Application of Technology, Knowledge and Practice from other Sectors

Landscaping Study

Final Report

WES_LS03_ER_TechTransfer

Revision	Date	Purpose of issue
1	27/06/2017	WES External Issue

Acknowledgements

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Executive Summary

Technology transfer may relate to fundamental physical principles, to knowledge or know-how, to adaptation of existing technology or to direct use of existing technology. Many examples of successful technology transfer across industries exist such as the adoption of Kevlar and Teflon in the consumer market, enabled by investment to meet space industry requirements.

The Wave Energy sector is an emerging and dynamic industry where numerous opportunities exist for novel applications of existing technologies and processes from other sectors. To achieve breakthroughs in affordability, wave energy conversion systems (WECS) must first secure survivability, high availability, a low capital and operational cost base and high performance. Drawing upon established or innovative technologies from other sectors offers the opportunity to accelerate progress.

Benchmarking of the existing wave energy sector has revealed a number of sub-system technology areas with large potential for improvement including: the control system, the WEC structure, the power-take-off (PTO) and the foundations and/or moorings.

An assessment has been carried out of the technological challenges facing the wave energy sector and of the cross-sector potential for technology transfer. As a result, a number of possibilities for future R&D activity have been proposed that could create substantial opportunities for the wave energy sector. These include:

- Adaptable structures technologies for survivability;
- Structural design optimisation technologies;
- Powertrain technologies;
- IT infrastructure and technology;
- Industry technology transfer workshop for:
    - Foundations and moorings
    - Connectors and cables

The proposed calls are based around technologies which have been identified as being proven or available from other industries.

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References

(1)	Tidal & Wave Energy Technology Benchmarking 2014 Update. Black & Veatch Ltd. ETI Marine Benchmarking. 05/06/2014
(2)	Marine Energy Technology Roadmap 2014. Energy Technology Institute and UK Energy Research Centre.
(3)	Qualification of New Technology. Recommended Practice. DNV-RP-A203. Det Norske Vertitas AS. July 2011

Definitions

Technology **Availability**: Measure of a technology's ability to contribute to enhanced reliability or maintainability.

Technology **Commonality**: Number of devices in which the specific technology is used

Technology **Cost**: Measure of the overall expense across all types of device. Inclusive of the CAPEX and OPEX cost for each of the technologies.

Technology **Performance**: Measure of a technology's ability to contribute to enhanced energy productivity across the spectrum of operational conditions.

Technology **Survivability**: Measure of the ability for the technology / device to survive peak loads / fatigue loads. Its load shedding ability / life expectancy / impact on FCMA or frequency of loading cycles etc. This may also include but is not limited to resistance to biofouling, corrosion and erosion.

Technology Element: Physical component / item / system / software considered to have technological value.

Process Element: Non-Physical process / methodology / system considered to have technological value.

Abbreviations

AC / DC:	Alternating Current / Direct Current
CAD / CAM:	Computer Aided Design / Computer Aided Manufacturing
CFD:	Computational Fluid Dynamics
CFRP:	Carbon Fibre Reinforced Plastic
FEA:	Finite Element Analysis
FMCA:	Failure Mode and Criticality Analysis
FMEA:	Failure Mode Effect Analysis
GFRP:	Glass Fibre Reinforce Plastic
GIS:	Geographic Information System
LCoE:	Levelised Cost of Energy
NDI:	Non Destructive Inspection
NDT:	Non Destructive Testing
O&M:	Operation and Maintenance
PTO:	Power Take Off
WEC:	Wave Energy Convertor
WES:	Wave Energy Scotland
WP:	Work Package
W.R.T:	With respect to

1 Introduction

To accelerate the journey towards affordability and to start contributing meaningfully to the global clean energy mix, the wave energy sector must draw more heavily upon knowledge and practice from other industrial sectors.

Transfer can happen at all levels of science, technology and engineering, including the use of fundamental physical principles, access of know-how, adaption of technology and direct use of existing solutions. There are many examples where the needs or developments of one sector have had resonance elsewhere. For instance, material technologies such as memory foam, Kevlar and Teflon were accelerated by the demands of Space but in parallel found productive terrestrial application.

This study seeks to identify key opportunities for novel application in wave energy of technology, knowledge and practice from other industry sectors that could help to accelerate the journey towards improved performance, reliability, affordability and survivability. These sectors include but are not limited to oil & gas, wind energy, marine operations, automotive, transport, mining, aerospace, civil and defence sectors.

The objective of this study is to provide guidance to WES on promising avenues for future R&D activity. A robust methodology has been applied to identify and assess priority technology areas and potential technology transfer solutions.

A brief statement of the project participants, work package structure and methodology is given in Chapters 2 and 3. This introduces the proposition that the requirements of the wave sector can be separated into physical technologies and know-how. This theme is expanded upon in Chapter 4 where these sub-system and process requirements are listed more fully.

The identified physical technologies (essentially the sub-systems that are currently used across the wave energy sector) are appraised in Chapter 5 against the core metrics that sit behind contribution to affordability, there being survivability, availability, performance and cost base. This exercise exposes where the opportunities exist for novel technologies and processes from other sectors to have a meaningful impact.

In Chapter 6, potential solutions to the technical requirements are outlined and potential impacts assessed. Identified potential solutions vary in how radical they are. In some cases, it is suggested that the industry looks more methodically and systematically at identifying existing components to meet its requirements whereas in others, more lateral solutions are identified.

Chapter 7 focusses more on know-how and process rather than on product. Across a range of industries, ways of doing things are identified that could impact positively on wave energy. Examples include optimisation of structural design and design optimisation and approaches to reliability, both areas of high relevance to wave energy and with deep knowledge in other industries.

Chapter 8, focuses more strongly on exploring further the lateral type of solution only partially covered in Chapter 6. Through a process of wide ranging horizon scanning, a range of emerging and more recent technologies are identified and their relevance to wave energy described.

Chapter 9 draws the core findings of the previous chapters together in a set of conclusions and recommendations. Analysis details which support the findings are provided in a set of Annexes.

2 Project Overview

2.1 Participants

The project has been undertaken by a broad-based team led by ODSL (the commercial arm of ORE Catapult) working closely with QinetiQ, the partnership reflecting balance between knowledge of needs and knowledge of other industries and technology transfer processes. ORE Catapult is the UK Government's flagship research organisation for the offshore renewables sector. QinetiQ has roots within the MoD but through privatisation and diversification has since 2001 successfully transferred expertise to many non-military industries.

Other partners have included Ricardo, Black & Veatch and DNV-GL. Ricardo is a global engineering, strategic and environmental consultancy which specializes in transport and energy. Black & Veatch (B&V) are marine energy consultants who have been at the forefront of wave energy development. DNV-GL provides classification and technical assurance services including to the wave sector.

Supporting partners have been Energy Technologies Institute and Carnegie Wave Energy Limited. ETI is a public-private partnership with a mission to promote innovation across the energy sector. Carnegie is a leading wave energy device developer with a coal-face perspective of technology requirements.

The project structure is shown in Figure 1.

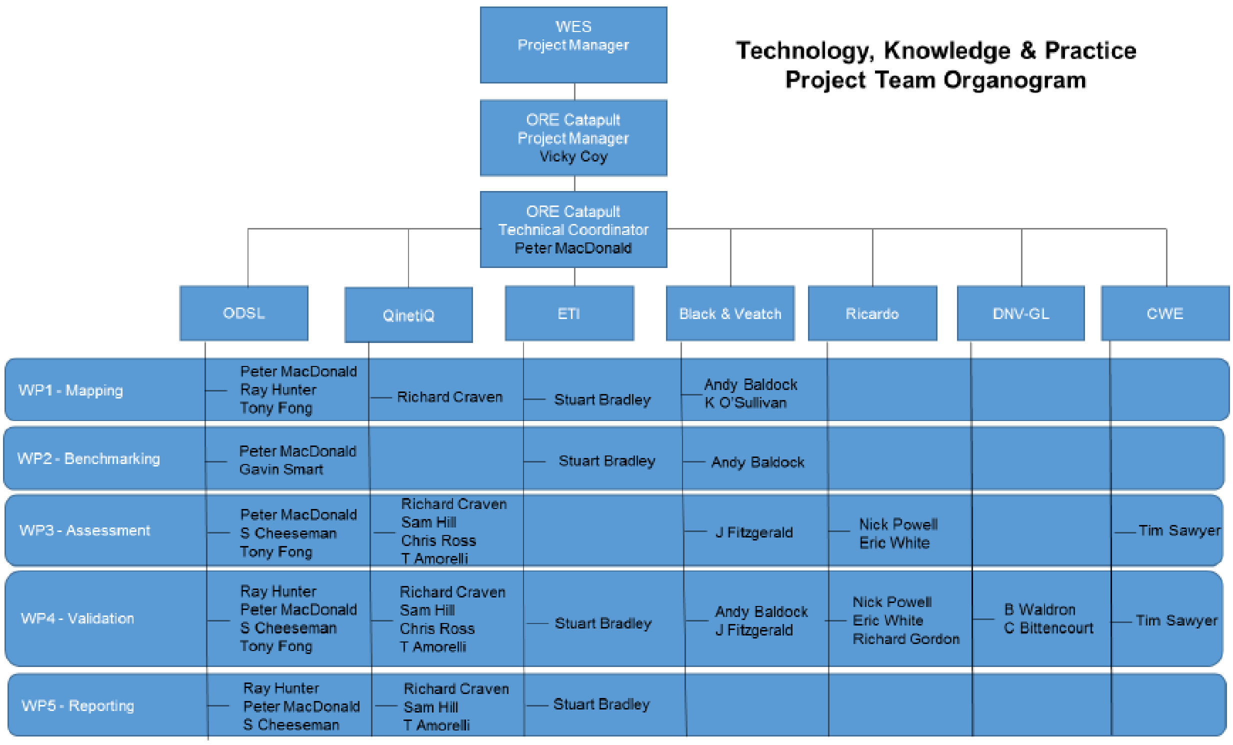


Figure 1: Project Participants

2.2 Work Packages

2.2.1 Introduction

Delivery of the project has involved five discrete work packages as indicated by Figure 2.

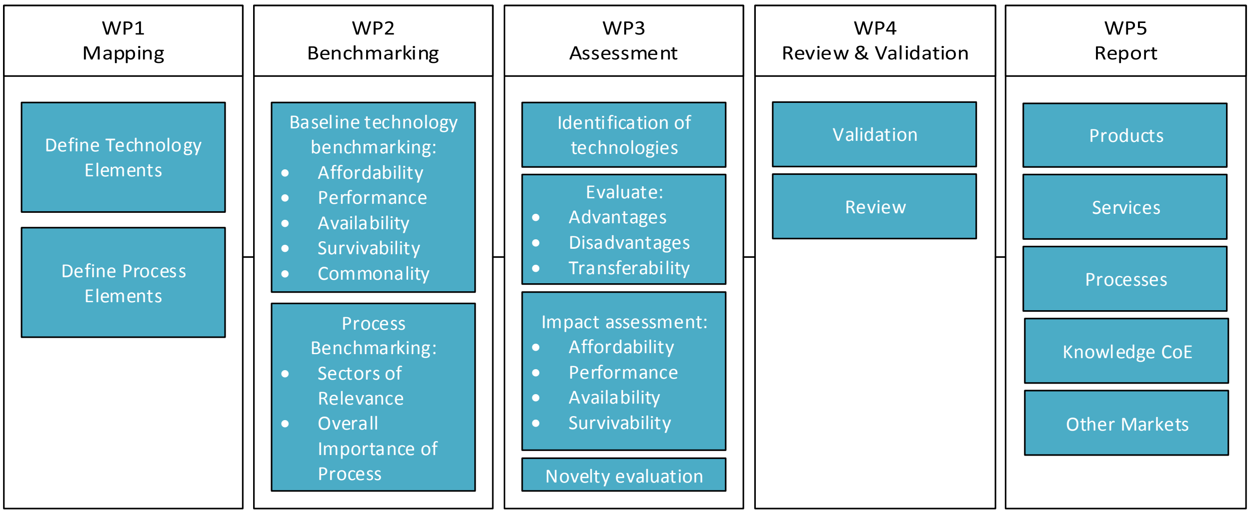


Figure 2: Project Structure Summary

2.2.2 Work Package 1 – Mapping

Mapping has involved identifying the primary technology and process elements across a core range of wave energy devices and, drawing on previous studies (Ref 1) and (Ref 2) and from expert input, prioritising the technology elements for further analysis.

2.2.3 Work Package 2 – Benchmarking

Benchmarking has involved taking the identified technology and process elements and assessing their current profile with respect to the core WES metrics of Performance, Availability, Survivability and Cost Base. Additionally, each element has been graded according to commonality across the wide variety of wave energy devices under development.

2.2.4 Work Package 3 – Assessment

Identification and assessment of prospective solutions for each of the technology and process elements has been carried out by the cross sector experts. Technologies have been evaluated for prospective use in wave energy, highlighting advantages, disadvantages, transferability, novelty and potential impact on WES metrics.

2.2.5 Work Package 4 – Candidate Output Review and Validation

Review and validation has involved opening up the provisional conclusions to wider scrutiny by the broad based team to ensure the technologies and processes are realistic and viable.

2.2.6 Work Package 5 – Report

The deliverables include the present report and associated PowerPoint slide deck (Annex B).

3 Assessment Methodology

A process for identifying and assessing technology transfer opportunities for the wave energy sector has been developed for this study. This categorises and benchmarks existing WEC technologies, identifies key areas and challenges, reviews technologies from other industries and assesses and prioritises potential technology transfer opportunities. An illustration of the methodology is shown in Figure 3.

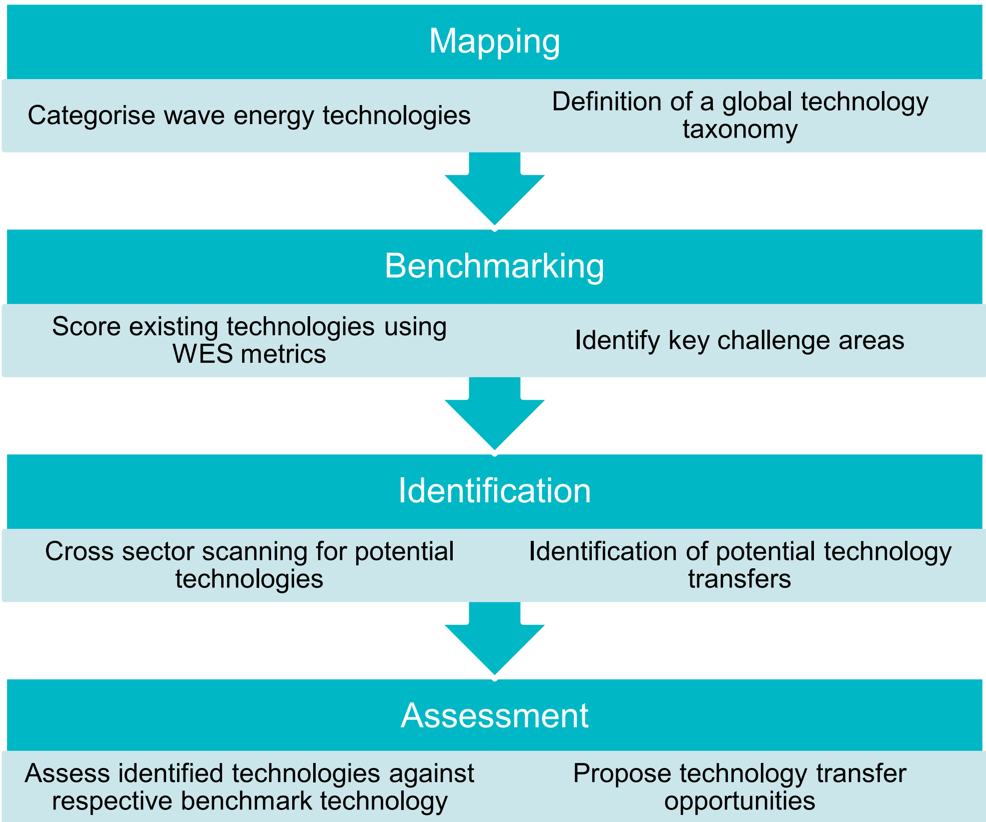


Figure 3: Technology Transfer Assessment Methodology

The mapping, benchmarking and assessment stages correspond respectively to Sections 4, 5 and 6-8 of this report. Detailed information on the process followed is contained within each.

All partners in the project had the opportunity to contribute to the identification stage. For the detailed information resulting from this phase please refer to Annex B.

4 Mapping

4.1 Introduction

An effective assessment of technology transfer opportunities is enabled by setting boundary conditions and using a robust methodology. Boundary conditions such as limiting the types of and current maturity of candidate technologies are applied to focus the scope of the assessment to areas which are identified as being most valuable. ORE Catapult led a mapping activity with feedback and review by all partners to:

- Identify existing wave industry technologies
- Evaluate the key technology areas in the Wave Energy Sector

Technology can be defined as 'The application of scientific knowledge for practical purposes'. Technology transfer need not relate solely to physical hardware. As shown in Figure 4, it can also relate to scientific, technical and engineering methodologies and processes.

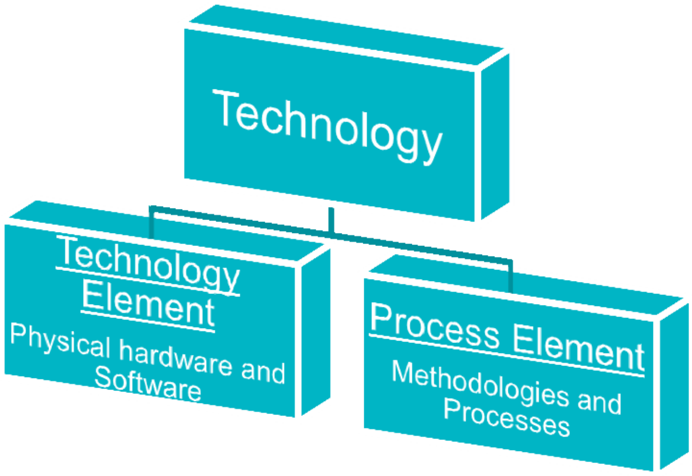


Figure 4: Technology Types

Technology Element and Process Element mapping activities were carried out to define suitably categories to which the fundamental technologies are applicable. Technology elements may consist of hardware and software where they physically exist. Process elements are one or more interrelated activities used to achieve a result. The following methodology shown in Figure 5 was implemented to insure this process was robust and suitable:

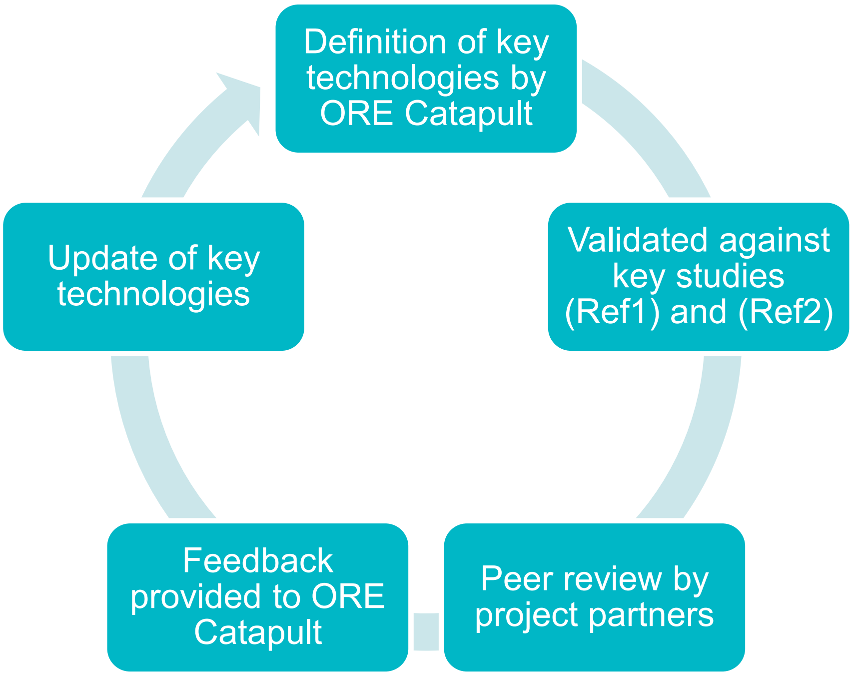


Figure 5: Technology Mapping Process

4.2 Device Configurations

Many differing wave energy devices exist, and although the categorisation has flaws, it is common practice to group devices according to the following ‘family’ descriptions:

- Attenuator
- Point Absorber
- Oscillating Water Column
- Overtopping / Terminator Device
- Pressure Differential
- Oscillating Wave Surge Device
- ‘Bulge Wave’ Device

It is assumed for this study that the families are representative of all current existing and development wave energy devices.

4.3 Technology Elements

Technology elements are defined as physical componentry or hardware commonly required and found within a wave energy converter, for example, a novel bearing. Technology elements were identified and categorised to allow the current state-of-the-art to be benchmarked against WES metrics and to allow subsequent mapping of cross sector technology transfer opportunities.

For consistency with existing technology assessment studies performed within the wave energy industry, (Ref 1) and (Ref 2), an existing breakdown of technology categories in the form of a universal taxonomy (applicable across all families of wave energy devices) was adopted from (Ref 1) which is tabulated in Table 1. This ensures that the recommendations provided are complementary to those previously reported.

Table 1: Technology Element Map

System	Element	Sub-Elements
Hydrodynamic Absorber	Bearing	
	Blade	
	Chain	
	Hub	
	Hydrofoil	
	Seals	
	Structure	Displacer Displacer Reactor Reactor Shroud
	Yoke / Yaw	
Power Take Off (PTO)	AC/DC/AC Converter	
	Accumulator	
	Air Turbine	
	Brake	
	Cable	
	Counterweight	
	Gearbox	
	Generator	Electric Linear Hydraulic Standard Hydraulic Novel Rotational Electric
	Hydraulic System (non-PTO)	Oil Water
	Pinion Gear	
	Pulley	
	Pump / Hose	
	Rack & Pinion	
	Shaft	
	Spring	
	Structure	Reservoir
	Transformer up to 11kV	
	Water Turbine	Francis Kaplan Pelton Wheel Novel
	Air Turbine	Lift (Bi-directional) Uni-Directional
	Valves	
	Subsea Connectors	
	Dynamic Cable	
	Mechanical Connect System	

System	Element	Sub-Elements
	Cooling System	High Complexity Low Complexity
Control	Blade Pitch System	
	Control System	High Complexity Low Complexity
	Cooling System	
	Yaw System	
Reaction / Stationing	Fixation	Gravity Base Monopile Pin Piled Torpedo
	Lifting Mechanism	
	Mooring	Tension Single Point Multi Point
	Structure	Ballast Chambers Breakwater Multi-turbine support Pontoon Shore Mounted Single turbine support Blockage

The Energy Technologies Institute (ETI) benchmarking, 2014, (Ref 1) and the UK Energy Research Centre (UKERC) Marine Energy Technology Roadmap, 2014 (Ref 2) highlighted improvements in certain technology elements as being vital for the development of marine energy. It was ensured that the proposed technology element breakdown in Table 1 was inclusive (explicitly or otherwise) of these. Priority technologies from (Ref 2) include:

- Installation / Recovery Methods
- Design for Maintenance
- Power Take Off
- Device Structure
- Hydraulic Systems
- Failure Modes & Conditioning Monitoring Techniques
- Array Electrical Systems
- Sub-sea Electrical Systems
- Offshore Umbilical / Wet Medium Voltage Connectors

Both reference reports also cover tidal energy. Recommendations relating to tidal (and indeed to trials and testing) have been removed for the purposes of the present work.

4.4 Process Elements

Process elements are defined as technologies with no associated physical componentry or hardware. For example a process element may be a design process or a methodology for optimisation which may be considered technologically valuable.

As with the technology elements, these process elements must be categorised and mapped to enable benchmarking and to define boundaries (including technology type and maturity) for which the project partners are able to perform cross sector technology assessments.

Process elements for the wave energy sector have not previously been fully categorised meaning that a new structure had to be developed for the project. The complete list of process elements, spanning the design to the decommissioning stage, is shown in Table 2.

The ETI Marine Technology Roadmap (Ref 1) highlights a number of key process elements and these are captured in the discipline and process categories.

Table 2: Process Element Map

Discipline	Process	Primary Wave Energy Role
Scientific Support	Physical Oceanography	measures/models/defines wave environment
	Hydrographic Surveying	maps the seabed
	Wave Hydrodynamics	designs an efficient primary convertor shape
	Geophysics/Morphology	understands the seabed and its geology
	Statistics and Probability	makes sense of stochastic data and extremes
	(Marine) Acoustics	advises on const'n/oper'l noise propagation
	Marine Biology	assesses impact on marine ecology
	Marine Archaeology	assesses impact on marine cultural heritage
	Hydrology	identifies/quantifies risks to water quality
	Geotechnics	defines engineering characteristics of seabed
	Experimental Hydrodynamics	confirms converter's performance/loading
	Testbed Testing	confirms sub-system behaviour/loading
	GIS	georeferences/processes the project data
Engineering Design: Structural / Marine	Coastal	designs fixed inshore wec structures
	Offshore Structural	designs fixed/floating offshore wec structures
	Naval Architecture	designs floating wec structures
	Mooring	designs to station-keeping tethering system
	Foundation	designs seabed fixings for the structure
Engineering Design: Mechanical	Hydraulic	designs oil based PTO systems and ancillaries
	Aerodynamic/Turbo	designs air turbine based PTO systems

Discipline	Process	Primary Wave Energy Role
Engineering Design: System	Systems	integrates sub-systems to optimise system
	Reliability	optimises the engineering to reduce failures
	Industrial & Production	designs for & optimises production techniques
	Interface management	co-ordinates all soft & hard connections
Engineering Design: Electrical & Power	Electro-Mechanical	designs/selects the generator
	Power-Electronic	designs/selects final stage power conditioning
	Cable	designs the umbilicals and collection system
	Sub-Sea	designs (E&M) connections & sub-sea plant
	Corrosion & Biofouling	selects surface protection systems for the hull
	Control	designs system to control, monitor & diagnose
Engineering Design: Support	Technical Management	leads concept development and optimisation
	Engineering Management	co-ordinates engineering
	Specification	creates requirements for procurement
	Project Management	co-ordinates activity, budget, timescales
	CAD	provides design support and design detailing
Engineering: Construction Phase: Off-site	Steel Fabrication (Cut, Form, Machine, Weld)	creates converter body elements
	Composite Fabrication (Layup, Mould, Bond)	creates converter body elements
	Concrete Precasting	creates converter body elements
	Structural Assembly/Fitting	assembles structural sub-elements
	NDT	ensures structural integrity
	Assembly/Fitting - mechanical	builds and installs mech sub-systems
	Assembly/fitting - hydraulic	builds and installs hydraulic sub-systems
	Assembly/fitting - precision	installs/sets-up precision mech components
	Assembly/fitting - electrical/control	builds and installs elec sub-systems
	Onshore transportation	moves materials and assembled units
	Onshore handling/lifting	lifts/transfers materials/assembled units
Engineering: Construction Phase: On-site	Dredging/Seabed Preparation	Dredging/Seabed Preparation
	Civil Construction	Civil Construction
	Offshore Construction	Offshore Construction
	Marine Operations	Marine Operations
	Cable Laying	Cable Laying
	Piling/Anchoring	Piling/Anchoring
	Sea Transportation/Towing	Sea Transportation/Towing
	Commissioning	Commissioning
	Offshore Project Management	Offshore Project Management
	Grid Connections	Grid Connections
	H&S Management	H&S Management

Discipline	Process	Primary Wave Energy Role
Engineering: Operational Phase	M'ment/Instrumentation	provides data on inputs, outputs, status
	Asset/O&M Management	looks after logistics of availability/performance
	Marine Operations	undertakes recovery/redeployment
	Control/Diagnostics	monitors data indicators from converters
	Structural O&M and Repair	maintains wec structure
	Mechanical O&M and Repair	maintains wec mechanical systems
	Hydraulic O&M and Repair	maintains wec PTO and ancillary hydraulics
	Electrical O&M and Repair	maintains wec electrical systems
Other Professions	Patents	secure IP protection for core innovations
	Economics	assesses viability/advises on LCoE drivers
	Financing	engineers the device/project capex investment
	Legal	secures all rights and contracts wrt law and risk
	Certification/TPV	Checks / approves the engineering systems
	Risk Assessment/Insurance	identifies/manages project risks
	External Relations	promotes project to wider stakeholders
	Project Developer	optimises/delivers project ; secures rights
	Environmental Planning/Management	ensures project is environmentally acceptable
	Sales & Marketing	promotes wec system to clients
	Purchasing	ensures efficient & effective procurement

5 Benchmarking

5.1 Introduction

Following initial mapping of the technologies and processes, their maturity against WES metrics was benchmarked to expose opportunities for improvement and thus for potential technology transfer. Metric benchmarking also provides a reference against which the impact of a technology transfer can be judged.

In addition to benchmarking and prioritising against the WES metrics of Cost Base, Performance, Availability and Survivability, the further factor of Commonality (i.e. the degree of applicability across the wave industry) was included.

A state-of-the-art benchmark for each technology element was generated in line with these metrics. To ensure consistency with previous studies, commonalities of technology elements were extracted from the ETI report (Ref 1). Although produced in 2014, it is assumed that these figures still represent the wave energy landscape. Benchmark metrics for technology elements were assessed by a multi-disciplinary team within ORE Catapult and then reviewed and bias-checked by the wider project team, as illustrated in Figure 6. The final, calibrated benchmark technology element matrix is given in Appendix 1 .

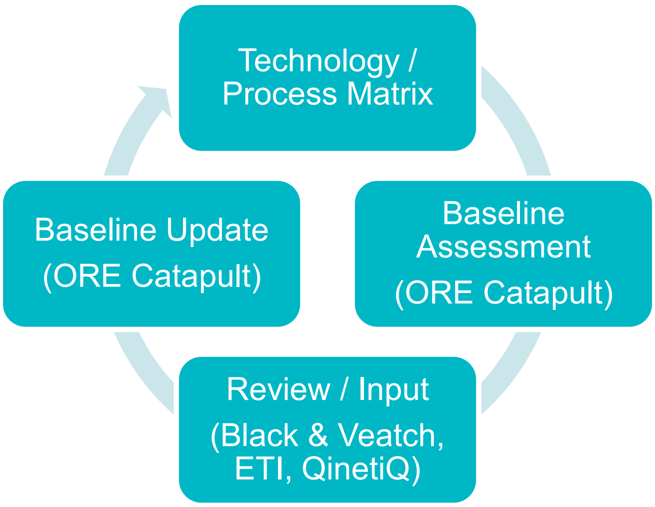


Figure 6: Technology Benchmark Benchmark Process

Benchmarking of the process elements was also carried out. The assessment suggests, by development stage, the relative importance of the process/knowledge to wave energy technology development and identifies the likelihood of finding that expertise in a range of other industries. In more detail, the process/knowledge area of interest is mapped according to:

- **Overall Importance** to the current Wave Energy Sector (a graded importance score, on a scale of 0 to 5, proposed by a wave sector expert based on experience followed by peer review by project partners)

- Wave Energy Technology Development Stages of Relevance:
    - Stage 1: Characterisation
    - Stage 2: Optimisation
    - Stage 3: Scale Prototype
    - Stage 4: Full Scale Demonstration
- Other **Industries of Potential Relevance** having relevant expertise/processes**:**
    - Oil & Gas
    - Utility (including renewables)
    - Process / Chemical
    - Automotive / Industrial Vehicles
    - Aerospace
    - Shipbuilding / Naval / Marine
    - Other Defence
    - Construction / Mining
    - Civil / Ports / Harbours
    - Information & Communication Technologies
    - Biomedical

ORE Catapult used a multi-disciplinary team to grade each respective process element against relevance and prospective industry. To ensure benchmarks were representative and un-biased, prospective grades were circulated to project partners (QinetiQ, ETI and Black and Veatch) for peer review and feedback as illustrated in Figure 6. The final benchmarks for process elements are given in Appendix 2 .

5.2 Prioritisation

5.2.1 Introduction

Following mapping and benchmarking, a prioritisation exercise was conducted to highlight technology and process elements having opportunities for greatest impact in technology transfer as illustrated in Figure 7.

Additionally, to capture technologies and processes of potential promise that the technology and process methodology had failed to identify, a more unstructured horizon scanning exercise was carried out.

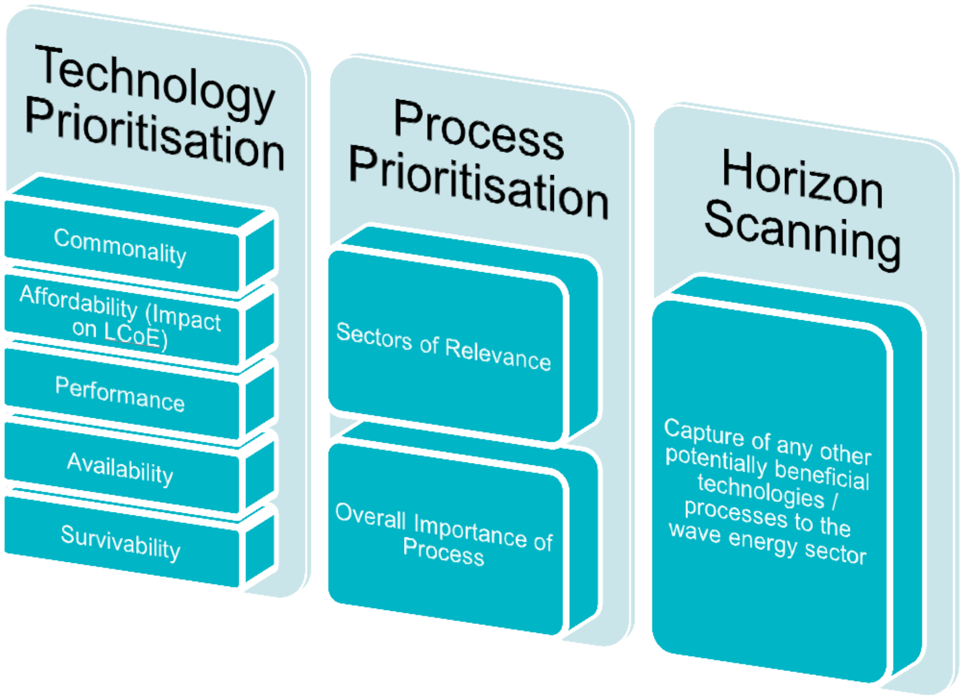


Figure 7: Prioritisation Criteria

5.2.2 Technology Prioritisation

Prioritisation highlights the technology elements, as mapped in Section 4.3, that are likely to be of greatest benefit to the wave energy sector and filters out low value opportunities. Scoring against the benchmarking criteria (Commonality, Affordability, Performance, Availability and Survivability) shown in Figure 7 and Table 3 prioritises the technology elements.

The scoring affords high scores to existing technology elements in the wave energy industry with high commonality and high scope for improvement i.e. high current cost, poor performance, poor availability and poor survivability.

Table 3: Technology Element Benchmark Criteria

Commonality	Cost	Performance	Availability	Survivability
1-29: Low	1: Low	1: Good	1: Good	1: Good
30-59: Moderate	2: Moderate	2: Moderate	2: Moderate	2: Moderate
60-89: High	3: High	3: Poor	3: Poor	3: Poor
90+: Very High	4: Very High	4: Very Poor	4: Very Poor	4: Very Poor

Using the peer reviewed and calibrated benchmarks), the overall technology prioritisation is produced by combining the 5 source metrics:

- Benchmark = Affordability + Performance + Availability + Survivability

- Normalised Benchmark = Benchmark / Maximum Benchmark
- Normalised Commonality = Commonality / Maximum Commonality
- Prioritisation Score = (0.7 * Normalised Benchmark) + (0.3 * Normalised Commonality)

The resulting top 30 opportunities for high impact technology transfer are listed in Table 4. The complete list of technology prioritisation scoring is given in Appendix 3

Table 4: Prioritised Technology Elements

System	Element	Sub-Element
Control	Control System	High Complexity[1] Low Complexity[2]
	Cooling System	
Hydrodynamic Absorber	Bearing	
	Blade	
	Seals	
	Structure	Displacer Displacer Reactor Reactor
	Yoke / Yaw	
Power Take Off (PTO)	AC/DC/AC Converter	
	Air Turbine	Lift (Bi-directional) Uni-Directional
	Water Turbine	Novel
	Dynamic Cable	
	Gearbox	
	Generator	Electric Linear Hydraulic Standard Hydraulic Novel Rotational Electric
	Hydraulic System (non-PTO)	Oil Water
	Spring	
	Subsea Connectors	
	Transformer up to 11kV	
Reaction / Stationing	Mooring	Single Point Multi Point

Figure 8 shows the benchmark metrics for the priority technology elements. A strong correlation between the Cost Base and Survivability metrics can be seen, emphasising these areas are related and are key challenges.

[1] High Complexity control systems are considered those with the ability to influence performance of the wave energy device. i.e. an active, real-time control system which can alter the operational characteristics of the device based on measured data in order to optimise power generation.
[2] Low Complexity control systems are considered those without the ability to influence performance. i.e. control systems for ballasting and de-ballasting of a device for maintenance and for general high-level supervisory functions.

