and the suitability of the materials in long term marine operation. However, there is significant commercial investment into maturing the technology.		

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Title	Rotating mass	ID:	12
Conversion	Wave > Mechanical (rotary)		

A image of the Wello Penguin Rotating Mass WEC installed as a full size demonstrator

Principle of operation	Current Use
Rotating mass devices are floating bodies which house a large mass which is free to rotate. As the body moves with the motion of the waves the mass falls to the lowest point, rotating and thus converting the energy of the waves into rotational energy. This motion is often amplified by the body being asymmetrical in order to capture motion in multiple directions. This rotational energy is converted to electrical power using a power take off (PTO) device.	The main rotating mass WEC in operation is the Wello Penguin. This device is rated to 500kW and has been continuously in operation in Orkney since March 2017, and has able to deliver power to the grid since this time. The delivered energy generation capability of this system is unknown. The company has announced plans to deploy a 10MW generation farm in Bali. A gyroscope wave power generation system has also been proposed and tested by a team at Kobe University. 3 prototype designs were tested with capacities between 5.5kW and 45kW.

Maturity Evaluation

Existing TRL	Justification	WEC TRL	Justification
8	As demonstrated by the Wello Penguin device, high rated rotating mass wave energy systems have been successfully deployed and survived long term sea trials.	8	As demonstrated by the Wello Penguin device, high rated rotating mass wave energy systems have been successfully deployed and survived long term sea trials.

Assessment against criteria

Criteria	Score	Justification
Operate in environment	(green)	A number of rotating mass devices have been successfully tested in marine environments and successfully generated power for over a year. Biofouling is unlikely to represent a major issue for rotating mass devices.
Survive loading	(amber)	The Penguin device has been operated successfully for a year. The main internal component which will suffer fatigue is the shaft on which the rotating mass is mounted. The rotation of the mass is directly proportional to the size of waves impacting the device. This may cause problems with high loading in extreme weather. Restraining the mass in extreme sea states will also require significant structural strength.

Title	Rotating mass		ID: 12
Controllable	Red	It is unlikely that the loading on the device is able to be controlled, however the rotation of the mass inside the device could be arrested through mechanical systems or through a torque demand on the PTO (such as an electrical generator).	
Convert at scale	Green	The penguin device has a capacity of 500kW. This represents power generation on a commercially viable scale.	
Tolerant of irregularity	Green	Depending on the shape of the hull power can be generated from waves in varying directions and frequencies. As long as the body is moving with the waves the mass will rotate, therefore the frequency of waves does not matter to the generation of power.	
Power density	Green	The power produced by the device is relatively high for the space it requires, the penguin is 30m by 16m and a mass of 220 tonnes. The Kobe University team had a capacity of 45kW from a 37 tonne device.	
Capital cost	Amber	The main body of the device is essentially a small ship hull with a large mass inside. There are no elements of this which should require great expenditure.	
Operating cost	Amber	The cost of maintenance may be high as the rotating mass shaft may require maintenance. As the device is designed to constantly move it may be difficult to maintain while deployed without significant safety systems isolating the rotating mass from the wave motion.	
Efficiency	Green	The efficiency for the Kobe University team from waves to electricity was found to be around 68%.	
Maturity risk	Green	Devices demonstrating this technology been in constant operation at sea for over a year. The delivered power generation capability of these demonstrated devices is unknown.	
Summary			
Economic opportunity	Amber	The main rotating mass device is currently the Wello Penguin. While other groups are developing rotating mass WEC devices they are mainly University groups and lack the funding or interest in developing the technology to a commercial level.	
Technical feasibility	Green	Rotating mass devices are a conventional technology that have been shown to be technically feasible.	

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7. Wello announced 10MW plant for installation in Bali. December 2017.

Title	Rotating mass	ID:	12
	https://wello.eu/2017/12/28/wello-supplying-10-mw-wave-energy-park-bali/ 8. Image Credit: https://upload.wikimedia.org/wikipedia/commons/2/25/JOE140514_128_Orkney.jpg		

Title	Bulge Wave	ID:	13
Conversion	Wave > Hydraulic flow Wave > Hydraulic pressure > Electric (with DEG)		

No open source image available.

Principle of operation	Current Use
The bulge wave concept converts a pressure wave impacting on one end of a sealed and fluid filled flexible rubber tube into a usable energy form to be exploited using a PTO. There are a number of models which explain the behaviour of the device. In general terms a bulge wave is formed within the tube which travels in front of the sea wave. The energy is then removed from the fluid flow in the tube and converted using a PTO. Some devices use a conventional PTO such as a water turbine, where others have dielectric elastomer elements in the tube walls, which directly generate energy as the bulge wave forces expansion and contraction of the flexible tube. Strictly speaking the bulge wave device is a WEC, with the elastomer being the PTO, however the architecture of some devices mean they are part of the same system. For this reason this sheet makes references to dielectric elastomers at the same time as the wave capture approach. The speed of the bulge wave down the tube is driven by the speed of the waves travelling outside the tube, and it also depends on the material properties of the tube and geometry of the tube.	This technology has only been investigated in wave energy. This technology is used in the ANACONDA WEC, currently being developed by Checkmate Seaenergy Ltd. This bulge wave WEC uses a sealed pressurised tube perpendicular to the direction of the waves travel. Waves impacting on tethered end of the device creates a bulge wave inside the flexible tube which travels at similar speeds to the external waves. The bulge wave gains energy and grows in amplitude as it travels along the tube. This internal bulge wave can be passed between high and low pressure reservoirs at one end of the tube and the energy can be extracted using a conventional turbine PTO. An alternative PTO for use with a bulge wave WEC is a dielectric elastomer. An example of this is used in the SBM S3 wave energy generator, where the walls of the bulge wave tube are made of a flexible dielectric material which generates power as it expands and contracts. A small scale prototype of the S3 concept was tested in a test ocean basin in France in 2010, with planned next steps being tests of scaled prototypes at sea. The target full scale S3 device would have a diameter of 4m, with a length of 400m and a generation capability of 2MW. Another bulge wave device is the AWS Electric Eel. This proposal has a dielectric elastomer integrated into the tube itself as the PTO, but they have also considered a hydraulic type PTO.

Maturity Evaluation			
Existing TRL	Justification	WEC TRL	Justification
4	In both the Anaconda and SBM S3 device concepts, small scale prototypes of the technologies have been demonstrated in tank tests.	4	In both the Anaconda and SBM S3 device concepts, small scale prototypes of the technologies have been demonstrated in tank tests.

Title	Bulge Wave		ID:	13
Assessment against criteria				
Criteria	**Score**	**Justification**		
Operate in environment	(green)	There are no current examples of bulge wave generators operating in marine environments however wave tank testing has been carried out. The main body of such a device would be made of rubber suitable for extended marine use and therefore able to operate in a sea water environment for an extensive period of time. There is no evidence to say that biofouling will cause major issues to the deformation of the tube.		
Survive loading	(amber)	Comparisons have been made by researchers between bulge wave concepts and other rubber or rubber-composite based products such as tyres. Over the life cycle of a tyre it will undergo many more cycles than would be expected by a bulge wave generator. Therefore it has been predicted that fatigue will not be a problem for such a device. The main technology element is the deformable tube, proposed to be made of rubber. Rubber undergoes instability when in the form of a pressurised tube. Aneurysms can develop due to imperfections in manufacturing, therefore careful quality control is required. If a non-homogeneous material was used other problems may occur over the life cycle as the multiple layers of the material flex, causing possible separation. Due to the nature of operation bulge wave devices are long compared to their diameter, and they may be acted upon by several waves at once across its length. In a high sea state this could cause the device to tear.		
Controllable	(red)	Much of the device will be passive (unless dielectric elastomers are used as a PTO) therefore it is unlikely that the loading on the device will be controllable and therefore the amount of power produced will be variable.		
Convert at scale	(green)	It has been estimated that a 7m diameter, 200m long ANACONDA style device would be capable of generating 1MW. The proposed full scale SBM S3 device has a diameter of 4m and length of 400m, which could potentially generate 2.5MW per device.		
Tolerant of irregularity	(amber)	Bulge wave generators are sensitive to direction as they must be perpendicular to incoming waves. Waves of varying frequency and wave height do not cause problems		
Power density	(green)	Proposed designs for bulge wave generators tend to have lengths over 100m and diameters around 7m. Such devices are extremely large however the materials used are relatively light weight. The hypothetical 1MW device was assumed to have a mass of 100 tonnes giving a specific power of 10W/kg or power density of 130W/m^3 if the power was taken off using a conventional turbine. This power density may increase with the use of specialist rubbers, or thorough the use of a dielectric elastomer material.		
Capital cost	(amber)	Bulge devices are expected to have a capital cost comparable or lower to existing wave energy converters. They typically use standard materials, and have minimal if any moving parts, however they would likely require custom tooling and manufacturing facilities. The capital costs of a S3 style device which uses a dielectric elastomer based PTO would cost more than a simple rubber bulge wave product, as the PTO material costs would be higher.		

