Radical innovation for the wave energy sector: An investigation of the potential of direct conversion as an enabling technology.

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Abstract

While wave energy has been under development for over 40 years, as of 2023 it has not reached commercialisation. The wave energy sector has yet to develop a low-cost device that can demonstrate a level of reliable long-term electricity generation. At present, cost of energy estimates for early wave energy arrays are around an order of magnitude higher than mature renewables such as wind and solar PV. Improvements in the wave energy sector's economic performance are therefore necessary for it to be competitive with other forms of low-carbon electricity supply. Performance improvements could come through incremental improvements which come alongside the scale-up and deployment of the technology. These incremental improvements are illustrated by the experience curve, where unit costs fall as a function of cumulative deployment. This experience curve relationship has been demonstrated in several mature, fully commercial, forms of renewable energy technology, such as solar PV and wind. Over time, the aggregation of these incremental improvements can make an initially expensive technology far more cost-competitive. These incremental cost reductions are derived from several 'learning effects', including: learning by doing, economies of volume, economies of scale and incremental technology innovation. Alternatively, the performance improvements needed for the wave energy sector could come in part through radical technology innovation. This would entail a significant redesign of wave energy converters or their subsystems. In contrast to the incremental improvements alongside deployment, radical innovation could lead to a step-change in the performance of wave energy. Technologies such as direct conversion (which was studied in this thesis) could be enablers of radical innovation in the wave energy sector. This research investigates if radical innovation could enable low-cost wave energy, and if direct conversion technologies may have potential to deliver radical innovation in the wave energy sector. To carry out this investigation, the research was broken down into three main parts.

The first part of the research had the aim of evaluating the level of subsidy investment that may be required to enable cost-competitive wave energy. This would consider incremental, deployment-related cost reductions, or cost reductions through radical innovation. To do this, a learning investment model was developed for the wave energy sector. Learning investment was calculated as the additional investment to subsidise the deployment of wave energy in comparison to the cost of an incumbent form of generation. This is similar to the total subsidy through market-pull policy mechanisms. To develop a baseline cost reduction scenario for the wave energy sector, representing incremental cost reductions achieved alongside deployment, the experience curve approach was used. LCoE estimates for early commercial wave energy arrays, and estimated learning rates from the literature, were used to develop the baseline scenario. Following this, a set of alternative cost reduction pathways were developed that also included step-change cost reductions through radical innovation. These innovations were represented as discontinuities in the baseline wave energy experience curve. The level of innovation cost reduction, cost to develop and time to develop the radical innovations in these scenarios was based on data from wave energy innovation programmes and sector guidance documents. The learning investment model was then used to evaluate the investment associated with both the baseline incremental cost reduction scenario and the scenarios that included radical innovation.

The results from the first part of the research were that, for the wave energy sector to achieve a target LCoE of 100 EUR/MWh (representing the cost of an incumbent technology) through deployment-related cost reductions under the baseline assumptions, around 59 billion EUR is required in learning investment. However, this represents a lower limit to this investment, using baseline assumptions which are themselves relatively optimistic. If less optimistic assumptions are used, still within the range given in the literature, this total learning investment could be several hundreds of billions of EUR to achieve the LCoE target. When step-change cost reductions were introduced as a result of radical innovation, a large reduction in the total level of learning investment to achieve the LCoE target was observed in comparison with the base case deployment-only cost reduction scenario. These reductions in learning investment far outweighed the estimated cost of carrying out innovation programmes. This highlights that if the objective is to reach low-cost wave energy at the lowest possible public investment, supporting innovation programmes, even with low success rates, may offer the lowest cost pathway. A journal article[1] was published based on the work that is presented in Part A of this thesis. This explored the learning investment associated with deployment and innovation related cost reduction scenarios for the wave energy sector.

Direct conversion technologies (DCTs) are a class of technology that directly convert mechanical energy to electrical energy. This class of technology has been identified as a potential enabler of radical innovation for the wave energy sector by several funding organisations. The second part of the research aimed to develop an assessment process to evaluate the potential of DCTs for wave energy applications, and then apply this process to a selection of DCTs. To do this, a set of measurable design agnostic parameters were identified which could indicate a DCT's potential in several areas required for a high-performance wave energy converter. These assessment parameters were based on the conversion efficiency, energy density, material cost, lifetime energy output, durability and embodied carbon of the conversion technologies. A screening process was then developed where minimum performance levels were set for these parameters to indicate viability of a DCT in wave energy applications. Once the screening process was developed, six direct conversion technologies were assessed using the process: dielectric elastomer generators (DEG), dielectric fluid generators (DFG), piezoelectric polymer generators, piezoelectric ceramic generators, triboelectric generators and magnetostriction generators.

The results of part two of this research were that, of the six technologies that were assessed, four were rejected (piezoelectric polymer, piezoelectric ceramic, triboelectric and magnetostriction generators), as they demonstrated that they could not meet the required cut-off values in one or more of the assessment parameters. The other two technologies (dielectric elastomer and dielectric fluid generators) were allowed to pass the screening process as neither demonstrated that they could not meet the required cut-off values in any parameters. However, the process highlighted that there is limited publicly available data for some of the assessment parameters for both technologies — especially the parameters that required data on fatigue lifetime. This highlights that, of the technologies evaluated, only dielectric elastomer generators (DEGs) and dielectric fluid generators (DFGs) could be

[1] P. Kerr, D. R. Noble, J. Hodges, and H. Jeffrey, "Implementing Radical Innovation in Renewable Energy Experience Curves," *Energies*, vol. 14, no. 9, p. 2364, Apr. 2021.

considered as viable options as an innovative technology for wave energy applications (using the cut-off values that were adopted in the screening process). Based on the parameters where comparable data existed, the most promising of these technologies was dielectric elastomer generators. Another significant benefit of having developed the process is its repeatability. The process was designed around parameters that should be measurable and relevant to a generic DCT that is considered for wave energy applications. Therefore, it can be used to assess other DCTs that are in future considered for wave energy applications, or to re-assess a technology if more data becomes available.

The third part of this research aimed to carry out a more in-depth evaluation of how the most promising DCT, identified in Part B of the research, could be developed for large-scale wave energy applications. As mentioned above, only dielectric elastomer generators and dielectric fluid generators were not rejected by the screening process. Of these two technologies DEGs were identified as the most promising DCT, based on the available comparable data. Part three of the research investigates the barriers to the development of dielectric elastomer generators for wave energy applications, along with actions that could be taken to address these barriers. To do this, the potential barriers to DEGs were identified though a literature review. As noted in Part B, in some areas there is limited data on DEGs for wave energy applications, given the sector's maturity. Therefore, to build upon the literature review, expert opinion was solicited by carrying out a series of semi-structured interviews with experts in the field of dielectric elastomer generators and wave energy. These interviews were used to identify what the experts saw as key barriers to DEG WEC development, and add any barriers not captured by the literature review. The interviews were also used to gather expert opinion on what actions could be taken to address the barriers to DEG WECs, how difficult these actions may be to carry out, and if the experts believed there was a prioritisation in which the barriers should be addressed.