	Existing Technology Baseline Benchmark			
Technology Element	**Cost**	**Performance**	**Availability**	**Survivability**
Control: Control Systems - High Complexity	1	2	1	2
Control: Control Systems - Low Complexity	1	2	1	2
Hydrodynamic Absorber: Bearings	2	1	3	1
Hydrodynamic Absorber: Blade	3	2	2	2
Hydrodynamic Absorber: Seals	1	2	2	3
Hydrodynamic Absorber: Structure - Displacer (non-steel)	4	2	1	4
Hydrodynamic Absorber: Structure - Displacer (steel)	4	2	1	2
Hydrodynamic Absorber: Structure - Displacer Reactor (non-steel)	4	2	1	4
Hydrodynamic Absorber: Structure - Displacer Reactor (Steel)	4	2	1	4
Hydrodynamic Absorber: Structure - Reactor (non-steel)	4	2	1	4
Hydrodynamic Absorber: Structure - Reactor (Steel)	4	2	1	4
Hydrodynamic Absorber: Structure - Reactor (Steel)	4	2	1	2
Hydrodynamic Absorber: Yoke/Yaw	4	2	1	4
Power Take Off: AC/DC/AC Convertor	2	1	2	1
Power Take Off: Air Turbine, Bi-Directional	2	2	2	3
Power Take Off: Air Turbine, Uni-Directional	3	2	2	3
Power Take Off: Dynamic Cable	4	2	1	4
Power Take Off: Gearbox	2	2	3	2
Power Take Off: Generator - Hydraulic (Standard)	2	2	2	2
Power Take Off: Generator - Linear Electric	2	2	2	3
Power Take Off: Generator - Rotational	2	2	2	2
Power Take Off: Generator - Rotational, Direct Electric	3	2	2	2
Power Take Off: Hydraulic System (non PTO) - Oil	2	2	2	3
Power Take Off: Hydraulic System (non PTO) - Water	2	2	3	3
Power Take Off: Spring	3	2	2	3
Power Take Off: Subsea Connectors	1	1	3	2
Power Take Off: Transformers up to 11kV	1	1	2	1
Power Take Off: Water Turbine, Novel	3	2	2	2
Reaction / Stationing: Mooring - Multi Point	3	1	2	2
Reaction / Stationing: Mooring - Single Point	3	1	2	2

Figure 8: Priority Technology Benchmark Metrics Summary

A number of trends are apparent from the benchmark data:

- Control system technology is a challenge from the perspective of system performance and survivability where current technologies are moderate in both aspects.
- Hydrodynamic Absorber Structure/Bearing/Seal technologies are a large challenge for cost and survivability. Typical existing wave energy structures are costly and/or are poor at surviving the extreme environmental conditions.
- Power-Take-Off technologies are challenging across all metrics where they score moderate on all metrics.
- Mooring technology is challenging from a cost perspective and is of moderate challenge on cost and availability metrics.

5.2.3 Process Prioritisation

Process element prioritisation highlights those processes with greatest relevance to wave energy and with greatest level of knowledge in other industries.

The process benchmark scores given in Appendix 2 highlight the most relevant processes and the most relevant industries. Relevance is graded from 1 to 5, where 1 is of low and 5 is of high importance.

Figure 9 highlights for each sector, the number of processes scoring 4 and 5 (high importance) on the scale of relevance to the wave energy sector. The Oil & Gas sector is highlighted as the sector with most relevant process technologies, followed by Aerospace and Utility.

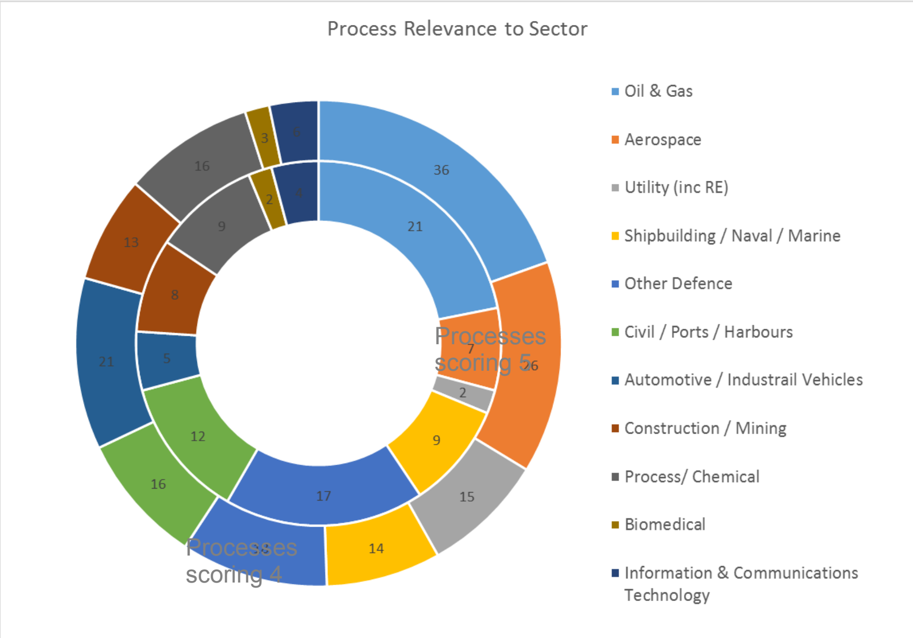


Figure 9: Process Relevance to Sector

Appendix 4 lists the prioritised process elements for each industrial sector.

5.3 Horizon Scanning

In recognising that benchmarking and prioritisation of the technology and process elements is unlikely to capture all solutions of potential relevance to wave energy, particularly in the case of technologies that are either new or of more 'lateral' relevance, the study includes a third, Horizon Scanning, category of search. By being less constrained, Horizon Scanning is arguably more likely to expose disruptive technologies than the methodical technology and process element search.

6 Assessment: Technology Elements

6.1 Introduction

Priority opportunities exposed by the mapping and benchmarking processes were described in Chapter 4 and 5. In the current chapter, the study moves to the cross-sector scan for potential solutions undertaken by the project partner network. Where potential technology transfers are identified, the transferability and potential impact on benchmarks (affordability, performance, survivability and availability) are assessed. This process is illustrated in Figure 10.

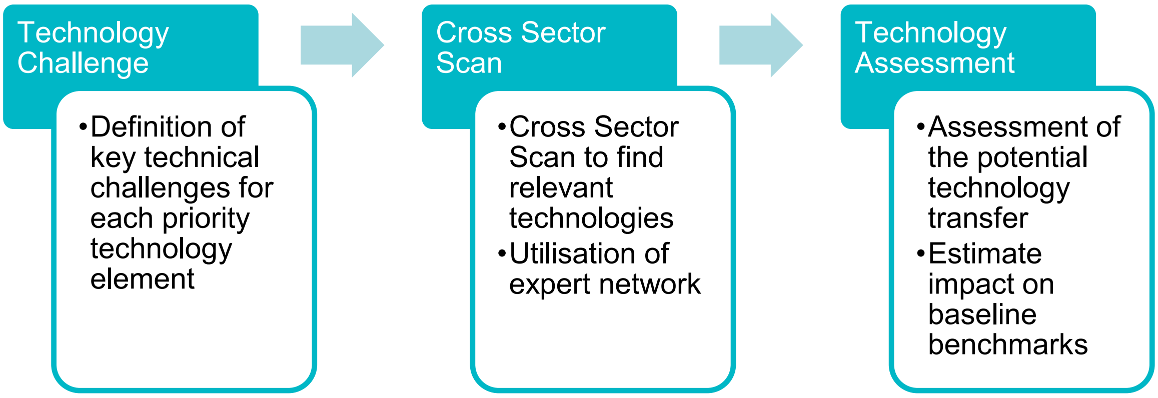


Figure 10: Technology Assessment Process

Definition of the technical challenge is enhanced for each opportunity by carrying out a high level assessment of the benchmarked current technology using Technology Risk categories from DNV-RP-A203 (3) which lists items of concern - causes of failure mechanisms. This enables the top level technical challenges to be captured in addition to the typical wave energy sector requirements.

System Description								Uncertainties						Failure - Materials							Failure - Mechanical Equipment											Failure - Eletrical Power Systems							Failure - Optical Systems				Failure - Pneumatic Systems				Failure - Hydraulic Systems				
Connections/Interfaces	Dimensions	Failure/Lifetime/Availability	Installation	Maintainence	Operation	Safety	Standards	Analysis	Dynamic Response	Input (design) Parameters/Enviro. Data	Loads	Sea Bed	Operational Life	Corrosion	Erosion	H2S	Material Compatability	Material Degradation	Mechanical Properties/Temperature	Buoyancy Migration	Balance	Bearings	Cavitation	Impact	Mating / Interface	Migration causing leak/sealing	Operation	Thermal expansion	Vibration	Water Lock	Wear	Ageing	Connectors (Mating/malfunction)	Electrical Insulation Degradation	High Voltage	Low Voltage	Migration	Transmission Losses	Cable Break	Cable Loss	Connector Losses	Electro-optical equipment malfunction	Clogging	Contamination and Condensation	Control System Loss	Pressure Loss	Clogging	Contamination	Control System Loss	Hydraulic Fluid Degradation	Pressure Loss

Figure 11: DNV-RP-A203 (3) Technology Risk Categories

An example of the technology element challenge definition is shown in Figure 12. Each of the definitions has undergone peer review and amendment, where necessary, by project partners. These challenge definitions were then used to help frame and constrain the cross sector scan for potential technology transfers of maximum value to the wave energy industry.

The complete list of challenge definitions for each of the priority technology elements is given in Appendix 5 .

<table>
<tr><th>Commonality</th><th>Cost</th><th>Performance</th><th>Availability</th><th>Survivability</th></tr>
<tr><td>Very High (109)</td><td>Low (1)</td><td>Moderate (2)</td><td>Moderate (2)</td><td>Poor (3)</td></tr>
<tr><td colspan="2">General Function:
To join or interface systems together, preventing leakage, containing pressure or excluding contamination</td><td colspan="3">Baseline Function:
• Prevent ingress of seawater / contaminants into absorber components or PTO interface (i.e. hydraulic cylinder wiper seals, bearing seals etc)</td></tr>
<tr><td colspan="5">Technical Challenges:</td></tr>
<tr><td colspan="2">• Connections/Interfaces: Required for interfaces between components where prevention of ingress or contamination is required (i.e. hydraulic cylinders)
• Failure / Lifetime / Availability: Failure can cause asset damage and complete loss of availability of the system. Likely to require a long life. Current survivability of seals in typical WEC environment is poor
• Maintenance: Seals may be difficult to access for maintenance and may have large cost implications if required.
• Operational Life: If replacement is required this could have a large cost implications (see maintenance)</td><td colspan="3">• Material Degradation / Wear: Seal degradation due to operation and environmental conditions may occur leading to decreased life and impact on efficiency
• Mechanical Properties / Temperature: Operation in low temperatures and continuously or periodically submerged in sea water
• Pressure Loss: Seal may be required to contain pressure in hydraulic system.
• Loads: Reciprocating duty cycles are challenge for current seal technologies and materials.</td></tr>
</table>

Figure 12: Example Technology Element Challenge Definition: Hydrodynamic Absorber – Seals

Each challenge definition was circulated across the partner knowledge in a cross sector expert search for potentially transferable technologies. For each identified technology transfer, a proposal table captures the key opportunities, transferability and the expected impact on the benchmarks. Figure 13 (use of polyurethane seals) is an example. The full set of technology proposal tables is given as Annex B.

<table>
<tr><th>Commonality</th><th>Cost</th><th>Performance</th><th>Availability</th><th>Survivability</th></tr>
<tr><td>Very High (109)</td><td>Low (1)</td><td>Moderate (2)</td><td>Moderate (2)</td><td>Poor (3)</td></tr>
<tr><td>Potential Solution:</td><td>High (3)</td><td>Moderate (2)</td><td>Good (1)</td><td>Poor (3)</td></tr>
<tr><td>Transferability:</td><td colspan="4">Commercially available product used in the wind turbine industry, but may not be sufficiently water tight for all applications on WEC (7)</td></tr>
<tr><td colspan="2">General Function:
To join or interface systems together, preventing leakage, containing pressure or excluding contamination</td><td colspan="3">Baseline Function:
• Prevent ingress of seawater / contaminants into absorber components or PTO interface (i.e. hydraulic cylinder wiper seals, bearing seals etc.)</td></tr>
<tr><td colspan="5">Potential Solution: Polyurethane Seals</td></tr>
<tr><td colspan="2">• Pro's
• Much harder wearing and longer life for harder to access and replaceable seals, developed for renewables industry for adjacent technology</td><td colspan="3">• Cons
• May not be as water tight as required for some applications.
• More expensive than standard rubber seals
• Currently only available in large diameter sizes
• Examples
• Wind turbine main drive shafts</td></tr>
<tr><td>References:</td><td colspan="4">http://www.skf.com/uk/industry-solutions/wind-energy/new-innovations/axial-excluder-seal-hrc1/index.html</td></tr>
</table>

Figure 13: Example Technology Transfer Proposal: Hydrodynamic Absorber – Seals – Polyurethane Seals

Appendix 6 provides a summary matrix of the potential impacts (expected changes to the benchmark metrics) of the technology transfers proposed by the search team.

6.2 Metric Analysis

6.2.1 Introduction

In this section, the potential impacts of the most promising technology transfers are summarised, metric by metric.

6.2.2 Affordability (Cost Base)

A number of technology transfers with cost reduction potential are identified in the areas of Hydrodynamic Absorber Structure / Yoke & Yaw / Bearings, Power Take Off Dynamic Cables and Moorings. Table 5 is an extract from the proposed technology transfers of Appendix 6 organised by perceived impact on cost (cost reduction) where -1 is a minor decrease in cost and -3 is a large decrease in cost.

Technology Element	Technology transfer description	Impact on Cost
Hydrodynamic Absorber: Structure - Reactor (Steel)	Active control through keel and rudders	-3
Hydrodynamic Absorber: Structure - Reactor (non-steel)	Concrete (unreinforced)	-2
Hydrodynamic Absorber: Structure - Displacer Reactor (non-steel)	Concrete (unreinforced)	-2
Hydrodynamic Absorber: Structure - Displacer Reactor (non-steel)	Composite (multi-material structure)	-2
Hydrodynamic Absorber: Structure - Displacer (non-steel)	Concrete (unreinforced)	-2
Hydrodynamic Absorber: Structure - Displacer (non-steel)	Composite (multi-material structure)	-2
Hydrodynamic Absorber: Structure - Displacer (steel)	Optimisation Software	-2
Hydrodynamic Absorber: Structure - Displacer (steel)	Standard Naval Architecture Software & Hydrodynamic Testing	-2
Hydrodynamic Absorber: Structure - Displacer (steel)	Modular construction of the displacer	-2
Hydrodynamic Absorber: Blade	Standard Naval Architecture Software & Hydrodynamic Testing	-2
Hydrodynamic Absorber: Blade	Composite (multi-material structure)	-2
Hydrodynamic Absorber: Blade	Use of Naval Architectural Design Software and Testing	-2
Hydrodynamic Absorber: Structure - Reactor (Steel)	Optimisation Software	-2
Hydrodynamic Absorber: Structure - Reactor (Steel)	Standard Naval Architecture Software & Hydrodynamic Testing	-2
Power Take Off: Dynamic Cable	Prefabricated Connections	-2
Hydrodynamic Absorber: Structure - Displacer Reactor (Steel)	Optimisation Software	-2
Hydrodynamic Absorber: Structure - Displacer Reactor (Steel)	Tuned Mass Damped / Tuned Liquid Damper System	-2
Hydrodynamic Absorber: Structure - Reactor (non-steel)	Composite Glass Fibre Reinforced Plastic (GFRP)	-1
Hydrodynamic Absorber: Structure - Reactor (non-steel)	Aluminium Alloys (Marine Grade)	-1
Hydrodynamic Absorber: Structure - Displacer Reactor (non-steel)	Composite Glass Fibre Reinforced Plastic (GFRP)	-1
Hydrodynamic Absorber: Structure - Displacer Reactor (non-steel)	Aluminium Alloys (Marine Grade)	-1
Hydrodynamic Absorber: Structure - Displacer (non-steel)	Composite Glass Fibre Reinforced Plastic (GFRP)	-1
Hydrodynamic Absorber: Structure - Displacer (non-steel)	Aluminium Alloys (Marine Grade)	-1
Hydrodynamic Absorber: Structure - Displacer (non-steel)	Thermoplastics	-1
Power Take Off: Dynamic Cable	JDR Umbilical Cables	-1
Power Take Off: Dynamic Cable	Technip Umbilical	-1
Power Take Off: Dynamic Cable	Prysmian Subsea Cables	-1
Power Take Off: Dynamic Cable	Cable Health Monitoring	-1
Hydrodynamic Absorber: Yoke/Yaw	Rudder Control Surface	-1
Hydrodynamic Absorber: Yoke/Yaw	Gyroscopic Stabilisation	-1
Hydrodynamic Absorber: Yoke/Yaw	Stabilisation Tanks	-1
Hydrodynamic Absorber: Yoke/Yaw	Weight Movement System	-1
Hydrodynamic Absorber: Structure - Displacer Reactor (Steel)	Mechanical Gyroscope / Angular Momentum Reactor	-1
Reaction / Stationing: Mooring - Single Point	Suction Piles	-1
Reaction / Stationing: Mooring - Single Point	Gravity Base	-1
Reaction / Stationing: Mooring - Single Point	Drag Anchors	-1
Reaction / Stationing: Mooring - Multi Point	Drag Anchors	-1

Table 5: Cost Reducing Technology Transfer Proposals

6.2.3 Performance

A number of technology transfer proposals have the potential to make minor improvements to wave device performance. These are in the areas of hydrodynamic absorber structure, control systems and power take off dynamic cables and generators. Table 6 shows an extract of the proposed technology transfers in Appendix 6 organised by the perceived impact on performance (performance increase) where 1 is a minor increase in performance and 3 would be a large increase in performance.

Technology Element	Technology transfer description	Impact on Performance
Hydrodynamic Absorber: Structure - Reactor (non-steel)	Concrete (unreinforced)	1
Hydrodynamic Absorber: Structure - Displacer Reactor (non-steel)	Concrete (unreinforced)	1
Hydrodynamic Absorber: Structure - Displacer Reactor (non-steel)	Composite (multi-material structure)	1
Hydrodynamic Absorber: Structure - Displacer (non-steel)	Concrete (unreinforced)	1
Hydrodynamic Absorber: Structure - Displacer (non-steel)	Composite (multi-material structure)	1
Hydrodynamic Absorber: Structure - Displacer (steel)	Modular construction of the displacer	1
Hydrodynamic Absorber: Blade	Composite (multi-material structure)	1
Power Take Off: Dynamic Cable	Prefabricated Connections	1
Hydrodynamic Absorber: Structure - Reactor (non-steel)	Composite Glass Fibre Reinforced Plastic (GFRP)	1
Hydrodynamic Absorber: Structure - Reactor (non-steel)	Aluminium Alloys (Marine Grade)	1
Hydrodynamic Absorber: Structure - Displacer Reactor (non-steel)	Composite Glass Fibre Reinforced Plastic (GFRP)	1
Hydrodynamic Absorber: Structure - Displacer Reactor (non-steel)	Aluminium Alloys (Marine Grade)	1
Hydrodynamic Absorber: Structure - Displacer (non-steel)	Composite Glass Fibre Reinforced Plastic (GFRP)	1
Hydrodynamic Absorber: Structure - Displacer (non-steel)	Aluminium Alloys (Marine Grade)	1
Hydrodynamic Absorber: Blade	Composite Glass Fibre Reinforced Plastic (GFRP)	1
Hydrodynamic Absorber: Blade	Aluminium Alloys (Marine Grade)	1
Power Take Off: Dynamic Cable	JDR Umbilical Cables	1
Power Take Off: Dynamic Cable	Technip Umbilical	1
Power Take Off: Dynamic Cable	Prysmian Subsea Cables	1
Power Take Off: Dynamic Cable	Cable Health Monitoring	1
Hydrodynamic Absorber: Seals	Water lubricated ceramic face seals	1
Hydrodynamic Absorber: Structure - Reactor (non-steel)	Nickel Aluminium Bronze (NAB)	1
Hydrodynamic Absorber: Structure - Displacer Reactor (non-steel)	Nickel Aluminium Bronze (NAB)	1
Power Take Off: Generator - Rotational	Direct Drive Permanent Magnet Generators	1
Power Take Off: Generator - Rotational	Variable Speed Generators	1
Hydrodynamic Absorber: Structure - Displacer (non-steel)	Nickel Aluminium Bronze (NAB)	1
Hydrodynamic Absorber: Structure - Displacer (non-steel)	Composite Sandwich Structures	1
Hydrodynamic Absorber: Structure - Displacer (non-steel)	Compliant structures with tailored buckling/bi-state response	1
Hydrodynamic Absorber: Structure - Reactor (Steel)	Lightweight Composite Yoke	1
Control: Control Systems - Low Complexity	Automotive Control Systems	1
Power Take Off: Generator - Rotational	Artemis Hydraulic Motor Generator	1
Power Take Off: Generator - Linear Electric	VIVACE Hydrokinetic Energy Convertor	1
Power Take Off: Generator - Linear Electric	Underwater linear electrical actuator/generator	1
Control: Control Systems - Low Complexity	Wind Turbine Control System	1
Control: Control Systems - High Complexity	Plant Control Systems	1
Hydrodynamic Absorber: Seals	Wartsila Seals	1
Hydrodynamic Absorber: Seals	Offshore Drilling Seals	1
Control: Control Systems - High Complexity	Fly By Wire	1
Control: Control Systems - High Complexity	ERTMS (European Railway Traffic Management System)	1

Table 6: Performance Increasing Technology Transfer Proposals

There are no proposed technology transfers which are likely to increase performance significantly, however the benchmarking activity indicates that technologies already in existence are within the moderate performance category, hence there is less priority on this metric than on cost and survivability which have a poor current profile.

6.2.4 Availability

Availability within the context of this study is defined as 'measure of a technology's ability to contribute to enhanced reliability or maintainability'. A number of technology elements proposed (bearings, seals, subsea connectors, transformers and moorings) can offer improvements to one or more of these aspects and thus are seen to have potential improvements to availability, these are listed in Table 7.

Technology Element	Technology transfer description	Impact on Availability
Hydrodynamic Absorber: Bearings	Cross Roller and Wire Race Bearings	2
Power Take Off: Subsea Connectors	Siemens Spectron / Digitron Subsea Connectors	2
Power Take Off: Subsea Connectors	Seacon Wetmate Connectors	2
Power Take Off: Subsea Connectors	Souriau Connectors	2
Hydrodynamic Absorber: Bearings	Recardo MultiLife Bearing	2
Hydrodynamic Absorber: Bearings	SKF Nautilus Bearing	2
Hydrodynamic Absorber: Seals	Water lubricated ceramic face seals	1
Hydrodynamic Absorber: Seals	Wartsila Seals	1
Hydrodynamic Absorber: Seals	Offshore Drilling Seals	1
Reaction / Stationing: Mooring - Single Point	Gravity Base	1
Reaction / Stationing: Mooring - Single Point	Offshore Piling	1
Reaction / Stationing: Mooring - Multi Point	Offshore Piling	1
Reaction / Stationing: Mooring - Multi Point	Gravity Base	1
Hydrodynamic Absorber: Seals	Polyurethane Seals	1
Power Take Off: Transformers up to 11kV	ABB Subsea Transformer	1
Power Take Off: Transformers up to 11kV	Solid State Transformers	1
Power Take Off: Generator - Linear Electric	Rockwell Scientific Linear Electric Generator	1
Reaction / Stationing: Mooring - Single Point	Drag Anchors	1
Reaction / Stationing: Mooring - Multi Point	Drag Anchors	1
Hydrodynamic Absorber: Bearings	Bearing vibration health monitoring	1
Reaction / Stationing: Mooring - Single Point	Turret Mooring System	1
Hydrodynamic Absorber: Blade	Composite Glass Fibre Reinforced Plastic (GFRP)	1
Hydrodynamic Absorber: Blade	Aluminium Alloys (Marine Grade)	1

Table 7: Availability Increase Technology Transfer Proposals

Bearings, gearboxes, subsea connectors and seals are among the most challenging technology elements with respect to availability. For these items the perceived low availability can be related to poor reliability and difficulty of installation and maintenance.

6.2.5 Survivability

Survivability is a challenging aspect for structures, seals, dynamic cables and power take off systems. It also poses a moderate challenge for other areas such as bearings and moorings. A number of proposed technology transfers could be beneficial on improving survivability, as shown in Table 8.

Technology Element	Technology transfer description	Impact on Survivability
Power Take Off: Generator - Linear Electric	Rockwell Scientific Linear Electric Generator	3
Hydrodynamic Absorber: Structure - Reactor (non-steel)	Nickel Aluminium Bronze (NAB)	3
Hydrodynamic Absorber: Structure - Displacer Reactor (non-steel)	Nickel Aluminium Bronze (NAB)	3
Hydrodynamic Absorber: Structure - Displacer (non-steel)	Nickel Aluminium Bronze (NAB)	3
Hydrodynamic Absorber: Structure - Displacer (non-steel)	Composite Sandwich Structures	3
Hydrodynamic Absorber: Structure - Displacer (non-steel)	Compliant structures with tailored buckling/bi-state response	3
Hydrodynamic Absorber: Structure - Reactor (Steel)	Lightweight Composite Yoke	3
Hydrodynamic Absorber: Structure - Reactor (Steel)	Active control through keel and rudders	3
Hydrodynamic Absorber: Yoke/Yaw	Weight Movement System	3
Hydrodynamic Absorber: Structure - Displacer (non-steel)	Thermoplastics	3
Power Take Off: Generator - Linear Electric	VIVACE Hydrokinetic Energy Convertor	3
Hydrodynamic Absorber: Seals	Wartsila Seals	2
Hydrodynamic Absorber: Seals	Offshore Drilling Seals	2
Hydrodynamic Absorber: Structure - Reactor (non-steel)	Concrete (unreinforced)	2
Hydrodynamic Absorber: Structure - Displacer Reactor (non-steel)	Concrete (unreinforced)	2
Hydrodynamic Absorber: Structure - Displacer Reactor (non-steel)	Composite (multi-material structure)	2
Hydrodynamic Absorber: Structure - Displacer (non-steel)	Concrete (unreinforced)	2
Hydrodynamic Absorber: Structure - Displacer (non-steel)	Composite (multi-material structure)	2
Hydrodynamic Absorber: Blade	Composite (multi-material structure)	2
Power Take Off: Dynamic Cable	Prefabricated Connections	2
Hydrodynamic Absorber: Structure - Reactor (non-steel)	Composite Glass Fibre Reinforced Plastic (GFRP)	2
Hydrodynamic Absorber: Structure - Reactor (non-steel)	Aluminium Alloys (Marine Grade)	2
Hydrodynamic Absorber: Structure - Displacer Reactor (non-steel)	Composite Glass Fibre Reinforced Plastic (GFRP)	2
Hydrodynamic Absorber: Structure - Displacer Reactor (non-steel)	Aluminium Alloys (Marine Grade)	2
Hydrodynamic Absorber: Structure - Displacer (non-steel)	Composite Glass Fibre Reinforced Plastic (GFRP)	2
Hydrodynamic Absorber: Structure - Displacer (non-steel)	Aluminium Alloys (Marine Grade)	2
Hydrodynamic Absorber: Blade	Aluminium Alloys (Marine Grade)	2
Power Take Off: Dynamic Cable	JDR Umbilical Cables	2
Power Take Off: Dynamic Cable	Technip Umbilical	2
Power Take Off: Dynamic Cable	Prysmian Subsea Cables	2
Power Take Off: Dynamic Cable	Cable Health Monitoring	2
Power Take Off: Generator - Linear Electric	Underwater linear electrical actuator/generator	2
Hydrodynamic Absorber: Structure - Displacer Reactor (Steel)	Optimisation Software	2
Hydrodynamic Absorber: Yoke/Yaw	Rudder Control Surface	2
Hydrodynamic Absorber: Yoke/Yaw	Gyroscopic Stabilisation	2
Hydrodynamic Absorber: Yoke/Yaw	Stabilisation Tanks	2
Hydrodynamic Absorber: Structure - Displacer Reactor (Steel)	Mechanical Gyroscope / Angular Momentum Reactor	2
Power Take Off: Subsea Connectors	Siemens Spectron / Digitron Subsea Connectors	1
Power Take Off: Subsea Connectors	Seacon Wetmate Connectors	1
Power Take Off: Subsea Connectors	Souriau Connectors	1
Hydrodynamic Absorber: Seals	Water lubricated ceramic face seals	1
Hydrodynamic Absorber: Seals	Polyurethane Seals	1
Reaction / Stationing: Mooring - Single Point	Turret Mooring System	1
Hydrodynamic Absorber: Structure - Displacer (steel)	Modular construction of the displacer	1
Control: Control Systems - Low Complexity	Wind Turbine Control System	1
Control: Control Systems - High Complexity	Fly By Wire	1
Hydrodynamic Absorber: Structure - Displacer Reactor (Steel)	Tuned Mass Damped / Tuned Liquid Damper System	1
Control: Control Systems - High Complexity	ERTMS (European Railway Traffic Management System)	1

Table 8: Survivability Improvement Technology Transfer Proposals

6.3 Technology Element Proposal Summary

6.3.1 Introduction

This section recaps the technology element categories which are critical areas for improvement with respect to the WES metrics and summarises the opportunities collated from the individual technology element proposals.

6.3.2 Structure

Structure technology transfer opportunities show a very high potential for **cost reduction**. Many structure material technology transfer solutions were highlighted including the use of concrete structures from the civil engineering and ship-building industry which can improve survivability as well as decrease material cost. Other material technology transfers from the automotive, marine and aerospace sectors including use of composite and GFRP materials have the opportunity to decrease cost through improvement of material properties (such as corrosion resistance, strength to mass ratio, modulus and resistance to impact). There are clear opportunities for technology transfer of materials for wave energy structures from the civil, marine, automotive and aerospace sectors. As such opportunities are being more fully covered within the scope of the separate WES Materials Landscaping study, here they are not investigated further.

Design optimisation technologies (software and testing) are also apparent technology transfers from the marine industry which can enable improved optimisation of hydrodynamic offshore structures. It is envisaged that these could be utilised to improve the structural optimisation and thus cost of the structure. These sit very closely to the design processes which are covered in more detail in the process elements section later.

Performance improvements could be achieved through transfer of material technology from other sectors. A number of material technologies are proposed in the assessment however discussions within this study are limited as this topic aligns directly with the scope of the WES Material Landscaping Study.

Structure technology transfer proposed includes products such as:

- The use of non-metallic structures which could improve performance through the removal of corrosion requirements, structures could be designed with less thickness as corrosion allowance would be removed. Additionally they may require less coating and corrosion maintenance, minimising the required service periods. Cost of structure is largely influenced by the manufacturing process (i.e. shaping, welding, machining), the use of non-metallic structures allows for changes in design and manufacturing of structures. Potential opportunities (and risks) will exist for use of composite materials compared to metallic structures, however these will depend on the specific device structure design and configuration.
- Other properties (fatigue performance, modulus, and strength) of composite materials (GFRP, CFRP, Sandwich structures etc.) in comparison to the benchmark metallic structures can also improve performance of the device by enabling further structural optimisation to decrease mass and/or increase buoyancy. Additional hydrodynamic optimisation may be possible due to the differing material properties and manufacturing processes for composite or plastic materials.
- Where mass is required for performance, concrete structures may enable large mass to be achieved with a relative low cost compared to steel, however density must also be considered. Concrete structures should be considered in parallel with fabrication, handling

and launching challenges as material cost alone is not the only challenge to overall structure cost.

- Improved sealing technology from industries such as offshore oil & gas and marine could also result in improved performance by increasing the availability of the device and enabling extended operating conditions.

Survivability of the structure is a common challenge for wave energy devices. A number of structural technologies were identified with potential for improving survivability, including:

- Materials – Many material technologies exist in other sectors including concrete, high strength steel, marine grade aluminium, carbon fibre reinforce plastic, glass fibre reinforced plastic, nickel aluminium bronze. These material technologies are well developed from sectors such as aerospace, automotive (for CFRP and GFPR) and marine (for marine grade aluminium, GFRP and nickel aluminium bronze) and have different advantages and disadvantages. For wave environments, high strength and resistance to corrosion are often desired. Use of materials from these industries could improve the survivability of the structure greatly.

- Sandwich Structures are often used within the aerospace and marine industries where low density, high stiffness structures are required. Sandwich structures consist of two faces (or more) and a core. Common face materials are GFRP, CFRP, Aluminium or Steel and common core materials are metal / non-metallic honeycomb and foam core. Sandwich structures can provide large strength and impact resistance which could improve survivability of WEC structures.

- Compliant Structures / Damage Tolerant Structure are often used within aerospace. Compliant structures are designed with tailored characteristics such that they deform (and comply) to the environmental loading in a controlled manner to avoid reacting excessive loads. This sort of behaviour could be obtained for hydrodynamic structures such that they alleviate any extreme loads to protect the structure or enable further optimisation. Also damage tolerant structures are utilised across various industries where safety and integrity of a system are critical (i.e. an aircraft). These sorts of structures are design to fail in a controlled manner in the event of unforeseen loading / circumstances, i.e. post buckling wing skins on aircraft are design to buckle for excessive loads, yet allowing the aircraft wing to remain intact and allow safe continued flight. Such technologies transferred to the wave industry could improve wave energy structures.

- Design Optimisation Software are used in every sector. The aerospace sector has significant experience and existing software technologies capable of analysing and performing complex optimisation of structures. In particular, software such as ANSYS and NASTRAN are leading packages capable of nonlinear analysis of impact loading on composite structures. Optimisation using such analysis during the design phase of wave energy structures could improve survivability of the device as well as reliability, performance and cost. In particular the use of optimisation software in the design phase can significantly reduce the requirement for hardware and system development, as long as sufficient data exist to validate the models being used. Validation data can be limited for wave energy devices, but extrapolation of similar systems can provide useful guidance in design activities.

6.3.3 Moorings

Mooring technologies from the oil and gas and civil industries are highlighted as areas of potential cost improvement. Many different configurations of mooring and anchoring technologies are available such as non-metallic mooring lines which offer corrosion and weight opportunities to improve cost. It is envisaged that improved cost solutions are available from these industries which closely align with wave energy requirements.

Mooring technologies which may offer **improved cost** include products such as:

- The development and use of suction piles as currently being demonstrated within the offshore wind sector. Suction piles use pressure difference (suction) produced by a 'bucket' which is installed into the seabed sediment, and which, upon a tensile pull out load being applied, reacts by developing a pressure difference across the inside and outside of the 'bucket'. Such technology can reduce installation cost and material requirements when compared to a traditional piled foundation. However application is limited to particular seabed compositions. Suction piles are currently limited to monopods and jacket structures for offshore oil and gas and wind sectors. There is currently no experience of use of suction piles for moorings and anchors.
- Gravity base foundations are currently being used in the offshore wind and oil and gas sectors as a means of reducing installation costs. They are typically used for non-buoyant structures. Gravity base foundations can be installed without the need of expensive vessels, typically they can be towed to the required location and installed by adding ballast to the structure, sufficient to produce the required gravitational reaction forces. However the trade-off between additional material (cost of material) and the vessel costs for installation of other foundations types must be assessed.
- Drag anchors are typically used in the marine industry, they can offer low installation costs due to minimal requirements for specialist vessels and fast installation times. Such technology could improve the affordability of moorings for the wave energy sector however are limited to particular seabed compositions. Drag anchors may require access for vessels for installation. In an array environment with space restrictions drag anchors can become problematic.

6.3.4 Control

Active control through keels and rudders, mechanical gyroscopes, tuned mass damper systems, stabilisation tanks and weight (ballast) movement systems, primarily from the marine industry, can be classified as control technologies which have a large cost reduction potential for wave energy. These types of technologies can improve survivability by mitigating loading from extreme events (discussed further in the following sections) but foreseeably enable the optimisation of the structure and associated cost reduction.

Control technologies offering **improved cost,** including products such as active control surfaces (keel, rudder etc.) and stabilisation systems (gyroscopes, active ballast and weight movement), are common on vessels in the marine sector and have aerodynamic equivalents in the aerospace sector.

Transfer from the aerospace sector is highly relevant to the wave sector, where load alleviation systems are installed on modern airliners. Such systems use aerodynamic spoilers and complex control systems to deploy automatically as required to reduce aerodynamic loading on the wing and remain within the design envelope. This enables highly optimised structures as the design margins can be reduced to levels which are controllable. Passive load alleviation systems also exist such as the design of tailored aero elastic structures.

Such control technology transfer could improve affordability by enabling further optimisation. Allowing a device to control its exposure to loading events (load alleviation) could greatly reduce the required design size / weight / cost and improve affordability.

Control of a wave energy device can enable **improved survivability** by allowing the device to be able to control its state and therefore its interaction with the environment. It can also be used to optimise performance though positioning and frequency management. In more detail, technologies proposed in the control category include:

- Active control through keel and rudders as commonly used within the marine industry to control vessels. Conventionally these systems use physical surfaces to alter the hydrodynamic flow and thus loading so as to control the vessel's relative motion. This typically requiring a flow of water over the surfaces, which is not necessarily available in wave energy environments. However, within this industry the use of 'propulsors' powered by electric motors (or otherwise) are also commonly used to control vessel position (i.e. ship stabilisation systems such as ABB's Azipod Electric Gearless Propulsors). This type of technology does not require flow of water to generate forces however does require electrical power to operate. Such control technology could be adopted within the wave energy sector to control the WEC's position to reduce or mitigate large loads from the environment, thus improving system survivability. The proven technology within the marine industry may also lead to an improvement of the survivability of the control technology currently applied in the wave energy sector.

- Weight Movement Systems are used within the marine and aerospace industries to alter the centre of mass of a vessel or aircraft, hence altering the static and dynamic behaviour of the system in its environment (whether water or air). Such technology could be transferred to the wave energy sector to enable control or tailoring of static and dynamic response of the system. This could improve survivability of the WEC by using control to manage the loading experienced by the device (i.e. by retracting the device below the water line to protect from wave impact, or to alter dynamic response or reduce dynamic loading).