Title	Bulge Wave		ID: 13
Operating cost			The rubber-composite tube would be expected to last the life time of the device and require very little maintenance. The power take off mechanism may require maintenance. A method of repairing localised failures or tears in the tube may be required depending on the rate at which manufacturing faults occur.
Efficiency			The capture efficiency of the bulge wave device itself is claimed by Southampton University to have a comparable efficiency to other conventional WEC designs, although no evidence has been found. The efficiency of the whole generation device depends heavily on the power take off system employed, conventional hydroelectric turbines have efficiencies of around 90%. Dielectric elastomer materials have been measured by PolyWEC to have conversion efficiencies of 30-35% under lab conditions although this will be significantly lower in a realistic environment. AWS claim efficiencies of 80-90% for their proposed electroactive polymer PTO material under optimum conditions. However AWS have not yet selected a particular material or identified how the PTO will be embedded in the walls of the bulge wave tube.
Maturity risk			Although it is currently possible to manufacture rubber tubes of the requisite size to the required tolerances, this type of rubber construction has not been tested under this kind of loading in this environment. Therefore there are maturity risks in scaling existing prototypes for full scale use. A dielectric elastomer tube on this scale may be more challenging to manufacture as it contains multiple layers which will be required to flex without breaking over many cycles.
Summary			
Economic opportunity			A dielectric bulge wave device could potentially offer power generation with an extremely low maintenance requirement, with a comparable capital cost to existing devices. However, it is uncertain if the balance between cost and efficiency would be sufficient to improve the overall LCOE.
Technical feasibility			The ANACONDA system is protected by a worldwide patent which limits development of the device to a single company (however the remit of this patent is not known). Manufacture of the main components of such devices are currently possible and so it is likely that working prototypes and test platforms could be developed for a reasonable level of investment. The WEC must still be proven to be capable of surviving in a marine environment for long periods of time without degrading or suffering damage from extreme loading.

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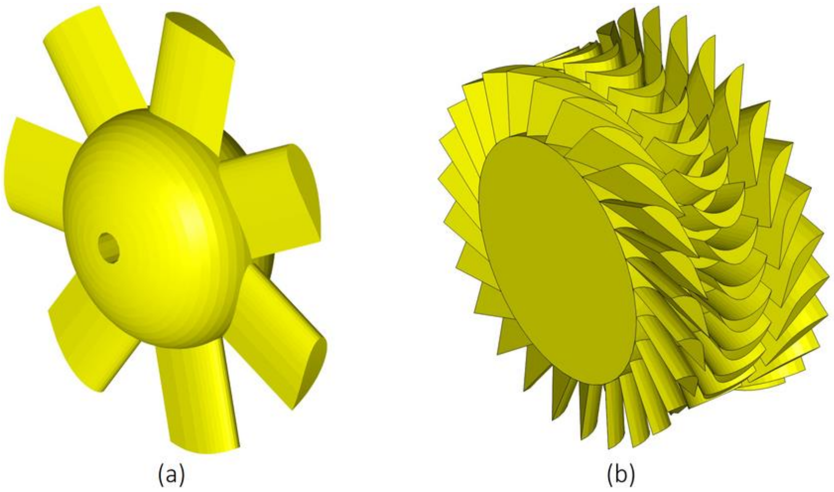
Title	Bulge Wave	ID:	13
7.	https://www.renewableenergyworld.com/articles/2008/07/anaconda-could-provide-up-to-20-mw-of-wave-energy-53012.html		

Title	Bi-radial Turbine	ID:	14
Conversion	Mechanical kinetic (fluid flow) > Rotating mechanical		



This diagram shows the difference in design between (a) a Wells style turbine, and (b), the biradial impulse turbine design

Principle of operation	Current Use
The Kymaner bi-radial turbine is a novel air turbine which aims to deliver a higher efficiency than a Wells turbine in a device with an oscillating fluid flow, such as an Oscillating Water Column (OWC). The bi-radial turbine is designed as an impulse turbine, which is highly axially compact and mechanically simple. The Kymaner design is based on an impulse turbine.	The Kymaner bi-radial turbine was developed as a part of the OPERA (Open Sea Operating Experience to Reduce Wave Energy Cost) programme. The Kymaner bi-radial turbine is designed to be mounted in an oscillating water column, with the intent of exceeding the conversion efficiency of a Wells Turbine by at least 50%, and improve the reliability of the PTO. Small scale tank testing proved the feasibility of the concept, and a 1:16 prototype has been tested in sea water at the Bimep wave energy test site. The theoretical peak efficiency of the turbine is over 80%, however average operating efficiencies will be lower than this value.

Maturity Evaluation

Existing TRL	Justification	WEC TRL	Justification
4	Scale prototypes of the technology have been demonstrated in a relevant tank test environment.	4	Scale prototypes of the technology have been demonstrated in a relevant tank test environment.

Assessment against criteria

Criteria	Score	Justification
Operate in environment		The bi-radial has been specifically designed for operation in air in a wave energy generation application. It is also mechanically simple and compact. Conventional management of corrosion (e.g. material selection) and biofouling (less likely in an air chamber) are likely to be sufficient.

Title	Bi-radial Turbine	ID: 14
Survive loading		Automated or manual valves can limit or stop airflow through the device, minimising the effects of extreme loading on the PTO. Fatigue design for rotary machinery is well understood.
Controllable		The airflow into the turbine is controllable through valves controlling the inlet flow. An inlet cut off valve is planned for inclusion in the design, which would increase protection in severe sea states. The controllability is also dependent on the generator used with the turbine. Loads on the turbine can be managed by altering the torque demand from the attached generator. The compressibility of air means that the load imparted on the rest of the WEC would not be very controllable.
Convert at scale		The turbine has been designed to be suitable for installations in excess of 1MW and, as it is physically compact, it would be suitable for mounting within a WEC device.
Tolerant of irregularity		Air turbines mounted in an OWC are highly tolerant of irregularity, and design solutions to smooth the rotational inertia of the turbine to smooth the power output have been proposed. For peak efficiency the turbine should operate at its design tip-speed ratio, which varies through a compression-expansion cycle.
Power density		The power density is likely to be comparable, if not greater than a Wells turbine. The power of a turbine is dependent on the volume flow rate of air and pressure across the turbine, both of which can be optimised by the system design. The efficiency is expected to be comparable to other PTOs. However, this has not yet been proven in a scale or full size demonstrator.
Capital cost		The capital cost of the full size bi-radial turbine is not known, however a key design goal of the development project is to reduce the levelised cost of energy by 30%, so it is likely that this could offer a benefit over current air PTO solutions.
Operating cost		The operating costs are likely to be highly comparable for a bi-radial turbine and a Wells turbine. Although it has a complex geometry it is a single component therefore the need for maintenance is likely to be minimal if made from robust material (e.g. a steel variant).
Efficiency		The theoretical peak efficiency of the scale prototype exceeds 80%, however the operating efficiency will be lower than this due to losses in the system, potential fouling, and suboptimal inlet conditions. Results from laboratory tests from the development of the bi-radial turbine indicate a 50% improvement in peak efficiencies over current air turbines.
Maturity risk		There is moderate maturity risk in implementing a bi-radial turbine at full scale as extended full load trials have not been completed. However there is funding in place and development plans to mature the technology to full scale sea trials.
Summary		
Economic opportunity		Bi-radial turbines have an opportunity to be an optimal air-based PTO. They can likely offer greater efficiencies and future designs may provide more consistent and smoother rotating mechanical output over existing Wells turbine designs.