In the literature review, four high-level categories of barrier were established for DEG WECs. These were: Performance of the DEG, Manufacturing the DEG at scale, System integration for DEG WEC and Environmental effects of DEG. Within these categories, 13 subcategories were identified. During the semi-structured interviews, the experts were asked if these categories and subcategories covered the main barrier areas for DEG WECs. Eight of the nine experts agreed with the categories, with only one key barrier that did not fit in the original categories identified by the experts. During the course of the interviews, 33 key barriers were identified by the experts, with 35 actions identified that would address these barriers. Several common barriers and actions were identified by different experts, which highlighted areas of consensus. These also had large agreement with the literature review. This points towards clear barriers that need to be broken down for dielectric elastomer wave energy converter development, and actions that form the basis of future R&D activities that should be taken to address these. However, for some of the barriers and actions there was less consensus between the experts. For these barriers and actions, further work to help form consensus, such as workshops including a wider range of experts, may be beneficial in establishing appropriate R&D actions. Overall, the barriers and actions identified over the course of the literature review and semi-structured interviews highlighted the diverse range of barriers to DEG WEC development. The need for strong multidisciplinary collaboration, especially between industry and research organisations, was highlighted by several interviewees in order to address these barriers. This emphasised that ongoing communication, and a shared vision for the development of the technology between key stakeholders, would probably be beneficial in furthering dielectric elastomer-based wave energy conversion.

To summarise, the first part of this thesis establishes the potential benefits that radical innovation could bring to the wave energy sector, in terms of reducing the total investment in wave energy deployment required to achieve cost-competitive wave energy. The second part develops an evaluation process to identify direct conversion technologies that may be enablers of radical innovation in the wave energy sector and uses this process to assess six direct conversion technologies. The third part of the thesis carries out a more detailed evaluation of the most promising of these technologies, dielectric elastomer generators, with regard to the key barriers to the technology's development and the actions that could be taken to overcome these barriers.

Lay Summary

Wave energy must reduce its costs to be competitive with other forms of low-carbon electricity generation technology. These cost reductions may be enabled by incremental improvements that occur alongside mass production and deployment of the technology. Alternatively, these cost reductions could come as the result of radical technology innovation, where a significant redesign of a wave energy converter or subsystem is developed. This radical innovation may result in a step-change reduction in cost compared to incumbent wave energy technologies. This thesis investigates the viability of both an incremental cost reduction and radical innovation pathway for the wave energy sector, and investigates the potential of a class of technology, direct conversion, as an enabler of innovation for the wave energy sector. To carry out this investigation, the research was split into three parts which are summarised below.

The first part of the thesis evaluates the public subsidy that could be required to achieve cost-competitive wave energy through either incremental improvements or radical technology innovation. This was done by modelling cost reduction trajectories for the wave energy sector with and without innovation related cost reductions. The findings of this were that radical innovation could significantly reduce the overall public subsidy required to enable cost-competitive wave energy. Additionally, based on the current cost estimates for the wave energy sector, the level of investment required to achieve cost-competitive wave energy way be un-viable in the absence of significant technology innovation.

The second part of the thesis goes on to investigate the potential of a class of technology, direct conversion, as a potential enabler of innovation in the wave energy sector. Direct conversion technologies directly convert mechanical to electrical energy and have several possible benefits in wave energy applications, including low cost, corrosion-free materials, reduction or removal of moving parts in the power take-off and potentially enabling distributed, highly redundant power take-off. A screening process was developed that was used to assess six direct conversion technologies. This found that four of the direct conversion technologies (piezoelectric ceramics, piezoelectric polymers, triboelectric, and magnetostriction materials) were not viable for wave energy applications, while the other two technologies (dielectric elastomers and dielectric fluids) may be viable. Of these two technologies, dielectric elastomer generators performed best in the areas where comparable data existed.

The final part of the thesis goes on to carry out a more detailed evaluation of the barriers that exist to the development of the most promising of the direct conversion technologies evaluated in Part B, dielectric elastomers, in wave energy applications. By carrying out both a literature review and a series of semi-structured interviews with experts, a more comprehensive list of the barriers than previously existed in the literature was developed, along with an evaluation of the difficulty of these barriers and the actions that could be taken to address them. This final part of the thesis could be used to help develop a strategic plan (such as a technology roadmap) for the development of dielectric elastomer wave energy converters.

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I would extend further thanks to Henry Jeffrey and the policy and innovation group for having me as an intern during my studies. This was a valuable experience for me and was a good way to take a step back from my research before writing my thesis.

Finally, I would like to thank my family and friends. A PhD is a lonely undertaking at times and their support kept me going. I would especially like to thank my parents for enduring the many conversations we have had about my research and being a source of continual encouragement.

Declaration

I wish to declare the following:

- This thesis has been composed solely by myself.
- The work presented in this thesis is my own, or where a contribution has been made from a fellow member of my research group it is clearly indicated and I (the PhD candidate) also made a substantial contribution to the work in question.
- The work has not been submitted to any other degree of professional qualification.
- Any included publications are my own work.
- Parts of this work have been previously published in: Kerr, P., Noble, D. R., Hodges, J., & Jeffrey, H. (2021). Implementing Radical Innovation in Renewable Energy Experience Curves. Energies, 14(9), 2364. https://doi.org/10.3390/en14092364

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Nomenclature

The nomenclature below was used throughout this thesis. This includes symbols and abbreviations used in equations and in the main text of the thesis, tables and captions. Some of the symbols vary from those presented in the sources to ensure consistency throughout the thesis.

Symbol	Definition
A	Area
a	Piezomagnetic constant
AAE	Annual absorbed energy
ACCW	Average climate capture width
ACE	ACE metric (Average Climate Capture Width per Characteristic Capital Expenditure)
AEP	Annual energy production
AG	Action group
AI	Artificial intelligence
b	Experience curve b value
B	Magnetic flux density
BEIS	department for Business Energy and Industrial Strategy
BG	Barrier group
b_{lBD}	Learning by doing b value
b_{lbr}	Learning by research b value
BOPP	Biaxially oriented polypropylene
C	Capacitance
CAPEX	Capital expenditure
CBEC	Component-based experience curve
CCE	Characteristic capital expenditure
CCGT	Combined cycle gas turbine
CCost	Component cost
CCS	Carbon capture and storage
CDC	Cumulative deployed capacity
CDC_0	Initial level of wave energy cumulative deployed capacity
CDC_c	Wave energy cumulative deployed capacity at start of experience curve
cf	Capacity factor
CO_{2e}	Carbon dioxide equivalent
CORDIS	Community Research and Development Information Service
Cost	Technology unit cost
$Cost_q$	Technology unit cost at start of experience curve
$Cost_t$	Technology unit cost at time t
CPO	CorPower Ocean