- Gyroscopic Stabilisation is often used in the marine industry to aid stabilisation of a system or the vessel. This technology has existed for many years in various industries and typically consists of a rotating mass with large inertia. The inertia generated by the gyroscope resists change in orientation, thus it can alter the dynamic response of a system. Gyroscopes can also produce reactive forces during the acceleration or braking of the rotating mass. Transfer of this technology to the wave energy sector could improve survivability by controlling the dynamic response of the system or controlling the orientation or forces on the device. Additionally, the storage of kinetic energy within the gyroscope could potentially be employed by a device for PTO energy storage (i.e. for electrical power conditioning). The integration of control and energy storage solutions may therefore be possible, reducing the number of components and systems which can improve reliability and availability.

- Tuned Mass Damper technology is used within the civil industry typically in large high rise buildings situated in earthquake prone regions but also on other large structures subject to dynamic oscillations (i.e. bridges). Tuned Mass Dampers are used to alter the dynamic response of the system, often damping the structure to prevent large oscillations or resonance resulting from excitation from the environment (earthquake, wind loading etc) typically to increase the survivability of the structure under extraordinary loading. Incorporation of such technology from these industries into a WEC device could improve survivability by damping the device (when required) to reduce the loads experienced.

6.3.5 Control System

Automotive, wind turbine and plant control systems all offer prospects for helping wave energy achieve performance and other metric improvements.

There are various control system technology transfers with the potential to **increase performance**.

- Automotive control systems include standardised protocols (such as CANBUS) which enable a diverse and competitive supply chain capable of mass production. This in turn can aid the development of flexible cost effective high performance systems. Prototyping systems are automotive sector standard practise and would be able to support the development of bespoke control systems in small quantities with good reliability at low cost.

- Wind Turbine control systems are tailored for optimal power capture. They also enable control at a farm level (multiple turbines) to obtain maximum power capture. Learning from this sector could improve the performance of wave energy control systems by drawing on transferable technologies such as sensors, computer systems and control algorithms.

- Plant control is undertaken by high reliability systems optimised for safety critical applications in power stations and chemical plants. Additionally, high integrity systems such as the

ERTMS (European Railway Traffic Management Systems) may offer reliability and robustness from the locomotive industry. Such technology transfer to wave energy could improve performance by increasing the reliability of the devices through advanced supervisory and diagnostic functions. This could be achieved by utilising transferable technologies such as sensors, computer systems and control algorithms.

A number of control systems technologies were identified within the assessment as having potential to impact on the **survivability** of wave energy devices. These are listed below however are not explored in detail due to the scope of other studies being carried out by WES specific to control system technologies (in progress at the time of writing of this report).

- ‘Fly By Wire’ control systems are used in many sectors now including aerospace, automotive and marine. As the name implies, the pioneering industry was aviation where the term ‘fly by wire’ was given to the implementation of a signal-based control system between pilot and aircraft rather than a direct mechanical or hydraulic system. The control system interprets pilot inputs and current aircraft behaviour, the algorithms then adjusts the control surfaces accordingly to achieve the desired change in aircraft behaviour (attitude, speed etc.). Such systems offer a number of advantages to aircraft, the most applicable for the wave energy sector is the ability to interpret the input being requested, and performing the change in a controlled manner within the design envelope of the structure / systems. This process enables the design of the control system such that the device operates in a ‘protected’ envelope and hence increases survivability of the system.

- Wind Turbine Control systems are optimised to maximise power generation in a stochastic environment (wind). Control technology in this respect from the wind industry is highly transferable to the wave sector. The monitoring strategy for turbine cut in / cut out scenarios could benefit wave energy devices in improving survivability while optimising for power generation.

6.3.6 Power Take Off: Cables

A number of promising cost reduction technology transfers related to cable systems were identified.

- Pre-fabricated cable connections have been used within the offshore wind industry. They displace on-site fabricated cable connections (for export and inter array cables) and can reduce cost due to reduced need for offshore/on-site operations time and resources. A factory based testing regime prior to installation offshore can also reduce cost associated with repair and re-work.

- Umbilical cables from the offshore oil & gas industry are designed to connect subsea equipment and surface platforms having relative motion. Learning from such technology may improve the affordability of dynamic cable solutions.

- Cable health monitoring from the utility and energy industries could provide potential cost saving opportunities for wave energy by enabling early identification of issues and efficient maintenance. Such technology could optimise the repair and maintenance of cables to reduce down time and cost of O&M.

A number of technology transfers could yield **performance improvements** in the areas of Dynamic Cables.

- Umbilical and subsea cable technology products exist where technology transfer to **dynamic cable** could be beneficial for device performance, products such as the JDR Umbilical, Technip Umbilical, HydroGroup and HydroBond PLC are used to connect subsea equipment to surface platforms and are typical in the offshore Oil & Gas industry. These products are proven for connection of subsea electrical equipment in a dynamic environment within an industry where performance is critical.

Deep water wave energy conversion generally requires electrical connection between the device and the seabed, these having relative motion. Repeated cycling can lead to failure of cables. Existing solutions are perceived as having poor survivability and reliability. Other offshore industries including Oil and Gas and floating offshore wind are currently faced with similar challenges where a connection is required between a floating system (with motion) and the seabed (stationary). A number of technologies could **improve survivability** of the device's electrical connection.

- JDR / Technip / Prysmian Umbilical Cables are used within the offshore oil & gas industry where they provide electrical connection between surface vessels / platforms and subsea equipment such as drilling equipment. In these industries, umbilicals are considered proven and reliable. Transfer of such technology to the wave energy sector could offer improvements in survivability of cable connections in this dynamic environment.
- Cable Health Monitoring systems are currently being developed for the offshore wind sector and are also employed in the Power & Utilities sector. This technology allows the monitoring of cable health and early identification of issues. This does not mitigate the dynamic cable challenge however it does enable problems to be identified early and corrective action to be carried out prior to complete failure. Current systems in development include QinetiQ Optasense and Freunhoffer ORCHIDS.

6.3.7 Power Take Off

Related to PTO technologies there are a number of proposed technologies which may offer potential for **performance improvements** in the areas of Generators.

- Generator improvements are being adopted across a number of sectors, generally for reasons of improved performance. Technology transfers on both rotational and linear generators are proposed. For example, Artemis digital displacement technology is a rotary hydraulic motor/generator technology currently being developed for a variety of sectors including automotive, rail and renewables (wind). By using innovative control, this technology can improve performance by reducing losses in the system.

- A number of new linear generator technologies are at the research or early design phase. Technologies are anticipated to provide improved performance for some wave devices as conversion of cyclic linear to rotary movement is not required, thus decreasing complexity and system loses. The reduced number of moving parts (reliability, cost) and efficiency potential of some of the linear generator/motor concepts could be very attractive for the wave energy sector

Typical generator technologies (rotary permanent magnet machines) are generally reliable and proven. However the survivability of the device components required to convert wave energy into suitable rotary motion can be poor. Linear generator technology can therefore in time offer the wave sector **improved survivability and reliability** by removing or reducing the complexity of the mechanical systems currently required. Linear generator technology is currently in-efficient (in comparison to traditional rotary generators) and/or still in early development phase. A number of linear generators currently in development have technology transfer potential for the wave sector.

- The **VIVACE Hydrokinetic** convertor is a slow flow device in the marine current sector, using vortex induced vibrations to create electricity using linear generators. This technology is still within early development however the linear generator technology may offer advantages if transferred to the wave sector.

- **Rockwell Scientific** is an organisation that has performed research and holds patents in the field of linear electric generators. This includes a 'Frictionless Linear Electrical Generator for Harvesting Motion Energy' reported in 2004. In this initial report, a concept of use for this generator in wave energy devices was evaluated. The device consists of a permanent magnet stack moving within the generator coils, the innovation is the use of ferromagnetic fluid which enables the magnets to pass without friction inside a long tube. Such technology may offer efficient linear electric generation for the wave sector.

6.3.8 Power Take Off: Subsea Connectors

Existing technologies primarily from the offshore oil & gas industry exist with potential for **improving availability, cost and survivability** of wave systems. These include:

- Siemens Spectron and Digitron subsea connectors. These are commercially available wet & dry mate connectors specified up to 10kV 630A rating, with high reliability. This technology is already within the offshore market however direct adaptation by the wave energy sector has been limited due to expense. Technology transfer of a cost effective solution while exploiting the advantages of such systems may provide improved availability to the wave energy sector.

- Lower capacity (voltage and current) connectors such as the Souriau and Seacon wet & dry mate connectors. These may offer improved availability as an already commercially established market exists for use in ROV and subsea equipment. Such technologies may offer availability improvements (lower cost, available supply) however are likely to be of lower performance and reliability in comparison to advanced Oil & Gas wet mate connectors.

Existing experience of subsea connectors within the wave energy sector exists where technology from the offshore oil & gas industries have been used. Typically, high performance connectors (i.e. oil filed connectors) have been prohibitively expensive to the sector, whereas low cost connectors (i.e. moulded plastic connectors) have shown poor survivability.

Failure of subsea electrical connectors is a recognised issue in the wave sector. Technology transfer from the Oil & Gas sector is already a consideration for the wave sector however high performance connectors are known to be prohibitively costly for many device developers. The use of low cost connectors has led to failures.

6.3.9 Bearings

A number of Bearing technologies offer **availability improvements** include products such as:

- Cross Roller and Wire Race Bearings. These are used in various industries including the mining sector where rotating equipment with large axial (thrust) loading is involved. These bearings have large capacity to react thrust as well as radial loads. Such technology transfer could increase the reliability of absorber bearings when experiencing large loads in directions other than radial, they may also offer differing dimensional constraints as this single interface may react more load degrees of freedom in comparison to traditional bearings.

- Bearing health monitoring systems. These are also being utilised within the wind sector. They could improve reliability, thus availability, by enabling diagnosis and early warning of failures so optimising maintenance planning. Predictive maintenance can decrease downtime.

- The Ricardo MultiLife bearing technology offers improved bearing life for bearings with a duty cycle which wear only a limited portion, leading to early replacement of the bearing being required. MultiLife bearing technology could increase the life and decrease maintenance requirements by managing the wear location (through rotation of the wear surface) of the bearing and alternating this surface accordingly to maximise the use of the entire bearing. Such technology transfer could improve availability of highly loaded bearing interfaces on a wave energy device.

- SKF Nautilus Bearing used within the wind energy sector, this bearing technology removes the requirement for a main shaft and connect directly to a gearbox / generator / hub etc. decreasing the number of components required.

6.3.10 Seals

Many sealing technologies exist and are used in other industries and applications. Most immediately applicable solutions are from the marine industry where subsea sealing is common. Sealing of mechanical systems such as propulsion systems or drilling equipment may offer advantages for **survivability** to the wave energy industry.

- **Offshore / Subsea / Marine** seals offer technologies for various environments and applications, ranging from typical rubber stock seals through to deep sea submarine seals. These include a range of high performance seals which are available 'off the shelf' suited to many different applications (static / moving interfaces, rotary / linear motion, oil / water lubricated, high / low pressure etc.). Leading seal manufacturers within this space include Wartsila, Freudenberg, Trelleborg. Use of appropriate seal technology can improve the system availability.

- **Polyurethane Seals** are typically used in hydraulic systems within other sectors. One primary advantage of polyurethane is increased life (it is harder wearing than conventional elastomers and typically has improved degradation behaviour over rubber) thus improving longevity and availability. However polyurethane seals are generally less water tight and more expensive than rubber seals. Polyurethane seals are made by various manufacturers (including SKF) for wind turbine main drive shafts where they enable long periods without maintenance.

- **Ceramic Face Seals** are used within the marine sector in submarines and ships and in the automotive sector as water pump seals, they can offer increased life in comparison to conventional rubber seals and are tolerant of sand/silt contamination. Oil based lubricant is not needed, however low rate water passage is required. Manufacturers who produce seals for the defence sector (warships and submarines) include Wartsila.

The seal technologies highlighted above could increase availability of wave energy devices through improved sealing and improved seal life. Many seal technologies aim to decrease maintenance requirements and thus also decrease downtime, so **increasing availability**. Changing fundamental designs and technologies to avoid the use or need for seals would be a potential opportunity for the wave sector.

7 Assessment: Process Elements

7.1 Introduction

The process areas prioritised in section 5.2.3 were distributed to relevant project partners for expert assessment. Notes and discussion from the expert network is compiled and available in Annex A – Process Transfer Discussions. A number of process elements have potential to realise significant impact or opportunity in the wave sector. These are captured within the following sections.

7.2 Design

7.2.1 Parametric Optimisation (Design Ladder)

<table>
<tr><td>Description</td><td>The design ladder process is a form of parametric optimisation used within other industries including the aerospace sector. This is a multidisciplinary process which uses numerical design models for structures to generate and assess trends and sensitivities with the objective of identifying key barriers for optimisation / most efficient road maps for optimisation. This process can be applied for optimisation of various parameters such as weight or cost, and should be driven by basic fundamental parameters such as structural arrangement, thickness of material, ultimate / fatigue strength of material.

Parametric optimisation has been used within the aerospace industry to identify at an early design stage, the barriers to weight optimisation for composite wing structures. This has allowed otherwise unforeseen limitations for weight optimisation to be identified early in the design process and to allow suitable design changes to be made to remove such barriers. This allows ‘blind alleyways’ to be identified and avoided thus improving confidence and accelerating development. ORE Catapult is currently leading the development of such processes for the offshore floating wind industry to enable early design optimisation of floating foundations.

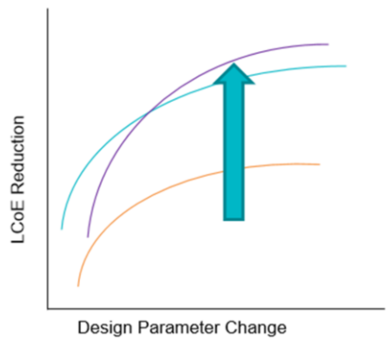
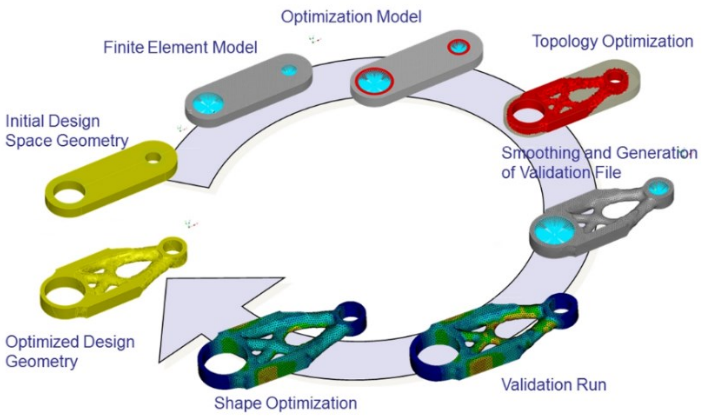


Figure 14: Illustration of Optimisation Trends on Design Ladder Concept</td></tr>
<tr><td>Current Industry</td><td>Aerospace, Automotive, Offshore Wind</td></tr>
<tr><td>Opportunities</td><td>Reveals information to enable effective optimisation of design (i.e.</td></tr>
</table>

	increase material thickness vs. additional stiffeners) Optimisation parameters can be adapted to requirement (weight / cost etc) Enables early identification of optimisation barriers such that designs can be modified to unlock these opportunities.
Risks	Reveals which items to optimise but not necessarily how to perform detailed optimisation. Requires good (multidisciplinary) understanding design/manufacture of entire system. Output is only as valuable as the quality of the input data. Until the limits of design are known, a conservative approach is required. Optimisation will occur when the envelope is well understood.
Technology Transfer	Use of topology optimisation design process to develop early designs for WEC devices.
Required Development	Development of specific numerical models for the design of the device. The optimisation processes are unlikely to be well appreciated by wave energy device developers. Wave Energy Scotland could consider commissioning a workshop to convey the basic concepts of the parametric optimisation process. The approach is entirely consistent with WES's desire to promote achievement of high 'Technology Performance Level' at early 'Technology Readiness Level'.
Transfer Timescale	☒ Short Term (~1 to 5 Years) ☐ Medium Term (~6 to 10 Years) ☐ Long Term (~10 Years +)

7.2.2 Topology Optimisation

Description	Topology optimisation is a computational (numerical) design optimisation process which can be applied at an early design phase. A mathematical algorithm (i.e. using FEA software such as ANSYS) is used to optimise material topology within a set of boundary conditions (i.e. size limits, loading, supports). By performing iterative analysis of the part and adjusting the topology, the part can be optimised for minimum material to perform its required function.

	 Figure 15: Illustration of Topology Optimisation Process
Current Industry	Automotive, Aerospace
Opportunities	Optimisation of structure for minimum material (weight, material cost)
Risks	Does not take into account manufacturing process and practicalities, requires knowledgeable supervision to ensure the conceptual structure is realistic and achievable. Also requires robust understanding and definition of boundary conditions to be effective.
Technology Transfer	This process could be used to reduce the mass and associated cost of the structural elements (reactor, displacer, foundation)
Required Development	The use of topology optimisation requires robust specification of the boundary conditions (loads, material properties, constraints etc.) which are not always thoroughly known in the wave industry. Poor specification of these boundaries will result in poor or unfeasible optimisation. As part of a wider design process workshop, Wave Energy Scotland could consider promoting wider awareness of these structural topology optimisation design processes and tools.
Transfer Timescale	☒ Short Term (~1 to 5 Years) ☐ Medium Term (~6 to 10 Years) ☐ Long Term (~10 Years +)
Examples	• http://empslocal.ex.ac.uk/people/staff/reverson/uploads/MoodSwings/chiandussi.pdf • http://resource.ansys.com/staticassets/ANSYS/staticassets/resourcelibrary/presentation/integrated-optimization-system-fedesign.pdf • http://www.altairhyperworks.co.uk/product/OptiStruct

7.2.3 Design for Manufacture / Installation

Description	Typically, in early design, manufacturing and installation aspects are not considered in detail. Within heavily optimised industries such as automotive and aerospace where the economics of manufacturing and installation have a large influence on the overall cost or production of the products, designing for manufacture and / or installation is included from

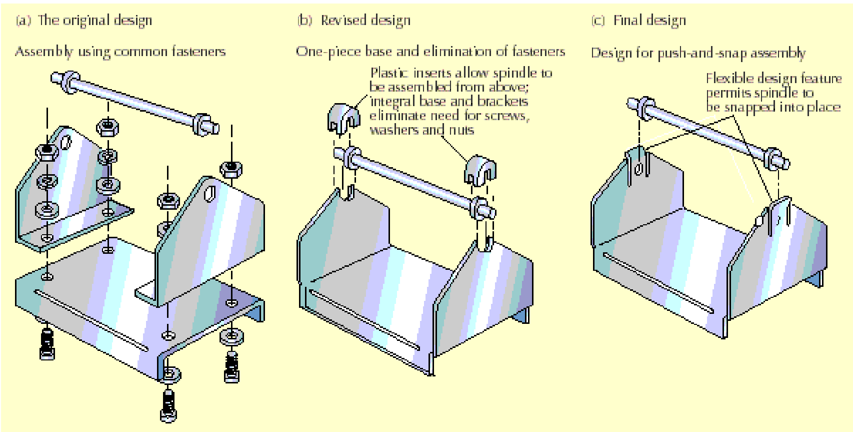
	the outset. The result of such a process ensures that complex technological items are cost effective to manufacture and produce. Where this type of process is not followed (common in bespoke designs for complex devices) optimisation may not be possible at a later stage due to inherent fundamental design decisions. This process can be achieved by employing / assigning production engineers to guide and provide support to the design team from the early design phase.
Current Industry	Automotive, Aerospace
Opportunities	Improved manufacturability and installability of designed structures and components.
Risks	Requires detailed knowledge of the manufacturing and installation process. Can increase the design time required as there are an increased number of parameters and trade-offs to perform.
Technology Transfer	Design for manufacture and installation process can be applied to WEC design to reduce cost and increase availability.
Required Development	Development of design processes specific to the supply chain required (i.e. cost metrics for various manufacturing and installation processes) such that they can be incorporated into early design. Training and development of design teams to incorporate knowledge of manufacturing and installation processes specific to their device / discipline.
Transfer Timescale	☒ Short Term (~1 to 5 Years) ☐ Medium Term (~6 to 10 Years) ☐ Long Term (~10 Years +)
Examples	An example of design for manufacture is the optimisation of welded joints. The welding process is typically expensive due to being resource intensive. The use of smaller welds or fewer welds can improve the cost and speed of manufacture, however is dependant on the structural configuration. Optimisation of a steel structure from the outset to reduce the length / thickness of welds and improve accessibility can have a positive impact on manufacturing while not affecting the performance of the structure. 

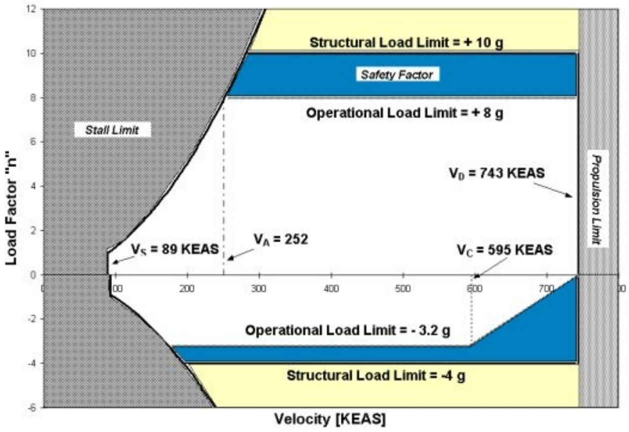
	Figure 16: Illustration of Design for Manufacture Process

7.2.4 Accelerated Innovation / Rapid Prototyping Process (Skunkworks)

Description	Accelerated innovation through an 'unconventional organisational approach' such as that of Skunkworks (Lockheed Martin) can enable the development of innovative technologies and products at an accelerated pace. This is primarily achieved through the organisational philosophy and organisational structure, such as having small empowered design teams with fully delegated control of a program requiring minimal reporting.  Figure 17: Examples of Skunkworks Projects
Current Industry	Aerospace, Defence, Automotive
Opportunities	Can develop disruptive technology solutions for a highly technical challenges at a fast pace while remaining reliable and robust.
Risks	Requires expert workforce to be in place, with adequate facilities for accelerated design > test > demo of concepts. Initial investment may be high. Limited documentation and reporting on the hardware development to support subsequent engineering tasks.
Technology Transfer	For areas where the wave industry is struggling to find suitable solutions (existing from other industries) such an approach could offer unique technologies to be developed specifically for the challenge at a fast pace. This could aid the development of technologies currently classified as available in the 'long term' and reduce the transfer timescales to more acceptable levels.
Required Development	Contractual and other legal agreements can often be a barrier for such philosophies, such as IPR ownership etc. Small, innovative wave technology development companies generally have the right structure and collective drive to embrace SkunkWorks methodologies. However, greater awareness of case studies from other industries and key lessons such as 'Kelly's 14 rules' would help promote more conscious appreciation and application of the processes.
Transfer Timescale	☒ Short Term (~1 to 5 Years) ☒ Medium Term (~6 to 10 Years)

	☐ Long Term (~10 Years +)
Examples	• http://www.lockheedmartin.co.uk/us/aeronautics/skunkworks/origin.html • http://www.lockheedmartin.co.uk/us/aeronautics/skunkworks/14rules.html

7.2.5 Target Load Design / Design Envelope

Description	The Target Loads design methodology, also referred to as the design envelope, is one employed within the design of civil aircraft. The Target Load Design / Design Envelope process enables effective simultaneous analysis of loads and design of the complete system and sub-systems by defining a Target Load / Design Envelope following an initial study on the expected loading or operation of a device. From this definition it is possible for all systems and sub-systems to be designed concurrently to be suitable for the limits of the defined envelope. This can be performed with a degree of independence and in parallel with other design activities hence is time efficient and cost effective. Utilisation of this methodology requires the definition of an envelope of operation for the aircraft which is provided by training of operators and/or implementation of control systems such that the safe operating envelope cannot be exceeded.  Figure 18: Example of Aircraft Design Envelope
Current Industry	Aerospace
Opportunities	Accelerated design of a device with reduced re-design requirements
Risks	Requires a method to restrict the device from operating out with of its intended design envelope.
Technology Transfer	Target Load Design / Design Envelope to the Wave Energy Industry
Required Development	Analysis and definition of achievable design envelope. This is another approach that is highly consistent with the idealised

	Technology Performance Level / Technology Readiness Level trajectory promoted by Wave Energy Scotland as it encourages optioneering and broad system definition at an early rather than late stage. Application of the approach to Stage 1 and 2 novel WEC development should be encouraged to develop sub-system envelopes.
Transfer Timescale	☒ Short Term (~1 to 5 Years) ☐ Medium Term (~6 to 10 Years) ☐ Long Term (~10 Years +)
Examples	• http://www.aerospaceweb.org/design/ucav/structures.shtml

7.3 Reliability

7.3.1 OREDA Reliability Database

Description

OREDA (Oil and gas REliability Database) provides high value reliability information about the hardware implemented in the oil and gas industry. Supported by ten oil companies; AGIP, BP, Elf, Esso, Norsk Hydro, SAGA, Shell, Statoil, and Total. SINTEF is the main contractor. OREDA has provided cost-effective solutions in designing, operating and maintaining topside and subsea oil and gas equipment. Non-OREDA members have access to the database when performing work under contract with aforementioned participants – handbook is publicly available. The OREDA taxonomy has been the foundations for the development of the ISO standard "Petroleum and natural gas industries - Collection and exchange of reliability and maintenance data for equipment“

Taxonomy no 1.1.1.1.1		**Item** Machinery Compressors Centrifugal Electric Motor Driven (100-1000) kW		
Population	**Installations**	**Aggregated time in service (10^6 hours)**		**No of demands**
5	2	**Calendar time** * 0.1248	**Operational time** † 0.0832	

Failure mode	**No of fail.**	**Failure rate (per 10^6 hours).** Lower	Upper	SD	MLE	**Active rep. hrs**	**Repair (manhours)** Min	Mean	Max
Critical	**23* 23†**	**1.31 2.02**	**827.93 1806.90**	**304.49 665.33**	**184.33 276.36**	**10.0**	**0.5**	**24.3**	**186.3**
Failed to start	1* 1†	0.94 0.29	22.20 61.58	7.02 22.41	8.01 12.02	-	13.0	13.0	13.0
Fail while running	14* 14†	0.97 1.28	499.13 1093.54	183.39 402.61	112.20 168.22	10.0	0.5	24.0	186.3
Unknown	1* 1†	0.94 0.29	22.20 61.58	7.02 22.41	8.01 12.02	-	11.4	11.4	11.4
Vibration	7* 7†	0.71 0.70	243.34 538.64	89.14 198.24	56.10 84.11	-	0.5	28.5	117.5
Degraded	**6* 6†**	**0.67 0.62**	**206.78 459.35**	**75.67 169.04**	**48.09 72.09**	-	**9.7**	**27.4**	**75.4**
Other	6* 6†	0.67 0.62	206.78 459.35	75.67 169.04	48.09 72.09	-	9.7	27.4	75.4
Incipient	**29* 29†**	**1.54 2.51**	**1047.12 2282.45**	**385.22 840.47**	**232.42 348.45**	**4.1**	**2.0**	**16.2**	**173.6**
External leakage	4* 4†	0.60 0.46	133.63 300.70	48.67 110.60	32.06 48.06	2.5	3.0	21.3	51.7
Overheated	1* 1†	0.94 0.29	22.20 61.58	7.02 22.41	8.01 12.02	-	173.6	173.6	173.6
Other	21* 21†	1.23 1.85	754.87 1648.38	277.58 606.95	168.30 252.33	4.4	2.0	9.0	62.3
Overhaul	1* 1†	0.94 0.29	22.20 61.58	7.02 22.41	8.01 12.02	2.0	3.0	3.0	3.0
Vibration	2* 2†	0.54 0.32	60.26 141.78	21.46 52.04	16.03 24.03	-	4.9	9.4	14.0
All modes	**58* 58†**	**2.64 4.90**	**2106.50 4580.93**	**775.38 1686.97**	**464.83 696.91**	**4.4**	**0.5**	**20.6**	**186.3**

Figure 19: Illustration of OREDA Reliability Database

Current Industry	Oil & Gas
Opportunities	Enable cost effective design, operation and maintenance of offshore equipment based on experience.
Risks	The wave industry may not have sufficient hardware in operation to collect in-situ reliability data. There may be too much variation in the wave energy devices architecture. Commercial resistance to sharing sensitive operational data
Technology Transfer	The existing OREDA information could be used directly if the same equipment is used in the wave industry. The database approach could be adopted in the wave industry from an early stage to enhance data sharing and provide stakeholders access to critical reliability information.
Required Development	Identification of applicable information transferable from the OREDA database to wave sector. Development, population and use of database specific for the Wave Sector. A number of similar databases for other industries also exist. Wave Energy Scotland could usefully commission a review of reliability data sources with a view to making recommendations on which ones the wave sector could employ and in what circumstances.
Transfer Timescale	☒ Short Term (~1 to 5 Years) ☒ Medium Term (~6 to 10 Years) ☐ Long Term (~10 Years +)
Examples	• https://www.oreda.com

7.3.2 Maintenance Schedules and Representative Testing

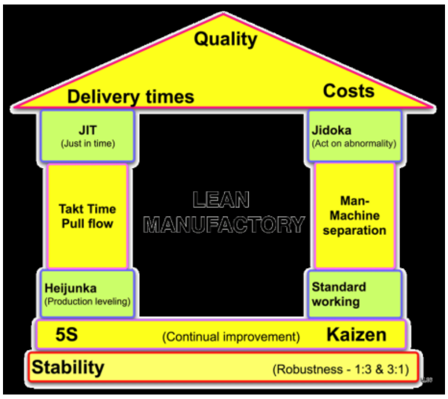
Description	A design for maintenance, and credible maintenance schedules based on thorough testing has been of demonstrable benefit in other industries. Automotive manufacturers have developed (through extensive testing) an excellent understanding of how to define appropriate maintenance regimes for their products. The wind power industry is beginning to follow in this direction, for example gearboxes are known to be a common failure, so to maintain credibility new turbines have been designed to enable easy gearbox exchange. Although more mature than wave, the wind industry is still developing maintenance schedules (based on representative testing) in some areas e.g. Leading edge erosion on blades
Current Industry	Automotive, Offshore Wind, Automotive, Rail, Aerospace, Civil
Opportunities	Well understood, predictable and well planned maintenance tasks can significantly reduce costs and increase availability.

	Increase reliability. Conduct more planned maintenance. Conduct less unplanned maintenance.
Risks	Will require upfront investment to develop a valuable system. Adequate and representative testing will have costs associated. Development of industry specific standards will be required and may take time. Testing and (computer) modelling needs to be validated by comparison to real world operating conditions and failure modes.
Technology Transfer	Development of maintenance schedules with process transferred from these other industries. Opportunity for cross industry collaboration on testing/environmental conditions/typical failure modes.
Required Development	Development of industry standards. Development and testing of computer modelling. Wave Energy Scotland could usefully encourage explicit design for maintenance at Stage 3 of the WEC development process.
Transfer Timescale	☐ Short Term (~1 to 5 Years) ☒ Medium Term (~6 to 10 Years) ☐ Long Term (~10 Years +)
Examples	• https://www.nts.com/services/industry_specific/automotive

7.4 Manufacturing

7.4.1 Lean Manufacturing

Description	Lean Manufacturing (or lean production) is a systematic method for the elimination of waste within the manufacturing system. Pioneered by Toyota within the automotive industry the process of lean manufacturing has since expanded across to other industries including aerospace. Through the reduction of waste in the system, an improvement of quality, cost and production time can be achieved. A number of process methodologies exist within lean manufacturing such as 'just in time' manufacturing which ensures optimal production of products as to minimise any residual costs. Closely linked to Lean Manufacture are more general lean management and lean processes. Central themes are avoidance of unnecessary or low value activity, avoidance of excessive reworking and the need for well interfaced information.

	 Figure 20: Lean Manufacturing Illustration
Current Industry	Automotive (Origin), Aerospace
Opportunities	Reduced manufacturing cost and improved quality.
Risks	Primarily applied to mass manufacturing market. Requires discipline and willingness of sector for effective implementation.
Technology Transfer	Use of Lean Manufacturing processes for production of wave energy devices to reduce cost and improve quality
Required Development	Cultural change in manufacturing chain required Adaptation of processes suitable for wave sector required (and training)
Transfer Timescale	☒ Short Term (~1 to 5 Years) ☐ Medium Term (~6 to 10 Years) ☐ Long Term (~10 Years +)
Examples	• http://www.toyota-global.com/company/vision_philosophy/toyota_production_system/

8 Assessment: Horizon Scanning

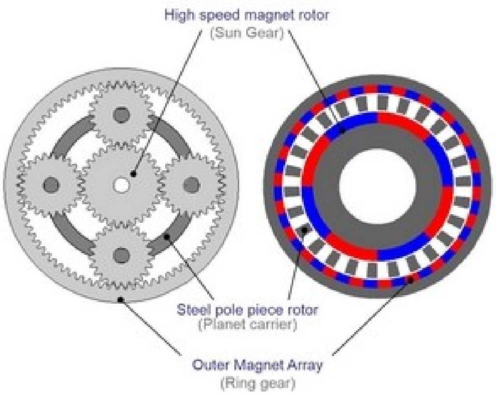
8.1 Introduction

Horizon Scanning was introduced to ensure good technology transfer opportunities, not captured by the Technology and Process Element mapping, were not overlooked.

There were no boundaries set for this part of the study, therefore the technologies (physical technologies or processes) have largely been identified and assessed according to expertise and awareness of competent persons within the wider project team. Items identified have been reviewed by the project partners for consistency with the other technology categories.

8.2 Power Take Off

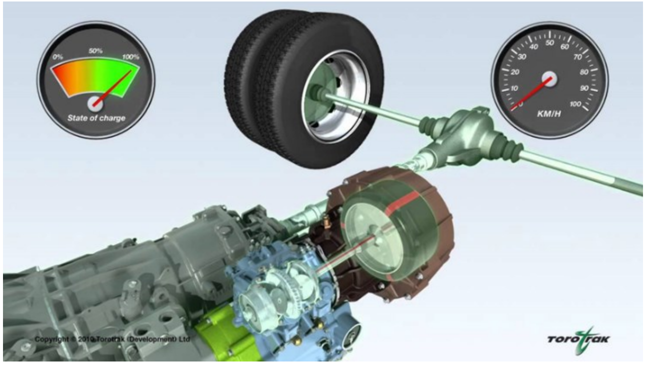
8.2.1 Magnetic Gearing

Description	Magnetic gear technology is under development for the automotive and other industries. Magnetic gearing provides inline gearing transmission without contact surfaces. For example, Magsplit applies magnetic gearing principles in highly integrated power split unit which does away with epicyclic gears, in a magnetically Controlled Variable Transmission. MAGSPLIT has just two rotating elements and can be powered with conventional inverters and is claimed to filter torsional vibration from an internal combustion engine without loss in efficiency. Magnomatics PDD® motors by and generators claim to overcome the torque limitations of conventional direct drive electrical machines, without the disadvantages of mechanically geared systems, by integrating a non-contact passive magnetic gear within a permanent magnet brushless machine Ricardo also apply a permanent magnet gearing solution in the Torqstor flywheel system which requires no external power.  Figure 21: Illustration of MagSplit Gearing compared to Epicyclic Gear
Current Industry	Automotive
Opportunities	Low friction, Efficient Removal of epicyclic gearing / non-inline transmission / bearings

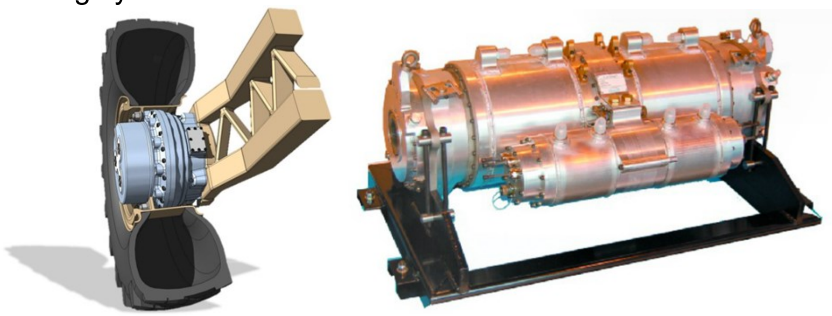
	Low maintenance requirements Will slip in event of over-torque, protecting the system Provides a hermetically sealed transmission solution (no driveshaft seals required)
Risks	Suitability and scalability to the requirements of wave energy applications would need to be assessed. Non-permanent magnet solutions require electrical power to operate
Technology Transfer	Inline magnetic gear transmission for use to convert low RPM to high RPM (i.e. high torque low speed rotation from displacer into low torque high speed rotation for PTO). Removes the need for complex transmission mechanisms. Integrated driveshaft / transmission / bearing system. Potential technology also for use within PTO.
Required Development	Marinisation of system for subsea use required Scaling up of technology is likely to be required for large torques Development of transmission ratios suitable for WEC required Consideration of integration challenges associated with mechanical rectification
Transfer Timescale	☒ Short Term (~1 to 5 Years) ☐ Medium Term (~6 to 10 Years) ☐ Long Term (~10 Years +)
Examples	• http://www.magnomatics.com/ • http://www.ricardo.com/en-GB/News--Media/Press-releases/News-releases1/2014/Ricardo-to-showcase-TorqStor-high-efficiency-flywheel-energy-storage-at-CONEXPO/ • http://www.magnomatics.com/pages/technology/pseudo-direct-drive.htm

8.2.2 Kinetic Energy Recovery System

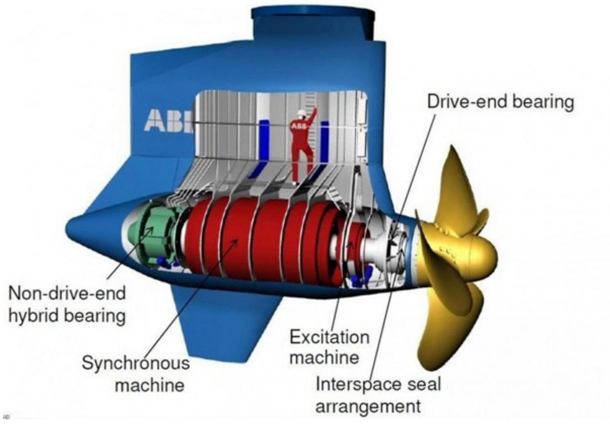
Description	Primarily designed to recover kinetic energy under braking for cars and other vehicles. Temporarily stores energy in a fast-moving flywheel (can operate at approximately 60,000 rpm in automotive applications) or by generating and storing electrical power using generator and batteries. Stored energy is then accessed as required using mechanical clutches for flywheel storage, or motors for electrical storage. Key advantage is the ability to consume and store large amounts of energy quickly, which can be deployed more slowly (to charge batteries for example) or deployed quickly (to accelerate the vehicle).