Title	Bi-radial Turbine		ID:	14
Technical feasibility		The bi-radial turbine concept requires further development and trials before use in a full scale wave energy converter. Published trials have not yet included operation over a long period onshore or offshore, so there is little data regarding maintenance, performance after biofouling impacts or resistance to high sea states. However, due to their simple operation they are likely to be feasible.		

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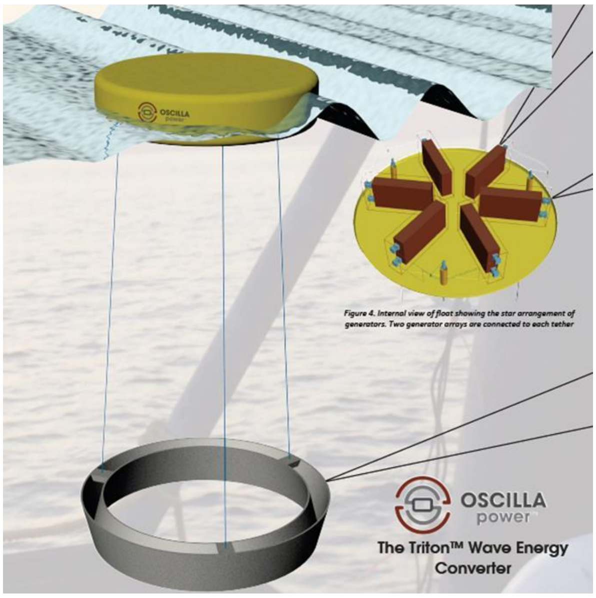
Title	Magnetostriction	ID:	15
Conversion	Mechanical (strain) > Electric		



Detail showing how six magnetostrictive generation elements were used in an early Oscilla Power concept

Principle of operation	Current Use
Magnetostriction is a property of some ferromagnetic materials, where a mechanical strain on the material changes its magnetic properties. Magnetostrictive generators work by exploiting specific alloys which produce significant magnetic flux changes under high force and low displacement mechanical loads. This changing magnetic field induces electric currents in coils of wire within the generator unit, allowing an effectively direct conversion of mechanical strain to electric energy. Magnetostrictive generators have few, if any, moving parts in the generation element, however may be combined with gearing mechanisms to amplify the displacement seen by the generator.	The most significant progress into wave energy magnetostrictive electricity generation is currently being led by Oscilla Power Inc, who are developing the 'Triton' WEC. This system uses a surface float tethered to a submerged heave plate, which the float can react against. The original design used six magnetostrictive generator elements mounted inside the surface float along with a gearing system which optimised the generator displacement for the wave state. There has been limited discussion of the magnetostrictive element in the last 3 years, with the focus being on the PTO technology through the WES programme. Previous designs of magnetostrictive generation were also proposed by Oscilla Power in the form of multiple small generators forming links of a chain tethering a buoyant body to the ocean floor. The concept proposed that electricity would be generated through the movement of the float tensioning and relaxing the mooring chains.

Maturity Evaluation

Existing TRL	Justification	WEC TRL	Justification
5	For generation purposes, magnetostrictive generation has been demonstrated with prototype devices, but not full system solutions.	4	Prototype magnetostrictive generation systems are under development in a laboratory marine environment.

Title	Magnetostriction	ID:	15

Assessment against criteria		
Criteria	**Score**	**Justification**
Operate in environment	Green	Magnetostrictive generators are ideally suited for operation in remote and marine environments, as they are robust, easily protected against water ingress and do not require regular maintenance.
Survive loading	Green	Surviving linear tensile loads should not be a major issue for these generators, and the generator mounting designs should be able to limit torsion loading.
Controllable	Red	The electricity generated will be directly proportional to the loading on the generator, which cannot be controlled itself. Use of gearing mechanisms can amplify or reduce the amplitude of the displacement, however this will add complexity to the system.
Convert at scale	Amber	Individual magnetostrictive generators are limited by the specialised materials available and the magnitude of the loading which can be placed upon them. This technology is highly suited to scale using arrays of generators, whether there are multiple PTO units in a single WEC device, or multiple WEC and PTO devices deployed in an area.
Tolerant of irregularity	Green	Magnetostrictive generators are highly tolerant of irregular inputs, however the electrical output will reflect the irregular input. The mechanical input can be smoothed using active gearing.
Power density	Amber	Magnetostrictive generators can produce energy at high efficiencies from the mechanical input, and can simply be mounted in dense formats alongside existing WEC concepts. The technology is highly suited to scale using arrays of generators, whether there are multiple PTO units in a single WEC device, or multiple WEC and PTO devices deployed in an area.
Capital cost	Amber	The manufacturing costs of a magnetostrictive generator may be moderately high, depending on the materials used, however if mounted in a simple surrounding structure as proposed by Oscilla Power, the overall cost of manufacture and installation of the wave to electrical energy system could be low compared to other devices.
Operating cost	Green	The operating cost of the generator technology is likely to be extremely low, as they are do not require much maintenance once installed. This is highly dependent on the WEC that the PTO generator is mounted in.
Efficiency	Green	The efficiency of magnetostrictive generators can be high. The published figures for the Triton WEC show a mechanical to electrical efficiency exceeding 75%, however it is unclear whether this is through the linear generator or magnetostrictive PTO.
Maturity risk	Amber	Although there has been significant investment and design effort into developing commercial magnetostrictive generation from wave energy, the maturity risk remains moderate as it has not been shown to perform at full scale, or for long enough to prove itself as a commercially secure option.
Summary		
Economic opportunity	Green	Magnetostrictive generation provides a potential opportunity for high volume energy conversion, with a low maintenance requirement. Installed in a suitable WEC device, the overall wave energy generation device could be

Title	Magnetostriction	ID:	15
		installed at low cost compared to other solutions, with a high likelihood of surviving extreme loading under high sea states.	
Technical feasibility		The technology has already been demonstrated at small scale, and is in development towards full scale trials. The magnetostrictive generator concept could be implemented in many forms of WEC, however this would require significant development and testing investment.	