Symbol	Definition
CS	Specific cost
CS-mode	Contact separation mode
CSCR	Capacity before Sustained Cost Reduction
CumInv	Cumulative investment
$CumInv_{total}$	Total cumulative investment
CW	Capture width
CWR	Capture width ratio
D	Dielectric displacement
d	Piezoelectric charge constant
DC	Direct current
DCT	Direct conversion technology
DE	Dielectric Elastomer
DECEX	Decommissioning expenditure
DEG	Dielectric Elastomer Generator
dep	Deployment in specific time step
DF	Dielectric Fluid
DFG	Dielectric Fluid Generator
dr	Discount rate
dr_s	Social discount rate
DS	Dielectric Solid
E	Electric field strength
EAP	Electroactive polymer
E_{BD}	Electrical breakdown strength
EC	Energy cost
ECO_2	Embodied CO_{2e} of DCT
ED	Electrical energy density
E_e	Electrical energy
EMEC	European Marine Energy Centre
EUR	Euro
E_w	Mechanical energy
FCR	Fixed charge ratio
FEP	Fluorinated ethylene propylene
f_g	Generation factor
FOM	Figure of merit
GBP	Great British Pound
Gen	Subsidised generation matrix
GFRP	Glass Fibre Reinforced Polymer
GHG	Greenhouse gas
GJ	Giga Joules
GW	Giga Watt

Symbol	Definition
h	Thickness
HASEL	Hydraulically amplified self-healing electrostatic actuators
HV	High voltage
IEA	International Energy Agency
Inv	Investment in deployment subsidy
Inv_I	Innovation investment
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
JRC	Joint Research Centre
k	Coupling coefficient
KS	Knowledge stock
L_{BD}	Learning by doing
LBR	Learning by research
LCA	Life Cycle Assessment
LCO_2	Lifetime CO_{2e} from DCT
LCoE	Levelised cost of electricity
$LCoE_c$	LCoE at start of experience curve
$LCoE_{target}$	LCoE target for experience curve
LEC	Lifetime energy cost of DCT
LED	Lifetime energy density of DCT
LR	Learning rate
LT	Lifetime
MFEC	Multi-factor experience curve
MJ	Mega Joule
MRL	Manufacturing readiness level
MTTF	Mean time to failure
MV	Mega volt
MW	Mega Watt
N	Number of fatigue cycles to failure
NPE	Discounted sum of energy production
NPV	Net Present Value
NR	Natural rubber
NREL	National Renewable Energy Laboratory
OECD	Organisation for Economic Collaboration and Development
OEE	Ocean Energy Europe
OES	Ocean Energy Systems
OPEX	Operational expenditure
OWC	Oscillating water column
OWSC	Oscillating wave surge converter
P	Piezoelectric polarisation

Symbol	Definition
PD	Electrical power density
PDMS	Polydimethylsiloxane
P_e	Electrical power
PET	Polyethylene terephthalate
P_m	Mechanical power
PM	Prime mover
PR	Progress ratio
PTFE	Polytetrafluoroethylene
PTO	Power take-off
PVDF	Polyvinylidene fluoride
PVMS	Polyvinylmethylsiloxane
PZT	Lead zirconate titanate
X	Cumulative production quantity
Q	Charge
X_q	Cumulative production quantity at start of experience curve
X_t	Cumulative production quantity at time t
R&D	Research and Development
RDD&D	Research, Development, Demonstration and Deployment
RE_{LCoE}	Relative LCoE after step-change innovation
RET	Renewable Energy Technology
RMS	Route mean square
S	Surface
SBM	SBM Offshore
SBR	Styrene-butadiene rubber
SFEC	Single-factor experience curve
SIN	System integration and networking
Solar PV	Solar photovoltaic
t	Time
T	Mechanical stress
T_y	Mechanical yield stress
T_I	Innovation development duration
T_p	Peak wave period
TAP	Technology Action Plans
TNA	Technology Needs Assessments
TPL	Technology Performance Level
TRL	Technology Readiness Level
TRM	Technology Roadmapping
T_{SP}	Support duration
T_{TR}	Transition duration between experience curves duration
TW	Tera Watt

Symbol	Definition
ULS	Ultimate limit state
UTS	Ultimate tensile strength
V	Voltage
W	Watt
WACC	Weighted average cost of capital
WE	Wave energy
WEC	Wave Energy Converter
WES	Wave Energy Scotland
Y	Young's modulus
y	Time period
Ω	Volume
ε	Permittivity
λ	Strain
μ	Magnetic permeability
σ	Surface charge density

1 Introduction

Addressing anthropogenic climate change is one of the biggest challenges faced by humanity. To limit global temperature increase to less than 1.5 ˚C above pre-industrial levels, as called for by the Paris Agreement, a 45% reduction (from 2010 levels) in global CO_{2e} emissions is needed by 2030, while Net Zero must be achieved by 2050 [1]. Many countries have announced Net zero pledges, which as of 2022 covered almost 90% of global carbon emissions[2] [2]. To achieve global Net zero by 2050, vastly increased electrification of our economies is required, along with rapid deployment of renewable energy to meet this increase in electricity demand. Modelling by the International Energy Agency (IEA) [3] calls for an approximately eight-fold increase in electricity generation from renewable energy compared to 2020 levels in order to meet Net Zero at a global level by 2050. This corresponds to an increase from around 3 TW of installed renewables capacity in 2020 to around 26.5 TW in 2050 [3]. Given the enormous future demand for low-carbon electricity if we are to meet our Net Zero obligations, there is a significant potential market for additional sources of low-carbon electricity supply, such as wave energy. This is especially true as having a portfolio of renewable energy technologies with different generation timeseries can present electricity system benefits by reducing storage or peaking generator requirements [4].

Gunn and Stock-Williams estimate the global theoretical wave energy resource (at 30 nautical miles from the coastline) to be around 18,500 TWh per year [5]. Even taking into account that only a small percentage of this would be harvestable, this would correspond to several hundred GW of deployment potential for the wave energy sector. However, while the demand for low-carbon energy is high and there is the potential to deploy hundreds of GW of wave energy converters (WECs) based on the available wave energy resource, the wave energy sector has yet to see this potential materialise. Wave energy has not progressed past the demonstration stage of development, and only around 31 MW of wave energy capacity has cumulatively been deployed worldwide between 2004 and the end of 2021, most of which is now decommissioned [6], [7]. For comparison, solar PV surpassed 1,100 GW of installed capacity in 2022, while wind surpassed 900 GW [8]. Additionally, the levelised cost of energy estimates for early commercial wave energy arrays (in the ballpark of 400 EUR/MWh, see Table 3-2) are around an order of magnitude higher than those of more mature renewable energy sources such as onshore wind energy or Solar PV [9]. This situation therefore poses the question of how wave energy could become an attractive source of renewable energy and deliver on its potential.

To be competitive with other forms of renewable energy, wave energy will need to significantly reduce its costs. This development will also need to be achieved at a viable level of public investment. Cost reduction for the wave energy sector could be achieved through both incremental cost reductions alongside commercial deployment (such as economies of scale, economies of volume and learning by doing) or a more radical innovation in wave energy converter design. The research presented in this thesis investigates the need for radical innovation in the wave energy sector and the potential of a class of innovative

[2] However, it should be noted that at present these pledges are highly unlikely to achieve the sub 1.5 ˚C of warming target, due to their implementation dates and other factors outlined by Climate Action Tracker [289].

technology, direct conversion, as a technology that could help deliver cost-competitive wave energy. Introductions to the topics of radical innovation and direct conversion technologies are presented in the Background Sections 1.1.2 and 1.1.1 respectively. This investigation was undertaken in three parts, which align with the three research questions which are outlined in Section 1.2:

1. The first part investigated the need for radical innovation in the wave energy sector. This specifically evaluated the learning investment (additional subsidy above the cost of an incumbent technology) that may be required to deliver cost-competitive wave energy, both in scenarios with and without a radical technology innovation.
2. The second part of the research investigated if direct conversion technologies may offer an innovation opportunity for the wave energy sector. This part of the research developed a process to evaluate direct conversion technologies for their viability in wave energy applications and applies this process to a selection of direct conversion technologies.
3. The final part of this thesis investigates the barriers to the development of the most promising direct conversion technology (dielectric elastomer generators) that was identified second part of the research. Using both a literature review and elicitation of expert opinion, this section makes a comprehensive list of these barriers to dielectric elastomer generator wave energy converter development and identifies actions that could be taken to overcome these barriers.