	 Figure 22: Illustration of Mechanical Flywheel in Automotive Industry
Current Industry	Automotive (including industrial vehicles)
Opportunities	Capture and storage of energy which otherwise would be discarded, and utilising/delivering the power as and when required to improve operating efficiency. Mechanical, Electrical or Hybrid solutions available. Potential to integrate flywheel gyroscopic effects with the wave converter's structural reaction system.
Risks	Currently used on relatively small scale (largest commercial application is for buses / large vehicles). Solution may differ dependant on WEC device configuration as the technology relies on relatively short duration cyclic operation to be effective. The flywheel needs a transmission system able to adjust the gearing to suit the input and output requirements. Infinitely variable speed transmissions are most desirable, but are more difficult to achieve. Some means of modulating the energy transfer may be required (clutch for example) and may not be trivial.
Technology Transfer	Capture excess PTO energy under peak load conditions Regulate energy transfer to PTO to provide more stable load to generator Transfer of mechanical components (flywheel, clutches etc) Transfer of electrical technologies (generator, battery, control)
Required Development	Identification of suitable system topologies, ratings and control strategies. Identification and development of suitable gearing solution. Scaling of technology required for expected WEC loads and forces. Marinisation of technology required for subsea use.
Transfer Timescale	☒ Short Term (~1 to 5 Years) ☐ Medium Term (~6 to 10 Years) ☐ Long Term (~10 Years +)
Examples	• http://www.torotrak.com/products-partners/products/flybrid/ • http://www.magnetimarelli.com/excellence/technological-excellences/kers • http://products.bosch-mobility-solutions.com/media/ubk_europe/db_application/downloads/pdf/safety_1/en_4/CC_Regenerative_Braking_Systems.pdf • http://www.ricardo.com/en-GB/News--Media/Press-releases/News-releases1/2014/Ricardo-to-showcase-TorqStor-high-efficiency-flywheel-energy-storage-at-CONEXPO/

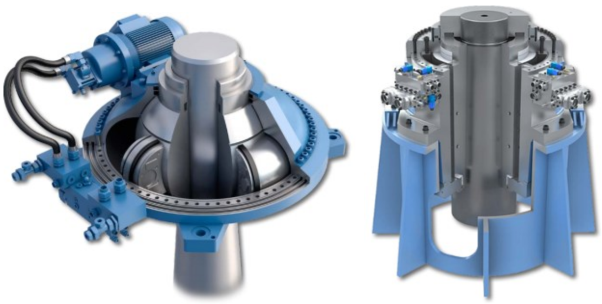
8.2.3 Hub Drive and E X-Drive

Description	Integrated solution of electric drive motor and gearbox within a hub. Designed for civilian and military vehicles. Combining high efficiency inverter-controlled permanent magnet motor/generator technology with gears, gear-change and friction brakes. Proven in harsh operating environment and challenging space constraints. Solutions to meet the loading cycle with minimal size and cost of motor  Figure 23: Examples of Hub Drive and E X-Drive systems by QinetiQ
Current Industry	Defence, Civilian Automotive
Opportunities	Expert experience in analysis of sizing versus duty cycles, efficiency. This knowledge and technology could assist in the application of high efficiency permanent magnet technology in Wave energy devices. Can be used as a motor or generator to enable optimised control (work in synchronisation to input for maximum energy harvest)
Risks	Currently only used at small scale on vehicles. High cost (low volume and rare material content)
Technology Transfer	Use of technology and experience to develop efficient and reliable permanent magnet PTO within challenging / limited spaces.
Required Development	Designed for the vehicle market. Requires marinisation. Scaling of technology required for expected WEC loads and forces
Transfer Timescale	☒ Short Term (~1 to 5 Years) ☐ Medium Term (~6 to 10 Years) ☐ Long Term (~10 Years +)
Examples	• www.qinetiq.com

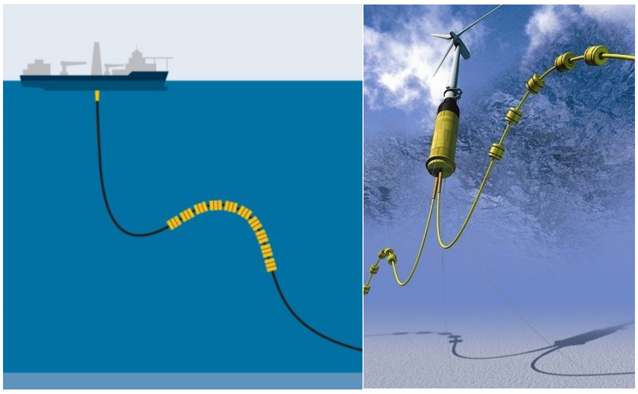
8.2.4 Azimuthing Podded Drive

Description	The Azimuthing Podded Drive system is a commercial marine product for vessels. It consists of an electrically driven propulsor with an AC motor incorporated in a streamlined azimuthing (steerable) pod unit with direct drive of a fixed-pitch propeller. Units up to 14MW in production by ABB.  Figure 24: Illustration of AziPod by ABB
Current Industry	Marine
Opportunities	Proven PM motor / generator system for marine use
Risks	System is designed to produce mechanical power from electrical power, PTO use would require to produce electrical power from mechanical rotation.
Technology Transfer	Reversal of system (i.e. rotation of the drive shaft to produce electrical power) could be used for WEC PTO. Potential transfer of sub-technologies such as bearing / seal designs for subsea use.
Required Development	Re-design system to reverse the function (producing electrical power from mechanical power). Consideration of options for integrating mechanical rectification into the drive system.
Transfer Timescale	☒ Short Term (~1 to 5 Years) ☐ Medium Term (~6 to 10 Years) ☐ Long Term (~10 Years +)
Examples	• http://www.shippingencyclopedia.com/term/azipod-azimuthing-podded-drive • http://www.wartsila.com/products/marine-oil-gas/propulsors-gears/thrusters/wartsila-steerable-thrusters • http://new.abb.com/marine/systems-and-solutions/electric-propulsion/azipod

8.2.5 Electrohydraulic Steering Gear

Description	Electrohydraulic Steering Gears have been commonly used within the marine industry over the last 50 years. Reliability is extensively proven. They operate by converting hydraulic pressure into a rotary motion of a shaft which is then used for turning a control surface. A variety of sizes and configurations are available for varying vessel sizes.  Figure 25: Illustration of Hydraulic Steering by Bosch
Current Industry	Marine
Opportunities	Reliable and proven technology for conversion of hydraulic pressure to rotary motion. Operating range (low angular rotation, high torque) is similar to typical WEC requirements. Hydraulic systems can be tolerant of marine environment and offer good power density
Risks	Current systems are not designed for duty cycles typically experienced across the life of a WEC. System may not be fully submersible in its current form. Old technology; industry generally is favouring electrical machines as they have the potential to be more efficient, less maintenance and lower pollution risk.
Technology Transfer	Potential utilisation within PTO if system is reversed (generate hydraulic pressure from rotating-oscillating shaft).
Required Development	Development of system to produce hydraulic pressure from mechanical power required. Scaling of the system to be suitable for oscillating range and hydraulic pressure required. Design of system for WEC duty cycles required. Full marinisation of system for subsea used required.
Transfer Timescale	☒ Short Term (~1 to 5 Years) ☐ Medium Term (~6 to 10 Years) ☐ Long Term (~10 Years +)
Examples	• http://www.rolls-royce.com/~/media/Files/R/Rolls-Royce/documents/customers/marine/steering-stabilisation-brochure.pdf

8.2.6 Lazy Wave (Dynamic Cable)

Description	Dynamic cables are commonly used in floating wind and offshore oil & gas sectors. This technology alleviates cable stresses which can be caused by the relative motion between a floating device and the seabed. The system functions by utilising a 'suspended' section of cable using buoyancy which provides slack in the system to accommodate relative motion.  Figure 26: Illustration of LazyWave dynamic cable
Current Industry	Floating Wind (Electrical Cables), Offshore Oil & Gas (Risers)
Opportunities	Proven systems in improving the reliability of offshore electrical cables while allowing for dynamic motion between a floating device and the seabed. Currently available for high voltage (33 and 66kV) ratings. May already be adopted by WEC devices. Key opportunity is to reduce cost of ancillary equipment required.
Risks	Requires additional equipment such as bouyancy modules, bend stiffeners and restrictors. These ancillaries often drive the cost of dynamic cables up. Connection to subsea point also a primary challenge for cost and survivability.
Technology Transfer	Potential utilisation in the wave sector to improve survivability and availability of devices by increasing the reliability of electrical cables.
Required Development	Extensive adaption unlikely to be required. Tailoring of system to meet WEC device duty requirements (electrical cable sizes, motion cycles etc.)
Transfer Timescale	☒ Short Term (~1 to 5 Years) ☐ Medium Term (~6 to 10 Years) ☐ Long Term (~10 Years +)
Examples	• http://www.2hoffshore.com/documents/papers/2010-DOT-Dynamic-Response-of-Deepwater-Lazy-Wave-Catenary-Riser.pdf

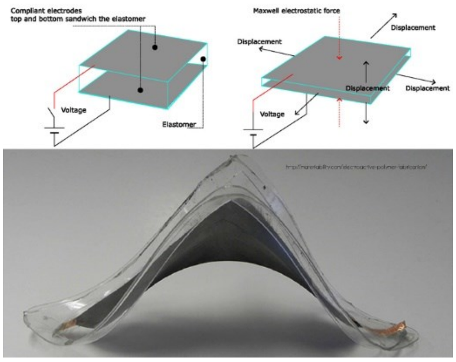
8.2.7 Polymer Bearings

Description	Polymer plain bearings are used within the wind industry (such as yaw bearings) and within the Oil & Gas industry. Polymer bearings have a number of advantages over conventional metallic bearings, polymer bearings are typically 'self lubricating' and such require less or no maintenance.  Figure 27: Example of Polymer Bearing
Current Industry	Wind Industry, Oil & Gas Industry
Opportunities	Robust, highly reliable, highly durable, very high load carrying capacities. Less sensitive to oscillating or low rotational paths than roller bearings. Cheap and easy to obtain, a mature industrial supply chain. A well developed and well understood technology. Could be used as main structural bearings in articulating wave devices.
Risks	May require redesign to integrate. In common with other bearing designs, contamination can lead to premature wear in the metallic parts (shaft for example)
Technology Transfer	Reliability of bearings could be increased Servicing may be reduced/avoided May enable design advantages; using variable preload systems (hydraulic/electromechanical) can maintain bearing tolerance and also enable clamping or braking functions
Required Development	Working to a representative duty specification, the high level compatibility of the polymer bearings requires to be verified and thereafter a programme of development/refinement and testing undertaken. Testing would be required in a realistic load and marine environment.
Transfer Timescale	☒ Short Term (~1 to 5 Years) ☐ Medium Term (~6 to 10 Years) ☐ Long Term (~10 Years +)
Examples	• http://www.ggbearings.com/en/markets/oil-gas • http://www.igus.eu/

8.2.8 Multilife Bearing

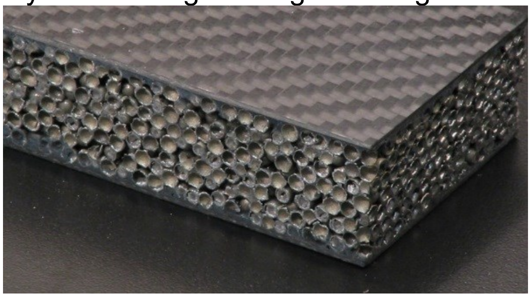
Description	Ricardo have developed an innovative bearing technology as a solution for a wind industry challenge. Bearings within the wind turbine often see increased rates of wear of large bearing assemblies as only a portion of the available bearing area is being regularly loaded / exercised. Multilife technology enables the bearing race to be rotated periodically, enabling increase area of the bearing to be utilised. This results in an increase in life of the bearing and decrease of required maintenance.  Figure 28: MultiLife Bearing by Ricardo
Current Industry	Wind Industry
Opportunities	Increase bearing life Decreased maintenance requirements
Risks	Increased complexity of bearing Increased cost of bearing Currently not designed for subsea use
Technology Transfer	Use of multilife bearing on highly loaded interfaces with partial / small rotations to increase life of bearing and decrease maintenance requirements. Could potentially be of benefit to a variety of bearing applications within wave technology but is likely to be device specific.
Required Development	Requires marinisation to a degree dependent upon specific application.
Transfer Timescale	☒ Short Term (~1 to 5 Years) ☐ Medium Term (~6 to 10 Years) ☐ Long Term (~10 Years +)
Examples	• http://www.ricardo.com/en-GB/News--Media/Press-releases/News-releases1/2015/First-wind-farm-trials-commence-of-Ricardo-MultiLifeTM-bearing-life-extension-technology/

8.2.9 Electroactive Polymers

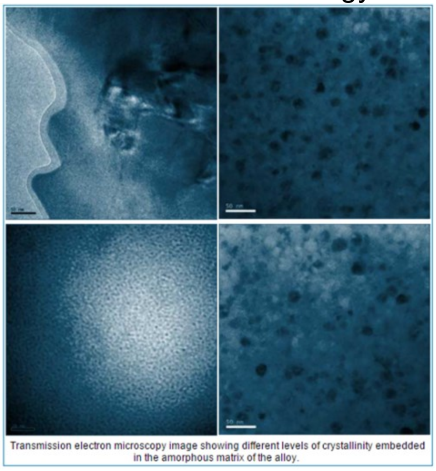
Description	Electroactive polymers are a classification of polymeric materials whose overall shape is related to the electrical potential through the material. This can be applied in two different applications. Electrical potential can be applied to the material to control / change its shape, or alternatively mechanically changing the shape of the material will result in an electrical potential being created by the material. The latter is being investigated for use as a WEC device in a programme named PolyWEC. The system is based on dielectric capacitive effects in which charge potential is related to work done in varying the separation of the charged surfaces.  Figure 29: Illustration of Electroactive Polymer Material
Current Industry	Research
Opportunities	Production of electrical energy through cyclic deformation of the material
Risks	In early research and development phase, far from commercial application.
Technology Transfer	Use of electroactive polymer transistor as PTO. The advent of useable technology could radically change the nature of wave energy conversion opening up the possibility of flexible rather than rigid body devices with power-take-off integrated into the prime mover/flexure body.
Required Development	Development of new device concepts and commercialisation of the dielectric technology and control systems.
Transfer Timescale	☐ Short Term (~1 to 5 Years) ☐ Medium Term (~6 to 10 Years) ☒ Long Term (~10 Years +)
Examples	• http://www.polywec.org/

8.3 Structures

8.3.1 Composite Metal Foam

Description	Composite Metal Foam sandwich structures can produce very lightweight yet stiff structures with high thermal shock resistance and insulation properties. Such structures are often used in the chemical industry (cryogenic storage and heat exchanger components) and also in the locomotive industry where a high strength to weight ratio is required.  Figure 30: Example of Composite Metal Foam
Current Industry	Chemical, Rail
Opportunities	High strength and stiffness to weight ratio for lightweight and strong structures.
Risks	Only failure mode is plastic deformation, once damaged repair is complex or component requires replacement. Expensive initial investment in production facilities. Sandwich structures are difficult to inspect (sub surface delamination's can exist and be difficult to detect). Moisture ingress into sandwich structure could lead to corrosion of metallic foam.
Technology Transfer	Potential use for lightweight WEC structures where high stiffness and low mass is required – this favours certain types of device e.g. submerged devices of low hydrodynamic stiffness.
Required Development	Development and material testing required for marine conditions. Identification and concept level engineering exploration of device families that would function well with such light weight materials.
Transfer Timescale	☒ Short Term (~1 to 5 Years) ☐ Medium Term (~6 to 10 Years) ☐ Long Term (~10 Years +)

8.3.2 Metallic Glass Steel Alloy

Description	The University of California San Diego have designed a new steel glass composite material (SAM2X5-630) claiming to have three times the elastic limit of tungsten carbide. It has an elastic limit of 12.5GPa in comparison to typically 0.2GPa for stainless steel. This makes the material very resistant to impacts. It is produced using a spark sintering process which also claims to be time and energy efficient.  Figure 31: Metallurgy Images of Metallic Glass Steel Alloy
Current Industry	Research
Opportunities	High impact resistant material High elastic limit
Risks	Very early in development phase Mass production of material not proven
Technology Transfer	Use of such materials in WEC structures may increase the survivability of the device due to the increased elastic limit and impact resistance.
Required Development	Development of material in quantities for large structures required Development of supply chain required Certification of material and properties required Design of structure with new material allowable required.
Transfer Timescale	☐ Short Term (~1 to 5 Years) ☐ Medium Term (~6 to 10 Years) ☒ Long Term (~10 Years +)
Examples	• http://nextbigfuture.com/2016/04/new-metallic-glass-steel-composite.html • http://jacobsschool.ucsd.edu/news/news_releases/release.sfe?id=1915 • http://www.nature.com/articles/srep22568

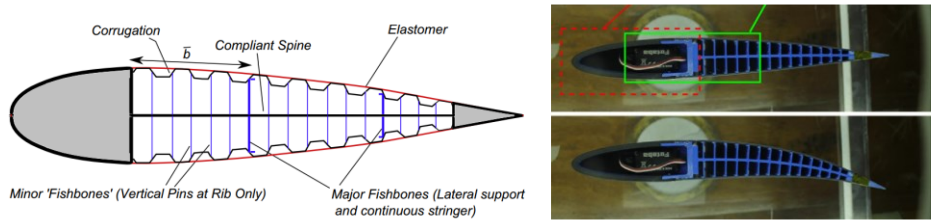
8.3.3 Float and Sink Gravity Base Foundations

Description	Various foundation types within the offshore wind industry exist which

	benefit from low installation cost. Gravity Base foundations are typically towed out to the site location and sunk through filling the structure with concrete or sand. Both types of technologies benefit from not requiring specialist and expensive vessels for drilling and installation of foundation structures. The general family includes polymer bag anchor systems.  Figure 32: Illustration of Gravity Base Foundations
Current Industry	Offshore Wind
Opportunities	Decreased installation cost of foundations, no need for specialised piling vessels etc. Foundation can be towed out to location and sunk.
Risks	Only suitable for specific sea beds, may require seabed preparations. Requires large mass to function, this could result in high cost. Wave loading conditions differ from offshore wind locations (deeper sea, further offshore) compared to wave energy conditions (closer to shore, shallower water) which are typically much more challenging.
Technology Transfer	Potential use for WEC foundations or large moorings as alternative to drilled or piled solutions to reduce on installation costs.
Required Development	Assessment of seabed / WEC specific configuration, design of foundation for each case.
Transfer Timescale	☒ Short Term (~1 to 5 Years) ☐ Medium Term (~6 to 10 Years) ☐ Long Term (~10 Years +)
Examples	• http://www.4coffshore.com/windfarms/gravity-based-support-structures-aid8.html

8.3.4 Compliant / Hydro-elastic Structures

Description	Compliant structures are designed to deform under excessive load to alleviate stresses from further loading, they 'comply' with the environment. This is achieved by tailoring the structural properties of the

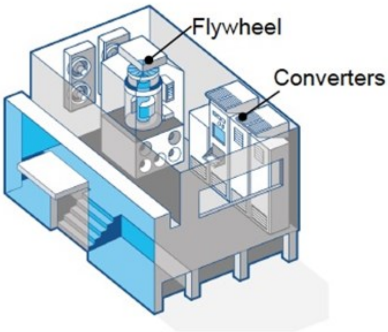
	component in design such that it deforms as desired under load. Such structures (aero-elastic structures) have been designed and are in development in the aerospace and automotive (Motorsport) sectors where they are utilised to optimise aerodynamic performance. Typically the structures consist of a ‘flexible’ skin which produces the aerodynamic profile, and underlying structure which is designed to deflect under load.  Figure 33: Example of Elastic Structures
Current Industry	Aerospace, Automotive (Motorsport)
Opportunities	Ability for structure to passively deform to improve hydrodynamic characteristics. Ability for structure to passively deform to alleviate excessive hydrodynamic loading.
Risks	Requires complex design considering fluid-structure interaction in order to achieve desired results. Increased flexibility in structure can result in dynamic response challenges and decreased structure fatigue life.
Technology Transfer	Potential to be applied on WEC devices to passively improve hydrodynamic performance or for load alleviation under extreme conditions. In principle the passive deformation technology might allow gross hydrodynamic performance to be achieved whilst avoiding high localised structural loads.
Required Development	Design of specific structure considering fluid-structure interaction. Selection of appropriate materials required to ensure feasible fatigue life and dynamic response.
Transfer Timescale	☒ Short Term (~1 to 5 Years) ☐ Medium Term (~6 to 10 Years) ☐ Long Term (~10 Years +)
Examples	• http://arc.aiaa.org/doi/abs/10.2514/1.44287?journalCode=ja • http://michael.friswell.com/PDF_Files/J256.pdf

8.4 External Energy Storage

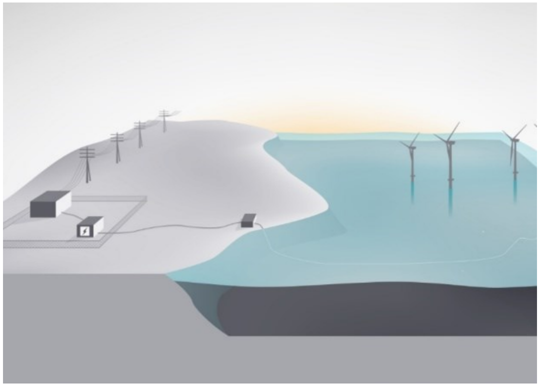
8.4.1 Sodium Batteries

Description	Sodium batteries have high power storage potential. Sodium is more readily available than lithium, hence is expected to be cheaper at a production level. Sodium battery technology is still currently in the development / early commercialisation phase and is being heavily invested in by the US Government. NGK currently advertise a sodium battery based energy storage solution capable of 1.2MW storage (consisting of 40 battery units) with an overall dimension of 10.2m x 4.4m x 4.8m, with a mass of approximately 132 tonnes. Such technology is advertised for use for renewables stabilisation, investment deferral, micro grids, generation management and ancillary systems.  Figure 34: Illustrations of NAS Energy Storage by NGK
Current Industry	Renewables, Utilities
Opportunities	Cost effective energy storage. Stabilisation of electrical generation. Use for micro grids.
Risks	In development / early commercialisation phase. Not proven.
Technology Transfer	Potential transfer to wave sector to provide energy stabilisation and generation management.
Required Development	Marinisation of storage technology required if desired for use offshore. Scaling of storage required to power levels suitable for WEC.
Transfer Timescale	☒ Short Term (~1 to 5 Years) ☐ Medium Term (~6 to 10 Years) ☐ Long Term (~10 Years +)
Examples	• http://www.greencarcongress.com/2015/12/20151210-martin.html • https://www.ngk.co.jp/nas/specs/

8.4.2 Flywheel Energy Storage

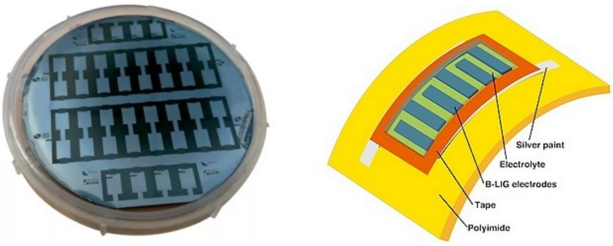
Description	Use of rotating flywheels to 'store' or buffer energy generated. Energy is transferred to a rotating mass when excess is generated and recovered when needed by using the rotating mass to power a generator ABB Powerstore is a commercial product for Energy Stabilisation using mechanical flywheel. It allows for stabilisation of energy produced prior to supply to the grid. This is performed on shore.  Figure 35: Illustration of Flywheel Energy Storage in Powerstore by ABB
Current Industry	Automotive, Renewables
Opportunities	Reduce apparent peak power to main drivetrain/generating components by smoothing peaks (seconds). Be a longer acting store of energy (minutes/hours) to provide energy corresponding to maximum economic benefit (grid price).
Risks	Added complexity. Potentially complex integration into offshore system. Reliability and maintenance of mechanical components.
Technology Transfer	Drivetrain (gearbox and generators) are likely to have been adopted/evolved from other industries where a fundamental design principle is (relatively) steady state operation. Means of reducing damaging/non-steady loadings on drivetrain components such as a gearbox giving the potential to allow use of smaller drivetrain components. Increases reliability by decreasing exposure to transients/peaks/shock load.
Required Development	Scaling of device to size / power storage required by WEC.
Transfer Timescale	☒ Short Term (~1 to 5 Years) ☐ Medium Term (~6 to 10 Years) ☐ Long Term (~10 Years +)
Examples	• http://www.gkn.com/landsystems/media/bauma/Documents/MK4_lowres.pdf • http://www.theengineer.co.uk/from-race-to-renewables/ • http://www.abb.com/industries/db0003db004332/324a96c40c8eb93ec1257a850040ebaf.aspx

8.4.3 BatWind

Description	BatWind is a pilot program for offshore wind within the Hywind project. The project shall demonstrate battery storage in an onshore station to optimise the electrical power distribution from an offshore wind farm, located off the coast in Peterhead, Scotland. The Batwind battery storage system is in development between Statoil, Scottish Government, ORE Catapult, Scottish Enterprise and Scottish Universities. It aims to mitigate intermittency and to optimise the output of windfarms, improving efficiency and lowering cost of offshore wind.  Figure 36: Illustration of BatWind project
Current Industry	Offshore Wind
Opportunities	Improve efficiency and lower cost of renewable generated power from optimisation of power distribution.
Risks	Currently in development phase, ongoing demonstration and trial.
Technology Transfer	Energy stabilisation of WEC generated electrical power
Required Development	Scaling and development for WEC farm output. Examination of wave energy output statistics to determine limit of grid-side smoothing that is possible without power shedding.
Transfer Timescale	☒ Short Term (~1 to 5 Years) ☐ Medium Term (~6 to 10 Years) ☐ Long Term (~10 Years +)
Examples	• http://www.statoil.com/en/NewsAndMedia/News/2016/Pages/21mar-batwind.aspx • https://ore.catapult.org.uk/-/statoil-launches-batwind-battery-storage-for-offshore-wind

8.4.4 Micro Super Capacitors

Description	Micro super capacitors are easy to make using readily available

	materials. They are solid state and robust capacitors with a long life, capable of significantly faster charging than typical batteries. Typical energy densities for such capacitors range from a moderate 6 Wh/kg to high power density of > 10kW/kg. Current technology store less energy per unit volume in comparison to lithium batteries however are capable of providing higher power outputs and are much more durable.  Figure 37: Illustration of Micro Super Capacitors
Current Industry	Research
Opportunities	Potential to deliver and uptake high power over short durations. Very long charge-discharge cycle life. Low cost and easy to manufacture.
Risks	Technology still in early development phase. Low overall storage capacity.
Technology Transfer	Potential use on WEC / WEC Farms for temporary energy storage, such as for energy stabilisation.
Required Development	Commercialisation required
Transfer Timescale	☐ Short Term (~1 to 5 Years) ☒ Medium Term (~6 to 10 Years) ☐ Long Term (~10 Years +)
Examples	• http://news.rice.edu/2015/12/03/scientists-see-the-light-on-microsupercapacitors-2/

8.4.5 Micro Grids

Description	Micro grids can distribute power from local renewable generation to local communities in remove areas and also back to grid. A micro grid can be powered by distributed generators, batteries and / or renewable resources. Micro grids have the ability to operate while connected to the grid but more importantly can disconnect from the grid and operate on its own local energy generation.
Current Industry	Utilities
Opportunities	Can be economical for remote communities where grid connections are not easily accessible.

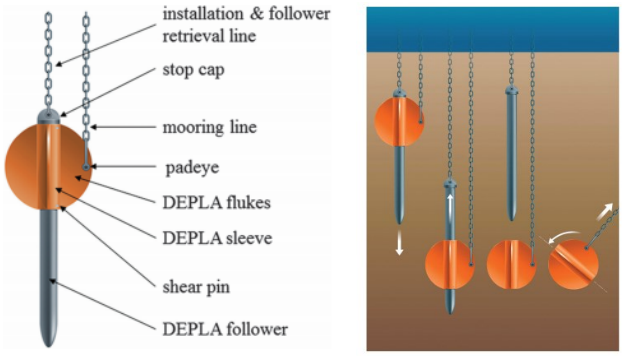
Risks	Infrastructure investment can be costly
Technology Transfer	Use of micro grid technology to enable remote communities to benefit from WEC technology
Required Development	Feasibility assessment of the use of micro grid for proposed locations. Assessment of nature and statistics of wave energy delivery and development of robust system architectures and control philosophies that will supply acceptable continuity of power.
Transfer Timescale	☒ Short Term (~1 to 5 Years) ☐ Medium Term (~6 to 10 Years) ☐ Long Term (~10 Years +)
Examples	• http://www.energy.gov/articles/how-microgrids-work

8.5 Moorings

8.5.1 Oil & Gas Moorings

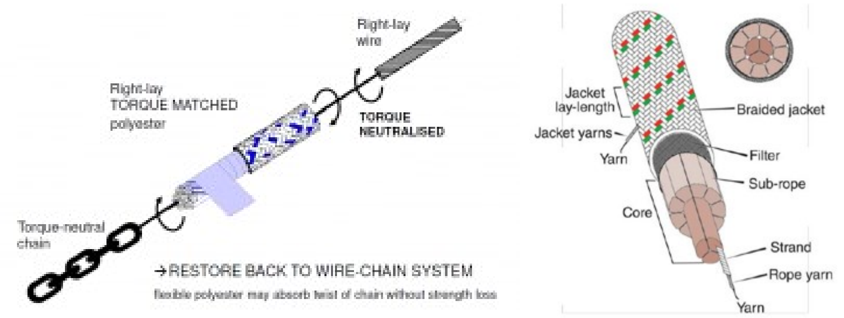
Description	The oil and gas sector have years of experience in designing and use of offshore moorings. Technology and knowledge around the engineering of moorings is available from this industry. A number of useful technology transfers include: • Reducing motion between mooring components • Better coatings or design with high corrosion/wear allowance • Corrosion resistant or non-corroding materials
Current Industry	Oil & Gas
Opportunities	Proven industry and experience available for offshore moorings (mooring configurations, installation methods, increased reliability and survivability of components, corrosion resistance, coating technologies)
Risks	Fundamental design parameters should be considered, direct transfer of technology may lead to inefficient solutions. Oil & Gas sector moorings may be extremely conservative in design.
Technology Transfer	Transfer of engineering and technologies for offshore mooring of WECs.
Required Development	Assessment of WEC requirements and design / transfer of technology and learning from the Oil & Gas Industry. Selection and refinement of mooring materials and configurations.
Transfer Timescale	☒ Short Term (~1 to 5 Years) ☐ Medium Term (~6 to 10 Years) ☐ Long Term (~10 Years +)

8.5.2 Dynamically Embedded Plate Anchor (DEPLA)

Description	The DEPLA is an anchor concept which enables low cost installation. The technology utilised gravity where the anchor is dynamically embedded into the seabed. The technology is currently owned by Vryhof. Other dynamically installed anchors / piles also exist within the industry. These types of solution enable low cost installation as no specialist vessels are required.  Figure 38: Illustration of DEPLA Anchor Concept
Current Industry	Oil & Gas.
Opportunities	Decreased installation cost and time.
Risks	Technology in development, not proven. Functionality will depend on seabed composition (i.e. will not work on rock)
Technology Transfer	Potential direct transfer of technology for low cost installation of WEC mooring anchors in areas of suitable seabed.
Required Development	Development for seabed type and WEC loads required.
Transfer Timescale	☒ Short Term (~1 to 5 Years) ☐ Medium Term (~6 to 10 Years) ☐ Long Term (~10 Years +)
Examples	• http://www.oedigital.com/component/k2/item/6435-going-down-under-for-anchor-innovation • http://subseaworldnews.com/2014/08/07/depla-anchor-developed-for-deep-water-use-aus/

8.5.3 Multi-material Mooring Lines

Description	Conventional mooring lines are typically constructed from steel (chain or wire) for strength, more recently non-metallic mooring lines are available (polyester / nylon type construction). Different mooring lines and technologies have associated performance or behaviour such as

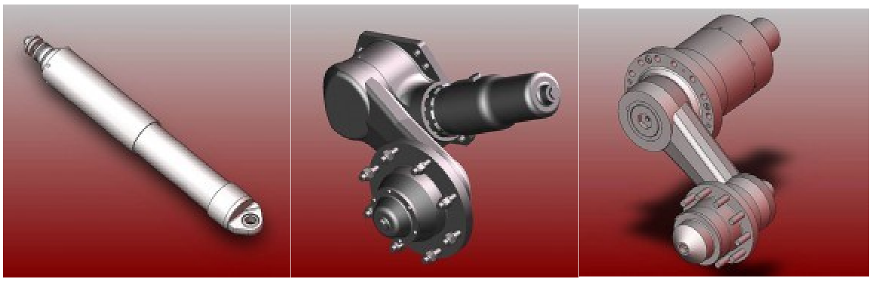
	corrosion resistance, strength, stiffness etc. The use of multi-material mooring lines are being considered in industries such as the floating wind industry, where optimisation of the line can be achieved to reduce weight and cost. This technology approach utilised a mooring line designed from various sections of materials depending on the particular requirements.  Figure 39: Illustration of Multi-material mooring lines
Current Industry	Offshore Wind, Oil & Gas, Marine
Opportunities	Weight and Cost reduction from improved optimisation
Risks	May result in bespoke solutions with limited suppliers
Technology Transfer	Use of multi material mooring lines for WEC mooring. Developments in respective mooring line material technology may be used for WEC moorings to improve survivability and reduce cost. Such as developments in fibre ropes and elastomeric mooring cables.
Required Development	Design and development of multi material mooring line for WEC requirements.
Transfer Timescale	☒ Short Term (~1 to 5 Years) ☐ Medium Term (~6 to 10 Years) ☐ Long Term (~10 Years +)
Examples	

8.5.4 Passive Weathervaning turret Mooring

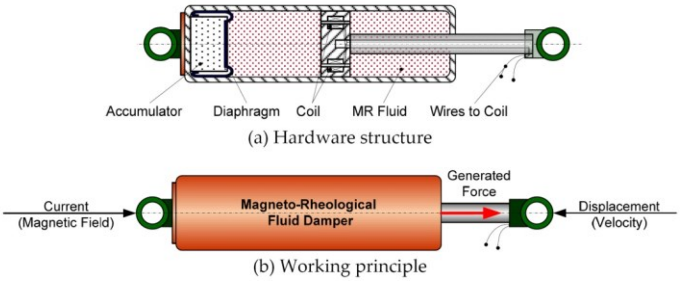
Description	Passive weathervaning is the ability for a floating vessel / device to yaw around its mooring due to the prevailing environmental forces it experiences such as wind or wave direction. A turret design within the Oil & Gas sector enables a vessel to weathervane about its mooring location about a central axis (the turret) which remains stationary and itself does not rotate. This allows riser equipment connected to subsea systems to remain decoupled in yaw from the yaw of the vessel.  Figure 40: Illustration of Oil & Gas turret Mooring
Current Industry	Offshore Oil & Gas
Opportunities	Allows floating device to be stationed yet allowing for passive weathervaning around a fixed location while allowing the turret to remain stationary in yaw.
Risks	Added complexity and structure required. Benefits specific to device stationing requirements.
Technology Transfer	Potential for use for floating WEC device where weathervaning about a fixed point is required.
Required Development	Specification and design of a system to meet WEC requirements is required. Assessment of compatibility with hydrodynamically active structures.
Transfer Timescale	☒ Short Term (~1 to 5 Years) ☐ Medium Term (~6 to 10 Years) ☐ Long Term (~10 Years +)

8.6 Control

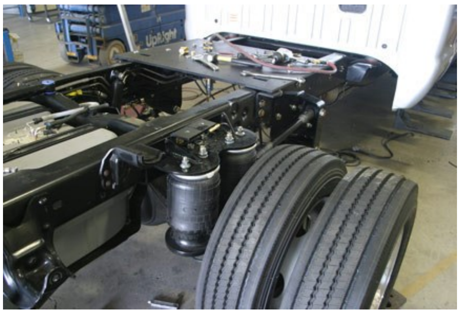
8.6.1 Automotive Active Suspension Systems

Description	Active suspension systems are used within the automotive industry, and also in the defence industry on military vehicles. Such systems have programmable spring, damping and end-stop behaviour which can be altered dynamically. Horstman are one organisation which provide such systems for military vehicles.  Figure 41: Illustration of Active Suspension Systems by Horstman
Current Industry	Automotive, Defence
Opportunities	Dynamically variable damping behaviour. Robust and proven technology in tough environment.
Risks	Currently utilised on onshore environment only
Technology Transfer	Potential use for variable damping or control of WEC device dynamic response to optimise performance or increase survivability in extreme conditions. Potential technology transfer of hydraulic design. Potential use of the system (or aspects of) as variable PTO solution. Transfer of the technical concepts rather than the engineered products.
Required Development	Marinisation required for offshore / subsea application of technology. Scaling of technology required suitable for WEC Loads. Development of WEC control system required to utilise dynamically adjustable damping.
Transfer Timescale	☒ Short Term (~1 to 5 Years) ☐ Medium Term (~6 to 10 Years) ☐ Long Term (~10 Years +)
Examples	• http://www.horstman.co.uk