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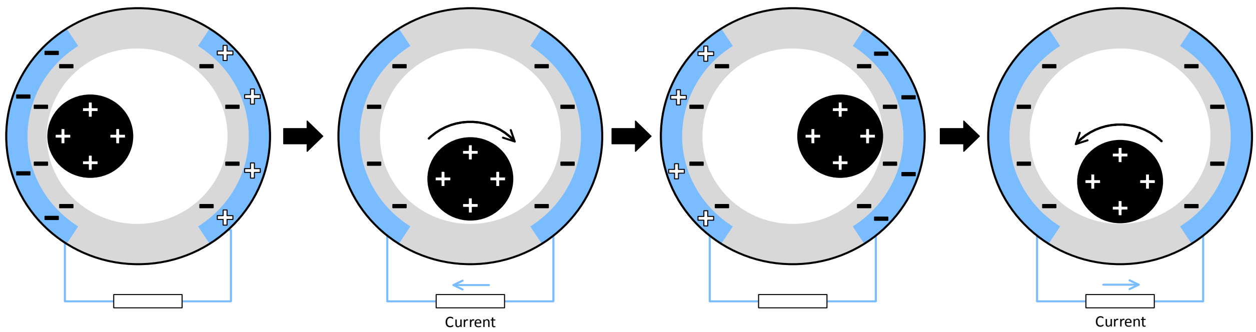
Title	Triboelectric Generation	ID:	16
Conversion	Mechanical > Electricity		



A diagram showing the working principle of a shell and ball design held triboelectric generator

Principle of operation	Current Use
Triboelectric generators work on the principle that some materials can become electrically charged through friction contact. This charge can be turned into a current via the use of diodes. These generators have also been proposed in concepts with small volumes and power outputs. These are referred to as "nanogenerators". Recent academic and industrial research has produced small devices which can produce electrical output from a mechanical input.	A research group at the Georgia Institute of Technology has been developing useful, low power triboelectric nanogenerators. They have produced a prototype triboelectric nanogenerator which is a disk about 10cm in diameter. At peak rotational speeds of 3000rpm, this prototype generated 1.5 watts, with an energy conversion efficiency of 24%. This is much greater than the efficiency of piezoelectric generators (typically around 5 - 10%). The high speed rotational format of the prototype generator is not overly suitable for wave energy use. The research group has proposed a wave energy generation array made from a multiple strings of 6cm diameter spherical generators suspended from a float. In this proposal, each generator could be agitated at 2 to 3Hz and produce 1 – 10mW. The team has demonstrated an array of 400 generators connected in a 4m^2 area. Based on the measured output of a single triboelectric nanogenerator unit in a wave environment, this could equate to a 1.15MW output for a 1km^2 array.

Maturity Evaluation

Existing TRL	Justification	WEC TRL	Justification
4	Demonstrations of triboelectric generation technology elements have been shown in a laboratory setting.	3	For wave energy applications, triboelectric options have been analysed, however no demonstrations have been published.

Title	Triboelectric Generation	ID:	16

Assessment against criteria

Criteria	Score	Justification
Operate in environment		The individual generators are housed in a sealed unit, and have been demonstrated in a water environment. The housing for the generators use conventional marine materials, so should be able to survive long term in the marine environment.
Survive loading		Individual generator units will be able to survive the peak loading, however the tethering mechanisms are unknown, and therefore there may be significant technical risks in developing a large scale array of tens to hundreds of thousands of generators.
Controllable		The power output or loading experienced by triboelectric nanogenerators is very difficult to control. The main method through which this could be done would be to physically isolate the generator unit from any mechanical input.
Convert at scale		In theory the array size for triboelectric nanogenerators could be technically viable at any scale, although in all instances it will be made from a large number of small elements.
Tolerant of irregularity		These generators would be highly tolerant of varying input, generating power from any wave direction, period and amplitude, however the output electricity will reflect this irregular input. The output power would likely require conditioning to allow it to be efficiently transferred and to reach grid quality.
Power density		A generator array suitable for grid supply power would likely be much larger than a more conventional WEC design. Current demonstrated technologies have a rough power density of $1W/m^3$
Capital cost		The capital cost per generator is unknown, as marine ready triboelectricity is still only at the laboratory development stage. It is likely that the installation costs of a triboelectric array would be lower than for a conventional WEC as it would only require simple tethering and conventional transmission systems. A key difficulty would be electrically connecting large numbers of elements.
Operating cost		The operating cost is likely to be lower than conventional WEC systems as minimal maintenance is required. An economic downside of a wide area system such as a triboelectric array would be that the total area required would exclude any other economic activities from occurring in that location. Multiple individual units could fail before requiring replacement.
Efficiency		The efficiency of triboelectric converters is higher than other energy harvesting devices. This device only has a single conversion in the conversion chain from mechanical wave energy to electricity.
Maturity risk		This is a very immature technology, and would likely require significant investment to develop both the technology in general and specifically for commercial scale wave energy use. However the simplicity of the technology and relative ease of developing prototypes lowers the maturity risk.

Summary

Economic opportunity		Individual triboelectric elements are simple and could be easily engineered to withstand the environment, leading to relatively low maintenance costs.

Title	Triboelectric Generation		ID:	16
		Also the elements are relatively simple so the capital cost is moderate. However the low power density tempers the opportunity.		
Technical feasibility		The use of triboelectric nanogeneration is feasible, as the technology has been demonstrated with simulated water agitation, however the very low power density means that generation at scale is not feasible as it will require vast devices in the current forms presented.		

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Title	Dielectric Elastomer Generators (DEG)	ID:	17
Conversion	Mechanical > Electric		

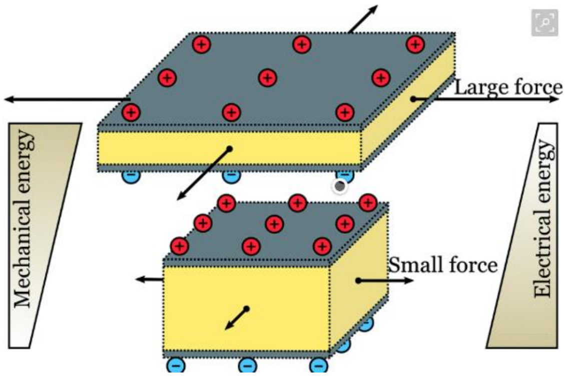

Diagram showing the basic principle of a mechanical load on a dielectric elastomer

Principle of operation	Current Use
A dielectric elastomer (DE) is a material which can turn an applied mechanical force into an electrical output. They are formed by layering elastomer films between electrodes. As the materials deform under loading and return to the original shape due to the elastic properties of the material, electric charge is collected on the electrodes, which can be exploited as electricity. The energy generated is determined by the strain placed on the material, this may be limited by the force available from the waves rather than material choice. The frequency of operation can be more varied than other sources such as piezoelectric generation as a slower motion will still cause energy to be produced.	For wave energy generation, DE technology has been tested by a number of research groups but is not currently in use on a commercial system. The EU funded PolyWEC project (2012- 2015) looked at three separate methods of capturing wave energy and converting it using DEs. Testing was carried out in lab conditions in a wave tank to determine the suitability of the use of DE in wave energy generation, including investigating potential power output and efficiency. In 2017, results were published from the University of Tokyo showing tests of prototype DE wave generators in a marine environment over a number of days. The trials proved that wave energy generation using a DE PTO was achievable, and was able to consistently generate power in simulated low sea states. Following this test, they are developing a full scale buoy generator capable of generating 2kW per unit for deployment in 2019. This unit will be made up of a small array of 20 DE generators. In 2013 Bosch published a report detailing their concept DE PTO device. This was a many layer stack of DE elements, which would be attached to the sea bed. This would be tethered to a floating point absorber, and the vertical motion of the float would stretch the DE PTO and generate power. There was no further evidence found that this concept was pursued to trial or prototype phase.

Title	Dielectric Elastomer Generators (DEG)		ID:	17
Maturity Evaluation				
Existing TRL	Justification	WEC TRL	Justification	
9	DE transducers are currently widely used for small scale strain gauges.	5	Very small scale prototype PTO devices have been tested in a marine environment	

Assessment against criteria		
Criteria	**Score**	**Justification**
Operate in environment	Green	The technology has currently been shown to work in wave tank and simulated marine environment testing. Flexible polymer coatings can be applied to the DE element, to provide protection from the marine environment, ensuring they have similar strain recovery properties to the DE. There are no current examples of the technology working in a marine environment over a long period of time. A research project has tested the technology over a period of 4 days with success, however there is confidence that the technology would be suitable for long term deployment.
Survive loading	Amber	Fatigue should be avoidable as long as the material is kept in the elastic region of strain. One study showed that devices with 25% linear strain suffered no degradation after 85,000 cycles. The loading of the material in extreme cases could cause the material to be damaged however this depends on how the mechanical load is applied from the waves to the DE. Particularly large areas of unrestrained DE are more susceptible to peaky/complex wave climates.
Controllable	Red	A flexible DE membrane in the form of a bulge wave WEC would lack the ability to be controlled easily or predictably. A larger device would be unwieldy and extremely difficult to control as it would interact with several waves at once. Control may be simpler when combined with other WEC concepts, however the control would likely have to be mechanical damping from the WEC, rather than from the PTO itself.
Convert at scale	Amber	Manufacture of large sheets of DEs is currently not possible to high tolerances. There were no working examples found of devices over the 25cm scale. Multiple layers of DE can be stacked to provide a greater power density although this depends on a suitable mechanism to transfer strain from the waves to the multiple layers. For some generation method, such as the surface sheet, scaling up may require many small sheets rather than a single large one in order to avoid having voltage vary dramatically between wave peaks and troughs disrupting the flow of power.
Tolerant of irregularity	Amber	DEs can generate power at a variety of frequencies. During very small scale testing, small quantities of power (e.g. suitable for powering an LED) have been generated with relatively small wave heights.