The three-part structure of the thesis is illustrated in Figure 1-1.

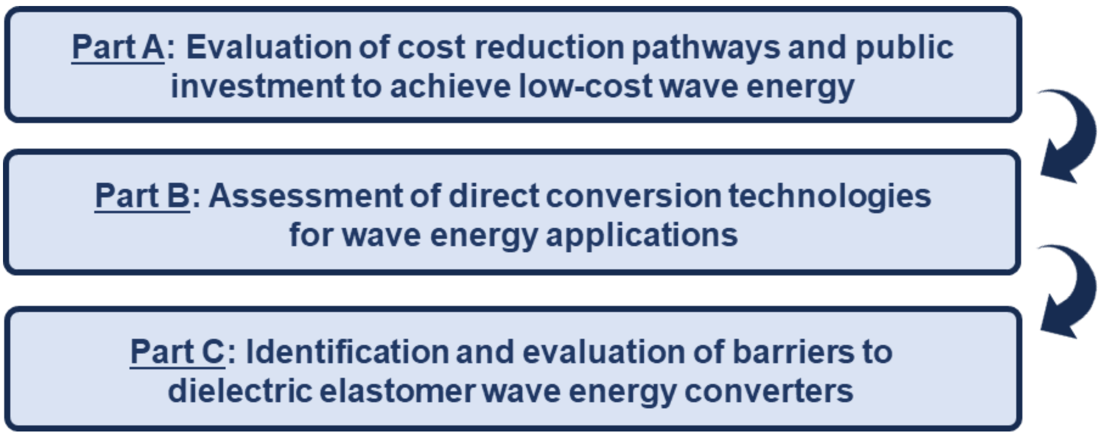

Figure 1-1. *Three parts of the thesis.*

In the remainder of this chapter, Section 1.1 presents a background on the wave energy sector and energy innovation. Then Section 1.2 presents the research questions and aims and objectives. Finally, a more detailed overview of the thesis structure is given in Section 1.3.

1.1 Background

The background is split into two sections. Firstly Section 1.1.1 gives an overview of the wave energy sector and introduces direct conversion. Then Section 1.1.2 introduces some of the key concepts around innovation that are referred to throughout this thesis.

1.1.1 Wave energy background

This section provides a background on wave energy technology. This starts by framing the overall priorities of a modern energy system, as the basis of what makes an energy technology viable. The status of the wave energy sector in terms of deployment and cost is then presented. This is followed by a summary of the wave energy resource. After this, the main types of wave energy converter are introduced, and the generic wave energy subsystems are covered. The section concludes with a short introduction to direct conversion technologies for wave energy applications.

Priorities of the energy system

Before wave energy specifically is discussed, the overall priorities of a modern energy system should be briefly considered. These are important as a framing for the attractiveness of wave energy as an energy supply technology. As discussed at the beginning of this chapter, the global energy system will require a rapid transformation, in terms of both electrification and a switch to low-carbon electricity sources in order to achieve Net Zero global emissions by 2050. For this energy system there are high-level requirements which wave energy should be aligned with. These requirements are commonly referred to as the energy trilemma [10]. The World Energy Council [11] creates an annual index of different countries' performance against the energy trilemma. They define the components of the energy trilemma as:

1. Energy security — the ability to meet current and future energy demand reliably, and to withstand and bounce back swiftly from system shocks with minimal disruption to supplies.
2. Energy Equity — a country's ability to provide universal access to affordable, fairly-priced and abundant energy for domestic and commercial use.
3. Environmental sustainability — the transition of a country's energy system towards mitigating and avoiding potential environmental harm and climate change impacts.

These areas represent the highest-level priorities of government decision-making around energy policy. They have been the cornerstone of UK energy policy in recent years [10], and are explicitly stated as the objective of the UK's Electricity Market Reform policy, which was introduced in 2013 [12]. Therefore, the allocation of government support towards developing and deploying new forms of energy technology — such as wave energy — in utility-scale applications, depends on the technology having a positive net impact on a country's energy system in these areas (at least in the long-term).

Status of the wave energy sector

Wave energy in its modern form has been under development since the 1970s, supported by two major waves of public research funding. An initial interest was built during the 1970s and 1980s during the energy crisis, followed by a lull and then renewed interest from the 2000s [13]. During this second wave of research interest, both the UK government, and government-affiliated organisations, laid out ambitious plans and roadmaps (published between 2000-2010) for the wave energy sector. These plans targeted several GW of wave energy capacity installed in the UK and Europe by 2020 [13]. However, several decades on from the initial research efforts, the wave energy sector has not progressed past the R&D and demonstration phases. The most mature wave energy devices that have been tested have reached full-scale demonstration in an ocean environment, or around TRL 8. Only a small amount of wave energy capacity has actually been deployed, approximately 31 MW of cumulative capacity worldwide between 2004 and the end of 2021 (most of which is now decommissioned). As is shown in Figure 1-2, this deployment has been relatively sporadic in nature, without a clear trend in the direction of larger annual capacity additions. Additionally, as more mature forms of renewable energy such as wind (and even in recent years tidal energy) have developed, a level of design convergence has occurred. However, as discussed by Hannon [13], the wave energy sector (between 2000-2017) has not seen a trend in increased device capacity or design convergence (see Figure 1-7).