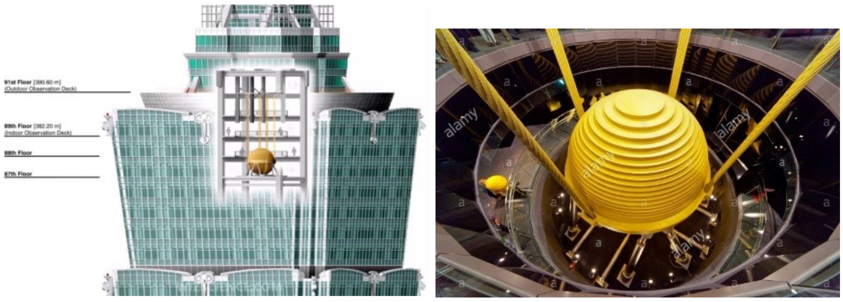
8.6.2 Magneto-Electro Rheological Fluids

Description	Magneto-electro rheological fluids are hydraulic fluids which are subject to changes in properties when subjected to a magnetic field. When utilised within a hydraulic damper, the viscosity characteristic of the fluid can be dynamically altered using electro-magnetic fields. This behaviour can be utilised for fast alterations to the damping behaviour of a hydraulic damper. As such, this technology is appealing and is used within the automotive industry for applications as shock absorbers on performance vehicles (Such as the Audi TT, Audi R8 and Ferrari 458).  Figure 42: Illustration of Magneto-Electric Rheological Fluid Damper
Current Industry	Automotive
Opportunities	Fast dynamic adjustment of damping behaviour
Risks	Currently in development
Technology Transfer	Potential use for variable damping or control of WEC device dynamic response to optimise performance or increase survivability in extreme conditions. Potential long term application for use of Rheological fluid in a hydraulic PTO system, where pressurised magnetic fluid is moved through a magnetic field to create electrical power.
Required Development	Development for offshore / subsea application required. Scaling of technology for WEC application required. Development of WEC control system required to utilise dynamically adjustable damping. Evaluation of overall energy capture of WEC when dissipating energy through a damper system.
Transfer Timescale	☒ Short Term (~1 to 5 Years) – For use as controlled damping ☒ Medium Term (~6 to 10 Years) – For use as potential PTO technology ☐ Long Term (~10 Years +)
Examples	• https://www.theengineer.co.uk/removing-shock-from-the-system-with-magnetic-fluids/

8.6.3 HGV Pneumatic Suspension Systems

Description	Pneumatic suspension systems are often found on heavy good vehicles, compromising of bellows / air bags, hoses, valves and pneumatic control systems. Such systems are subject to large loads and arduous duty cycles of millions of cycles. Systems are designed for low maintenance and high reliability  Figure 43: Example of Pneumatic Suspension System
Current Industry	Automotive
Opportunities	Low cost, high reliability, low maintenance pneumatic systems, low pollution risk.
Risks	Not designed for offshore or subsea use, air pump design for subsea operation may be challenging.
Technology Transfer	Potential transfer of high reliability and low cost pneumatic technologies (bellows, hoses, valves and pneumatic control system) to wave devices working at high pneumatic pressure.
Required Development	Requires marinisation Development or transfer of particular components of the system useful for a WEC would be required.
Transfer Timescale	☒ Short Term (~1 to 5 Years) ☐ Medium Term (~6 to 10 Years) ☐ Long Term (~10 Years +)

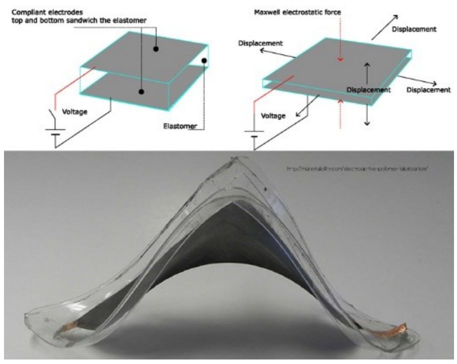
8.6.4 Tuned Mass Damper

Description	Tuned mass damper systems are often found in large civil structures such as sky scrappers or bridges. They are used control or alter the dynamic response of the structure. This can be for extreme load conditions such as earthquakes or storms, where a the damper system can be tuned such that the building vibration is kept to a minimum to ensure it survives the event. Alternatively active damping systems can be used on structures such as bridges to ensure subjected loading (wind, traffic etc) does not result in large excitations, thus improving the life of the structure.  Figure 44: Example of a TMD system in Tapei 101
Current Industry	Civil
Opportunities	Can be used to tune / optimise the dynamic response of a system Systems are proven in the civil industry where structure survivability is key.
Risks	Systems currently not designed for subsea / offshore use. Control systems and dynamics are complex. Requires additional and often large structure / mass.
Technology Transfer	Use on WEC device to reduce loading in large sea states (to improve survivability). Use on WEC device to increase dynamic response in low sea states (to improve performance). Use of technology to enable / inspire new WEC configurations.
Required Development	Development of systems suitable for subsea use. Development of complex control systems for specific WEC device dynamics.
Transfer Timescale	☒ Short Term (~1 to 5 Years) ☐ Medium Term (~6 to 10 Years) ☐ Long Term (~10 Years +)
Examples	• http://www.taipei-101.com.tw/en/observatory-damper.aspx

8.6.5 Morphing Structures

Description	Morphing structures (such as wings – wing warping) are semi-flexible structures which can be actuated to change shape. This is performed by internal actuators and the use of flexible structure design. The advantages of such devices for the aerospace market is the improvement in aerodynamic performance due to the removal of any gaps or mechanisms which typically impinge on the aerodynamic profile and increase drag. An additional benefit is that the mechanical systems can be completely sealed within the wing, with no exposure to the outer environment, aiding longevity of the systems.  Figure 45: Example of Morphing Wing Structure by FlexSys
Current Industry	Aerospace
Opportunities	Improve aerodynamic (or hydrodynamic) performance due to the removal of mechanical features on the outer profile. Full enclosure of mechanical systems from outer environment, reducing environmental degradation such as corrosion or moisture ingress.
Risks	Currently used for aerodynamics, hydrodynamic opportunities need to be assessed. Increased difficultly for maintenance and inspection as all systems are internal.
Technology Transfer	Use of morphing structures for control of WEC devices could lead to hydrodynamic improvements and also enable full internal control systems to aid survivability. Unlike wind, wave devices are seldom controlled at the front-end by varying geometry but by the PTO. With suitable technology, front end control systems could have distinct advantage by preventing large loads to enter the system.
Required Development	Hydrodynamic benefits and control of WEC need to be assessed. The suitability of the sub-surface actuators needs also to be assessed. Flexible structure concept designs suitable for wave energy use require to be developed.
Transfer Timescale	☒ Short Term (~1 to 5 Years) ☐ Medium Term (~6 to 10 Years) ☐ Long Term (~10 Years +)
Examples	• http://www.flxsys.com/

8.6.6 Electroactive Polymers

Description	Electroactive polymers are a classification of polymeric materials whose overall shape is related to the electrical potential through the material. This can be applied in two different applications. Electrical potential can be applied to the material to control / change its shape, or alternatively mechanically changing the shape of the material will result in an electrical potential being created by the material. The former can be utilised for control of a device, where the shape / configuration of the structure can be altered by applying electrical current, requiring no mechanical systems. Current research and development of such technology exists within the medical industry where they are targeted for use as artificial muscles.  Figure 46: Example of Electroactive Polymer
Current Industry	Research, Prosthetics
Opportunities	Control of structure shape without mechanical systems or actuators
Risks	In early research and development phase, far from commercial application.
Technology Transfer	Use of electroactive polymers in WEC structures as a morphing material to control shape of the primary capture device.
Required Development	Commercialisation of technology Concept design and cost-benefit assessment of WEC device structure and control system required to utilise electroactive polymers as a control technology
Transfer Timescale	☐ Short Term (~1 to 5 Years) ☐ Medium Term (~6 to 10 Years) ☒ Long Term (~10 Years +)
Examples	• http://eap.jpl.nasa.gov/

8.6.7 Azimuthing Podded Dynamic Positioning Systems

Description	The Azimuthing Podded Drive system is a commercial marine product for vessels. It consists of an electrically driven propulsor with an AC motor incorporated in a streamlined azimuthing (steerable) pod unit with direct drive of a fixed-pitch propeller. Such devices are used in conjunction with a control system on offshore vessels for dynamic positioning systems. These systems provide thrust in the directions as required to maintain position and stability of the vessel against prevailing environmental conditions (wind, wave, current etc.).  Figure 47: Example of Positioning System Thrusters by ABB
Current Industry	Marine
Opportunities	Positioning and stability control of floating vessel
Risks	Requires electrical power and control system Added complexity to a system
Technology Transfer	Potential use for dynamic control or positioning of WEC device Alternatively transfer of technology used in reverse as PTO technology
Required Development	Design of floating WEC device integration Development of control system for WEC
Transfer Timescale	☒ Short Term (~1 to 5 Years) ☐ Medium Term (~6 to 10 Years) ☐ Long Term (~10 Years +)
Examples	• http://new.abb.com/marine/systems-and-solutions/electric-propulsion/azipod • http://new.abb.com/marine/systems-and-solutions/electric-propulsion/azipod/for-ships

8.7 Information & Communication Technology

8.7.1 5G Networks

<table>
<tr><td>Description</td><td>The International Mobile Telecommunications programme IMT-2020 defines a ‘5G’ performance target including peak data rates (ideal, to one device) of 10-20 Giga bits per second, whilst users can expect to experience data rates (in a typical shared coverage area) of 100 Mega bits per second, a network round-trip latency of 1 millisecond and provision of services to mobile platforms travelling at speeds up to 500 kilometres an hour
The system will suit applications requiring very low latency and reliable communications. These include: delivery of cloud services, control of industrial manufacturing machinery and autonomous transportation
The system will enable massive scale machine-to-machine communications including the increase in device density anticipated from the Internet of Things (IoT)

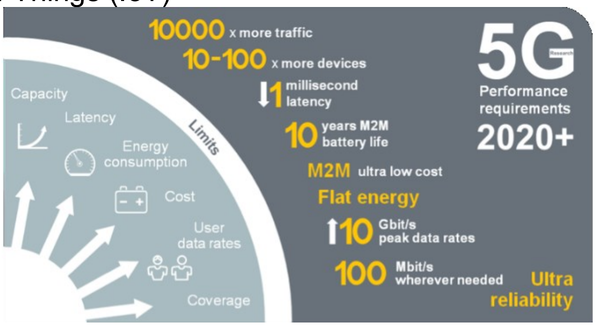
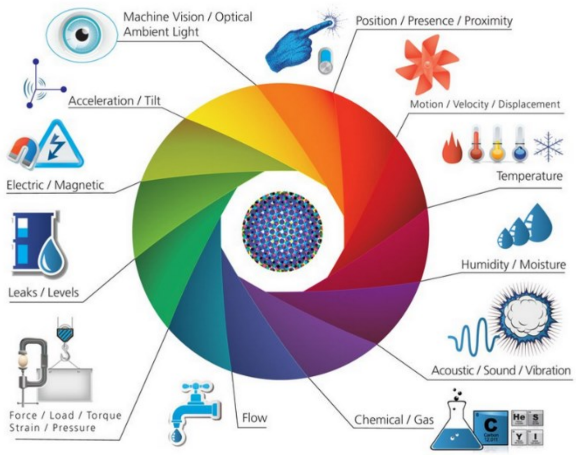


Figure 48: Illustration of 5G Network</td></tr>
<tr><td>Current Industry</td><td>Telecommunications</td></tr>
<tr><td>Opportunities</td><td>High-speed wireless communications.
As part of a wider network of sensors, transducers, communications and processors, the 5G technology could enable a step change in the level of system sensing and available to wave energy control and diagnostic systems. This will help enable advanced control based on real-time data.</td></tr>
<tr><td>Risks</td><td>Initial hardware investment may be expensive
Coverage currently unknown</td></tr>
<tr><td>Technology Transfer</td><td>Use of high speed wireless connections for transmission of WEC data to control room.</td></tr>
<tr><td>Required Development</td><td>Development of network and coverage required
Repeater / transmitter / receiver hardware required at WEC location / shore.</td></tr>
<tr><td>Transfer Timescale</td><td>☐ Short Term (~1 to 5 Years)
☒ Medium Term (~6 to 10 Years)
☐ Long Term (~10 Years +)</td></tr>
<tr><td>Examples</td><td>• https://www.itu.int/net/pressoffice/press_releases/2015/27.aspx#.VsQvNXLcsdU</td></tr>
</table>

8.7.2 Internet of Things

Description	Internet of Things are a range of low cost sensors and networking systems being developed for numerous commercial and consumer applications. The range of sensors are extensive.  Figure 49: Illustration of Internet of Things
Current Industry	Consumer
Opportunities	Low cost sensor technology for control systems. Merged with 5G communications, step change increases in low cost data could enable a step change in the sophistication of wave device control. Pressure sensors with IoT compatability are likely to be of particular relevance.
Risks	Un-proven in prolonged exposure to marine environment Dependant on 3rd party development
Technology Transfer	Use of IoT equipment for control systems of WEC to reduce cost and increase availability through the monitoring of various systems otherwise not monitored due to cost.
Required Development	Development and testing of IoT sensors in marine environment. Design of control system and monitoring solutions for specific WEC device.
Transfer Timescale	☒ Short Term (~1 to 5 Years) ☐ Medium Term (~6 to 10 Years) ☐ Long Term (~10 Years +)

8.7.3 Optical Communications

Description	Optical communications have been developed for commercial and defence industry applications. This technology utilises laser and LED based designs to communicate wireless in the marine environment. It supports both all through water and air-water interface communications. The communications are jam resistant and have data rates much larger than radio or acoustic solutions. QinetiQ have designed various optical communication systems based on user requirements, such as a LED based unit with 900kbps bi-directional communications for underwater use.  Figure 50: Illustration of Optical Communications by QinetiQ
Current Industry	Marine, Defence, Oil & Gas
Opportunities	High speed underwater wireless communications Proven in harsh environments
Risks	High cost Limited to line of sight connections
Technology Transfer	Utilisation by WEC devices in a farm for wireless communication to hub device to feed data to shore, reducing number of wired data connections. Potential utilisation on WEC device during periodic maintenance where direct wireless communication can be accessed from vessel in line of sight.
Required Development	Integration into existing WEC control systems
Transfer Timescale	☒ Short Term (~1 to 5 Years) ☐ Medium Term (~6 to 10 Years) ☐ Long Term (~10 Years +)
Examples	• https://www.qinetiq-na.com/wp-content/uploads/catalog_ts.pdf

8.7.4 LineWatch

Description	QinetiQ's LineWatch technology is currently used in the civil and military sectors for monitoring of low and medium voltage power cables. It is designed to monitor power cables and grids for faults, losses and asset management. The monitoring technology is quick and flexible to install and integrated with existing communications networks.  Figure 51: Example of LineWatch cable monitoring by QinetiQ
Current Industry	Civil, Defence
Opportunities	Proven power cable monitoring technology
Risks	Not currently design for underwater use
Technology Transfer	Use for WEC power export cables to improve availability and performance by monitoring power for losses and faults, enabling optimisation and maintenance as required.
Required Development	Integration with existing communications network Scaling if required for power cable specifications of WEC Development for subsea offshore use
Transfer Timescale	☒ Short Term (~1 to 5 Years) ☐ Medium Term (~6 to 10 Years) ☐ Long Term (~10 Years +)
Examples	• https://www.qinetiq-na.com/wp-content/uploads/catalog_ts.pdf

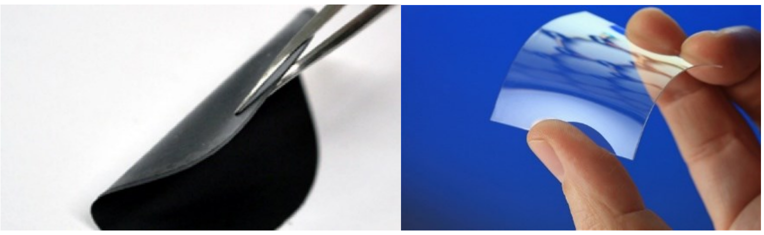
8.7.5 Machine to Machine Communications

Description	Machine to Machine (M2M) communications is a technology which allows direct communications between machines without the manual assistance of people. Such technology is currently seen in industry and consumer applications with Internet of Things (IoT) technologies. For example M2M communications may enable a printer to automatically order supplies from a vendor when it detects the consumables are running low, without the need for human intervention.
Current Industry	Consumer, Civil

Opportunities	Optimisation of communication channels
Risks	Currently a technology still in development Lacking in standards for transmission, data format etc Security challenges to be overcome to ensure robustness
Technology Transfer	Use for WEC to WEC communication within a farm to share condition monitoring data in order to optimise performance as a farm.
Required Development	Development of control and instrumentation technologies to benefit from M2M.
Transfer Timescale	☐ Short Term (~1 to 5 Years) ☒ Medium Term (~6 to 10 Years) – Dependant on use with wave farm ☐ Long Term (~10 Years +)
Examples	• https://www.cpni.gov.uk/Documents/Publications/2015/05-June-2015-Emerging%20Technologies%202015%20-%20V2_PV.pdf

8.8 Operations

8.8.1 Graphene (Anti Biofouling)

Description	Graphene is a new material which comprises of a single layer of carbon atoms arranged in a hexagonal lattice. Graphene has been shown to be an effective antifouling material in several laboratory tests focusing on membrane bio reactors for processing of human waste.  Figure 52: Examples of Graphene
Current Industry	Research
Opportunities	Anti-biofouling coating
Risks	Material currently in early development phase. Currently cannot be produced in sufficient quantities to be of use. Material is currently expensive. Durability of graphene in the marine environment unknown.
Technology Transfer	Use on WEC structures as a coating for anti-biofouling to improve performance and decrease maintenance requirements.
Required Development	Industrialised manufacture of graphene required. Application of graphene as a coating for WEC structures needs

	development. Development and testing of material in offshore environment.
Transfer Timescale	☐ Short Term (~1 to 5 Years) ☐ Medium Term (~6 to 10 Years) ☒ Long Term (~10 Years +)

8.8.2 Autonomous UAV / ROV

Description	UAV and ROVs are being utilised within other industries to improve accessibility to difficult or hazardous areas for inspection and / or maintenance tasks. An example of UAV use in industry are the use for Blade inspections in offshore wind, where UAVs are used to obtain high resolution imagery used to inspect blade condition, removing the need for rope access. An example of ROV use in industry is the use within the offshore Oil & Gas where they can be utilised for inspection and basic maintenance tasks along subsea pipelines.  Figure 53: Examples of ROV and UAV technologies
Current Industry	Offshore Wind, Oil & Gas, Utilities, Marine, Military, Civil
Opportunities	Remote inspection and basic maintenance in difficult to access / hazardous areas.
Risks	Primary use for inspection, limited scope for carrying out maintenance
Technology Transfer	Use for WEC remote inspection, reduces the requirement for diver access. Use for basic WEC maintenance tasks where possible.
Required Development	N/A
Transfer Timescale	☒ Short Term (~1 to 5 Years) ☐ Medium Term (~6 to 10 Years) ☐ Long Term (~10 Years +)

8.8.3 Remote Subsea Excavators

Description	Remote excavators are vehicles capable of operating in subsea

	conditions for excavation / dredging of the sea bed, typically for the preparation or burial of pipelines / cables or preparation for foundation installation. Such devices are typically connected by umbilical to the operation vessel and operated remotely from the vessel.  Figure 54: Example of Remote Underwater Excavator
Current Industry	Offshore Oil & Gas, Offshore Wind, Civil
Opportunities	Proven technology operating in harsh environment. Remote excavation of seabed from a vessel.
Risks	Potentially expensive, need for remote excavator and vessel capable of deploying and operating from.
Technology Transfer	Transfer and use of excavator remotely controlled technology (hydraulics and control etc) in WEC devices. Adaptation of excavator to perform maintenance or installation tasks remotely (i.e. cutting / welding / NDT / assembly / bolting etc.)
Required Development	Development of remote maintenance equipment (cutters/welders etc) suitable for excavator platform.
Transfer Timescale	☒ Short Term (~1 to 5 Years) – For use as excavator ☒ Medium Term (~6 to 10 Years) – For use as maintenance vehicle ☐ Long Term (~10 Years +)
Examples	• https://subseaworldnews.com/2014/12/18/video-swire-seabeds-excavator-vehicle-in-action/ • http://www.jandenul.com/en/pressroom/press-releases/remote-marine-hydraulic-excavator-for-offshore-applications

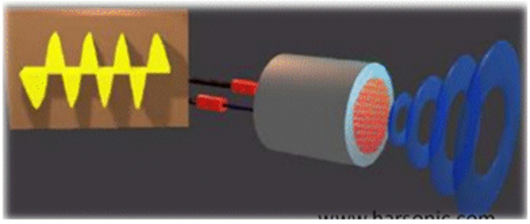
8.8.4 Supacat Launch and Recovery Vehicle

Description	This vehicle technology enables the launch and recovery of small vessels without the need for infrastructure such as ramps etc. The tracked vehicle is capable of delivering the vessel into the splashzone / shallow water and release the vessel.  Figure 55: Example of Launch and Recovery Vehicle by Supacat
Current Industry	Marine
Opportunities	Launch of vessels without need for infrastructure such as a ramp / dock / crane etc.
Risks	Technology currently only suitable for small vessels (but concept is scalable)
Technology Transfer	Use of launch technology to launch WEC devices, removing the need for expensive infrastructure. Potential use of technology to 'launch' or recover WEC devices from shore out to site location.
Required Development	Scaling up of device required to carry WEC devices. Full marinisation of device to launch devices further from shore. Evaluation of feasibility to launch devices further from shore.
Transfer Timescale	☒ Short Term (~1 to 5 Years) – For use as 'on-shore' deployment ☒ Medium Term (~6 to 10 Years) – For use deploying further off-shore ☐ Long Term (~10 Years +)
Examples	• http://www.supacat.com

8.8.5 Hull Cleaning Robot

Description	ROVs capable of autonomously cleaning vessel hulls are used within the marine industry. They are used to remove bio-foul without the need for human intervention, or the need for diver access / dry docks. Systems typically clean using an ultrasonic device.  Figure 56: Example of Hull Cleaning Robot
Current Industry	Marine
Opportunities	Remote autonomous cleaning of bio-foul
Risks	Limited cleaning abilities, may not be effective on heavily fouled surfaces. Access to intricate areas may not be possible (such as in mechanical joints etc.) Vessel hull is a relatively even surface, whereas WEC structure is often more complicated.
Technology Transfer	Use of autonomous cleaning ROVs to remove bio-foul from WEC devices
Required Development	Development of cleaning system suitable for WEC access and coverage of bio-foul expected.
Transfer Timescale	☒ Short Term (~1 to 5 Years) ☐ Medium Term (~6 to 10 Years) ☐ Long Term (~10 Years +)
Examples	• http://gac.com/shipping/hull-cleaning-solution/

8.8.6 Ultrasonic Hull Cleaning

Description	Ultrasonic transducers can be used to remove bio-foul from submerged structures. The use of ultrasound is environmentally friendly, requiring no potentially harmful substance.  Figure 57: Illustration of Ultrasonic Wave
Current Industry	Marine
Opportunities	Use for removal of bio-foul from WEC structure
Risks	Requires access method (ROV / Diver etc)
Technology Transfer	Direct application of technology
Required Development	Development of suitable delivery method
Transfer Timescale	☒ Short Term (~1 to 5 Years) ☐ Medium Term (~6 to 10 Years) ☐ Long Term (~10 Years +)
Examples	• http://www.cwrmglobal.co.za/huc.pdf

9 Conclusions and Recommendations

9.1 Introduction

Broad ranging studies have been conducted to identify the opportunities for technology transfer from other sectors to improve the profile of wave energy in terms of the core metrics that will affect long-term affordability - survivability, reliability, availability and cost-base. Earlier sections of this document provide a detailed description of the processes of identification and assessment of promising technology transfer opportunities. In this section, conclusions are drawn based on the information presented.

9.2 Technology Transfer Assessment Process

The technology transfer assessment process adopted within this study has evolved over the course of the project and has provided learning in itself. From the outset a structured benchmark technology identification and benchmarking process enables key trends of technology challenge to be identified and evaluated, for example cost and survivability are the key challenges for structural technologies. The structured approach enables a systematic scan across industries for relevant technologies and processes, with technology transfer potential being able to be identified organisations both with and without experience of the wave energy sector.

Initial technology transfers identified and proposed within Section 6 consist primarily of directly interchangeable technologies, for example the use of different bearings over conventional bearings. These technologies are not the primary focus for this study. However the systematically gathered data are fundamental in steering the horizon scanning process in Section 8. Providing an overview of the most relevant sectors for particular technologies reveals the challenges of transfer for directly interchangeable products and provides the required context for effective horizon scanning.

For example, the identification of composite materials for structure technologies in the Technology Element Process highlights that materials such as GFRP and CFRP are technologies available from the marine, aerospace and automotive industries. Such materials are known to the wave sector however are typically cost prohibitive due to manufacturing or raw material cost. With this known, the horizon scanning activities can respond in a more targeted way. As a result, load alleviating and compliant structure are proposed as technologies for transfer from the aerospace sector which could decrease loads and subsequently reduce material quantity and cost. Additionally design for manufacture and topology optimisation are process technologies proposed for transfer from the automotive industry also with the potential to reduce manufacturing cost and material quantity.

The hybrid approach to technology transfer assessment developed within this study (structured assessment followed by unstructured horizon scanning) has been successful in identifying high potential technologies from other sectors while ensuring the fundamental opportunities to the wave sector are realised and captured.

9.3 Technologies and Processes

9.3.1 Introduction

Many technologies are proposed with potential to improve one or more of the WES metrics through transfer to the wave sector. WES guidance is that short term (available within 5 years) to medium term (available within 10 years) technologies with a degree of novelty and high potential of improvement against the fundamental metrics are most applicable for this landscaping study.

9.3.2 Compliant and Load Alleviating Structures

The benchmarking activities carried out in Section 5 reveal that current structural technologies are very poor in terms of affordability (high cost). This is linked to survivability in the extreme environment (the need for large or strong structures increases cost).

When considering structural technology transfer to improve affordability, the effect on survivability and vice versa must be considered. Introduction of compliant and load alleviating structures within wave energy devices may enable improved survivability and affordability. The ability to reduce extreme loads on the structure either by design (passive) or through the use of control systems could lead to large improvement in affordability. Structures that can be more compliant as opposed to resistant (in particular to extreme events) are likely to be more affordable. Clearly, any increase in design complexity of the structure and/or the control system must also be evaluated to ensure overall cost effectiveness.

Load alleviating structure technology is proven within the aerospace sector, where commercial airliners use actuated control surfaces combined with active control systems to alter the airflow over the wing during extreme events (for example extreme turbulence) to reduce the forces on the structure. As a result, aircraft wing structures can be further weight and cost optimised without compromising survivability. The wind turbine sector also employs similar technologies, where control of blade pitch is used to feather (and stop) the blades and reduce loading on the blades and turbine during high winds. These solutions require active control systems, however the aerospace sector has also considered passive load alleviation through compliant flexible (bi-stable) structures which are designed to change shape without the need for actuation or control when undesired loads are experienced.

Technologies with the potential to enable such an approach to WECs include Compliant / Hydro Elastic Structures from the aerospace and marine industries, Morphing Structures from the aerospace and marine industries, Tuned Mass Damper technology from the civil industry and Suspension Systems from the automotive industry.

9.3.3 Structure Design and Optimisation

Experience and process technologies for structural design and optimisation exist in other industries and have potential to improve wave energy structures. Some of the large costs of wave energy structures are manufacturing and maintenance related.

The automotive industry offers many processes for optimisation for manufacture and quality improvement which can lead to cost savings (through reducing concessions etc.). Lean Manufacturing and Design for Manufacture processes pioneered by the automotive industry and now adopted by other industries including aerospace, are proven in achieving increased quality while decreasing cost and time. Such processes can be applied to wave energy industry structures. Involving manufacturing engineers from the early design phase of a device, ensures the device is cost effective to manufacture from the outset. Such an approach may seem obvious but it is often overlooked when faced with technical and financial project constraints. Transfer of processes such as these from the automotive industry could prove highly effective in ensuring device structures remain affordable.

Within the aerospace industry structural designs are optimised for performance and survivability - they are required to be lightweight yet strong. Structural design technologies exist within this sector which could be of benefit to the wave energy industry. The use of parametric optimisation process and topological design optimisation software are two methods which have the potential to aid WEC structure affordability and survivability. Parametric optimisation can be implemented at the early design phase to highlight key opportunities and barriers to structural optimisation. The aviation industry has used such processes in the design of next generation composite aircraft structures to ensure development and testing is targeted at areas with the largest opportunity. Topology Optimisation technology has also been used in the aerospace and automotive sectors where highly optimised structures can be achieved through shape and material positioning based on fundamental load requirements. To maximise the effectiveness of such software it must be applied at an early design phase where significant influence is still available.

9.3.4 Cable and Connector

Cable and Sub Sea connector technologies within the wave industry are challenged by survivability. They have a significant impact on affordability as they have a direct impact on power production - failure of a cable of connector can result in long downtime (reducing availability) and expensive repair. Thus survivability of cables and connectors are vital.

Existing subsea connector technologies (wet mate and dry mate) are available within the Oil and Gas sector. Such technologies, specifically the lower cost options such as moulded plastic connectors, have been utilised within the wave sector and have subsequently failed. More costly options such as the oil filed connectors used in offshore oil & gas subsea equipment have been prohibitively expensive for wave energy devices. Transfer of technologies from the offshore oil & gas industry for offshore connectors could provide a cost effective yet survivable solution for the wave energy sector. Adaptation of robust connector solutions to the wave sector requires evaluation of the difference in requirements (function, duty cycle, certifications etc.) between wave and oil & gas, enabling a cost effective yet robust connector technology.

To reduce loading on cables and connectors, the offshore floating wind and oil & gas industries utilise dynamic cable technology. 'Excess' cable suspended by buoyancy enables a degree of dynamic decoupling of the relative motion between attachments to the device and the seabed. This approach is directly applicable to floating wave energy devices.

9.3.5 PTO and Drive Train

Power Take Off and Drive Train technologies are critical to a WEC's performance and availability. High efficiency and reliability are desired alongside low cost and maintenance.

Drive train gearing and transmission can have a large impact on performance and are typically spots for reliability due to the arduous duty cycles they experience. Normally for efficient electrical generation, high speed and low torque rotation is required, yet a typical wave device captures low speed and high torque rotation (due to wave behaviour). The automotive industry in recent years has been advancing magnetic gear systems which are capable of translating the captured low speed and high torque rotation and converting to high speed and low torque rotation. Magnetic gearing has the ability to do this efficiently due to the avoidance of mechanical friction. Additionally it can offer improved reliability through the decreased number of parts and contact surfaces, reducing wear and hence any subsequent maintenance.

The marine sector offers various technologies which are proven to be highly reliable and efficient. Azimuthing Podded Drive technology is used within the marine industry for vessel control and propulsion. These devices are permanent magnetic motors packaged in a modular pod design (inclusive of drive shaft, bearing, seal, and control technologies). They have a proven track record for reliability and efficiency in offshore conditions. Transfer of the drive train technology (drive shafts, bearings, seals, control system etc.) may have short term direct applicability to the wave energy sector and improve existing technologies in these areas. The technology and processes utilised in the design of a robust integrated and modular motor propulsion system could positively influence PTO design where there is a strong cross over of challenges such as rotary seals, drive shaft technology and permanent magnet motor/generators.

The marine sector also offers various hydraulic control technologies used on vessels which have potential for use on WEC PTO systems. Hydraulic vessel steering systems provide high torque / low rotation control moments to a rudder. This lends itself in reverse to the typical operating envelope of an oscillating wave energy device (high torque and low oscillating rotations). Technology transfer from these products in the marine industry has the potential to improve rotary hydraulic PTO systems as they are proven in a similar environment.

9.3.6 Control

Control is recognised as being central to WEC affordability and the ability to vary dynamic and potentially hydrodynamic parameters is vital for realising performance potential, it can also provide control strategies to improve survivability of WEC devices in extreme conditions. Several control technologies have been identified from other sectors with the potential to increase survivability and performance of devices in the wave sector.

Tuned mass damper techniques and technology are utilised within the civil industry to improve the survivability of large structures subject to environmental loads such as seismic activity or extreme wind loading (typhoons and hurricanes). This technology operates by tuning the dynamic response of the structure such that the structure is adequately damped or detuned to avoid excessive loads. Transfer of this technology to the wave sector could enable improved survivability of WEC structures through altering the dynamic response under extreme sea states, ensuring structural loads are kept to acceptable levels, improving survivability of the structure or enabling further optimisation to reduce cost. Alternatively such technology could be used to tune the dynamic response of a WEC structure such that additional performance can be achieved (i.e. tuning the system to operate near or within its resonant envelope).

Active hydraulic and pneumatic damper systems in the automotive sector enable the control of suspension damping characteristics of a vehicle. Some of the control technology might be relevant to the hydraulic or pneumatic PTO systems used in the wave sector and might help optimise performance and survivability.

9.3.7 Energy Storage

At a system level, energy storage can have a positive impact on all the core WES metrics. Temporary storage of energy (for power conditioning and smoothing) has already shown demonstrable benefit whilst the advantages of longer term storage (to try to capture energy at peak WEC performance and deliver power at peak demand) have yet to be fully verified.

Mechanical flywheels are used in various industries including automotive (within commercial vehicles as a kinetic energy recovery system) and power generation industry (for power conditioning). In both applications the energy storage by the flywheel is short term. A wave energy device could benefit from mechanical flywheels for smoothing power generation. The natural behaviour of waves (highly variable power levels from second to second and irregular high peaks of power) is typically undesirable for power generation and requires additional electrical systems to condition the electrical generation for export. The use of mechanical flywheel energy storage can provide power stabilisation. In theory, an additional opportunity from a flywheel derives from its rotational inertia which, through gyroscopic restoring forces, could be used for dynamic control of the WEC motion. Integration of control and energy storage could reduce the required number of parts in the system in comparison with a configuration with standalone energy storage and power conditioning.

Energy storage using battery technology is a technology proven in other renewables industries such as wind and solar where they are primarily used to condition the power over a range of timescales. Similar to wave energy other forms of renewables are also periodic and variable driven by environmental conditions hence the electrical power generated may also be periodic and variable. Energy storage technology can be applied to improve power quality and grid services. Both commercial products and projects in the development phase are available in the renewables industry for battery energy storage technology. Both applications strive to achieve high levels of storage with fast rate of charge to ensure high rate of power generation can be captured, high energy density to reduce battery size and a low rate of self-discharge to ensure efficient longer term storage.

9.4 Proposals for R&D Activity

9.4.1 Introduction

Based on the findings of this study a number of proposed potential future R&D activity and initiatives for technology transfer from other industries with the largest perceived opportunities for the Wave Energy Sector (with respect to cost base, availability, survivability and performance) have been proposed. These are detailed within the following sections and comprise:

a. technology transfer based R&D into the use of morphing structures and structures with adaptable physical properties to reduce loading, improve survivability and reduce cost,

b. training in the use of structural optimisation and design for manufacture techniques,

c. broadening of the power-take-off R&D programme to include technology transfer R&D activity around a range of relevant technologies including magnetic gears and podded thruster drives,

d. inclusion, in any future activity on control technologies, of R&D into the relevance and potential use of new emerging technologies, specifically low cost sensors from the internet of things and high capacity communications from developments such as 5G,

e. raising of awareness of technologies that are available for mooring, sealing and electrical cables & connectors and initiatives to pull the most relevant expertise more firmly into the sector.

9.4.2 Survivable Structures

The benchmarking activity shows due to mutual trade-off that current structural technology within the Wave Energy sector has either poor survivability or poor cost-base due to the onerous operating environment. A number of technology transfers of structural technology from various industries, primarily aerospace, oil & gas, civil and automotive have the potential to improve survivability of structures and enable cost reduction.

With development control surfaces or morphing structures from the aerospace industry could potentially enable control strategies for wave energy devices to limit the operational envelope and limit the loads to which the structure is subjected (load alleviation systems). Transfer of these technologies and strategies from the aerospace sector could enhance survivability of wave energy structures and allow for improved optimisation and cost reduction. Within the civil sector the use of tuned mass damper technology is proven in large buildings. These alter the dynamic response and improve survivability in extreme events such as typhoons and/or seismic activity. Within the wave energy environment, tuned mass damper principles and techniques could improve survivability or alternatively alter the dynamic response of the WEC to optimise performance (i.e. it could be used to both increase or decrease the response of the WEC). These technologies require active control to monitor and react to environmental conditions and as such the associated condition and health monitoring systems from these industries should be investigated to ensure an effective technology transfer.

Passive structures / systems are also available within the Aerospace industry where aeroelastic structures deform by design to improve aerodynamic performance. Such technology could be transferred to the wave sector to reduce high localised loading based on passive deformation of the structure. By design, a ‘hydroelastic’ structure could improve survivability by passively alleviating load where necessary.

It is therefore proposed that the transfer of technologies and processes from industries such as Aerospace and Civil sectors be included within a future R&D activity around the topic of Survivable Structures.

9.4.3 Structural Design Optimisation

Many optimisation processes and technologies are used for design of high performance structures such as in the aerospace industry or in optimisation for manufacture, particularly in the automotive industry. Although typical design optimisation technologies such as iterative FEA and Design have been implemented by many wave energy device developers, these offer incremental optimisations only.