Title	Dielectric Elastomer Generators (DEG)	ID: 17
Power density		With currently demonstrated materials and WEC combinations, the power density is very low. However, proposals for dielectric PTOs with a bulge wave and point absorber WEC could generate small scale power, in the very wide range of 2kW up to 1MW. This is likely to be less power dense than current solutions. Current dielectric elastomer materials available from Parker Hannifan offer specific power of about 170W/kg, with a material density around 1000kg/m^3. Scaling this into a 1.5mm thick film generator, the power density of this generator would be 255W/m^2. Scaling this value indicates that a 1MW generator requires a dielectric elastomer area of approximately 4000m^2.
Capital cost		DEs can be made from readily available materials, and the manufacturing processes are known and comparable to conventional composite rubber manufacturing. Cost estimates from the PolyWEC project are in the region of €250-€2000 per KW. For a hypothetical 1MW system, this could indicate capital costs comparable to current options.
Operating cost		Maintenance of the DE PTO should be minimal, the only replaceable part would be the electrodes. Piezoelectric elements are typically zero maintenance devices, however total replacement is required when they fail. Maintenance of the DEG is highly variable on the WEC prime mover it is used with. Operating costs for a conventional style device using a DEG PTO will have similar maintenance costs to current mechanical devices.
Efficiency		PolyWEC measured efficiency of 30-35% under lab conditions although this will be significantly lower in a realistic environment. This is notably lower than other PTOs.
Maturity risk		There are many components of large scale and viable DE generators which require significant development before the technology is ready for commercial use. There is little data available regarding multi layered DE devices used in generation conditions. Current DE elements are physically small scale, generating small amounts of power. Scaling this up may have significant technical issues to overcome, to manufacture large devices, and also to enable useful levels of power generation, which would be out of WES's target timescales. Previous studies have noted that DEs are not ready for use yet.
Summary		
Economic opportunity		Dielectric elastomers are lightweight, fairly inexpensive and can easily be formed into multilayer sheets. However there is significant technical risk in maturing this technology, which would require a step change in power output for wide spread use in wave energy applications. The advantage is that it could be used as the PTO alongside many WEC concepts, and can produce power effectively from small waves at low frequencies
Technical feasibility		With current materials DE wave energy generation is not feasible. It is likely that it would require significant investment to mature the technology options for use in a deployable system, including multiple trials to prove its ability to survive extended use over multiple years, and extreme weather conditions in order to be a viable source of power generation.

Title	Dielectric Elastomer Generators (DEG)	ID:	17
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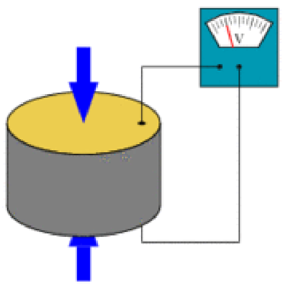
Title	Piezoelectric generators	ID:	18
Conversion	Mechanical > Electric		



This shows a simple representation of a piezoelectric generator. An applied force across the piezo element can generate a usable current output.

Principle of operation	Current Use
A piezoelectric generator relies on the piezoelectric effect, which is the conversion of mechanical energy to electrical energy by applying a stress to a piezoelectric material. Many materials exhibit this effect, including natural crystals such as quartz, synthetic ceramics, and biological materials such as bone or some proteins. Piezoelectric generators can be used to generate power either by applying stress directly to a piezoelectric material or by using a thin layer of a piezoelectric material applied to a flexible backing. In this from it gives a material similar to a dielectric elastomer.	There are currently no commercially operating WECs using piezoelectric generation. They are commonly used as sensors, for example in strain gauges and power monitoring, and can be used as actuators by applying a voltage to the material. There have been many published studies into the potential for piezoelectric electricity harvesting. This includes generating energy from the vibrations produced by pedestrian or vehicle traffic. An academic study, published in 2013 investigated integrating piezoelectric elements within a thin statically mounted panel, which was excited when struck by a wave. This was placed on the wall of a small scale wave tank. This study demonstrated that it was possible to generate power from wave energy using a piezoelectric PTO, and showed a positive correlation between the wave force and power output. Flexible piezoelectric devices have also been tested in academic studies in various orientations to determine efficient positioning as well as methods to predict performance of such devices. There have been academic proposals for large flexible membranes which would sit on the ocean surface and generate power as they flex with the waves motion, in a similar motion to a flag flapping in the wind. There have also been proposed floating structures which suspend flexible piezo generating materials below the surface. A prototype point absorber using a piezoelectric PTO was tested in 2013 which used a wave excited pendulum to strike a piezo element. The test lasted one day in sea state 1, and generated 9mW, and proved suitability in generating electricity for very low power sensor applications.

Title	Piezoelectric generators		ID:	18
Maturity Evaluation				
Existing TRL	Justification	WEC TRL	Justification	
9	Piezoelectric transducers are currently widely used for many applications in industry. They have also been demonstrated in small scale energy harvesting applications.	5	Simple ocean tests have proven power generation potential for piezoelectric PTOs. Laboratory tests have demonstrated higher power solutions using a water tank test using generated waves as the mechanical input.	

Assessment against criteria

Criteria	Score	Justification
Operate in environment		The technology has been shown to work in lab testing for both fixed panels and flexible applications. Piezo elements are simple to design to be resistant to the marine environment by sealing them in a flexible material. There were no relevant applications found of this technology operating in a power generation marine environment.
Survive loading		There is insufficient data on the long term survivability of piezoelectric generators in marine environments, however it is likely that the ability to survive loading would be comparable to existing wave energy systems. Piezoelectric generators are likely to require engineering of the supporting systems to be able to operate within their elastic limits however this is also required in many current conventional wave energy systems. Large scale sheets of piezoelectric material resting on the ocean surface spread over a number of wave crests could experience fatigue failure depending on the specific material employed. The panel-style devices demonstrated in the wave tank tests used multiple conventional piezoelectric elements, which should be able to survive high sea state loading.
Controllable		The controllability of the system depends on the mechanical system employed to transfer the force between the PTO and the waves, it is unlikely that the piezomaterial itself can be controlled.
Convert at scale		Most current large scale energy generation methods using piezoelectricity involve harvesting from vehicle traffic. Scaled experiments have shown capabilities of generating up to 450kWh. However this relies on the higher frequency traffic oscillating input, rather than the lower 0.05-2 Hz frequency that wave inputs would provide. Static panel style piezo generators intended for use in waves will likely have significantly lower power density than current wave energy conversion methods.
Tolerant of irregularity		Panel style wave energy devices will be sensitive to the orientation of the waves in order to generate power. Flexible sheet style devices could be suitable for use in all wave directions. Piezo electric devices in general tend to operate at much higher frequencies than those found in wave loading so many of the proposed devices transfer this energy through another mechanical link first, in order to maximise the amount of useful energy that can be captured by the converter.