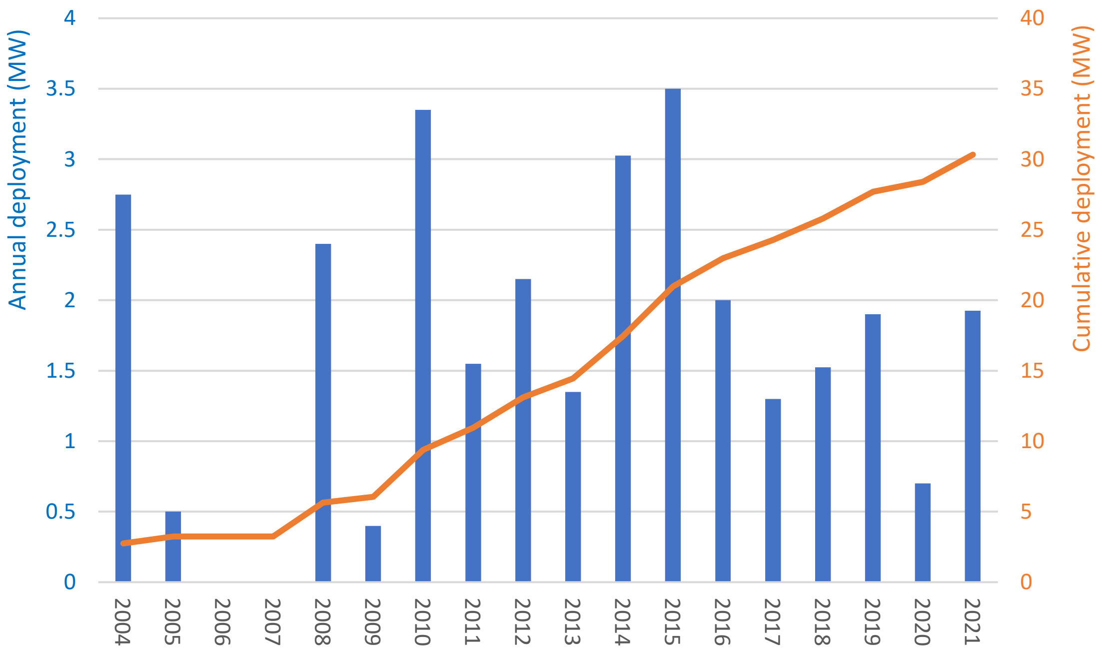

Figure 1-2. *Global deployment of wave energy from 2004-2021. Data from IRENA (2004-2010)* [6] *and Ocean Energy Europe (2010-2021)* [7]. *It should be noted that this data was estimated from plots presented in IRENA and Ocean Energy Europe reports and therefore may contain small rounding errors.*

Part of the reason that wave energy has not commercialised is the high estimated cost of energy in comparison to other forms of electricity generation. As shown in Figure 1-3, the estimated Levelised Cost of Energy (LCoE) of early commercial wave energy projects is far higher than other low-carbon sources of electricity such as wind, solar PV or nuclear.

The wave energy sector has also not demonstrated long-term reliable electricity generation. The highest through-life energy production demonstrated by a wave energy plant stands at around 2 GWh, over a period of 10 years (as of 2020) [14]. It should be noted that this was a breakwater integrated plant which is likely to be easier to maintain than an offshore device. For comparison, 2 GWh of electricity generation could be achieved by a large offshore wind turbine in around two weeks [15]. This is important to note, as the studies that estimate LCoE and life cycle assessment (including lifecycle CO_{2e} emissions) for wave energy generally assume a 20-year design life [15]–[18] for a device of several hundred kW rated capacity. This represents a level of reliability that, to date, the wave energy sector has not demonstrated.

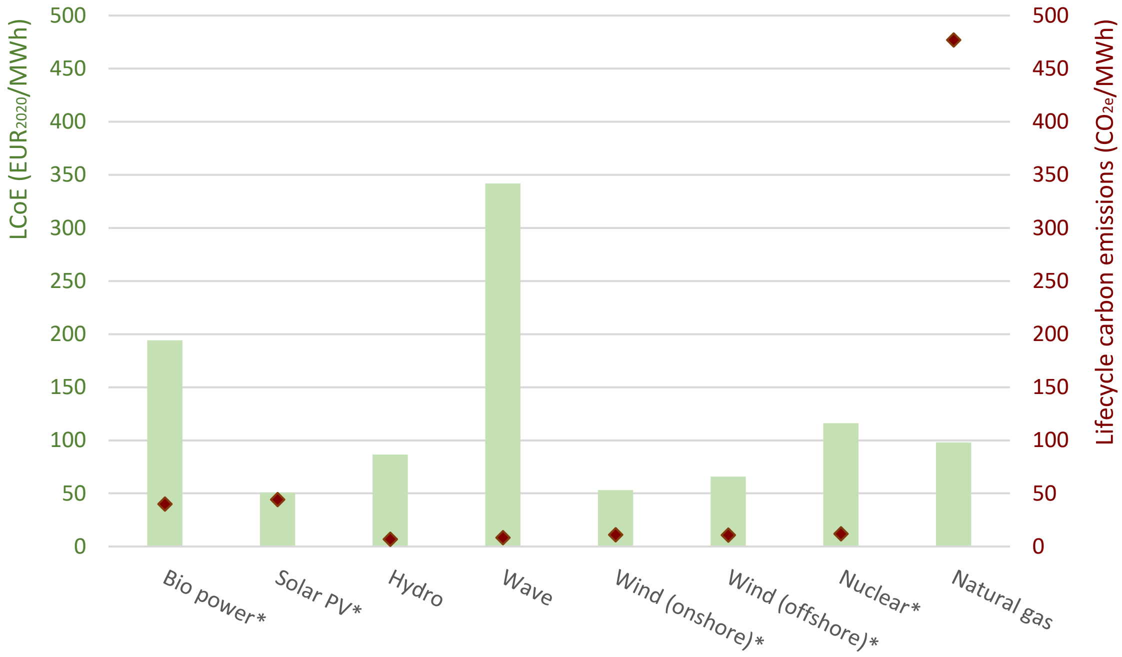

Figure 1-3. *LCoE and lifecycle CO_{2e} for a selection of electricity generation technologies. LCoE data from BEIS are estimates for commercial projects commissioning in 2025. Both solar PV and Hydro refer to large-scale projects* [15]*. Data for median lifecycle CO_{2e} from NREL* [19]*. *Harmonised lifecycle CO_{2e} data (for example, onshore wind LCA estimates are adjusted to have consistent capacity factor, lifetime and system boundaries). All other LCA data is unharmonised.*

For wave energy to be an attractive technology as part of our energy mix and contribute to the energy trilemma, it needs to become more competitive on a cost basis to address energy affordability. Additionally, the wave energy sector will need to demonstrate long-term reliable operation for it to be considered a secure source of energy supply. As lifecycle carbon emissions estimates for the wave energy sector are also made based on a ~20-year lifetime, proven long-term electricity generation is also essential to demonstrate the sector's sustainability. Without these improvements, other forms of low-carbon energy supply will continue to offer far better solutions to our energy needs.

Resource for wave energy conversion

When considering the opportunity offered by the development of wave energy, it is important to briefly discuss the resource available in ocean waves. The power in an ocean wave is a function of the wave height (H) and wave period (T_{wave}). This is shown in Equation 1-1 for deep water waves (water depth is over half the wavelength) where ρ is water density, g is the gravitational constant and P_e is the mechanical power in a metre crest of wave. This means that a wave resource can be represented in units of Watts per metre.

$$P_e \approx \frac{\rho g^2 H^2 T_{wave}}{32\pi}$$

Equation 1-1. *Power in a deep water ocean wave* [20].

The most powerful sea states are those with large amplitude and long periods. It can be assumed that waves can be superimposed in deep water. It follows that the average power level of a wave energy site can be calculated based on the distribution of wave heights and wave periods of a sea state. Key parameters that describe these distributions are discussed in Chapter 3 of Pecher and Kofoed [21]. While a greater average wave energy resource will be available at locations with higher wave heights and wave periods, the ability of a wave energy converter to extract and convert this energy into electricity depends on its power matrix. This is similar to a wind turbine's power curve and characterises the electrical power output of a wave energy device in a particular sea state. The power matrix for a Pelamis P2 WEC is shown in Figure 1-4.