Technologies from the Aerospace and Automotive sectors can offer step change improvements for structural performance and also optimisation for low cost manufacturing. Design optimisation technologies should be adopted in early design to maximise effectiveness; implementation at mature design phases is less effective due to the inevitable inflexibility in later stage design. Adoption of design optimisation technologies within the wave energy sector might enable step changes in survivability, availability, performance and cost base that cannot readily be realised by conventional design processes.

Parametric and Topology optimisation are analysis software can perform complex numerical optimisation of structures by carrying out design iterations based on varying fundamental design specifications and geometry respectively. Such tools are used within the aerospace and automotive industries where high performance (high strength, low weight) structures are imperative. The direct application of this technology within the wave energy sector is possible, however accurate definition of boundary conditions such as environmental loads are required. This technology could enable large reduction in structure material (hence cost) if implemented at the early design phase.

The target load/design envelope methodology used within the aerospace sector is a process technology. By defining the envelope of operation (target loads) for a device, the various design activities (structure design, systems design, detailed load analysis etc) can be performed in parallel, compressing the overall design time required. Such design requires a control method such that the designed operational envelope of the device cannot be exceeded. However this process enables a series of design activities to be performed in parallel where project timescales are demanding.

These techniques may be of relevance to wave energy both in encouraging early stage optimisation and in enabling acceleration of engineering. It is proposed that awareness of structural design and optimisation processes from the Aerospace and Automotive sectors is raised through a structural design approach workshop. The workshop should also include transfer of experience from these industries on how to include ‘design for manufacture’ considerations from an early stage.

9.4.4 Powertrain

9.4.4.1 Introduction

The technology transfer assessment carried out within this study has revealed a number of powertrain related technologies in existence within other sectors which are believed to contain the potential for enabling improvements within the wave energy sector. It is appreciated that WES already has a power-take-off programme of R&D underway. However, it is apparent that the programme would benefit from including a tranche of work based upon technology and knowledge transfer from existing industries. Focus should be made on Magnetic Transmission and Gearing; Energy Storage; and Marine Propulsion Systems. These areas of technologies are shown within this study to offer the most potential for improvement to wave energy technology. The merits of technology transfer for each of these areas within the drivetrain are outlined below.

9.4.4.2 Magnetic Transmission and Gearing

Magnetic transmission and gear technology from the automotive industry offers low friction and low rate of wear solution for transmission of rotating forces. Such technology may have direct applications in WEC PTO systems where the transfer of rotational movement is required from one system to another with a step change in speed, such as the transfer of low rotation and high torque motion from an oscillating WEC device to a fast rotation and low torque motion required by a rotational generator. Advantages include reduction in contacting parts and wear (reducing maintenance requirements), torque or speed limited rotation to protect the system in extreme events, low friction to improve performance and reduced space requirements and mass in comparison to conventional technologies.

Further evolution of such technology may also enable the transmission of rotating motion from the subsea environment to an enclosed structure without the need for seals which will improve reliability and survivability.

It is thought that Magnetic Transmission and Gearing technology from the automotive sector has sufficient merit to justify inclusion in future PTO R&D activity.

9.4.4.3 Energy Storage

Assessment of energy storage technologies within this study highlights various technologies from other sectors of potential benefit to the wave energy sector. Typical energy storage technology solutions can be categorised as short term or long term. Short term storage is typically used for conditioning of electrical power prior to export / transmission. Long term storage is typically used to optimise the supply of electrical power based on market demand by storing power as generation is available, and exporting when financially optimum. Both types could have a potentially positive impact on the performance and affordability of a wave energy device, however large scale implementation of such systems are still in the developmental stage (technologically and commercially) within the renewables industry such as offshore wind.

Kinetic Energy Recovery Systems (KERS) are used within the automotive industry with popularity being driven by incorporation in Formula 1 race cars, where 'waste' kinetic energy (typically produced when braking to reduce speed) from the vehicle is used to charge batteries and subsequently power electric motors at a later point when additional kinetic energy is required. The developed technology is now common in consumer and industrial hybrid vehicles where improvements in efficiency and/or performance have been dramatic. This technology offers a number of potential opportunities to the wave energy industry including a compact and reliable integrated PTO system; a short term energy storage solution for power conditioning; a long term energy storage solution for availability and export optimisation. Alternatively these systems could be utilised to harvest small amounts of power from the WEC to provide electrical power for on board / offshore systems (i.e. control systems) reducing the need for power to be provided from land.

Within the utilities industry, short term storage for conditioning of electrical power can also be achieved by mechanical energy storage using flywheels. Flywheels are also used in the automotive industry on commercial vehicles such as buses as a form of kinetic energy recovery. Flywheels are proven technology with interesting opportunities for the wave energy sector such as conditioning of mechanical energy from the WEC device to provide more stable kinetic energy to the PTO; use of mechanical flywheel inertia as a form of control to alter the dynamic response of the WEC and combination of energy storage and control as an integrated solution, reducing overall part count.

9.4.4.4 Marine Propulsion Systems

Initiatives already exist within the wave energy sector which are striving towards the development of integrated and common PTO solutions. A number of marine propulsion technologies were identified and assessed within this study which could offer potential technological benefit to the wave sector. Propulsion systems such as the Azimuth Podded Electric Propulsion system are integrated and modular systems consisting of motor, drive shaft, bearings, seals, control and structure. This technology is proven in the marine industry for robust operation within a marine environment. The transfer of technology and knowledge from the marine industry, effectively investigating the 'reverse' implementation of a propulsion system generating electrical power by turning a shaft, may be beneficial to the wave energy sector in the development of an integrated PTO and drivetrain systems which are robust and affordable.

The transfer of discrete technologies within such propulsion systems and additionally the best practice and knowledge from the design of these systems to the wave energy sector could be highly beneficial in achieving improvements in affordability, availability, survivability and performance.

9.4.5 Information Technology

9.4.5.1 Introduction

A number of developments in information technologies have been identified as having potential benefit to the wave energy sector. Specifically in relation to WEC Control, an aspect extensively covered within a separate Landscaping Study commissioned by WES, a number of emerging technologies are believed to be of potential significant benefit to the wave energy sector. These generally relate to new hardware that is either faster, more powerful or more affordable. Collectively, they could enable a level of system information and sophistication in system control that hitherto has been technically or economically unfeasible. Technologies include sensors being developed as part of the Internet of Things and high capacity communications technologies (such as 5G networking) which could have the potential to provide low cost distributed data collection and high speed transmission for wave energy devices.

It is proposed that any future WEC control R&D activity should make provision for deeper examination of the potential use and impact of such technologies. Details regarding the respective technology areas within IT and Communication Technologies is described below, where benefits of technology transfer are highlighted. The development of a pathway for the adaptation of Internet of Things technologies, integration with suitable data communications and control strategies is required to realise fully the benefits of technology transfer to the wave sector.

9.4.5.2 Internet of Things (IoT)

Internet of Things are a range of low cost sensors and networking systems being developed for numerous commercial and consumer applications. Whereas existing sensor technology typically utilised within the wave energy sector are expensive, thus often limiting the quantity and types of sensors implemented on a device, the availability of low cost sensors may enable increased levels of monitoring and ultimately unlock control strategies which would otherwise be unfeasible. For example, being able to define the real time pressure field on the surface of a WEC structure could significantly improve the extent of data available to the dynamic control system.

A future call within this area would require assessment of control requirements and the identification of sensor requirements. The transfer of these technologies will require development and adaptation for use in the offshore environment which will likely increase the cost base for this technology however should still be of a lower cost than comparable technologies used within the industry.

9.4.5.3 Communications

Various communication technologies have been identified within this study from other industries such as the offshore oil and gas and consumer telecommunications industries. Wireless underwater communications technology used in the oil and gas industry with sensor systems such as those used to detect pipe leakage could enable high speed communications between subsea WEC systems without the requirement for installation of wires. Coupling such technologies with developments in the IoT technologies could unlock potential for the development of low cost subsea monitoring network systems.

Current developments of telecommunications networks towards 5G communication will boost wireless communication bandwidth for data transfer. Such increase in communication potential could also couple with IoT technologies to enable large amounts of monitoring data to be transmitted from offshore WEC systems to onshore data centres for processing. The availability of such data could improve WEC performance, availability, affordability and survivability through increased knowledge of real life system performance and subsequent optimisation of device control.

9.4.6 Industry Workshop/Awareness

9.4.6.1 Introduction

A number of challenging technology areas for the wave energy sector were identified within this study where there are shortfalls within the experience of the wave sector, yet mature technology and processes seem to exist within other sectors which are thought to be ‘fit for purpose’ for the wave sector with minimal or no development.

For these technologies is it proposed that an awareness initiative is undertaken to highlight best practice for the specification and selection of adequate ‘fit for purpose’ solutions based on the experience and expertise from other sectors. Such initiatives may take the form of facilitated industry workshops, training or networking however may not be limited to these methods.

The areas identified where industry awareness is likely to be required include Offshore Foundations and Moorings; Subsea Cables and Connectors. Further details about the benefits of such technologies from other sectors are presented below.

9.4.6.2 Offshore Foundations and Moorings

Foundations and Moorings are highlighted as priority areas in (Ref 2) and also within the benchmarking process of this study. Technology in this area is costly and is survival-critical - failure in foundations or mooring can lead to loss of the complete device.

The offshore oil & gas and offshore wind industries offer potential technology however direct transfer is unlikely to be possible for technical and economic reasons. Differences in marine loads (wind, wave and current) are substantially different from typical deep water oil & gas structures whilst offshore wind turbine foundations are also subject to a largely different loading regime with foundation design being primarily driven by the aerodynamic loads on the installed turbine structure. Economic and safety differences between oil & gas and renewables should also be taken into account when transferring such technology – the risk implications of an offshore oil and gas structure are substantially different from those of a wave energy device. This difference can result in unfeasibly expensive structures if offshore oil and gas technology is applied directly to the wave sector, hence these differences need to be considered and technology adapted accordingly.

Both industries offer knowledge of designing for survival and installation in the offshore environment. Foundation selection and design can be influenced by local infrastructure (i.e. use of specialist vessels and launch/port requirements) where a large amount of technology also resides. Deployment, installation and foundation technologies should be considered concurrently to ensure a holistic assessment has been made. Transfer of technologies, learning and best practice from these sectors could improve survivability, availability and cost of wave energy sector structures.

It is proposed that transfer and adaption of foundation and mooring technology and design processes from the offshore oil & gas and offshore wind industries be incorporated in future activities to identify a clear pathway to improved metrics.

9.4.6.3 Subsea Cables and Connectors

Subsea cables and connectors are highlighted within this study as technology areas with a large influence on the availability of a wave energy device. Failure or poor performance of a cable or connector can result in prolonged downtime of generation from the wave energy device.

Numerous existing and proven technologies have been identified primarily from the offshore oil & gas and offshore wind industries where subsea cables and connectors are used for connection to subsea equipment and power export cables respectively.

Dynamic cable technology exists within the oil & gas and offshore wind industries where compliance is required between a fixed cable position and a floating or moving platform. This technology is proven however can be costly due to the ancillaries required (bouyancy devices, bend restrictors, seabed connections etc.). The transfer of technology from these sectors to the wave energy sector could enable improvements to the availability of WEC devices through improvement in reliability of the export cables. Development is required for the translation of this technology to the wave energy sector due to the differences in environmental conditions and loads which WEC devices experience in comparison to far from shore floating wind turbines and / or oil & gas operations, however the technology and principles are proven.

Cable connectors are commonly used in the offshore oil & gas industry where products are available in wet-mate (subsea connection / disconnection) and dry-mate (connection / disconnection in a dry environment) varieties. High specification wet-mate connectors (such as oil filed connectors) are typically expensive and often cost prohibitive for use within the wave energy sector, these connectors perform well and could enable reliable subsea connections for wave energy devices. Lower cost connectors (such as moulded plastic connectors) have limited track record for performance in wave energy device conditions.

Appendix 1 Technologies Benchmark

Technology Element				Lifecycle influence on CoE *From (1)		BASELINE BENCHMARK			
Description	**Description**	**Description**	**Commonality**	**Min**	**Max**	**Affordability (LCoE)**	**Performance**	**Availability**	**Survivability**
Hydrodynamic Absorber	Bearing		129	2%	5%	2	1	3	1
	Blade		50	5%	10%	3	2	2	2
	Chain		8	1%	2%	1	1	1	1
	Hub		30		1%	1	1	1	1
	Hydrofoil		2	2%	5%	2	1	1	1
	Seals		109	1%	2%	1	2	3	3
	Structure	Displacer (Non-Steel)	6	10%	20%	4	2	1	4
		Displacer (Steel)	56	10%	20%	4	2	1	2
		Displacer Reactor (Non-Steel)	8	10%	20%	4	2	1	4
		Displacer Reactor (Steel)	16	10%	20%	4	2	1	2
		Reactor (Non-Steel)	9	10%	20%	4	2	1	4
		Reactor (Steel)	40	10%	20%	4	2	1	2
		Shroud	7	1%	2%	1	2	3	3
	Yoke / Yaw		1	1%	2%	1	3	3	3
Power Take Off	AC/DC/AC Connverter		147	2%	5%	2	1	2	1
	Accumulator		34	1%	2%	1	1	1	1
	Air Turbine	Uni-directional	16	5%	10%	3	2	2	3
		Bi-directional	4	2%	5%	2	2	2	3
	Brake		47	1%	2%	1	1	1	1
	Cable		5		1%	1	2	2	2
	Counterweight		1		1%	1	1	1	1
	Gearbox		45	2%	5%	2	2	3	2
	Generator	Electrical Linear	14	2%	5%	2	2	2	3
		Hydraulic Standard	26	2%	5%	2	2	2	2
		Rotational	102	2%	5%	2	2	2	2
		Rotational Direct Electric	13	5%	10%	3	2	2	2
		Hydraulic Novel	1	5%	10%	3	2	2	2
	Hydraulic System (non-PTO)	Oil	30	2%	5%	2	2	2	3
		Water	25	2%	5%	2	2	3	3
	Pinion Gear		1		1%	1	1	1	2
	Pulley		2	1%	2%	1	1	1	2
	Pump / Hose		1	5%	10%	3	1	1	2
	Rack & Pinion					1	1	1	2
	Shaft		55	1%	2%	1	1	1	2
	Spring		1	5%	10%	3	2	2	3
	Structure	Reservoir / Blockage	3	20%		4	2	2	1
	Transformer up to 11kV		148		1%	1	1	2	1
	Water Turbine	Francis				1	2	2	2
		Kaplan	7	2%	5%	2	2	2	2
		Pelton Wheel	17	2%	5%	2	1	1	2
		Novel	1	5	10%	3	2	2	2
	Valves		22	2%	5%	2	1	1	2
	Subsea connectors		137	1%	2%	1	1	3	2
	Dynamic Cable		71	2%	5%	2	1	3	2
	Mechanical connect system		15	1%	2%	1	1	2	2
	Cooling System				1%	1	2	2	2

Technology Element				Lifecycle influence on CoE *From (1)		BASELINE BENCHMARK			
Description	Description	Description	Commonality	Min	Max	Affordability (LCoE)	Performance	Availability	Survivability
Control	Blade Pitch System		11	1%	2%	1	2	1	2
	Control System	High Complexity	31		1%	1	2	1	2
		Low Complexity	78		1%	1	2	1	2
	Cooling System					1	1	1	1
	Yaw System		5	1%	2%	1	2	1	2
Reaction / Stationing	Anchor	Drag embedment	19	2%	5%	2	2	1	2
		Gravity	47	2%	5%	2	2	1	1
		Pile	6	2%	5%	2	1	1	1
		Torpedo				1	1	1	1
		Gravity Base	16	10%	20%	4	1	1	1
		Monopile	12	10%	20%	4	1	1	1
		Pin Piled	12	5%	10%	3	1	1	1
		Tri/Quadrapod	6	10%	20%	4	1	1	1
	Lifting Mechanism		5	2%	5%	1	1	1	2
	Mooring	Tension	11	5%	10%	3	1	2	2
		Single Point	40	5%	10%	3	1	2	2
		Multi Point	31	5%	10%	3	1	2	2
	Structure	Ballast chambers				1	1	1	1
		Breakwater	3	20%		4	1	1	1
		Turbine Support	30	10%	20%	4	1	1	1
		Turbine Support	13	10%	20%	4	1	1	1
		Pontoon	6	5%	10%	3	1	1	1
		Shore Mounted	1	20%		4	1	1	1
		Blockage	3	20%		4	1	1	1

Appendix 2 Processes Benchmark

Category	Discipline/Process	Main Wave Energy Process Roles/Activities	Importance 1-5	Development Stage of Relevance (coded by importance)				Sectors of Relevance (coded by importance)										
				Stage 1	Stage 2	Stage 3	Stage 4											
			Overall	Characterisation	Optimisation	Scale Prototype	Full Scale Demonstration	Oil & Gas	Utility (inc RE)	Process/ Chemical	Automotive / Industrail Vehicles	Aerospace	Shipbuilding / Naval / Marine	Other Defence	Construction / Mining	Civil / Ports / Harbours	Information & Communications Technology	Biomedical
Scientific Support	Physical Oceanography	measures/models/defines wave environment	5	3	3	5	5	4	3	0	0	0	5	2	1	3		
Scientific Support	Hydrographic Surveying	maps the seabed	4	0	1	4	4	4	3	0	0	0	1	1	2	3	3	
Scientific Support	Wave Hydrodynamics	designs an efficient primary convertor shape	5	5	5	3	3	3	1	0	0	0	4	3	0	2		
Scientific Support	Geophysics/Morphology	understands the seabed and its geology	3	1	2	3	3	5	2	0	0	0	0	1	4	4		
Scientific Support	Statistics and Probability	makes sense of stochastic data and extremes	4	3	4	4	4	3	4	2	4	4	3	3	1	3	5	
Scientific Support	(Marine) Acoustics	advises on const'n/oper'l noise propagation	2	1	1	2	3	3	3	1	3	3	3	2	2	3		4
Scientific Support	Marine Biology	assesses impact on marine ecology	2	1	2	3	4	3	2	2	0	0	1	2	2	1		3
Scientific Support	Marine Archaeology	assesses impact on marine cultural heritage	2	0	0	2	2	2	2	0	0	0	1	1	1	1		
Scientific Support	Hydrology	identifies/quantifies risks to water quality	3	1	2	3	3	4	2	3	0	0	2	2	2	5		
Scientific Support	Geotechnics	defines engineering characteristics of seabed	4	0	3	4	4	4	3	0	0	0	0	1	3	4		
Scientific Support	Experimental Hydrodynamics	confirms converter's performance/loading	5	5	5	3	3	5	1	0	1	0	5	3	0	2		
Scientific Support	Testbed Testing	confirms sub-system behaviour/loading	5	2	3	5	5	4	4	4	4	3	3	3	3	1		
Scientific Support	GIS	georeferences/processes the project data	2	0	1	3	4	4	4	0	0	0	0	4	3	4	4	
Engineering: Structural / Marine	Coastal	designs fixed inshore wec structures	3	2	4	4	4	2	1	0	0	0	0	1	2	5		
Engineering: Structural / Marine	Offshore Structural	designs fixed/floating offshore wec structures	5	2	4	5	5	5	4	0	0	0	2	2	2	0		
Engineering: Structural / Marine	Naval Architecture	designs floating wec structures	5	2	4	5	5	4	2	0	0	0	5	4	1	0		
Engineering: Structural / Marine	Mooring	designs to station-keeping tethering system	4	2	3	4	4	4	2	0	0	0	3	2	1	3		
Engineering: Structural / Marine	Foundation	designs seabed fixings for the structure	3	2	3	4	4	4	2	0	0	0	2	2	3	5		
Engineering: Structural / Marine	Stress Analysis	conducts detailed stressing studies	4	2	3	4	4	4	3	2	3	4	4	4	3	4	3	4
Engineering: Mechanical	Hydraulic	designs oil based PTO systems and ancillaries	5	4	4	5	5	5	3	4	3	4	4	4	4	0		4
Engineering: Mechanical	Aerodynamic/Turbo	designs air turbine based PTO systems	3	3	3	5	5	1	5	2	1	3	1	2	3	0		4
Engineering: Systems	Systems	integrates sub-systems to optimise system	4	3	4	3	3	3	3	3	4	5	5	5	2	1		5
Engineering: Systems	Reliability	optimises the engineering to reduce failures	4	3	3	4	5	4	4	4	5	5	5	4	3	4		5
Engineering: Systems	Industrial & Production	designs for & optimises production techniques	2	1	2	3	4	3	3	3	5	4	4	4	3	3		
Engineering: Systems	Interface management	co-ordinates all soft & hard connections	3	2	3	4	5	4	3	3	5	5	3	3	2	2	4	
Engineering: Electrical / Power	Electro-Mechanical	designs/selects the generator	3	2	2	3	4	3	4	3	2	3	3	2	4	0		5
Engineering: Electrical / Power	Power-Electronic	designs/selects final stage power conditioning	3	1	2	3	4	3	4	3	3	4	3	2	4	1		
Engineering: Electrical / Power	Cable	designs the umbilicals and collection system	3	1	2	3	4	5	4	2	2	2	1	2	2	2		
Engineering: Electrical / Power	Sub-Sea	designs (E&M) connections & sub-sea plant	4	1	3	4	4	5	3	2	2	2	2	5	3	1		
Engineering: Electrical / Power	Corrosion & Biofouling	selects surface protection systems for the hull	3	1	2	3	4	4	3	2	3	2	4	2	3	2		4
Engineering: Electrical / Power	Control	designs system to control, monitor & diagnose	5	3	4	5	5	3	4	3	3	5	2	5	5	1	5	
Engineering: Support	Technical Management	leads concept development and optimisation	5	5	5	4	3	4	3	3	5	5	5	5	3	3		
Engineering: Support	Engineering Management	co-ordinates engineering	4	3	4	5	5	5	4	4	5	5	5	5	4	5		
Engineering: Support	Specification	creates requirements for procurement	3	2	3	4	4	3	3	3	5	5	5	4	3	4		
Engineering: Support	Project Management	co-ordinates activity, budget, timescales	3	3	3	3	3	4	4	3	4	4	3	3	3	4		
Engineering: Support	CAD	provides design support and design detailing	3	1	2	3	4	4	3	3	5	5	4	4	5	3		
Engineering: Construction, Offsite	Steel Fabrication (Cut, Form, Machine, Weld)	creates converter body elements	4	2	3	4	5	5	3	4	4	3	5	3	3	4		

Category	Discipline/Process	Main Wave Energy Process Roles/Activities	Importance 1-5	Development Stage of Relevance (coded by importance)				Sectors of Relevance (coded by importance)										
				Stage 1	Stage 2	Stage 3	Stage 4											
			Overall	Characterisation	Optimisation	Scale Prototype	Full Scale Demonstration	Oil & Gas	Utility (inc RE)	Process/ Chemical	Automotive / Industrail Vehicles	Aerospace	Shipbuilding / Naval / Marine	Other Defence	Construction / Mining	Civil / Ports / Harbours	Information & Communications Technology	Biomedical
Engineering: Construction, Offsite	Composite Fabrication (Layup, Mould, Bond)	creates converter body elements	3	2	3	4	5	2	2	1	4	5	4	3	1	1		
Engineering: Construction, Offsite	Concrete Precasting	creates converter body elements	3	2	3	4	5	4	2	2	0	0	3	2	4	5		
Engineering: Construction, Offsite	Structural Assembly/Fitting	assembles structural sub-elements	4	1	2	4	5	5	2	2	3	4	5	3	3	4		
Engineering: Construction, Offsite	NDT	ensures strutural integrity	4	1	2	3	5	5	3	5	3	5	5	4	3	3		
Engineering: Construction, Offsite	Assembly/Fitting - mechanical	builds and installs mech sub-systems	5	1	2	4	5	5	3	4	4	5	4	4	2	4		
Engineering: Construction, Offsite	Assembly/fitting - hydraulic	builds and installs hydraulic sub-systems	5	1	2	4	5	5	3	3	4	5	5	4	2	1		
Engineering: Construction, Offsite	Assembly/fitting - precision	installs/sets-up precision mech components	5	1	2	4	5	4	3	3	4	5	2	4	1	1		
Engineering: Construction, Offsite	Assembly/fitting - electrical/control	builds and installs elec sub-systems	5	1	2	4	5	4	4	3	3	5	3	4	2	1		
Engineering: Construction, Offsite	Onshore transportation	moves materials and assembled units	3	1	2	4	5	3	3	2	2	5	4	3	4	3		
Engineering: Construction, Offsite	Onshore handling/lifting	lifts/transfers materials/assesmbled units	4	2	2	4	5	5	3	2	3	5	4	3	4	4		
Engineering: Construction, Onsite	Dredging/Seabed Preparation	prepares seabed for bottom standing devices	3	1	2	3	4	4	3	0	0	0	1	0	2	5		
Engineering: Construction, Onsite	Civil Construction	builds bottom mounted device structures	3	2	3	4	5	4	4	2	0	0	1	2	1	5		
Engineering: Construction, Onsite	Offshore Construction	deploys large pre-constucted structures	3	1	2	3	4	5	4	0	0	0	4	1	2	1		
Engineering: Construction, Onsite	Marine Operations	conducts sea-based ops (eg mating, handling)	5	2	3	4	5	5	4	0	0	0	4	4	0	1		
Engineering: Construction, Onsite	Cable Laying	deploys and protects sub-sea cabling & umbilicals	4	2	3	3	5	5	5	0	0	0	2	1	0	3		
Engineering: Construction, Onsite	Piling/Anchoring	fixes structures/fixings to seabed	3	2	3	3	4	4	4	0	0	0	1	1	1	4		
Engineering: Construction, Onsite	Sea Transportation/Towing	moves/tows converters from port to site	4	2	3	4	5	4	3	0	0	0	4	3	0	3		
Engineering: Construction, Onsite	Commissioning	tests & brings into operation all systems	4	2	3	3	4	4	4	4	3	0	3	2	1	4		
Engineering: Construction, Onsite	Offshore Project Management	ensures project is deployed to plan	4	2	3	4	5	5	5	4	0	0	3	3	4	1		
Engineering: Construction, Onsite	Grid Connections	secures grid connection from DNO/TSO	3	1	2	3	5	3	5	3	0	0	0	1	3	3		
Engineering: Construction, Onsite	H&S Management	ensures safety of all opeartions	5	2	3	5	5	5	5	5	2	0	4	2	5	4		
Engineering: Operational	M'ment/Instrumentation	provides data on inputs, outputs, status	5	2	3	5	5	5	4	4	4	5	3	4	5	3	3	5
Engineering: Operational	Asset/O&M Management	looks after logistics of availability/performance	4	1	2	3	4	4	4	4	2	4	2	3	3	3		
Engineering: Operational	Marine Operations	undertakes recovery/redeployment	4	1	2	4	5	4	3	1	0	0	2	2	1	1		
Engineering: Operational	Control/Diagnostics	monitors data indicators from converters	5	1	2	5	5	4	4	4	4	4	2	4	2	1	4	4
Engineering: Operational	Structural O&M and Repair	maintains wec structure	3	0	1	3	3	4	3	3	0	2	2	2	1	4		
Engineering: Operational	Mechanical O&M and Repair	maintains wec mechanical systems	4	1	3	5	5	4	3	3	4	4	2	4	4	2		
Engineering: Operational	Hydraulic O&M and Repair	maintains wec PTO and ancillary hydraulics	4	1	3	5	5	4	3	3	3	4	1	4	4	1		
Engineering: Operational	Electrical O&M and Repair	maintains wec electrical systems	4	1	3	5	5	4	3	3	3	4	1	4	4	1		
Other Profession	Patents	secure IP protection for core innovations	4	5	4	2	2	4	3	3	4	4	2	4	2	1		
Other Profession	Economics	assesses viability/advises on lcoe drivers	5	5	5	4	3	3	4	3	3	4	3	2	5	2		
Other Profession	Financing	engineers the device/project capex investment	5	3	4	5	5	3	4	2	2	2	4	1	3	3		
Other Profession	Legal	secures all rights and contracts wrt law and risk	3	2	2	4	4	4	4	2	2	3	1	1	5	3		
Other Profession	Certification/TPV	checks/rubber stamps the engineering systems	4	2	3	5	5	4	4	3	3	4	4	3	2	3		
Other Profession	Risk Assessment/Insurance	identifies/manages project risks	4	2	3	5	5	4	3	3	2	4	3	4	2	3		
Other Profession	External Relations	promotes project to wider stakeholders	2	2	2	2	3	3	4	4	4	3	2	3	4	4		
Other Profession	Project Developer	optimises/delivers project ; secures rights	3	0	1	4	4	5	5	4	0	1	0	2	5	5		
Other Profession	Environmental Planning/Management	ensures project is environmentally acceptable	3	0	1	4	4	5	5	4	0	3	2	2	5	5		
Other Profession	Sales & Marketing	promotes wec system to clients	3	1	2	3	5	2	3	2	5	4	2	1	1	3		
Other Profession	Purchasing	ensures efficient & effective procurement	3	1	2	4	4	4	4	4	5	4	3	3	3	3		

Appendix 3 Prioritised Technology Elements

Technology Element	Benchmark Score	Normalised Benchmark Score 70%	Normalised Commonality 30%	Prioritisation Score	Priority
Hydrodynamic Absorber - Seals -	9	0.573	0.221	0.794	1
Power Take Off - Subsea connectors -	7	0.445	0.278	0.723	2
Hydrodynamic Absorber - Structure - Reactor (Non-Steel)	11	0.700	0.018	0.718	3
Hydrodynamic Absorber - Structure - Displacer Reactor (Non-Steel)	11	0.700	0.016	0.716	4
Power Take Off - Generator - Rotational	8	0.509	0.207	0.716	5
Hydrodynamic Absorber - Structure - Displacer (Non-Steel)	11	0.700	0.012	0.712	6
Hydrodynamic Absorber - Bearing -	7	0.445	0.261	0.707	7
Power Take Off - Hydraulic System (non-PTO) - Water	10	0.636	0.051	0.687	8
Hydrodynamic Absorber - Structure - Displacer (Steel)	9	0.573	0.114	0.686	9
Hydrodynamic Absorber - Blade -	9	0.573	0.101	0.674	10
Power Take Off - Air Turbine - Uni-directional	10	0.636	0.032	0.669	11
Power Take Off - Gearbox -	9	0.573	0.091	0.664	12
Hydrodynamic Absorber - Structure - Reactor (Steel)	9	0.573	0.081	0.654	13
Power Take Off - Dynamic Cable -	8	0.509	0.144	0.653	14
Hydrodynamic Absorber - Yoke / Yaw -	10	0.636	0.002	0.638	15
Power Take Off - Spring -	10	0.636	0.002	0.638	16
Power Take Off - Hydraulic System (non-PTO) - Oil	9	0.573	0.061	0.634	17
Power Take Off - Transformer up to 11kV -	5	0.318	0.300	0.618	18
Power Take Off - AC/DC/AC Connverter -	5	0.318	0.298	0.616	19
Hydrodynamic Absorber - Structure - Displacer Reactor (Steel)	9	0.573	0.032	0.605	20
Power Take Off - Generator - Electrical Linear	9	0.573	0.028	0.601	21
Power Take Off - Generator - Rotational Direct Electric	9	0.573	0.026	0.599	22
Reaction / Stationing - Mooring - Single Point	8	0.509	0.081	0.590	23
Power Take Off - Air Turbine - Bi-directional	9	0.573	0.008	0.581	24
Power Take Off - Generator - Hydraulic Novel	9	0.573	0.002	0.575	25
Power Take Off - Water Turbine - Novel	9	0.573	0.002	0.575	26
Reaction / Stationing - Mooring - Multi Point	8	0.509	0.063	0.572	27
Power Take Off - Generator - Hydraulic Standard	8	0.509	0.053	0.562	28
Control - Control System - Low Complexity	6	0.382	0.158	0.540	29
Control - Control System - High Complexity	6	0.382	0.063	0.445	30
Reaction / Stationing - Mooring - Tension	8	0.509	0.022	0.531	31
Power Take Off - Water Turbine - Kaplan	8	0.509	0.014	0.523	32
Reaction / Stationing - Structure - Turbine Support	7	0.445	0.061	0.506	33
Reaction / Stationing - Anchor - Drag embedment	7	0.445	0.039	0.484	34
Reaction / Stationing - Anchor - Gravity Base	7	0.445	0.032	0.478	35
Reaction / Stationing - Anchor - Gravity	6	0.382	0.095	0.477	36
Reaction / Stationing - Structure - Turbine Support	7	0.445	0.026	0.472	37
Reaction / Stationing - Anchor - Monopile	7	0.445	0.024	0.470	38
Reaction / Stationing - Anchor - Tri/Quadrapod	7	0.445	0.012	0.458	39
Power Take Off - Cable -	7	0.445	0.010	0.456	40
Reaction / Stationing - Structure - Breakwater	7	0.445	0.006	0.452	41
Reaction / Stationing - Structure - Blockage	7	0.445	0.006	0.452	42
Power Take Off - Pump / Hose -	7	0.445	0.002	0.447	43
Reaction / Stationing - Structure - Shore Mounted	7	0.445	0.002	0.447	44
Power Take Off - Water Turbine - Francis	7	0.445	0.000	0.445	45
Power Take Off - Cooling System -	7	0.445	0.000	0.445	46
Power Take Off - Shaft -	5	0.318	0.111	0.430	47
Power Take Off - Valves -	6	0.382	0.045	0.426	48
Power Take Off - Water Turbine - Pelton Wheel	6	0.382	0.034	0.416	49
Power Take Off - Mechanical connect system -	6	0.382	0.030	0.412	50
Reaction / Stationing - Anchor - Pin Piled	6	0.382	0.024	0.406	51
Control - Blade Pitch System -	6	0.382	0.022	0.404	52
Reaction / Stationing - Structure - Pontoon	6	0.382	0.012	0.394	53
Control - Yaw System -	6	0.382	0.010	0.392	54
Power Take Off - Brake -	4	0.255	0.095	0.350	55
Reaction / Stationing - Anchor - Pile	5	0.318	0.012	0.330	56
Reaction / Stationing - Lifting Mechanism -	5	0.318	0.010	0.328	57
Power Take Off - Accumulator -	4	0.255	0.069	0.323	58
Hydrodynamic Absorber - Hydrofoil -	5	0.318	0.004	0.322	59
Power Take Off - Pulley -	5	0.318	0.004	0.322	60
Power Take Off - Pinion Gear -	5	0.318	0.002	0.320	61
Power Take Off - Rack & Pinion -	5	0.318	0.000	0.318	62
Hydrodynamic Absorber - Hub -	4	0.255	0.061	0.315	63
Hydrodynamic Absorber - Chain -	4	0.255	0.016	0.271	64
Power Take Off - Counterweight -	4	0.255	0.002	0.257	65
Control - Cooling System -	4	0.255	0.000	0.255	66
Reaction / Stationing - Anchor - Torpedo	4	0.255	0.000	0.255	67
Reaction / Stationing - Structure - Ballast chambers	4	0.255	0.000	0.255	68

Appendix 4 Prioritised Process Elements

Oil & Gas

Process / Discipline		Importance 1-5	Development Stage of Relevance (coded by importance)				Sectors of Relevance (coded by importance)
			Stage 1	Stage 2	Stage 3	Stage 4	
	Main Wave Energy Process Roles/Activities	Overall	Characterisation	Optimisation	Scale Prototype	Full Scale Demonstration	Oil & Gas
Engineering: Mechanical - Hydraulic	designs oil based PTO systems and ancillaries	5	4	4	5	5	5
Engineering: Structural / Marine - Offshore Structural	designs fixed/floating offshore wec structures	5	2	4	5	5	5
Engineering: Construction, Onsite - H&S Management	ensures safety of all opeartions	5	2	3	5	5	5
Engineering: Operational - M'ment/Instrumentation	provides data on inputs, outputs, status	5	2	3	5	5	5
Engineering: Construction, Onsite - Marine Operations	conducts sea-based ops (eg mating, handling)	5	2	3	4	5	5
Engineering: Construction, Offsite - Assembly/Fitting - mechanical	builds and installs mech sub-systems	5	1	2	4	5	5
Engineering: Construction, Offsite - Assembly/fitting - hydraulic	builds and installs hydraulic sub-systems	5	1	2	4	5	5
Scientific Support - Experimental Hydrodynamics	confirms converter's performance/loading	5	5	5	3	3	5
Engineering: Support - Engineering Management	co-ordinates engineering	4	3	4	5	5	5
Engineering: Construction, Offsite - Steel Fabrication (Cut, Form, Machine, Weld)	creates converter body elements	4	2	3	4	5	5
Engineering: Construction, Onsite - Offshore Project Management	ensures project is deployed to plan	4	2	3	4	5	5
Engineering: Construction, Offsite - Onshore handling/lifting	lifts/transfers materials/assesmbled units	4	2	2	4	5	5
Engineering: Construction, Offsite - Structural Assembly/Fitting	assembles structural sub-elements	4	1	2	4	5	5
Engineering: Construction, Onsite - Cable Laying	deploys and protects sub-sea cabling & umbilicals	4	2	3	3	5	5
Engineering: Construction, Offsite - NDT	ensures strutural integrity	4	1	2	3	5	5
Engineering: Electrical / Power - Sub-Sea	designs (E&M) connections & sub-sea plant	4	1	3	4	4	5
Other Profession - Project Developer	optimises/delivers project ; secures rights	3	0	1	4	4	5
Other Profession - Environmental Planning/Management	ensures project is environmentally acceptable	3	0	1	4	4	5
Engineering: Electrical / Power - Cable	designs the umbilicals and collection system	3	1	2	3	4	5
Engineering: Construction, Onsite - Offshore Construction	deploys large pre-constucted structures	3	1	2	3	4	5
Scientific Support - Geophysics/Morphology	understands the seabed and its geology	3	1	2	3	3	5
Scientific Support - Testbed Testing	confirms sub-system behaviour/loading	5	2	3	5	5	4