Title	Piezoelectric generators	ID:	18
Power density	(red)	Power densities for a variety of designs were calculated in the study on piezoelectric devices for ocean energy by Jbaily and Yeung. This found that bodies fixed to the bottom of the ocean this would have a power density around 13W/m^2. Flexible surface membranes could provide power up to 20mW/m^2 and as such would require vast areas to provide a meaningful amount of power. This is significantly lower than current wave energy devices.	
Capital cost	(amber)	Piezoelectric elements can be relatively cheap and easily sourced. Panel style devices could be easily produced on a large scale for a low capital cost. However significant numbers and area of panels would have to be used in an array to generate at scale. A more conventional device which transfers the wave energy through a mechanical linkage to a piezoelectric device could also be a viable option although the costs per device are likely to be similar to current prices as the prime mover and mechanical conversion systems would be broadly similar to what is currently available while the generation capacity would be reduced.	
Operating cost	(green)	Piezoelectric elements are typically zero maintenance devices, however total replacement is required when they fail. Maintenance of the WEC used with the piezo PTO will likely be less than existing devices.	
Efficiency	(amber)	Maximum efficiencies for conversion of mechanical strain to electricity are around 50%. Flexible piezoelectric devices have a higher efficiency than rigid devices.	
Maturity risk	(red)	Piezoelectric elements are current available at low cost and can be mass produced in a variety of forms suitable for power generation. Many of the current devices are used to harvest power from high frequency sources and significant development effort is required for use with lower frequency wave generation. For wave energy applications, this technology has only been demonstrated on small scale laboratory tests, not a marine environment. There are a number of possible routes which development could focus on from flexible membranes, piezoelectric panels and conventional devices where the method of harvesting power is through a piezo electric device.	
Summary			
Economic opportunity	(amber)	Although piezoelectric generation appears to be a robust, low maintenance technology, the low power density and risk of technology development mean that the opportunity is moderate at best. Devices such as panels have potential on a small scale to generate power in particular applications such as for harbour walls or generating small amounts of power at the base of existing structures however lack strong potential for power generation on a commercial MW scale.	

Title	Piezoelectric generators		ID:	18
Technical feasibility		It is already possible to produce piezoelectric devices at low unit cost and it seems feasible for them to operate in the marine environment with a moderate amount of protection. However, many piezoelectric devices would be required for useful scale power generation, and testing of such devices in realistic marine environments has not been done. Without significant investment and step change improvements in performance, it is unlikely that piezoelectric devices have suitable power density and able to convert at scale to be competitive with current wave energy technologies.		

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Title	Magnetohydrodynamics	ID:	19
Conversion	Mechanical > Electricity		

SARA Inc MHD generator – 100kW demonstrator

Principle of operation

Magnetohydrodynamics (MHD) refers to the physical interaction effects between magnetic fields and the motion of electrically conducting fluids. The principle is that a conductive fluid moving within a magnetic field can induce an electrical charge (generating power) and conversely, magnetic field and electrical charge can induce movement within a conductive fluid. Seawater is a conductive fluid, although it has relatively low conductance.

MHD generation conventionally utilises a high temperature working fluid, typically a plasma (ionised, and therefore conductive, gas) produced by fossil fuel combustion. This process produces useful energy at a high theoretical efficiency, however traditional fossil fuel generation using steam turbines can achieve higher operational efficiencies at a significantly lower cost, so MHD generation has not been widely used on a large scale.

Current Use

In the marine environment, MHD principles are most commonly used for propulsion, using strong electromagnetic fields and electrodes to produce a jet of water. This has been proven in prototype commercial and military ships, and has advantages over conventional propulsion due to near silent operation, and minimal moving parts.

The concept of using magnetohydrodynamics to generate power from wave or ocean energy has been around for a long time, as shown in patents from 1991 and 1977.

A company called SARA Inc, based in California, have patented a proof of concept 100kW MHD generation demonstrator unit. The patent concept involves a MHD unit suspended in deep water, connected to a surface float arrangement. The reciprocating motion of the float relative to the deep water unit forces water up and down through the submerged MHD device. The water flows through tubes in the MHD device inside a strong magnetic field, which develops an electric current in the moving fluid. Electrodes within the tubes pick up the current and remove it for transmission or storage. Detailed evidence of this concept being manufactured or results from testing was not available, and SARA Inc does not seem to be currently pursuing any wave energy systems.

More recent research has focused on using a liquid metal as the working fluid. This concept involves capturing the reciprocating wave motion or surface waves in a floating tube device. This motion causes a liquid metal to move back and forth in a channel within a powerful magnetic field

Title	Magnetohydrodynamics	ID:	19
	to generate an electric charge. This charge is collected through electrodes mounted in the channel. As with the SARA Inc device, there was no evidence found of manufacturing or testing a liquid metal MHD device such as this. Limited research has been done into very small scale (~0.1-10 watts) MHD power harvesting. It has been identified that MHD generation could be a valid source of power for marine biosensing and data logging equipment, however the predicted power output is very low, and likely unsuitable for commercial wave energy generation.		

Maturity Evaluation

Existing TRL	Justification	WEC TRL	Justification
7	MHD in use in conventional power generation.	2	Concept designs identified, no evidence of prototypes or results found.

Assessment against criteria

Criteria	Score	Justification
Operate in environment	Green	Although no evidence of wave energy capturing devices have been found operating in the marine environment long term, MHD principles in the form of propulsors have been proven to work in the marine environment.
Survive loading	Green	The MHD generator itself is a solid state system, which could easily be designed to withstand marine loading. There are multiple mechanisms which could be used to direct water through the generation channel, and it is perceived that these could simply be designed or modified from existing and proven marine devices.
Controllable	Green	The power output from the device could be controllable through electrical control of the electrodes. However mechanical means of altering the flow through could also be used. Both methods might be possible for altering the loading on the device.
Convert at scale	Amber	Individual MHD generators may be difficult to scale to the specific use case or location requirements, as a flow of fluid is required to drive them, however smaller MHD generators could be used in an array to produce the desired output. Proposed systems for other applications have been ~100kW.
Tolerant of irregularity	Amber	The design of the fluid inlet should allow smoothing of wave irregularity, however the electrical output will likely require typical levels of power conditioning.
Power density	Red	Assuming flow speed of 10m/s, sea water conductivity of 5S/m and magnetic field strength of a commercially available Magnetic Resonance Imager (1.5T) provides a power density of ~280W/m^3, however such MRIs focus this over a very small area and have a much greater power draw of 18kW. Therefore a comparable device would actually consume energy. Power produced scales with the square of field strength, however more power would also be required. Permanent magnets produce less than 1T

Title	Magnetohydrodynamics	ID: 19
		(leading to <60W/m^3) which is poor compared to a Wells turbine with a density of over 5000 W/m^3.
Capital cost		The capital cost of a MHD generator is likely to be relatively high due to the specialised permanent magnets (required to minimise power draw), large volume to achieve sufficient power and high conductivity materials which may be required to achieve the high efficiencies of conversion which are desired.
Operating cost		An operational MHD system should have low operating costs as it should require minimal maintenance as the technology has few if any moving parts. Biofouling may be an issue, however this could be managed through self cleaning designs.
Efficiency		The efficiency of sea water MHD for power generation is currently unknown, but is likely to be moderate (assuming permanent magnets are used).
Maturity risk		MHD is at an extremely low TRL in the marine generation environment, and there is significant technical risk in developing a concept design to a usable prototype suitable for marine deployment.
Summary		
Economic opportunity		MHD requires flow through it, therefore it is analogous to a water turbine. A key benefit is the lack of moving parts making maintenance easier, however the likely relatively low power density and relatively high cost are detractors. There are significant technical hurdles to overcome to produce a financially viable prototype.
Technical feasibility		MHD approaches have been used for marine drives, and some investigation into marine generators has been undertaken, however a sizeable investment would likely be required to develop this technology to a reasonable TRL.