Signficant Wave Height (meters)	Wave Period (seconds)																
	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0	10.5	11.0	11.5	12.0	12.5	13.0
1.0		22	29	34	37	38	38	37	35	32	29	26	23	21			
1.5	32	50	65	76	83	86	86	83	78	72	65	59	53	47	42	37	33
2.0	57	88	115	136	148	153	152	147	138	127	116	104	93	83	74	66	59
2.5	89	138	180	212	231	238	238	230	216	199	181	163	146	130	115	103	92
3.0	129	198	260	305	332	340	332	315	292	266	240	219	210	188	167	149	132
3.5		270	354	415	438	440	424	404	377	362	326	292	260	230	215	203	180
4.0			462	502	540	546	530	499	475	429	384	366	339	301	267	237	213
4.5			544	635	642	648	628	590	562	528	473	432	382	356	338	300	266
5.0				739	726	731	707	687	670	607	557	521	472	417	369	348	328
5.5				750	750	750	750	750	737	667	658	586	530	496	446	395	355
6.0					750	750	750	750	750	750	711	633	619	558	512	470	415
6.5					750	750	750	750	750	750	750	743	658	621	579	512	481
7.0						750	750	750	750	750	750	750	750	676	613	584	525
7.5							750	750	750	750	750	750	750	750	686	622	593
8.0								750	750	750	750	750	750	750	750	690	625

Figure 1-4. *Power matrix of the Pelamis P2 WEC, reproduced from Reikard et al.* [22]. *This shows the electrical power output of a Pelamis P2 WEC for different combinations of wave height and wave period. It can be noted that some of the most energetic sea states do not achieve the full rated power of 750 kW.*

It is highlighted in Gunn and Stock Williams that the estimated theoretical wave energy resource incident at a buffer 30 nautical miles from the world's coastlines is around 18,500 TWh per year [5]. While only a small percentage of this could be extracted by arrays of wave energy converters, this still results in in the potential for several hundreds of GW of wave energy capacity to be installed worldwide [5]. However, this resource for wave energy conversion is not distributed evenly around the world's coastlines. This is due in large part to different fetch lengths at different coastal locations and different wind speeds. As can be seen in Figure 1-5, the areas of most dense theoretical wave energy resource are between the lines of 40th and 60th degrees latitude north and south, with higher wave energy density found in the southern hemisphere.

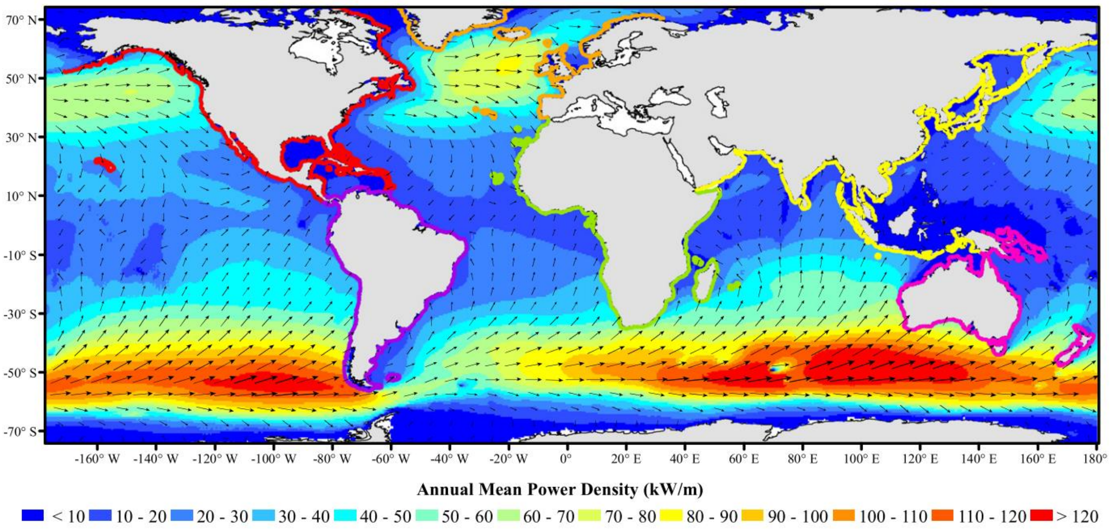

Figure 1-5. *The global wave energy resource, reproduced from Gunn and Stock-Williams* [5]*. The land buffers used in Gunn and Stock-Williams study are coloured by continent.*

It is highlighted by Petcher and Kofoed [21, p. 13] that a wave energy resource of at least 15 kW/m is considered a good resource for wave energy conversion. Therefore, it can be seen that several large spans of coastline have, at least in theory, the potential for economic wave energy conversion. Pecher and Kofoed [21, p. 13] additionally note that a good wave energy resource generally has an average wave steepness of over 1.5%, a low ratio of maximum wave height to mean wave height, low seasonal variability, close proximity to the coast and reasonable water depth. It should also be highlighted that the same WEC may not be suitable for different locations which have different wave energy resources. For example, Gunn and Stock-Williams found that, while the theoretical resource in the southern hemisphere is significantly larger, more wave energy could be extracted by Pelamis P2 WECs in the northern Hemisphere. This was because the sea states in the southern hemisphere often exceeded the maximum operating conditions of the P2, which is likely to have been designed for less energetic UK climates [5]. This highlights that WECs of different scales or designs may be needed to economically operate in different locations.

Conventional wave energy converter types

Several different types of wave energy converter can be defined based on their operating principles. The European Marine Energy Centre uses a classification of 9 different categories of device [23], which are briefly outlined below:

a) Point absorber — Floating structure that absorbs wave energy from all directions, at or close to the water’s surface. This converts the relative motion between the buoyant top of the device and the stationary bottom into electrical power.
b) Overtopping device — Device that captures water in a storage reservoir as waves break. The water then flows through a low head turbine back to the sea.
c) Oscillating wave surge converter (OWSC) — Extracts energy from wave surges. The arm oscillates at a pivoted joint in response to the waves.
d) Submerged pressure differential — Submerged device with a fixed bottom part and moving top part. As waves move over the device, they cause an oscillating pressure.

This drives the vertical motion of the top part of the device, and the relative motion between the top and bottom parts can be used to generate electrical energy.

e) Oscillating water column (OWC) — Partially submerged hollow structure with an opening to the sea below the water line. Waves cause the water level within the hollow structure to rise and fall, which in turn drives air through a turbine.
f) Rotating mass — Heaving and swaying of waves can be used to drive an eccentric weight or gyroscope causing gyroscopic precession. In either case the rotation can be used to drive a generator within the device.
g) Attenuator — Device that operates parallel to the wave effectively rides along the waves surface. The difference in motion at the joints of the attenuator can be used to harvest energy.
h) Bulge wave — Elastic tube filled with seawater. Water can enter the tube at one end and exit at the other. Waves cause a pressure variation inside the tube, creating a bulge that moves along the tube's length. This can be forced through a low head turbine at the end of the device.
i) Other — Other devices, such as devices based on flexible structures.

Illustrations of the first eight of these classes of device and their basic modes of operation are shown in Figure 1-6.