Aerospace

Process / Discipline	Main Wave Energy Process Roles/Activities	Importance 1-5	Development Stage of Relevance (coded by importance)				Sectors of Relevance (coded by importance)
			Stage 1	Stage 2	Stage 3	Stage 4	
		Overall	Characterisation	Optimisation	Scale Prototype	Full Scale Demonstration	Aerospace
Engineering: Support - Technical Management	leads concept development and optimisation	5	5	5	4	3	5
Engineering: Operational - M'ment/Instrumentation	provides data on inputs, outputs, status	5	2	3	5	5	5
Engineering: Construction, Offsite - Assembly/Fitting - mechanical	builds and installs mech sub-systems	5	1	2	4	5	5
Engineering: Construction, Offsite - Assembly/fitting - hydraulic	builds and installs hydraulic sub-systems	5	1	2	4	5	5
Engineering: Construction, Offsite - Assembly/fitting - precision	installs/sets-up precision mech components	5	1	2	4	5	5
Engineering: Construction, Offsite - Assembly/fitting - electrical/control	builds and installs elec sub-systems	5	1	2	4	5	5
Engineering: Electrical / Power - Control	designs system to control, monitor & diagnose	5	3	4	5	5	5
Engineering: Support - Engineering Management	co-ordinates engineering	4	3	4	5	5	5
Engineering: Systems - Reliability	optimises the engineering to reduce failures	4	3	3	4	5	5
Engineering: Systems - Systems	integrates sub-systems to optimise system	4	3	4	3	3	5
Engineering: Construction, Offsite - NDT	ensures strutural integrity	4	1	2	3	5	5
Engineering: Construction, Offsite - Onshore handling/lifting	lifts/transfers materials/assembled units	4	2	2	4	5	5
Engineering: Systems - Interface management	co-ordinates all soft & hard connections	3	2	3	4	5	5
Engineering: Support - CAD	provides design support and design detailing	3	1	2	3	4	5
Engineering: Support - Specification	creates requirements for procurement	3	2	3	4	4	5
Engineering: Construction, Offsite - Composite Fabrication (Layup, Mould, Bond)	creates converter body elements	3	2	3	4	5	5
Engineering: Construction, Offsite - Onshore transportation	moves materials and assembled units	3	1	2	4	5	5
Other Profession – Economics	assesses viability/advises on lcoe drivers	5	5	5	4	3	4
Engineering: Operational - Control/Diagnostics	monitors data indicators from converters	5	1	2	5	5	4

Utility (Including Renewables)

Process / Discipline	Main Wave Energy Process Roles/Activities	Importance 1-5 Overall	Development Stage of Relevance (coded by importance) Stage 1 Characterisation	Stage 2 Optimisation	Stage 3 Scale Prototype	Stage 4 Full Scale Demonstration	Sectors of Relevance (coded by importance) Utility (inc RE)
Engineering: Construction, Onsite - H&S Management	ensures safety of all opeartions	5	2	3	5	5	5
Engineering: Construction, Onsite - Offshore Project Management	ensures project is deployed to plan	4	2	3	4	5	5
Engineering: Construction, Onsite - Cable Laying	deploys and protects sub-sea cabling & umbilicals	4	2	3	3	5	5
Other Profession - Project Developer	optimises/delivers project ; secures rights	3	0	1	4	4	5
Other Profession - Environmental Planning/Management	ensures project is environmentally acceptable	3	0	1	4	4	5
Engineering: Construction, Onsite - Grid Connections	secures grid connection from DNO/TSO	3	1	2	3	5	5
Engineering: Mechanical - Aerodynamic/Turbo	designs air turbine based PTO systems	3	3	3	5	5	5
Other Profession – Economics	assesses viability/advises on lcoe drivers	5	5	5	4	3	4
Other Profession – Financing	engineers the device/project capex investment	5	3	4	5	5	4
Scientific Support - Testbed Testing	confirms sub-system behaviour/loading	5	2	3	5	5	4

Ship Building / Naval / Marine

Process / Discipline	Main Wave Energy Process Roles/Activities	Importance 1-5 Overall	Development Stage of Relevance (coded by importance) Stage 1 Characterisation	Stage 2 Optimisation	Stage 3 Scale Prototype	Stage 4 Full Scale Demonstration	Sectors of Relevance (coded by importance) Shipbuilding / Naval / Marine
Engineering: Support - Technical Management	leads concept development and optimisation	5	5	5	4	3	5
Engineering: Construction, Offsite - Assembly/fitting - hydraulic	builds and installs hydraulic sub-systems	5	1	2	4	5	5
Scientific Support - Experimental Hydrodynamics	confirms converter's performance/loading	5	5	5	3	3	5
Scientific Support - Physical Oceanography	measures/models/defines wave environment	5	3	3	5	5	5
Engineering: Structural / Marine - Naval Architecture	designs floating wec structures	5	2	4	5	5	5
Engineering: Support - Engineering Management	co-ordinates engineering	4	3	4	5	5	5
Engineering: Systems - Reliability	optimises the engineering to reduce failures	4	3	3	4	5	5
Engineering: Systems - Systems	integrates sub-systems to optimise system	4	3	4	3	3	5
Engineering: Construction, Offsite - NDT	ensures strutural integrity	4	1	2	3	5	5
Engineering: Construction, Offsite - Structural Assembly/Fitting	assembles structural sub-elements	4	1	2	4	5	5
Engineering: Construction, Offsite - Steel Fabrication (Cut, Form, Machine, Weld)	creates converter body elements	4	2	3	4	5	5
Engineering: Support – Specification	creates requirements for procurement	3	2	3	4	4	5
Scientific Support - Wave Hydrodynamics	designs an efficient primary convertor shape	5	5	5	3	3	4
Other Profession – Financing	engineers the device/project capex investment	5	3	4	5	5	4
Engineering: Construction, Onsite - Marine Operations	conducts sea-based ops (eg mating, handling)	5	2	3	4	5	4

Other Defence

Process / Discipline	Main Wave Energy Process Roles/Activities	Importance 1-5	Development Stage of Relevance (coded by importance)				Sectors of Relevance (coded by importance)
			Stage 1	Stage 2	Stage 3	Stage 4	
		Overall	Characterisation	Optimisation	Scale Prototype	Full Scale Demonstration	Other Defence
Engineering: Support - Technical Management	leads concept development and optimisation	5	5	5	4	3	5
Engineering: Electrical / Power - Control	designs system to control, monitor & diagnose	5	3	4	5	5	5
Engineering: Support - Engineering Management	co-ordinates engineering	4	3	4	5	5	5
Engineering: Systems - Systems	integrates sub-systems to optimise system	4	3	4	3	3	5
Engineering: Electrical / Power - Sub-Sea	designs (E&M) connections & sub-sea plant	4	1	3	4	4	5
Engineering: Operational - Control/Diagnostics	monitors data indicators from converters	5	1	2	5	5	4
Engineering: Construction, Onsite - Marine Operations	conducts sea-based ops (eg mating, handling)	5	2	3	4	5	4

Civil / Ports / Harbours

Process / Discipline	Main Wave Energy Process Roles/Activities	Importance 1-5	Development Stage of Relevance (coded by importance)				Sectors of Relevance (coded by importance)
			Stage 1	Stage 2	Stage 3	Stage 4	
		Overall	Characterisation	Optimisation	Scale Prototype	Full Scale Demonstration	Civil / Ports / Harbours
Engineering: Support - Engineering Management	co-ordinates engineering	4	3	4	5	5	5
Other Profession - Environmental Planning/Management	ensures project is environmentally acceptable	3	0	1	4	4	5
Other Profession - Project Developer	optimises/delivers project ; secures rights	3	0	1	4	4	5
Engineering: Construction, Offsite - Concrete Precasting	creates converter body elements	3	2	3	4	5	5
Engineering: Structural / Marine - Foundation	designs seabed fixings for the structure	3	2	3	4	4	5
Scientific Support - Hydrology	identifies/quantifies risks to water quality	3	1	2	3	3	5
Engineering: Structural / Marine - Coastal	designs fixed inshore wec structures	3	2	4	4	4	5
Engineering: Construction, Onsite - Dredging/Seabed Preparation	prepares seabed for bottom standing devices	3	1	2	3	4	5
Engineering: Construction, Onsite - Civil Construction	builds bottom mounted device structures	3	2	3	4	5	5

Automotive / Industrial Vehicles

Process / Discipline	Main Wave Energy Process Roles/Activities	Importance 1-5	Development Stage of Relevance (coded by importance)				Sectors of Relevance (coded by importance)
			Stage 1	Stage 2	Stage 3	Stage 4	
		Overall	Characterisation	Optimisation	Scale Prototype	Full Scale Demonstration	Automotive / Industrail Vehicles
Engineering: Support - Technical Management	leads concept development and optimisation	5	5	5	4	3	5
Engineering: Support - Engineering Management	co-ordinates engineering	4	3	4	5	5	5
Engineering: Systems - Reliability	optimises the engineering to reduce failures	4	3	3	4	5	5
Other Profession - Purchasing	ensures efficient & effective procurement	3	1	2	4	4	5
Engineering: Systems - Interface management	co-ordinates all soft & hard connections	3	2	3	4	5	5
Engineering: Support - CAD	provides design support and design detailing	3	1	2	3	4	5
Engineering: Support - Specification	creates requirements for procurement	3	2	3	4	4	5
Other Profession - Sales & Marketing	promotes wec system to clients	3	1	2	3	5	5
Engineering: Systems - Industrial & Production	designs for & optimises production techniques	2	1	2	3	4	5
Scientific Support - Testbed Testing	confirms sub-system behaviour/loading	5	2	3	5	5	4
Engineering: Operational - Control/Diagnostics	monitors data indicators from converters	5	1	2	5	5	4

Construction / Mining

Process / Discipline	Main Wave Energy Process Roles/Activities	Importance 1-5	Development Stage of Relevance (coded by importance)				Sectors of Relevance (coded by importance)
			Stage 1	Stage 2	Stage 3	Stage 4	
		Overall	Characterisation	Optimisation	Scale Prototype	Full Scale Demonstration	Construction / Mining
Engineering: Electrical / Power - Control	designs system to control, monitor & diagnose	5	3	4	5	5	5
Engineering: Operational - M'ment/Instrumentation	provides data on inputs, outputs, status	5	2	3	5	5	5
Engineering: Construction, Onsite - H&S Management	ensures safety of all opeartions	5	2	3	5	5	5
Other Profession - Economics	assesses viability/advises on lcoe drivers	5	5	5	4	3	5
Engineering: Support - CAD	provides design support and design detailing	3	1	2	3	4	5
Other Profession - Environmental Planning/Management	ensures project is environmentally acceptable	3	0	1	4	4	5
Other Profession - Project Developer	optimises/delivers project ; secures rights	3	0	1	4	4	5
Other Profession - Legal	secures all rights and contracts wrt law and risk	3	2	2	4	4	5

Process / Chemical

Process / Discipline	Main Wave Energy Process Roles/Activities	Importance 1-5	Development Stage of Relevance (coded by importance)				Sectors of Relevance (coded by importance)
			Stage 1	Stage 2	Stage 3	Stage 4	
		Overall	Characterisation	Optimisation	Scale Prototype	Full Scale Demonstration	Process/ Chemical
Engineering: Construction, Onsite - H&S Management	ensures safety of all opeartions	5	2	3	5	5	5
Engineering: Construction, Offsite - NDT	ensures strutural integrity	4	1	2	3	5	5
Engineering: Operational - M'ment/Instrumentation	provides data on inputs, outputs, status	5	2	3	5	5	4
Scientific Support - Testbed Testing	confirms sub-system behaviour/loading	5	2	3	5	5	4
Engineering: Operational - Control/Diagnostics	monitors data indicators from converters	5	1	2	5	5	4
Engineering: Mechanical - Hydraulic	designs oil based PTO systems and ancillaries	5	4	4	5	5	4
Engineering: Construction, Offsite - Assembly/Fitting - mechanical	builds and installs mech sub-systems	5	1	2	4	5	4

Biomedical

Process / Discipline	Main Wave Energy Process Roles/Activities	Importance 1-5	Development Stage of Relevance (coded by importance)				Sectors of Relevance (coded by importance)
			Stage 1	Stage 2	Stage 3	Stage 4	
		Overall	Characterisation	Optimisation	Scale Prototype	Full Scale Demonstration	Biomedical
Engineering: Operational - M'ment/Instrumentation	provides data on inputs, outputs, status	5	2	3	5	5	5
Engineering: Systems - Reliability	optimises the engineering to reduce failures	4	3	3	4	5	5
Engineering: Systems - Systems	integrates sub-systems to optimise system	4	3	4	3	3	5
Engineering: Electrical / Power - Electro-Mechanical	designs/selects the generator	3	2	2	3	4	5
Engineering: Operational - Control/Diagnostics	monitors data indicators from converters	5	1	2	5	5	4
Engineering: Mechanical - Hydraulic	designs oil based PTO systems and ancillaries	5	4	4	5	5	4

Information & Communication Technology

Process / Discipline	Main Wave Energy Process Roles/Activities	Importance 1-5	Development Stage of Relevance (coded by importance)				Sectors of Relevance (coded by importance)
			Stage 1	Stage 2	Stage 3	Stage 4	
		Overall	Characterisation	Optimisation	Scale Prototype	Full Scale Demonstration	Information & Communications Technology
Engineering: Electrical / Power - Control	designs system to control, monitor & diagnose	5	3	4	5	5	5
Scientific Support - Statistics and Probability	makes sense of stochastic data and extremes	4	3	4	4	4	5
Engineering: Operational - Control/Diagnostics	monitors data indicators from converters	5	1	2	5	5	4
Engineering: Systems - Interface management	co-ordinates all soft & hard connections	3	2	3	4	5	4
Scientific Support - GIS	georeferences/processes the project data	2	0	1	3	4	4

Appendix 5 Technology Element Challenge Definitions

Hydrodynamic Absorber: Seals

Commonality	Cost	Performance	Availability	Survivability
Very High (109)	Low (1)	Moderate (2)	Moderate (2)	Poor (3)

General Function:
To join or interface systems together, preventing leakage, containing pressure or excluding contamination

Baseline Function:
- Prevent ingress of seawater / contaminants into absorber components or PTO interface (i.e. hydraulic cylinder wiper seals, bearing seals etc)

Technical Challenges:

- *Connections/Interfaces: Required for interfaces between components where prevention of ingress or contamination is required (i.e. hydraulic cylinders)*
- *Failure / Lifetime / Availability: Failure can cause asset damage and complete loss of availability of the system. Likely to require a long life. Current survivability of seals in typical WEC environment is poor*
- *Maintenance: Seals may be difficult to access for maintenance and may have large cost implications if required.*
- *Operational Life: If replacement is required this could have a large cost implications (see maintenance)*
- *Material Degradation / Wear: Seal degradation due to operation and environmental conditions may occur leading to decreased life and impact on efficiency*
- *Mechanical Properties / Temperature: Operation in low temperatures and continuously or periodically submerged in sea water*
- *Pressure Loss: Seal may be required to contain pressure in hydraulic system.*
- *Loads: Reciprocating duty cycles are challenge for current seal technologies and materials.*

Power Take Off: Subsea Connectors

Commonality	Cost	Performance	Availability	Survivability
Very High (137)	Low (1)	Good (1)	Poor (3)	Moderate (2)

General Function:
Subsea connection of electrical system/components to electrical cable

Baseline Function:
- Subsea connection of electrical export cable to the power take off system

Technical Challenges:

- *Interface: connection of various electrical cables required including large export cables.*
- *Failure / Lifetime / Availability: Connection is critical for the export of power from the WEC.*
- *Installation / Maintenance: Connectors are critical for installation of the device and are desired to be easy to connect / disconnect.*
- *Loads: Connector is subjected to loading from the cable itself and environmental loads from the ocean conditions.*
- *Operational Life: Long operational life is desired such that expensive operations are not required to service the connectors should the system not require to be disconnected.*
- *Operation: Marine growth / biofoul expected in offshore environment, connector must be operational for connect and disconnect with this is account. Connectors could have a wet-mate requirement.*
- *Corrosion: Metallic components within the connector may be at risk of corrosion if moisture / seawater contaminate the system.*
- *Material Degradation / Ageing: Connector materials will be subject to subsea conditions which may degrade particular materials used.*
- *Sealing: The ability for the connect to seal any sensitive components from water may be required*
- *Wear: Connection/disconnection of connector over multiple uses may wear the connector or electrical contacts over use.*
- *Electrical Insulation Degradation: Subsea and electrical operation may degrade the insulation over use.*
- *Transmission Loss: electrical transmission loss of the connector will have a direct impact on LCoE.*

Hydrodynamic Absorber: Structure – Reactor (Non Steel)

Commonality	Cost	Performance	Availability	Survivability
Low (9)	Very High (4)	Moderate (2)	Good (1)	Very Poor (4)

General Function:
Provide reaction force (static inertia)

Baseline Function:
- Structural body that provides reaction forces for the displacer

Technical Challenges:

- *Loads: Large loads from the displacer to be reacted by the structure. Extreme environmental loading currently results in poor survivability and large structure typically results in very high cost.*
- *Interfaces: The structure requires an interface with the displacer, where forces are very high and typically localised and components of different materials are required to interface.*
- *Dimensions: The reactor structure is typically of large dimensions increasing the challenge for physical operations. Current size of structures leads to very high cost.*
- *Failure: Could lead to catastrophic loss of the device / displacer or large associated costs for repair*
- *Installation / Maintenance: Large size and mass of the component and location subsea can make it challenging for installation and maintenance of the structure.*
- *Dynamic Response: dynamic behaviour of the structure under wave conditions and ability to tailor by design is critical*
- *Operation: Marine Growth / Biofoul expected in offshore conditions, structure should operate with expected conditions.*
- *Operational Life: Long life desired, if maintenance is required this could have a large cost implications.*
- *Erosion: exposure to offshore conditions may lead to erosion of material over operation life.*
- *Material Compatibility: Other structures / components are typically attached to the reactor, compatibility with these materials required.*
- *Material Degradation: subjected to long term offshore conditions (UV, temperature, submersion etc.) material degradation may be a challenge.*
- *Impact: continual impact loading from waves.*
- *Sealing: Sealing of structure (if required) from environment.*

Hydrodynamic Absorber: Structure – Displacer Reactor (Non Steel)

Commonality	Cost	Performance	Availability	Survivability
Low (9)	Very High (4)	Moderate (2)	Good (1)	Very Poor (4)

General Function:
Provide reaction force (static inertia)

Baseline Function:
- Structural body that provides reaction forces for the displacer

Technical Challenges:

- *Loads: Large loads from the displacer to be reacted by the structure. Extreme environmental loading currently results in poor survivability and large structure typically results in very high cost.*
- *Interfaces: The structure requires an interface with the displacer, where forces are very high and typically localised and components of different materials are required to interface.*
- *Dimensions: The reactor structure is typically of large dimensions increasing the challenge for physical operations. Current size of structures leads to very high cost.*
- *Failure: Could lead to catastrophic loss of the device / displacer or large associated costs for repair*
- *Installation / Maintenance: Large size and mass of the component and location subsea can make it challenging for installation and maintenance of the structure.*
- *Dynamic Response: dynamic behaviour of the structure under wave conditions and ability to tailor by design is critical*
- *Operation: Marine Growth / Biofoul expected in offshore conditions, structure should operate with expected conditions.*
- *Operational Life: Long life desired, if maintenance is required this could have a large cost implications.*
- *Erosion: exposure to offshore conditions may lead to erosion of material over operation life.*
- *Material Compatibility: Other structures / components are typically attached to the reactor, compatibility with these materials required.*
- *Material Degradation: subjected to long term offshore conditions (UV, temperature, submersion etc.) material degradation may be a challenge.*
- *Impact: continual impact loading from waves.*
- *Sealing: Sealing of structure (if required) from environment.*

Power Take Off: Generator – Rotational

Commonality	Cost	Performance	Availability	Survivability
Very High (102)	Moderate (2)	Moderate (2)	Moderate (2)	Moderate (2)

Function: Generate electrical power from rotational motion	**Baseline Function:** • Generate electrical power from rotational motion generated by the displacer/reactor
Technical Challenges:	
• *Interfaces: Mechanical connection required to the displacer/reactor* • *Failure / Lifetime / Availability: The performance of the system is directly influenced by the generator performance.* • *Installation / Maintenance: Location of the component offshore makes it difficult to access for installation and maintenance.* • *Design Parameters: Mechanical power provided will be dependant on environmental conditions and performance of the system. May be challenging for design.* • *Loads: The loading on the generator may be large or variable (i.e if no storage of mechanical energy).* • *Operation: Additional function of generator may be regenerative mode i.e. for reactive control.*	• *Operational Life: Long operational life desired due to associated difficulties with offshore/subsea maintenance. Operating environment is challenging for generator equipment.* • *Balance / Vibration: Balance of rotating components important for decrease of vibrations to ensure long fatigue life.* • *Bearings: high performance and robust bearings required to achieve maximum performance from the generator.* • *Sealing: Required to prevent water ingress into undesired components of the generator.* • *Wear: Generator should withstand the continual operation of the life of the WEC.*

Hydrodynamic Absorber: Structure – Displacer (Non Steel)

Commonality	Cost	Performance	Availability	Survivability
Low (6)	Very High (4)	Moderate (2)	Good (1)	Very Poor (4)

Function: Structure which has motion generated by the waves. Strong interaction with productive sea states, low interaction with extreme sea states desired.	**Baseline Function:** • Non-Steel structure which has motion generated by the wave motion (buoyancy / water mass)
Technical Challenges:	
• *Loads: Large loads from the waves to be reacted by the structure. Good survivability at a low cost is desired. Challenging to achieve a device which can interact at certain energetic conditions but mitigate large loads from extreme conditions.* • *Interfaces: The structure requires an interface with the reactor, where forces are very high and typically localised and components of different materials are required to interface.* • *Dimensions: The displacer structure is typically of large dimensions increasing the challenge for physical operations. Current size of structures leads to very high cost.* • *Failure: Could lead to catastrophic loss of the device / displacer or large associated costs for repair* • *Installation / Maintenance: Large size and mass of the component and location subsea can make it challenging for installation and maintenance of the structure.* • *Impact: continual impact loading from waves.*	• *Dynamic Response: dynamic behaviour of the structure under wave conditions and ability to tailor by design is critical* • *Operation: Marine Growth / Biofoul expected in offshore conditions, structure should operate with expected conditions.* • *Operational Life: Long life desired, if maintenance is required this could have a large cost implications.* • *Erosion: exposure to offshore conditions may lead to erosion of material over operation life.* • *Material Compatibility: Other structures / components are typically attached to the reactor, compatibility with these materials required.* • *Material Degradation: subjected to long term offshore conditions (UV, temperature, submersion etc.) material degradation may be a challenge.* • *Sealing: Sealing of structure (if required, i.e for buoyancy) from environment.*

Hydrodynamic Absorber: Bearing

Commonality	Cost	Performance	Availability	Survivability
Very High (129)	Moderate (2)	Good (1)	Poor (3)	Good (1)

Function:
Allows constrained relative motion between two components or parts

Baseline Function:
- Enable constrained relative motion between moving components on the wave energy convertor

Technical Challenges:

- *Loads: Large axial and radial loads often to be reacted. Motion is typically reciprocating at relatively low speed with high force regime.*
- *Interface: precision tolerance typically required with interfacing components.*
- *Dimensions / Installation: large size of bearing and interfaced components increases difficulty of operations such as installation.*
- *Failure / Lifetime / Availability: Linked directly to the performance of the WEC. Current availability due to bearing performance is poor.*
- *Maintenance / Operational Life: Typically in difficult to access areas, any maintenance requirement is costly, long maintenance interval / no maintenance is desired.*
- *Analysis / Design Parameters: bearing design can be complex, WEC parameters differ from each device and ocean conditions are not well defined near shore.*
- *Corrosion: harsh subsea environment, corrosion risk to any metallic components.*
- *Material Compatibility: Bearing shall interface with other components, materials are required to be compatible (strain / thermal etc.)*
- *Material Degradation / Seals / Wear: Onerous environment and long service intervals, challenge for degradation and wear of the bearing and seals.*
- *Mechanical Properties / Temperature: Temperature change may occur due to environmental and operational conditions, this could have complex relationship with performance and life.*
- *Cavitation: Cavitation of bearing lubrication can be problematic with low RPM / low rotation systems.*

Power Take Off: Hydraulic System (Non PTO) - Water

Commonality	Cost	Performance	Availability	Survivability
Low (25)	Moderate (2)	Moderate (2)	Poor (3)	Poor (3)

Function:
Produce hydraulic pressure (using water) from linear or rotational motion

Baseline Function:
- Produce pressurised water from linear or rotational mechanical power from the displacer/reactor

Technical Challenges:

- *Dimensions: Large pressures and subsequent large volumes of water required for performance of the PTO.*
- *Failure / Lifetime / Availability: Performance of the WEC is directly related to the performance of the water hydraulic system. Failure (pressure containment/sealing/complete loss) of collection pipework under operating conditions and severe environmental conditions has been experienced.*
- *Installation / Maintenance / Operation / Operational Life: Typically in difficult to access areas, any maintenance requirement is costly, long maintenance interval / no maintenance is desired. Can be challenging to locate damage remotely prior to service.*
- *Analysis / Design Parameters: Design dependant on environmental conditions and performance of the WEC*
- *Loads: Large loads / moments likely from WEC to be converted into pressure. Onerous cyclic loading.*
- *Corrosion: Both internal in hydraulic system and external due to environment.*
- *Cavitation: cavitation's in the system could result in performance loss and potential damage.*
- *Water Lock / Clogging: blockages in the system can cause damage and reduce in performance, maintenance to rectify difficult due to location of the system and can be expensive due to the length of the collection pipework.*
- *Sealing / Contamination: Reliable sealing of system is required to avoid need for costly and difficult maintenance*
- *Control System Loss: Failure of the control system (control of the pressure/forces) could potentially occur.*
- *Hydraulic Fluid Degradation: Water in system requires filtering/treatment to avoid contamination/growth etc.*
- *Pressure Loss: Any decrease in pressure will adversely affect system performance and LCoE*

Hydrodynamic Absorber: Structure – Displacer (steel)

Commonality	Cost	Performance	Availability	Survivability
Moderate (56)	Very High (4)	Moderate (2)	Good (1)	Moderate (2)

Function: Structure which has motion generated by the waves. Strong interaction with productive sea states, low interaction with extreme sea states desired.	**Baseline Function:** • Steel structure which has motion generated by the wave motion (buoyancy / water mass)
Technical Challenges:	
• *Loads: Large loads from the waves to be reacted by the structure. Good survivability at a low cost is desired. Challenging to achieve a device which can interact at certain energetic conditions but mitigate large loads (load avoidance) from extreme conditions.* • *Interfaces: The structure requires an interface with the reactor, where forces are very high and typically localised and components of different materials are required to interface.* • *Dimensions: The displacer structure is typically of large dimensions increasing the challenge for physical operations. Current size of structures leads to very high cost.* • *Failure: Could lead to catastrophic loss of the device / displacer or large associated costs for repair* • *Installation / Maintenance: Large size and mass of the component and location subsea can make it challenging for installation and maintenance of the structure.* • *Impact: continual impact loading from waves.*	• *Dynamic Response: dynamic behaviour of the structure under wave conditions and ability to tailor by design is critical* • *Operation: Marine Growth / Biofoul expected in offshore conditions, structure should operate with expected conditions.* • *Operational Life: Long life desired, if maintenance is required this could have a large cost implications.* • *Erosion: exposure to offshore conditions may lead to erosion of material over operation life.* • *Material Compatibility: Other structures / components are typically attached to the reactor, compatibility with these materials required.* • *Corrosion: harsh subsea environment, corrosion risk to any metallic components.* • *Sealing: Sealing of structure (if required, i.e for buoyancy) from environment.*

Hydrodynamic Absorber: Blade

Commonality	Cost	Performance	Availability	Survivability
Moderate (50)	High (3)	Moderate (2)	Moderate (2)	Moderate (2)

Function: Produce lift/drag from the flow of water using hydrodynamic principles	**Baseline Function:** • Produce lift/drag from the wave motion by use of hydrodynamic principles
Technical Challenges:	
• *Interface / Material Compatibility:: Requires interface with reaction structure, typically of different materials, where concentration of load occurs in a joint which is critical for effective installation of removal.* • *Dimensions: Blade may be of large dimensions to capture maximum energy from the wave* • *Failure / Lifetime / Availability: Could lead to catastrophic loss of the device / displacer or large associated costs for repair. Directly linked to WEC performance and LCoE.* • *Installation / Maintenance: Typically installed onshore onto the WEC, however offshore removal / installation of blades may be required and are challenging. Low / no maintenance is desired.* • *Analysis / Design Parameters / Environ. Data: Blade design dependant on environmental design parameters. Data for near shore locations may be limited.*	• *Dynamic Response / Operational Life: Highly cyclic in loading, dynamic response is critical to the fatigue life of the component. Offshore operations for maintenance or repair are costly and have impact on LCoE.* • *Loads: High hydrodynamic loads, highly cyclic* • *Corrosion: Blades subject to offshore submerged conditions, where metallic, corrosion is an issue.* • *Erosion / Material Degradation / Wear: Continual exposure to waves and current with particulates, material erosion and degradation is potential challenge.* • *Balance / Vibration: Balance of blades and vibration (low frequency) can have a large effect on cyclic loading and subsequent life.* • *Impact: Potential impacts from sealife / vessels etc on structure* • *Operation: Marine Growth / Biofoul expected in offshore conditions, structure should operate with expected conditions.*

Power Take Off: Air Turbine, uni-directional

Commonality	Cost	Performance	Availability	Survivability
Low (16)	High (3)	Moderate (2)	Moderate (2)	Poor (3)

Function:	Baseline Function:
Use change of pressure as fluid (air) flows through (in one direction only) to extract energy	• Extract energy (rotational motion) from air flow (in one direction) which have been generated by the wave energy convertor

Technical Challenges:

- *Pressure Loss: Loss of pressure in turbine or pneumatic system will reduce performance of the WEC and directly effect LCoE. Primary challenge in leakage in the system and durability of external rectification system.*
- *Interface: Requires interface with pressurised system (i.e. pipe)*
- *Dimensions: Turbine dimensions may drive location of the system (offshore/onshore, subsea/platform/floating etc.)*
- *Failure / Lifetime / Availability: Performance of the WEC is directly related to the performance of the water hydraulic system. Survivability of existing system perceived as poor*
- *Installation / Maintenance: Installation may be costly and difficult if offshore. Maintenance requires downtime of the turbine which will affect performance and LCoE.*
- *Operational Life: turbine survivability is poor to date, increased operational life is required to be economical.*
- *Corrosion: Offshore environment results in corrosion challenge for metallic structures / systems.*
- *Erosion / Wear: Continuous operation of air system may lead to erosion and wear of turbine elements.*
- *Balance / Vibration: Balance of rotating elements within the system is critical for vibration.*
- *Bearings: Low maintenance, low friction bearings would be required to maximise efficiency of the turbine.*
- *Control System Loss:*

Power Take Off: Gearbox

Commonality	Cost	Performance	Availability	Survivability
Moderate (45)	Moderate (2)	Moderate (2)	Poor (3)	Moderate (2)

Function:	Baseline Function:
Transfer rotational force from one shaft to secondary shaft with differing rotational speed/torque.	• Transfer rotational force from the Wave Energy Convertor to the generator at a different shaft speed and/or torque.

Technical Challenges:

- *Operation: operating condition of gearbox is a challenge (environment, low speed, reversible / reciprocating, high torque / gearing ratio requirement)*
- *Interfaces: Requires interface with torque shaft from WEC device.*
- *Failure / Lifetime / Availability: Current availability of existing solutions is poor. Reliability of gearbox operating with large loads in harsh environment is challenging.*
- *Installation / Maintenance: Installation may be costly and difficult if offshore. Maintenance requires downtime of the turbine which will affect performance and LCoE.*
- *Analysis / Design Parameters: bearing design can be complex, WEC parameters differ from each device and ocean conditions are not well defined near shore.*
- *Loads: Gearbox will be subjected to large loads from the displacer and require high gearing ratio (see operation).*
- *Operational Life: Long life desired, if maintenance is required this could have a large cost implications.*
- *Corrosion: Onerous offshore conditions can lead to corrosion of metallic components. Adequate protection is required to mitigate.*
- *Bearings: Low maintenance, low friction bearings would be required to maximise efficiency of the gearbox. Bearings may be subject to high loads and low speeds (see challenges for bearings)*
- *Wear: Prolonged operation of gearbox is subject to wear of components which could reduce performance and potentially fail causing maintenance challenges.*

Hydrodynamic Absorber: Structure, Reactor (Steel)

Commonality	Cost	Performance	Availability	Survivability
Moderate (40)	Very High (4)	Moderate (2)	Good (1)	Moderate (2)

Function:
To provide reaction to the displacer (static inertia)

Baseline Function:
- A body to provide adequate reaction to the displacer.

Technical Challenges:

- *Loads: Large loads from the displacer to be reacted by the structure. Extreme environmental loading currently results in poor survivability and large structure typically results in very high cost.*
- *Interfaces: The structure requires an interface with the displacer, where forces are very high and typically localised and components of different materials are required to interface.*
- *Dimensions: The reactor structure is typically of large dimensions increasing the challenge for physical operations. Current size of structures leads to very high cost.*
- *Failure: Could lead to catastrophic loss of the device / displacer or large associated costs for repair*
- *Installation / Maintenance: Large size and mass of the component and location subsea can make it challenging for installation and maintenance of the structure.*
- *Dynamic Response: dynamic behaviour of the structure under wave conditions and ability to tailor by design is critical*
- *Operation: Marine Growth / Biofoul expected in offshore conditions, structure should operate with expected conditions.*
- *Operational Life: Long life desired, if maintenance is required this could have a large cost implications.*
- *Corrosion: onerous environmental conditions leads to corrosion of metallic structures. Adequate protection required*
- *Erosion: exposure to offshore conditions may lead to erosion of material over operation life.*
- *Material Compatibility: Other structures / components are typically attached to the reactor, compatibility with these materials required.*
- *Material Degradation: subjected to long term offshore conditions (UV, temperature, submersion etc.) material degradation may be a challenge.*
- *Impact: continual impact loading from waves.*
- *Sealing: Sealing of structure (if required) from environment.*

Power Take Off: Dynamic Cable

Commonality	Cost	Performance	Availability	Survivability
High (71)	Moderate (2)	Good (1)	Poor (3)	Moderate (2)

Function:
Electrical cable with connection to a moving (dynamic) body

Baseline Function:
- Import / Export electrical cable connected to a moving floating or semi-submersible body

Technical Challenges:

- *Interface: Connection to system must withstand the sustained dynamic loading.*
- *Dimensions: Cable diameters relatively large in order to support the voltage for export/transmission.*
- *Failure / Availability / Lifetime: Current availability of dynamic cables is poor. Electrical cable has a direct impact on LCoE if unavailable (downtime).*
- *Installation / Maintenance: Installation and maintenance of offshore cable is an expensive operation. Connect and disconnect of cable is also challenging (see subsea connectors)*
- *Loads: Experiences large dynamic loads due to the relative motion of the floating/semi-submersible body and the seabed or cable reaction structure.*
- *Dynamic Response: Design Parameters:*
- *Corrosion: onerous environmental conditions leads to corrosion of metallic components. Adequate protection required*
- *Material / Electrical Insulation degradation: onerous environmental condition can lead to degradation of materials and electrical insulation.*
- *Impact: Subject to regular impact from waves, and potential impacts with vessels / debris.*
- *Vibration: Oscillations (low frequency) due to dynamic response may occur.*
- *Wear / Ageing: Wear from friction/support during operation and ageing from environmental conditions (UV, biological, etc)*
- *High Voltage: High voltage export/transmission preferred to reduce losses.*
- *Transmission Losses: Directly linked to LCoE, minimising transmission losses will increase performance.*

Hydrodynamic Absorber: Yoke / Yaw

Commonality	Cost	Performance	Availability	Survivability
Low (1)	Low (1)	Poor (3)	Poor (3)	Poor (3)

Function: Device to achieve optimal yaw alignment	**Baseline Function:** • To control and achieve optimal yaw alignment
Technical Challenges:	
• *Interface: The system must interface with the device to be aligned and possibly also the reaction structure.* • *Dimensions: The large size of typical WEC structure requiring alignment with the waves is a major challenge due to the large forces involved.* • *Failure / Lifetime / Availability: Current technologies show poor availability and survivability in the harsh environments and extreme loadings.* • *Installation / Maintenance: May be installed on device prior to installation, however maintenance is challenging offshore and is costly.* • *Operation: Active systems are challenging. Failure to operate may lead to downtime and further damage of the WEC* • *Dynamic Response: Will effect and also be dependant on the response of the overall system to wave interaction.*	• *Loads: Large loading likely to be required to change/alter orientation of the WEC structure.* • *Corrosion: onerous environmental conditions leads to corrosion of metallic components. Adequate protection required* • *Balance: May effect the overall stability of the system* • *Impact: Subject to regular impact from waves, and potential impacts with vessels / debris.* • *Vibration: Oscillations (low frequency) due to dynamic response may occur.* • *Wear / Ageing: Wear from friction/support during operation and ageing from environmental conditions (UV, biological, etc)*

Power Take Off: Spring

Commonality	Cost	Performance	Availability	Survivability
Low (1)	High (3)	Moderate (2)	Moderate (2)	Poor (3)

Function: To store mechanical power	**Baseline Function:** • To store mechanical energy from the WEC from part of the wave cycle to another or to return components to position
Technical Challenges:	
• *Interface: Must interface with the displacer and reaction structure.* • *Dimensions: Large dimensions of typical device may require large forces to return/change its position.* • *Failure / Lifetime / Availability: Survivability of such technology currently Poor. Failure can result in downtime and potential further damage occurring to the asset.* • *Installation / Maintenance: May be installed on device prior to installation, however maintenance is challenging offshore and is costly.* • *Dynamic Response: Dynamic behaviour of the spring can have an effect on the behaviour and performance of the overall system.* • *Safety: Large stored energy is potential safety risk to people and the asset.*	• *Loads: Large loading likely to be required to change/alter orientation of the WEC structure.* • *Operational Life: Cyclic loading over the life of the component. Replacement of components is undesirable due to cost and challenge with offshore operations.* • *Corrosion: onerous environmental conditions leads to corrosion of metallic components. Adequate protection required* • *Mechanical Properties / Temperature: Important to the performance of the spring. Operation typically in low temperature.* • *Wear: Continual compression/tension of spring will wear the spring and interfacing system. Minimising maintenance and repair is desired as offshore operations are costly and challenging.*

Power Take Off: Hydraulic System (Non PTO), Oil

Commonality	Cost	Performance	Availability	Survivability
Moderate (30)	Moderate (2)	Moderate (2)	Moderate (2)	Poor (3)

Function:
Produce hydraulic pressure (using oil) from linear or rotational motion using

Baseline Function:
- Produce pressurised oil from linear or rotational mechanical power from the displacer/reactor. Typical use of large hydraulic cylinders, motors, accumulators etc.