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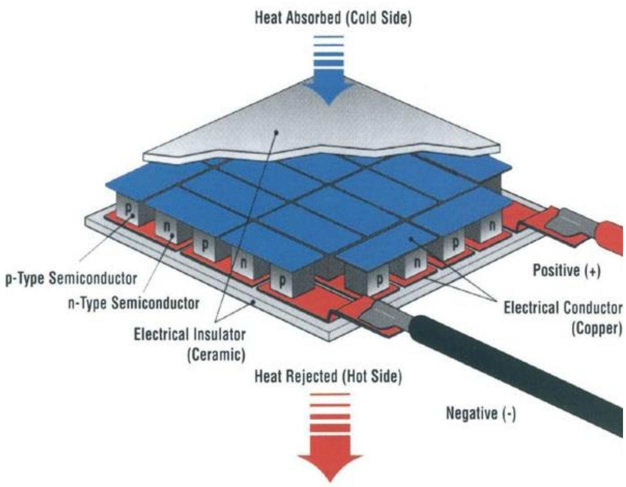
Title	Thermoelectric Generators	ID:	20
Conversion	Heat > Electricity		



A schematic of a thermoelectric generator panel

Principle of operation	Current Use
A thermoelectric generator works by turning a heat flux into electrical energy. Two dissimilar metals joined together at different temperatures may create a voltage difference providing electrical power (Seebeck effect, discovered early 1800s). Electrons flow from the hot side to the cold side. Sought after material properties are a high electrical conductivity and a low thermal conductivity. There is a limited set of materials suitable for use in thermoelectric power harvesting, however more are being developed through academic and industry research. The major limitation with this technology is its reliance on a large temperature gradient during operation. The Carnot efficiency of the system depends on the temperature difference between the plates, a higher difference in temperature will give a higher efficiency.	There are currently no devices using thermoelectric generators in wave energy applications. A potential application of this technology to wave energy is as an add-on to an existing generator to capture waste system heat using the ocean as a cooling source. In other applications, thermoelectric power is widely used on long range space craft traveling to the outer solar system where the heat source is a radioisotope. There are also a number of small scale personal devices which use thermoelectric generation to harvest power from people such as wrist bands. Another area of development has been devices fitted to car exhausts to harness waste heat. Such devices have also been proposed to harvest waste heat in industrial processes and power generation.

Maturity Evaluation

Existing TRL	Justification	WEC TRL	Justification
9	Thermoelectric generators have been widely used in some specialised applications, and qualified through long term use.	2	Thermoelectric generation has not been applied to a wave energy device, however it has been proven in a marine application.

Title	Thermoelectric Generators	ID:	20

Assessment against criteria

Criteria	Score	Justification
Operate in environment		There are no current examples of thermoelectric devices being used in a marine environments for long periods of time. However they are solid state devices, with no moving parts and can be sealed. Biofouling on the plate could cause the system to operate inefficiently as the temperature differential decreases. Current thermoelectric devices work in a variety of extreme environments including space applications and high temperature car exhausts.
Survive loading		Thermoelectric generators already exist which function under high temperature loading. The device is unlikely to be subjected to any large mechanical loading although this depends on how it is employed. They are solid state devices, with no moving parts and can be sealed. Extreme temperature loading to the point that the device would be damaged is extremely unlikely using currently available materials and a wave energy use case.
Controllable		The power output of a thermoelectric generator depends on the temperature difference. This would not be easily controllable in a wave energy scenario.
Convert at scale		Thermoelectric generators currently work at much smaller power levels than of interest to wave energy conversion. To increase this either a large surface area would need to be utilised, or a very high heat generated, both of which are unlikely in a WEC. It is possible to fit thermoelectric generators to many existing types of generator where there is waste heat. The technology is capable of converting large amounts of heat energy to electrical energy however this depends on the amount of waste heat generated in existing devices. It is unlikely that significant amounts of waste heat energy could be converted to electricity to provide a step change in the total electricity output of a device.
Tolerant of irregularity		Thermoelectric generation is extremely robust, power is generated as long as a temperature gradient exists between the hot and cold plates.
Power density		Power density of tested thermoelectric devices are low compared to systems used in conventional wave energy.
Capital cost		A standard commercial off the shelf 17W capacity thermoelectric generator costs around £50. A simple linear scaling, ignoring potential economies of scale and costs designing the array, gives a cost per MW of £2.9 million. However this is reliant on the maximum output from the thermoelectric unit which requires an unrealistic temperature gradient in the order of 400°C.
Operating cost		The devices are solid state and therefore require very little maintenance. Removal of biofouling may be required on the ocean side cold plate to prevent a reduction in efficiency which could be costly.
Efficiency		The efficiency of thermoelectric devices depends on the temperature difference. Most existing devices have efficiencies of between 5% and 10%. They may be useful as a secondary form of generation where the primary generation gives off waste heat however are unlikely to be a viable method of generating power from wave energy alone.

Title	Thermoelectric Generators		ID:	20
Maturity risk	(green)	As thermoelectric generators are solid state and only require a temperature differential across them it is possible for them to be built into a sealed unit (managing the thermal properties) and deployed in a marine environment. The key immaturity is having a system that can generate sufficient heat to convert.		
Summary				
Economic opportunity	(red)	Thermoelectric devices are very simple and robust devices, however their low power density and low efficiency make them inappropriate to be the primary PTO of a WEC. Thermoelectric devices may be used to marginally improve the efficiency of existing technologies which produce heat as a waste product. Adding minor generation capacity to a current device may be useful in some cases but is not likely to be economically viable or lead to a step change reduction in the cost of wave energy.		
Technical feasibility	(green)	It would be technically feasible to integrate a thermoelectric generator into a wave energy system due to their solid-state nature.		
References				

1. Image Credit: https://topmagneticgenerator.com/images/Thermoelectric-Generator-Diagram.jpg
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Title	Electrokinetic	ID:	21
Conversion	Wave > Electric		

No open source image available.

Principle of operation	Current Use
Generators based on the electrokinetic principle allow a direct conversion from wave energy to electric potential through solid state components. The electrokinetic effect generates power by exploiting the properties of the weak NaCl solution which makes up seawater. The fluid moves up and down a partially submerged electrokinetic generator from wave motion, and causes a periodic potential difference. The peak power output corresponds to the time of peak wave height. This type of power generation is highly suited to low frequency wave loading, and the initial studies suggest that the power output scales with the area of generator deployed.	The most developed proof of concept demonstrating electrokinetics in a wave energy application has been published by a research group at Jinan University in China. This team created film type electrokinetic generators, which tested various concentration combinations of graphene and carbon black powder as the film material. Electrodes were attached to the top and bottom of each 3cm by 5cm generator. The generators were tested in a small scale wave tank containing sea water. The generators are angled so that waves wash up the inclined surface of the generator. This study tested various parameters of the electrokinetic generators, including installation angle, water temperature, material dosage, wave frequency, and trialled different series and parallel generator arrangements. The power output from the generators was cyclical in correlation with the wave frequency, and had a peak power output of 297(±263) μW/m^2 demonstrating high uncertainty. Scaled linearly, and taking the mid value of 297μW/m^2, this corresponds to a generator film area exceeding 300km^2 to generate a peak output of 100 kW. There were no other examples found which considered the use of electrokinetics in a wave energy power generation scenario.

Maturity Evaluation

Existing TRL	Justification	WEC TRL	Justification
3	Small scale laboratory experiments have proven that it is possible to generate power using sea water electrokinetics.	3	Small scale laboratory experiments have proven that it is possible to generate power using sea water electrokinetics.