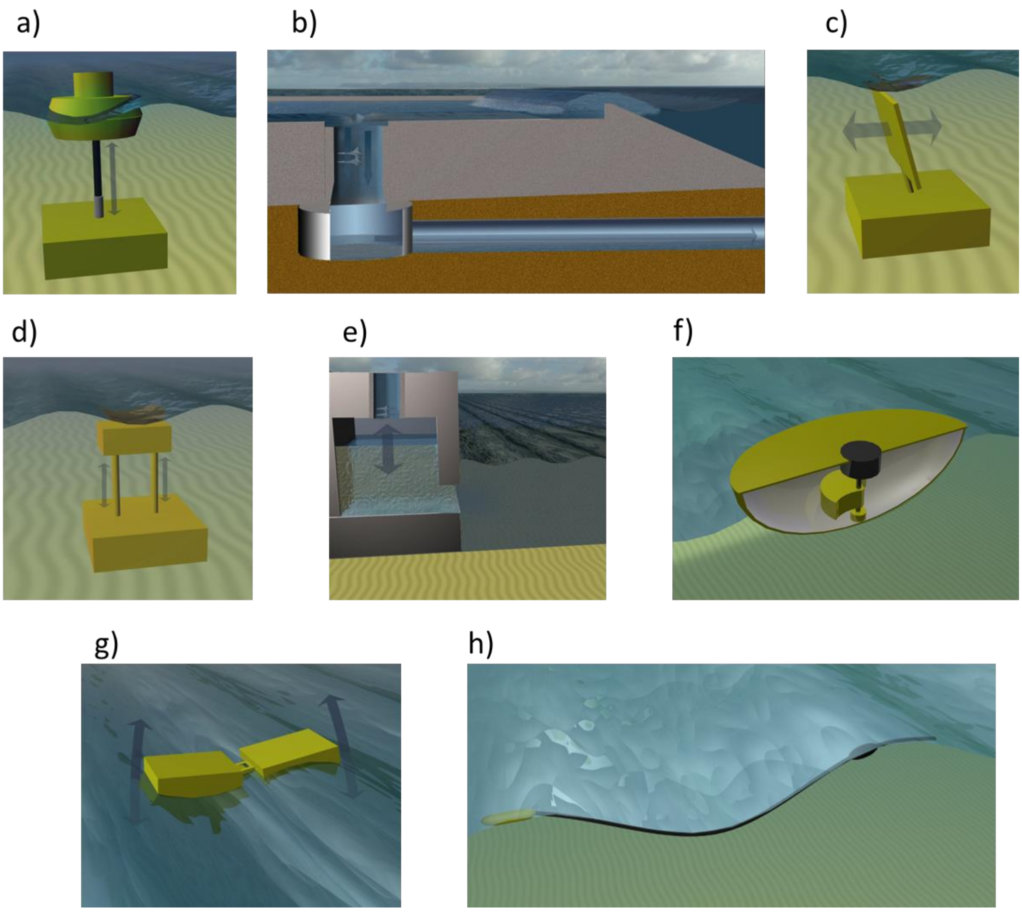

Figure 1-6. Wave Energy Converter architectures, all images reproduced from Aquaret [24]. *a) Point absorber b) Overtopping device c) Oscillating wave surge converter d) Submerged pressure differential e) Oscillating water column f) Rotating mass g) Attenuator h) Bulge wave.*

The European Marine Energy Centre (EMEC) keeps an extensive register of known wave energy developers, which was last updated in 2020. The developers are grouped by the class of device they are working on. The wave energy developers in the EMEC data base, grouped by class of device, are shown in Figure 1-7 (the devices that were not given a class by EMEC have been removed from the data).

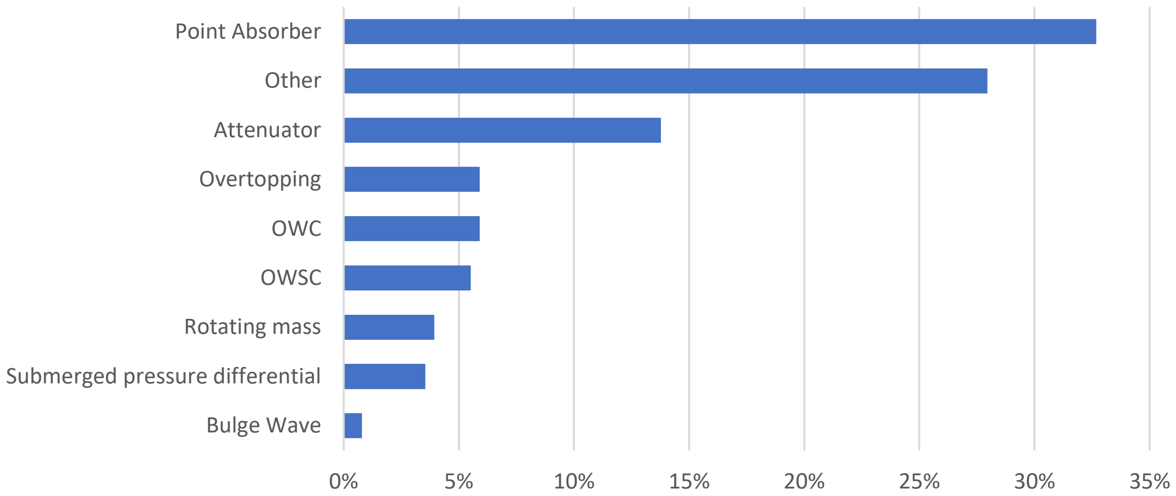

Figure 1-7. *Wave energy developers known to the European Marine Energy Centre grouped by device type, total number of developers = 254 (with unclassified device types removed). Data from the European Marine Energy Centre* [25].

It can be seen in Figure 1-7 that the most common wave energy device type is the Point absorber, which makes up almost 1/3 of the database. This is followed by devices that fall into the 'other' category, which make up a little over 1/4 of the database. Overall, the data from the EMEC database shows that there is a significant amount of heterogeneity in wave energy device development. It could be argued that this is typical of a sector that is still in the research, development and demonstration phase, and is yet to see a dominant class of device emerge [26]. Another factor that is likely to have contributed to this design heterogeneity is that wave characteristics are different in various deployment locations (onshore, nearshore, and offshore). Therefore, the wave energy sector may converge on a serise of WEC architectures which are tailored to different deployment locations.

Architecture of a wave energy converter

While there are several WEC device classes, there are sub-systems which are generally common between these different devices. These subsystems and their interactions are shown in Figure 1-8 from Pecher and Kofoed [21, p. 4]. This figure shows forces/motions (purple arrows), measured signals (blue arrows), command signals (green arrows), electrical power (red arrows) and environmental loading (black arrows).