Technical Challenges:

- *Dimensions: Large pressures / volumes* required for performance *of the PTO, leading to large cylinders / accumulators / motors etc.*
- *Failure / Lifetime / Availability: Performance of the WEC is directly related to the performance of the oil hydraulic system. Survivability experience is currently poor.*
- *Installation / Maintenance / Operation / Operational Life: Typically in difficult to access areas, any maintenance requirement is costly, long maintenance interval / no maintenance is desired. Can be challenging to locate damage remotely prior to service.*
- *Analysis / Design Parameters: Design dependant on environmental conditions and performance of the WEC*
- *Loads: Large loads / moments likely from WEC to be converted into pressure. Onerous cyclic loading.*
- *Corrosion: Both internal in hydraulic system and external due to environment.*
- *Cavitation: cavitation's in the system could result in performance loss and potential damage.*
- *Water Lock / Clogging: blockages in the system can cause damage and reduce in performance, maintenance to rectify difficult due to location of the system.*
- *Sealing / Contamination: Reliable sealing of system is required to avoid need for costly and difficult maintenance*
- *Control System Loss: Failure of the control system (control of the pressure/forces) could potentially occur.*
- *Hydraulic Fluid Degradation: Oil in system requires filtering/treatment to avoid contamination/growth etc.*
- *Pressure Loss: Any decrease in pressure will adversely affect system performance and LCoE*

Power Take Off: Transformer up to 11kV

Commonality	Cost	Performance	Availability	Survivability
Very High (148)	Low (1)	Good (1)	Moderate (2)	Good (1)

Function:
Increase voltage of electrical power

Baseline Function:
- To increase electrical voltage offshore for transmission to shore (reducing cost of cables)

Technical Challenges:

- *Dimensions: Size of the transformer may affect the location of the equipment (integrated to WEC / Standalone installation).*
- *Failure / Lifetime / Availability: The availability is highlighted as the main area for improvement. This is driven by the reliability of power electronics in onerous environment (subsea, vibration/accelerations, lack of access for maintenance etc.)*
- *Installation / Maintenance / Operational Life / Ageing: Typically in difficult to access areas, any maintenance requirement is costly, long maintenance interval / no maintenance is desired.*
- *Standards: Power electronics tend to be standard 'off the shelf' components from other industries or applications (i.e. offshore wind). The standard design of these components may be unsuitable for certain WEC applications (such as location in WEC where accelerations are high and cyclic) leading to decreased reliability.*
- *Standards: High commonality of technology across devices may benefit from standardisation of technology.*
- *Dynamic Response / Vibrations / Loads: Where the equipment is housed within the WEC or moving components, the transformer may be subject to loads and vibrations dependant on the dynamic response of the system.*
- *Sealing / Connectors: Whether housed in the WEC of separate installation, the Transformer will require robust sealing from the subsea conditions and a means of connection to the system, yet be modular or removable should maintenance be required.*
- *Electrical Insulation Degradation: Insulation of the power electronics from the other systems and the external environment shall be required. A low maintenance regime is desired, hence the degradation of this materials should be adequate for the foreseeable operational life.*

Power Take Off: AC/DC/AC Convertor

Commonality	Cost	Performance	Availability	Survivability
Very High (147)	Moderate (2)	Good (1)	Moderate (2)	Good (1)

Function:
Rectifies alternating current (AC) to direct current (DC) and creates AC

Baseline Function:
- To convert low quality AC electricity to high quality AC electricity, by converting to from AC>DC>AC.

Technical Challenges:

- *Dimensions: Size of the power electronics may affect the location of the equipment (integrated to WEC / Standalone installation).*
- *Failure / Lifetime / Availability: The availability is highlighted as the main area for improvement. This is driven by the reliability of power electronics in onerous environment (subsea, vibration/accelerations, lack of access for maintenance etc.)*
- *Installation / Maintenance / Operational Life / Ageing: Typically in difficult to access areas, any maintenance requirement is costly, long maintenance interval / no maintenance is desired.*
- *Standards: Power electronics tend to be standard 'off the shelf' components from other industries or applications (i.e. offshore wind). The standard design of these components may be unsuitable for certain WEC applications (such as location in WEC where accelerations are high and cyclic) leading to decreased reliability.*
- *Standards: High commonality of technology across devices may benefit from standardisation of technology.*
- *Dynamic Response / Vibrations / Loads: Where the equipment is housed within the WEC or moving components, the convertor may be subject to loads and vibrations dependant on the dynamic response of the system.*
- *Sealing / Connectors: Whether housed in the WEC of separate installation, the Transformer will require robust sealing from the subsea conditions and a means of connection to the system, yet be modular or removable should maintenance be required.*
- *Electrical Insulation Degradation: Insulation of the power electronics from the other systems and the external environment shall be required. A low maintenance regime is desired, hence the degradation of this materials should be adequate for the foreseeable operational life.*

Hydrodynamic Absorber: Structure, Displacer Reactor (Steel)

Commonality	Cost	Performance	Availability	Survivability
Low (16)	Very High (4)	Moderate (2)	Good (1)	Moderate (2)

Function:
Provide reaction force

Baseline Function:
- System which provides a reaction force without using a dedicated reactor (i.e. a system of displacers with relative motion to create a reaction force for the displacer)

Technical Challenges:

- *Interfaces: The structure requires an interface with the displacer, where forces are very high and typically localised and components of different materials are required to interface.*
- *Dimensions: The reactor structure is typically of large dimensions increasing the challenge for physical operations. Current size of structures leads to very high cost.*
- *Failure: Could lead to catastrophic loss of the device / displacer or large associated costs for repair*
- *Installation / Maintenance: Large size and mass of the component and location subsea can make it challenging for installation and maintenance of the structure.*
- *Dynamic Response: dynamic behaviour of the structure under wave conditions and ability to tailor by design is critical*
- *Loads: Large loads from the displacer to be reacted by the structure. Extreme environmental loading currently results in poor survivability.*
- *Operation: Marine Growth / Biofoul expected in offshore conditions, structure should operate with expected conditions.*
- *Operational Life: Long life desired, if maintenance is required this could have a large cost implications.*
- *Corrosion: Onerous offshore conditions can lead to corrosion of metallic components. Adequate protection is required to mitigate.*
- *Erosion: exposure to offshore conditions may lead to erosion of material over operation life.*
- *Material Compatibility: Other structures / components are typically attached to the reactor, compatibility with these materials required.*
- *Impact: continual impact loading from waves.*
- *Sealing: Sealing of structure (if required) from environment.*

Power Take Off: Generator, Linear Electric

Commonality	Cost	Performance	Availability	Survivability
Low (14)	Moderate (2)	Moderate (2)	Moderate (2)	Poor (3)

Function:
Generate electrical power from linear motion

Baseline Function:
- Generate electrical power from linear motion generated by the displacer/reactor

Technical Challenges:

- *Dimensions: Maintaining minimum air gap between translator and stator required to maximise efficiency. Due to linear motions captured by WEC, translation length tends to be large, thus maintaining minimum air gap across large translation is challenging and can be costly.*
- *Operation / Losses: In relation to typical rotational generator, only a given portion of the stator at a given time is 'working' while the translator moves. This results in lower 'capital efficiency'. Additionally the system needs to be able to cope with transient loading regime where power quality is typically 'low quality'*
- *Failure / Lifetime / Availability / Loads: The availability and survivability are highlighted as areas for improvement. This is likely to be driven by the low speed-high force load regime typically experienced by linear generators leading to severe damage in the event of a failure, compared to rotational generators which tend to be high speed-low force.*
- *Installation / Maintenance / Operational Life / Ageing: Typically in difficult to access areas, any maintenance requirement is costly, long maintenance interval / no maintenance is desired.*
- *Interface: Required to interface with displacer and reactor, handling large loads associated.*
- *Dynamic Response: May be desirable for some systems if reactive control using the generator is possible.*
- *Design Parameters: Likely to be bespoke which has impact on cost / performance. Is there another industry that could generate sufficient volume to produce impact on cost / performance / reliability?*
- *Corrosion: Onerous offshore conditions can lead to corrosion of metallic components. Adequate protection is required to mitigate.*
- *Sealing: Linear translator will see large reversing translations to match displacer motions. Sealing will be required to seal internal/external environments during these translations.*
- *Ageing / Degradation: Low maintenance regime is desired. Ageing and degradation of the power electronics and seals should be adequate.*

Power Take Off: Generator, Rotational Direct Electric

Commonality	Cost	Performance	Availability	Survivability
Low (13)	High (3)	Moderate (2)	Moderate (2)	Moderate (2)

Function:
Generate electrical power from direct (low speed) rotational motion

Baseline Function:
- Generate electrical power from direct (no gearbox) low speed rotational motion generated by the displacer/reactor

Technical Challenges:

- *Dimensions: Typically consists of a large permanent magnet generator controlled by power electronics. Ability to utilise low speed-high torque typically results in large and costly generator.*
- *Operation / Losses: Where no energy storage is used, transients will propagate from the WEC resulting in 'low quality torque', hence the generator will have to be able to cope with this, resulting in a challenge for efficiency and losses.*
- *Failure / Lifetime / Availability / Loads: The availability and survivability are highlighted as areas for improvement. This is likely to be driven by the low speed-high force load regime typically experienced by linear generators leading to severe damage in the event of a failure.*
- *Installation / Maintenance / Operational Life / Ageing: Typically in difficult to access areas, any maintenance requirement is costly, long maintenance interval / no maintenance is desired.*
- *Interface: Required to interface with displacer and reactor, handling large loads associated.*
- *Dynamic Response: May be desirable for some systems if reactive control using the generator is possible.*
- *Design Parameters: Likely to be bespoke which has impact on cost / performance. Is there another industry that could generate sufficient volume to produce impact on cost / performance / reliability?*
- *Corrosion: Onerous offshore conditions can lead to corrosion of metallic components. Adequate protection is required to mitigate.*
- *Sealing: Generator will see large reciprocating rotation to match displacer motions. Sealing will be required to seal internal/external environments.*
- *Ageing / Degradation: Low maintenance regime is desired. Ageing and degradation of the generator and seals should be adequate.*

Reaction / Stationing: Mooring, Single Point

Commonality	Cost	Performance	Availability	Survivability
Moderate (40)	High (3)	Good (1)	Moderate (2)	Moderate (2)

Function:
Attachment of device to reacting structure by a single connection

Baseline Function:
- Attachment of the wave energy convertor to the seabed/reacting structure by single connection allowing rotation ('weathervane')

Technical Challenges:

- *Interface / Loads: Single point interface with WEC, and other interface to seabed/reacting structure. High localised loading in difficult environment. High loads typically results in increased cost (i.e. piles required to react loads which results in large installation cost).*
- *Failure / Lifetime / Availability: Single point mooring is critical to the survival of the WEC. Failure can lead to reduced availability and catastrophic loss of the asset.*
- *Installation / Maintenance / Operation: Mooring installation typically requires commissioning of or connection to subsea foundation or anchor. These operations are of high cost. Reduction of time and resource required for installation is desired.*
- *Standards / Analysis / Design Parameters: Offshore standards available for moorings / foundation structures (Oil & Gas, Wind) however loading will differ due to loading regime and location of structures. Best practice applicable however specific design parameters are not always available.*
- *Dynamic Response: Mooring behaviour can have affect on dynamic response of the system, this may or may not be required by the WEC. Ability to tailor should be advantageous.*
- *Seabed: Conditions of seabed have a large impact on the design of the mooring technology, leading to bespoke mooring solutions which increase cost.*
- *Operational Life / Wear: Low (zero) maintenance operation is desired from mooring and foundation structure.*
- *Corrosion / Material Degradation: Onerous offshore conditions can lead to corrosion of metallic components and degradation of materials. Adequate protection is required to mitigate.*
- *Erosion: exposure to offshore conditions may lead to erosion of material over operation life.*
- *Bearings: or means of free / restrained rotation of device around the single point mooring may be required.*

Power Take Off: Air Turbine, bi-directional

Commonality	Cost	Performance	Availability	Survivability
Low (4)	Moderate (2)	Moderate (2)	Moderate (2)	Poor (3)

Function:
Use change of pressure as fluid (air) flows through (in both directions) to extract energy

Baseline Function:
- Extract energy from air flow (in both directions) which has been generated by the wave energy convertor

Technical Challenges:

- *Pressure Loss: Loss of pressure in turbine or pneumatic system will reduce performance of the WEC and directly effect LCoE. Primary challenge in leakage in the system and durability of external rectification system.*
- *Interface: Requires interface with pressurised system (i.e. pipe)*
- *Dimensions: Turbine dimensions may drive location of the system (offshore/onshore, subsea/platform/floating etc.)*
- *Failure / Lifetime / Availability: Performance of the WEC is directly related to the performance of the air system. Survivability of existing system perceived as poor*
- *Installation / Maintenance: Installation may be costly and difficult if offshore. Maintenance requires downtime of the turbine which will affect performance and LCoE.*
- *Operational Life: turbine survivability is poor to date, increased operational life is required to be economical.*
- *Corrosion: Offshore environment results in corrosion challenge for metallic structures / systems.*
- *Erosion / Wear: Continuous operation of air system may lead to erosion and wear of turbine elements.*
- *Balance / Vibration: Balance of rotating elements within the system is critical for vibration.*
- *Bearings: Low maintenance, low friction bearings would be required to maximise efficiency of the turbine.*
- *Control System Loss:*

Power Take Off: Generator, Hydraulic, Novel

Commonality	Cost	Performance	Availability	Survivability
Low (1)	High (3)	Moderate (2)	Moderate (2)	Moderate (2)

Function	Baseline Function
Function: Generate electrical power from hydraulic pressure	**Baseline Function:** • Novel (non-off-the-shelf) generation of electrical power (using rotational shaft power) from hydraulic pressure produced by the wave energy convertor

Technical Challenges:

- *Operation: Latency (soft/slow) typical of off the shelf generator solutions. High speed reactive control, low latency is required for efficient generation. Digital displacement gives fast acting controllability in comparison to traditional swash-plate controlled motors. Traditional hydraulic motor is bent axis / swash plate. Innovations in this space which might give better performance or control would be beneficial.*
- *Failure / Lifetime / Availability / Loads: The availability and survivability are highlighted as areas for improvement. Remediation operations are challenging and costly due to environment and location.*
- *Installation / Maintenance / Operational Life / Ageing: Typically in difficult to access areas, any maintenance requirement is costly, long maintenance interval / no maintenance is desired.*
- *Interface: Required to interface with the cylinder/pump, use of reliable hydraulic connections.*
- *Dynamic Response: Desirable if reactive control using the generator is possible (i.e. ARTEMIS).*
- *Corrosion: Onerous offshore conditions can lead to corrosion of metallic components. Adequate protection is required to mitigate.*
- *Ageing / Degradation / Seal: Low maintenance regime is desired. Ageing and degradation of the system and seals should be adequate.*

Power Take Off: Water Turbine, Novel

Commonality	Cost	Performance	Availability	Survivability
Low (1)	High (3)	Moderate (2)	Moderate (2)	Moderate (2)

Function	Baseline Function
Function: Produce electrical power from a water pressure / flow	**Baseline Function:** • Novel (non-off-the-shelf) generation of electrical power from a water pressure / flow produced by the wave energy convertor.

Technical Challenges:

- *Dimensions: Overtopping devices – Low head hydro. Costs high as low head high volume results in large structures being required.*
- *Sealing / Loads : Pipework to the Turbine from the WEC is challenging. Costly to install from WEC location (offshore) to the turbine location (typically on shore). Pipework prone to leaks or damage due to extreme environmental conditions present offshore.*

Reaction / Stationing: Mooring, Multipoint

Commonality	Cost	Performance	Availability	Survivability
Moderate (31)	High (3)	Good (1)	Moderate (2)	Moderate (2)

Function:
Attachment of device to reacting structure by multiple connection points

Baseline Function:
- Attachment of the wave energy convertor to the seabed/reacting structure by multiple connection points

Technical Challenges:

- *Interface / Loads: Single point interface with WEC, and other interface to seabed/reacting structure. High localised loading in difficult environment. High loads typically results in increased cost (i.e. piles required to react loads which results in large installation cost).*
- *Failure / Lifetime / Availability: Single point mooring is critical to the survival of the WEC. Failure can lead to reduced availability and catastrophic loss of the asset.*
- *Installation / Maintenance / Operation: Mooring installation typically requires commissioning of or connection to subsea foundation or anchor. These operations are of high cost. Reduction of time and resource required for installation is desired.*
- *Standards / Analysis / Design Parameters: Offshore standards available for moorings / foundation structures (Oil & Gas, Wind) however loading will differ due to loading regime and location of structures. Best practice applicable however specific design parameters are not always available.*
- *Dynamic Response: Mooring behaviour can have affect on dynamic response of the system, this may or may not be required by the WEC. Ability to tailor should be advantageous.*
- *Seabed: Conditions of seabed have a large impact on the design of the mooring technology, leading to bespoke mooring solutions which increase cost.*
- *Operational Life / Wear: Low (zero) maintenance operation is desired from mooring and foundation structure.*
- *Corrosion / Material Degradation: Onerous offshore conditions can lead to corrosion of metallic components and degradation of materials. Adequate protection is required to mitigate.*
- *Erosion: exposure to offshore conditions may lead to erosion of material over operation life.*

Power Take Off: Generator, Hydraulic, Standard

Commonality	Cost	Performance	Availability	Survivability
Low (26)	Moderate (2)	Moderate (2)	Moderate (2)	Moderate (2)

Function:
Generate electrical power from hydraulic pressure

Baseline Function:
- Generation of electrical power (using rotational shaft power) from hydraulic pressure produced by the wave energy convertor using standard hydraulic component/systems (off-the-shelf)

Technical Challenges:

- *Failure / Lifetime / Availability / Loads: The availability and survivability are highlighted as areas for improvement. Remediation operations are challenging and costly due to environment and location.*
- *Installation / Maintenance / Operational Life / Ageing: Typically in difficult to access areas, any maintenance requirement is costly, long maintenance interval / no maintenance is desired.*
- *Standards: Typical systems may consist of off the shelf components which are standard for other industries. This can reduce cost however the components may not be suited to the offshore environment and operational loads.*
- *Interface: Required to interface with the cylinder/pump, use of reliable hydraulic connections.*
- *Dynamic Response: Desirable if reactive control using the generator is possible.*
- *Corrosion: Onerous offshore conditions can lead to corrosion of metallic components. Adequate protection is required to mitigate.*
- *Ageing / Degradation / Seal: Low maintenance regime is desired. Ageing and degradation of the system and seals should be adequate.*

Control: Control Systems, Low Complexity

Commonality	Cost	Performance	Availability	Survivability
High (78)	Low (1)	Moderate (2)	Good (1)	Moderate (2)

Function:	Baseline Function:
Sensors / Computer System / Control Algorithms that control the operation of the system	• Sensors / Computer System / Control Algorithms that controls the system to operate as intended but does not significantly increase performance
Technical Challenges:	
• *Operation: Start-up / shutdown / synchronisation / safe operating of plant / Condition monitoring & diagnostics* • *Failure / Lifetime / Availability: High reliability is required due to direct impact on survivability of the WEC. High integrity / robustness / reliability desired for low complexity control system.* • *Looking for ultra high reliability control of plant (i.e chemical process). Robustness / Integrity of control system (even during failure)* • *Design Parameters: The environment and behaviour of the system is a challenge to define as the external environment is of stochastic nature.*	• *Ageing: Low maintenance is desired for all offshore equipment, control system should not be adversely affected with age.*

Control: Control Systems, High Complexity

Commonality	Cost	Performance	Availability	Survivability
Moderate (31)	Low (1)	Moderate (2)	Good (1)	Moderate (2)

Function:	Baseline Function:
Sensors / Computer System / Control Algorithms that control the operation of the system	• Sensors / Computer System / Control Algorithms that controls the system to operate as intended and can improve performance
Technical Challenges:	
• *Operation: Complex operation and sophisticated control of the system / parts of the system which directly affect the performance of the WEC. i.e. extreme load mitigation via the control of hydraulic systems.* • *Failure / Lifetime / Availability: Ultra high reliability is required due to direct impact on survivability of the WEC. High integrity / robustness / reliability also required to ensure maximum performance.* • *Design Parameters: The environment and behaviour of the system is a challenge. Trying to control high complexity system with non linear response in stochastic environment. Similar applications are Aerospace systems, Missile Systems or Submarine Systems.*	• *Ageing: Low maintenance is desired for all offshore equipment, control system should not be adversely affected with age.*

Appendix 6 Technology Element Proposals

Impact of Technology: These show the impact (the change in score from the benchmark) expected to result on the benchmark scores following implementation of the proposed technology. Where positive values show an increase in the respective metric and vice versa (i.e. -2 Cost shows a moderate decrease in cost, and +1 Performance shows a small increase in performance due to the use of the proposed technology).

Novelty Assessment: Each technology has been assessed in terms of technology uncertainty and its area of application (in wave energy). Technologies with no technical uncertainties and known application areas are not novel.

Technology Proposal Matrix (Part 1)

				IMPACT OF NEW TECHNOLOGY				NOVELTY ASSESSMENT			
Technology Element	**Technology transfer description**	**Type**	**Transferability**	**Cost**	**Performance**	**Availability**	**Survivability**	**Technology Uncertainty**	**Application Area**	**Score**	**Novelty**
Hydrodynamic Absorber: Seals	Wartsila Seals	Off The Shelf	10	2	1	1	2	None	Known	1	Not Novel
Hydrodynamic Absorber: Seals	Polyurethane Seals	Off The Shelf	7	1	0	1	1	None	New	3	Medium Novelty
Hydrodynamic Absorber: Seals	Offshore Drilling Seals	Off The Shelf	10	2	1	1	2	None	Limited Knowledge	2	Low Novelty
Hydrodynamic Absorber: Seals	Water lubricated ceramic face seals	Off The Shelf		0	1	1	1	None	Limited Knowledge	2	Low Novelty
Power Take Off: Subsea Connectors	Siemens Spectron / Digitron Subsea Connectors	Off The Shelf	10	2	0	2	1	None	Limited Knowledge	2	Low Novelty
Power Take Off: Subsea Connectors	Seacon Wetmate Connectors	Off The Shelf	10	2	0	2	1	None	Limited Knowledge	2	Low Novelty
Power Take Off: Subsea Connectors	Souriau Connectors	Off The Shelf	10	2	0	2	1	None	Limited Knowledge	2	Low Novelty
Hydrodynamic Absorber: Structure - Reactor (non-steel)	Composite Glass Fibre Reinforced Plastic (GFRP)	Material	10	-1	1	0	2	None	Limited Knowledge	2	Low Novelty
Hydrodynamic Absorber: Structure - Reactor (non-steel)	Aluminium Alloys (Marine Grade)	Material	10	-1	1	0	2	None	New	3	Medium Novelty
Hydrodynamic Absorber: Structure - Reactor (non-steel)	Nickel Aluminium Bronze (NAB)	Material	8	0	1	0	3	None	New	3	Medium Novelty
Hydrodynamic Absorber: Structure - Reactor (non-steel)	Concrete (unreinforced)	Material	7	-2	1	0	2	None	Limited Knowledge	2	Low Novelty
Hydrodynamic Absorber: Structure - Displacer Reactor (non-steel)	Composite Glass Fibre Reinforced Plastic (GFRP)	Material	10	-1	1	0	2	None	Limited Knowledge	2	Low Novelty
Hydrodynamic Absorber: Structure - Displacer Reactor (non-steel)	Aluminium Alloys (Marine Grade)	Material	10	-1	1	0	2	None	New	3	Medium Novelty
Hydrodynamic Absorber: Structure - Displacer Reactor (non-steel)	Nickel Aluminium Bronze (NAB)	Material	10	0	1	0	3	None	New	3	Medium Novelty
Hydrodynamic Absorber: Structure - Displacer Reactor (non-steel)	Concrete (unreinforced)	Material	10	-2	1	0	2	None	Limited Knowledge	2	Low Novelty
Hydrodynamic Absorber: Structure - Displacer Reactor (non-steel)	Composite (multi-material structure)	Design	7	-2	1	0	2	Technical Uncertainty	Limited Knowledge	3	Medium Novelty
Power Take Off: Generator - Rotational	Direct Drive Permanent Magnet Generators	Component Type	8	0	1	0	0	None	Limited Knowledge	2	Low Novelty
Power Take Off: Generator - Rotational	Artemis Hydraulic Motor Generator	Off The Shelf	6	1	1	0	0	Technical Challenges	Limited Knowledge	3	Medium Novelty
Power Take Off: Generator - Rotational	Variable Speed Generators	Component Type	10	0	1	0	0	Technical Challenges	New	4	High Novelty
Hydrodynamic Absorber: Structure - Displacer (non-steel)	Composite Glass Fibre Reinforced Plastic (GFRP)	Material	10	-1	1	0	2	None	Limited Knowledge	2	Low Novelty
Hydrodynamic Absorber: Structure - Displacer (non-steel)	Aluminium Alloys (Marine Grade)	Material	10	-1	1	0	2	None	New	3	Medium Novelty
Hydrodynamic Absorber: Structure - Displacer (non-steel)	Nickel Aluminium Bronze (NAB)	Material	10	0	1	0	3	None	New	3	Medium Novelty
Hydrodynamic Absorber: Structure - Displacer (non-steel)	Concrete (unreinforced)	Material	10	-2	1	0	2	None	New	3	Medium Novelty
Hydrodynamic Absorber: Structure - Displacer (non-steel)	Composite (multi-material structure)	Design	7	-2	1	0	2	Technical Uncertainty	Limited Knowledge	3	Medium Novelty
Hydrodynamic Absorber: Structure - Displacer (non-steel)	Thermoplastics	Material		-1	-2	0	3	None	New	3	Medium Novelty
Hydrodynamic Absorber: Structure - Displacer (non-steel)	Composite Sandwich Structures	Material		0	1	0	3	None	New	3	Medium Novelty
Hydrodynamic Absorber: Structure - Displacer (non-steel)	Compliant structures with tailored buckling/bi-state response	Design		0	1	0	3	Technical Challenges	New	4	High Novelty
Hydrodynamic Absorber: Bearings	Recardo MultiLife Bearing	Off The Shelf		2	0	2	0	Technical Uncertainty	New	4	High Novelty
Hydrodynamic Absorber: Bearings	SKF Nautilus Bearing	Off The Shelf	7	2	0	2	0	Technical Uncertainty	New	4	High Novelty
Hydrodynamic Absorber: Bearings	Cross Roller and Wire Race Bearings	Off The Shelf	8	0	0	2	0	None	New	3	Medium Novelty
Hydrodynamic Absorber: Bearings	Bearing vibration health monitoring	Component Type	8	0	-1	1	0	Technical Challenges	New	4	High Novelty
Power Take Off: Hydraulic System (non PTO) - Water				NO SCORE	NO SCORE	NO SCORE	NO SCORE			#N/A	#N/A
Hydrodynamic Absorber: Structure - Displacer (steel)	Optimisation Software	Design	8	-2	0	0	0	None	Limited Knowledge	2	Low Novelty
Hydrodynamic Absorber: Structure - Displacer (steel)	Standard Naval Architecture Software & Hydrodynamic Testing	Design	8	-2	0	0	0	None	Known	1	Not Novel
Hydrodynamic Absorber: Structure - Displacer (steel)	High Strength Steel	Material		0	0	0	0	None	Known	1	Not Novel
Hydrodynamic Absorber: Structure - Displacer (steel)	Marine Stainless Steel	Material		0	0	0	0	None	Known	1	Not Novel
Hydrodynamic Absorber: Structure - Displacer (steel)	Modular construction of the displacer	Design		-2	1	0	1	None	Limited Knowledge	2	Low Novelty
Hydrodynamic Absorber: Blade	Standard Naval Architecture Software & Hydrodynamic Testing	Design	8	-2	0	0	0	None	Known	1	Not Novel
Hydrodynamic Absorber: Blade	Composite Glass Fibre Reinforced Plastic (GFRP)	Material	10	-1	1	0	0	None	Known	1	Not Novel

Technology Proposal Matrix (Part 2)

				IMPACT OF NEW TECHNOLOGY				NOVELTY ASSESSMENT			
Technology Element	**Technology transfer description**	**Type**	**Transferability**	**Cost**	**Performance**	**Availability**	**Survivability**	**Technology Uncertainty**	**Application Area**	**Score**	**Novelty**
Hydrodynamic Absorber: Blade	Aluminium Alloys (Marine Grade)	Material	10	-1	1	0	2	None	New	3	Medium Novelty
Hydrodynamic Absorber: Blade	Composite (multi-material structure)	Design	7	-2	1	0	2	Technical Uncertainty	Limited Knowledge	3	Medium Novelty
Hydrodynamic Absorber: Blade	Use of Naval Architectural Design Software and Testing	Design	8	-2	0	0	0	None	Known	1	Not Novel
Power Take Off: Air Turbine, Uni-Directional				NO SCORE	NO SCORE	NO SCORE	NO SCORE			#N/A	#N/A
Power Take Off: Gearbox				NO SCORE	NO SCORE	NO SCORE	NO SCORE			#N/A	#N/A
Hydrodynamic Absorber: Structure - Reactor (Steel)	Optimisation Software	Design	8	-2	0	0	0	None	Limited Knowledge	2	Low Novelty
Hydrodynamic Absorber: Structure - Reactor (Steel)	Standard Naval Architecture Software & Hydrodynamic Testing	Design	8	-2	0	0	0	None	Known	1	Not Novel
Hydrodynamic Absorber: Structure - Reactor (Steel)	High Strength Steel	Material		0	0	0	0	None	Known	1	Not Novel
Hydrodynamic Absorber: Structure - Reactor (Steel)	Marine Stainless Steel	Material		0	0	0	0	None	Known	1	Not Novel
Hydrodynamic Absorber: Structure - Reactor (Steel)	Lightweight Composite Yoke	Component Type		0	1	0	3	None	New	3	Medium Novelty
Hydrodynamic Absorber: Structure - Reactor (Steel)	Active control through keel and rudders	Component Type		-3	0	0	3	None	Limited Knowledge	2	Low Novelty
Power Take Off: Dynamic Cable	JDR Umbilical Cables	Off The Shelf	10	-1	1	0	2	None	Limited Knowledge	2	Low Novelty
Power Take Off: Dynamic Cable	Technip Umbilical	Off The Shelf	9	-1	1	0	2	None	Limited Knowledge	2	Low Novelty
Power Take Off: Dynamic Cable	Prysmian Subsea Cables	Off The Shelf	10	-1	1	0	2	None	Limited Knowledge	2	Low Novelty
Power Take Off: Dynamic Cable	Cable Health Monitoring	Instrumentation	9	-1	1	0	2	Technical Uncertainty	Limited Knowledge	3	Medium Novelty
Power Take Off: Dynamic Cable	Prefabricated Connections	Component Type	10	-2	1	0	2	Technical Uncertainty	Limited Knowledge	3	Medium Novelty
Hydrodynamic Absorber: Yoke/Yaw	Rudder Control Surface	Component Type	good	-1	0	0	2	None	New	3	Medium Novelty
Hydrodynamic Absorber: Yoke/Yaw	Gyroscopic Stabilisation	Component Type	good	-1	0	0	2	None	New	3	Medium Novelty
Hydrodynamic Absorber: Yoke/Yaw	Stabilisation Tanks	Component Type	good	-1	0	0	2	None	New	3	Medium Novelty
Hydrodynamic Absorber: Yoke/Yaw	Weight Movement System	Component Type	good	-1	0	0	3	None	New	3	Medium Novelty
Power Take Off: Spring				NO SCORE	NO SCORE	NO SCORE	NO SCORE			#N/A	#N/A
Power Take Off: Hydraulic System (non PTO) - Oil				NO SCORE	NO SCORE	NO SCORE	NO SCORE			#N/A	#N/A
Power Take Off: Transformers up to 11kV	ABB Subsea Transformer	Component		2	0	1	0	Technical Uncertainty	New	4	High Novelty
Power Take Off: Transformers up to 11kV	Solid State Transformers	Component Type		2	0	1	0	Technical Challenges	New	4	High Novelty
Power Take Off: AC/DC/AC Convertor				NO SCORE	NO SCORE	NO SCORE	NO SCORE			#N/A	#N/A
Hydrodynamic Absorber: Structure - Displacer Reactor (Steel)	Optimisation Software	Design	8	-2	0	0	2	None	Limited Knowledge	2	Low Novelty
Hydrodynamic Absorber: Structure - Displacer Reactor (Steel)	High Strength Steel	Material		0	0	0	0	None	Known	1	Not Novel
Hydrodynamic Absorber: Structure - Displacer Reactor (Steel)	Marine Stainless Steel	Material		0	0	0	0	None	Known	1	Not Novel
Hydrodynamic Absorber: Structure - Displacer Reactor (Steel)	Tuned Mass Damped / Tuned Liquid Damper System	Component Type		-2	-2	0	1	Technical Uncertainty	New	4	High Novelty
Hydrodynamic Absorber: Structure - Displacer Reactor (Steel)	Mechanical Gyroscope / Angular Momentum Reactor	Component Type		-1	-1	0	2	Technical Uncertainty	New	4	High Novelty
Power Take Off: Generator - Linear Electric	Rockwell Scientific Linear Electric Generator	Off The Shelf	6	2	0	1	3	Technical Challenges	New	4	High Novelty
Power Take Off: Generator - Linear Electric	VIVACE Hydrokinetic Energy Convertor	Off The Shelf	4	1	1	-2	3	Technical Challenges	New	4	High Novelty
Power Take Off: Generator - Linear Electric	Underwater linear electrical actuator/generator	Component Type	5	1	1	0	2	Technical Uncertainty	New	4	High Novelty
Power Take Off: Generator - Rotational, Direct Electric				NO SCORE	NO SCORE	NO SCORE	NO SCORE			#N/A	#N/A
Reaction / Stationing: Mooring - Single Point	Suction Piles	Component Type		-1	0	0	0	Technical Uncertainty	New	4	High Novelty
Reaction / Stationing: Mooring - Single Point	Offshore Piling	Component Type		0	0	1	0	None	Known	1	Not Novel
Reaction / Stationing: Mooring - Single Point	Gravity Base	Component Type		-1	0	1	0	None	Limited Knowledge	2	Low Novelty
Reaction / Stationing: Mooring - Single Point	Drag Anchors	Component Type		-1	-1	1	0	None	Limited Knowledge	2	Low Novelty
Reaction / Stationing: Mooring - Single Point	Turret Mooring System	Component Type		0	-1	1	1	None	New	3	Medium Novelty
Power Take Off: Air Turbine, Bi-Directional				NO SCORE	NO SCORE	NO SCORE	NO SCORE			#N/A	#N/A
Power Take Off: Water Turbine, Novel				NO SCORE	NO SCORE	NO SCORE	NO SCORE			#N/A	#N/A
Reaction / Stationing: Mooring - Multi Point	Suction Piles	Component Type		0	0	0	0	Technical Uncertainty	New	4	High Novelty
Reaction / Stationing: Mooring - Multi Point	Offshore Piling	Component Type		0	0	1	0	None	Known	1	Not Novel
Reaction / Stationing: Mooring - Multi Point	Gravity Base	Component Type		0	0	1	0	None	Limited Knowledge	2	Low Novelty
Reaction / Stationing: Mooring - Multi Point	Drag Anchors	Component Type		-1	-1	1	-2	None	Limited Knowledge	2	Low Novelty
Power Take Off: Generator - Hydraulic (Standard)				NO SCORE	NO SCORE	NO SCORE	NO SCORE			#N/A	#N/A
Control: Control Systems - Low Complexity	Smart Home Devices	Component Type	5	0	0	0	0	None	New	3	Medium Novelty
Control: Control Systems - Low Complexity	Automotive Control Systems	Component Type	7	0	1	0	0	None	New	3	Medium Novelty
Control: Control Systems - Low Complexity	Wind Turbine Control System	Component Type	8	1	1	0	1	None	Limited Knowledge	2	Low Novelty
Control: Control Systems - High Complexity	Plant Control Systems	Component Type	9	1	1	0	0	None	New	3	Medium Novelty
Control: Control Systems - High Complexity	Fly By Wire	Component Type		2	1	0	1	None	New	3	Medium Novelty
Control: Control Systems - High Complexity	ERTMS (European Railway Traffic Management System)	Off The Shelf	4	2	1	-1	1	None	New	3	Medium Novelty

Contact

ORE Catapult
Inovo
121 George Street
Glasgow, G1 1RD

T +44 (0)333 004 1400
F +44 (0)333 004 1399

ORE Catapult
National Renewable Energy Centre
Offshore House
Albert Street, Blyth
Northumberland, NE24 1LZ

T +44 (0)1670 359 555
F +44 (0)1670 359 666
Info@ore.catapult.org.uk

Ore.catapult.org.uk