Title	Electrokinetic	ID: 21
Assessment against criteria		
Criteria	**Score**	**Justification**
Operate in environment		The very early stage study into sea water electrokinetic power generation indicated that the technology would be suitable for operation in the environment. The implications of suitability of long term deployment are unknown, particularly around the ability to operate with biofouling.
Survive loading		It is unknown how electrokinetic generators would survive under high impact loading. Technology development could focus on improving the resistance to impact, and investigating how the generators may be housed to improve the survivability without hindering operation. It is likely that they would have to be supported by a robust steel/concrete structure.
Controllable		The electrokinetic generator itself would not be controllable, and the energy generated would be proportional to the wave loading.
Convert at scale		As the research is so immature for the wave energy use case, it is highly likely that the generation capacity of electrokinetics could be improved following further research trialling different materials, however the level of achievable improvement is unknown. Development to grid scale generation capability would have significant technical challenges, given the issues around loading and biofouling. The current generator area required to produce suitable power outputs is not suitable for grid scale use. In order to be suitable for use in grid scale generation, the required step change increase in power density would likely have to exceed 100 times the current demonstrated capability. The power output from a generator farm should scale linearly with generator area.
Tolerant of irregularity		This type of energy generation is highly tolerant of irregularity, however depending on the housing design, may be sensitive to wave orientation.
Power density		Currently the power density achieved is not suitable for grid scale generation. Further development is likely to improve the density, however an improvement of 2 or more orders of magnitude is likely required for the technology to be a suitable alternative to conventional solutions. This level of improvement would be challenging and may be unachievable, given the issues around loading and biofouling.
Capital cost		The capital cost is unknown. Although the graphene and carbon base materials used in the demonstrator were low cost, the amount of material required to produce suitable quantities of electricity is large. It is highly dependent on the base materials and housing designs. Installation, tethering and power transmission costs should be comparable to existing wave devices.
Operating cost		The operating costs are unknown, but likely to be small due to the steady state approach.
Efficiency		The wave energy capture and conversion efficiencies are unknown.
Maturity risk		This is a very immature technology, with limited development and published research. There are many aspects which could be developed to improve the operating capability and suitability for use in a wave energy generation system.

Title	Electrokinetic	ID:	21

Summary		
Economic opportunity		The estimated LCOE from the published study was 0.17$/kWh. This is significantly lower than current wave energy solutions. However significant further research is required to validate this figure, and to consider the large step change improvements in performance which are required to have suitable power density to be competitive with current wave energy technologies.
Technical feasibility		Although the published results have demonstrated the principle, the technology and research is too immature to consider it technically feasible at scale due to its very poor power density.

References

1. Generators to harvest ocean wave energy through electrokinetic principle. Tana et al., https://www.sciencedirect.com/science/article/pii/S2211285518301733

Title	Magnetic Gearing	ID:	22
Conversion	Mechanical > Mechanical		

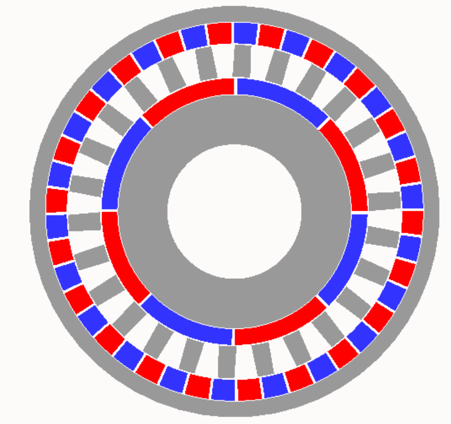

Diagram of a simple rotary to rotary magnetic gearing system

Principle of operation	Current Use
A magnetic gearing system is similar in concept to a traditional gearing system, however instead of transmitting force through the gear teeth, the force is transmitted through magnetic fields. This technology allows efficient transmission of high load mechanical torque, without contact between the input and output shafts, which minimises wear, potential for damage and can reduce mechanical losses in the system. A key characteristic of magnetic gearing is that the system allows for slippage if the forces exceed rated values without causing harm to the mechanism. Similar to a traditional gearbox, a magnetic gear system can convert rotary to rotary motion or between linear and rotary motion. Rotary to rotary gearing can have high ratios up to 200:1, which is suited for the low frequency input from wave loading and can step up to higher speeds more appropriate for a mechanical generator. Linear to rotary gearing allows conversion from low speed, high force linear motion into low torque, high speed rotor speed.	Magnetic gearing systems have been considered for use in many industries such as wind power generation and drilling to replace and improve upon applications using mechanical gearing systems. In most applications, the magnetic gearing system replaces a conventional gear system, however most proposals for use in wave energy generation combine the magnetic gearing system with a conventional PTO, to convert mechanical input into electric output in a single unit. Current prototype systems which have published results of development and testing have been rated to up to 10kW. Under the WES PTO programme, ECOSSE Subsea Systems are developing the Power Electronic Controlled Magnet Gear (PECMAG) system, which is an integrated magnetic gear unit and PTO. A partnership of ABB and Resolute Marine developed a prototype magnetic gear and generator system for use with an Oscillating Wave Surge Converter prime movers. It is not clear whether this programme is continuing beyond the production of the 10kW demonstrator.

Maturity Evaluation			
Existing TRL	Justification	WEC TRL	Justification
8	Magnetic gearing systems have been implemented in multiple industries, including long term deployments in harsh environments.	5	Magnetic gearing PTO technologies have been developed specifically for wave energy generation, however have not been fully tested in a marine environment.

Title	Magnetic Gearing	ID:	22

Assessment against criteria

Criteria	Score	Justification
Operate in environment		Magnetic gearboxes are suitable for operation in the environment, and would require similar protections against the marine environment as a conventional gearbox and electrical generator. The lower maintenance burden may make them a more suitable option for installation in remote or locations of low accessibility. However lessons may be learnt from the wind turbine industry, which has historically had high maintenance burden from EC&I issues, rather than from mechanical failures.
Survive loading		The magnetic gearing is capable of transferring the rated forces for power generation, and due to its safe slipping capability can safely handle overload.
Controllable		Magnetic gear systems can use digital control to provide precision system damping, regulation and smoothing.
Convert at scale		Current prototype systems which have published results of development and testing have been rated to up to 10kW. PECMAG are considering development and testing of systems capable of 100kW to 1MW.
Tolerant of irregularity		Magnetic Gears are highly tolerant of irregular input, however the output power will reflect the input irregularity.
Power density		With current magnetic gearing systems, the power density is not as high as conventional PTOs, however development is highly likely to achieve densities equal to or greater than current technology.
Capital cost		The PECMAC project has determined that the cost of a magnetic gearing and PTO system would be comparable to a similar output hydraulic system.
Operating cost		Magnetic gearing systems have a lower wear and lubrication requirements than a conventional gearing systems, which would indicate lower operating costs for a system with a magnetic gear PTO. However, other comparable industries have seen that EC&I systems can be the greatest maintenance burden on a system.
Efficiency		Some magnetic gear systems claim peak shaft to shaft efficiencies exceeding 99%. The PECMAG project claims efficiencies exceeding 80% across the full range of operating wave conditions for sea-states at prospective sites for WEC deployment.
Maturity risk		Current systems are not suitable for deployment in a grid scale wave energy system, however development is currently proceeding to build suitable scale systems.
Summary		
Economic opportunity		There is good opportunity for magnetic gearing systems to deliver a higher efficiency gearbox and PTO solution than conventional rotary mechanical or hydraulic systems. The magnet gear based systems could be more capable in safely handling peak loads, and require less maintenance.
Technical feasibility		Magnetic gears have been proven to be a capable technology in many industries, and the key features could be advantageous if used in a wave energy generator. The magnetic gearing PTO concept is applicable to many different WECs, in a rotary to rotary form as well as a linear to rotary form. However, current individual systems are not suitable for large scale power

Title	Magnetic Gearing		ID:	22
		generation, and development is underway to design and manufacture these larger systems.		

References

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Frazer-Nash Consultancy Ltd
The Cube
1 Lower Lamb Street
Bristol
BS1 5UD

T +44 (0)117 9226242
F +44 (0)117 9468924

www.fnc.co.uk

Offices at:
Bristol, Burton-on-Trent, Dorchester,
Dorking, Glasgow, Plymouth, Warrington
and Adelaide