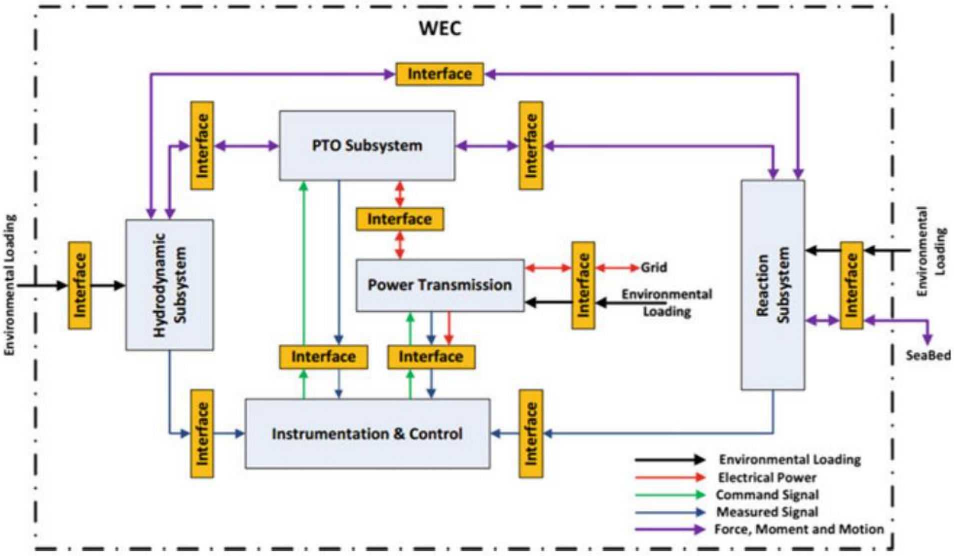

Figure 1-8. *Generic WEC system architecture, reproduced from Pecher and Kofoed* [21].

These different sub-systems are described below, based on Pecher and Kofoed [21]:

- The hydrodynamic subsystem — This is the primary wave absorption system that absorbs wave power. This is connected to both the reaction subsystem and the PTO, against which it transfers forces and motion.
- The power take-off (PTO) — This system converts the absorbed wave energy into electrical energy. This may contain one or more intermediate steps based on the PTO type — for instance a hydraulic PTO converts absorbed wave energy into pressurised fluid, which is then run through a turbine that drives a rotary generator.
- The reaction subsystem — This system creates a reaction point for the WEC, for example mooring and foundations can keep the WEC in a fixed position relative to the seabed.
- The control and instrumentation subsystem — This part of the system controls the WEC's operation and its measurements.

A slightly different breakdown of subsystems to represent a WEC's cost centres is often presented for technoeconomic assessment [27]–[29]. This is described below for WEC CAPEX cost centres, based on Hodges et al. [29]:

- Structure and prime mover — This is the hydrodynamic subsystem of the WEC along with any supporting structure.
- Power take-off (PTO) and control — Same as described above, PTO and control are often grouped in technoeconomic assessment of WECs.
- Connection — This is the system that transfers electricity generated by the WEC to shore.
- Foundations and moorings — This is the way that the WEC is held in place, essentially the same as the reaction subsystem.
- Installation — This is the process by which the WEC is installed.

Within these subsystems many different options exist. A few non-exhaustive examples follow. Structural components could be made of steel, concrete or polymer materials. Multiple PTO options exist including hydraulics, air turbines, water turbines or mechanical/magnetic transmissions. The foundations and moorings may also be catenary moorings, taut mooring or seabed mounted.

In addition to these variations, some novel technologies, such as dielectric elastomers, may allow the PTO to be embedded and distributed in the WEC's structure, in effect combining these two subsystems. As these are the focus of Parts 2 and 3 of the thesis, these direct conversion technologies are introduced below.

Direct conversion technologies in wave energy applications

The second and third parts of this thesis investigate the potential of direct conversion technologies (DCTs) as innovation enablers for the wave energy sector. DCTs are a class of materials that directly convert mechanical energy to another form of energy, and have garnered significant interest in recent years as a technology that could be applied in wave energy applications [30][31]. DCTs could be implemented in wave energy converters in several ways, both as the replacement of a PTO in a conventional wave energy converter or by enabling novel device designs.

One of the classes of DCT that was investigated during the course of this thesis are dielectric elastomer generators (DEGs). Some of the possible applications of DEGs in wave energy converters are highlighted by Moretti et al. [32] in Figure 1-9. This shows both the application of DEGs in conventional wave energy converter architectures (a-c) and an example of a distributed integrated DEG power take-off (d).

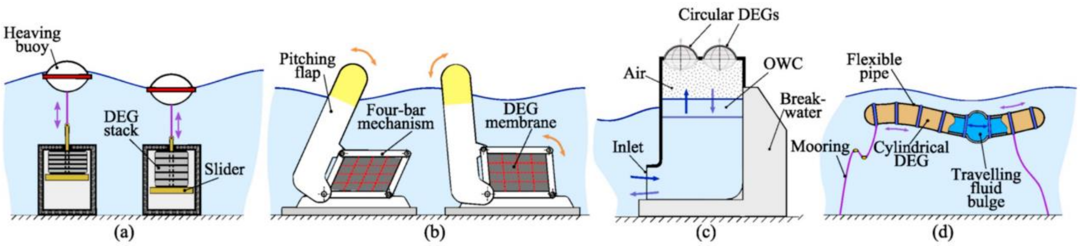

Figure 1-9. *Example wave energy converter architectures utilising dielectric elastomer power take-offs, reproduced from Moretti et al.* [32]*. a) Point absorber b) Oscillating surge wave energy converter c) Oscillating water column d) Bulge wave with distributed DEG PTO integrated within WEC structure.*

In recent years, DCTs have seen growing research interest in wave energy applications (see Appendix B.2 — Direct conversion technology publication data) and other sectors like wearable electronics. However, there has been limited work to create a common framework to evaluate the viability of a DCTs for wave energy applications. In general, DCT technologies are at a low TRL in large-scale electricity generation applications. Of the DCTs that were assessed during this thesis, the most mature have been tested in wave energy prototypes at the single watt scale (around TRL 4-5). Therefore, significant development is still required to generate useful amounts of electrical energy. Some of the potential benefits of utilising DCTs in wave energy applications include:

- Radical redesign of WEC architecture — Some direct conversion technologies may enable radical redesign of a WEC, where the PTO is distributed and integrated within the wave energy converter's structure. This could enable a higher level of redundancy against PTO failure.
- Combination with low-cost structural components — Some DCTs (such as DEGs or polymeric piezoelectric generators) may be well suited to integration with low-cost polymeric structural components.
- Removal of moving parts — DCTs typically do not require as many moving parts as conventional PTOs and are therefore may be less susceptible failure. This is important as the PTO in a WEC is typically the least reliable wave energy subsystem, especially in the case of hydraulic PTOs [33].
- Low-cost materials — Some DCTs are made of low-cost materials. If volume manufacturing processes are developed these could reduce the cost of the PTO compared to conventional devices.

During the course of this research, six direct conversion technologies were explored. These are briefly outlined below:

1. **Dielectric elastomer generators (DEGs)** — DEGs consist of a deformable dielectric material sandwiched between compliant electrodes. The DEG's capacitance varies as it is stretched. Charging the DEG in a high capacitance (stretched state) and discharging the stored charge through a load in a low capacitance (relaxed state) converts mechanical energy into electrical energy. Dielectric materials used for DEGs are made of a flexible, stretchable dielectric polymers.
2. **Dielectric fluid generators (DFGs)** — DFGs are also variable capacitors, however the dielectric medium between the electrodes is a fluid. Varying the volume of fluid between the electrodes in a DFG varies its capacitance. Charging the DFG in a high capacitance state (low fluid volume) and discharging through a load at a low capacitance state (high fluid volume) converts mechanical energy into electrical energy. The dielectric fluid generator is made up of a flexible (sometimes additionally stretchable) dielectric polymer material encapsulating a dielectric fluid, which is typically an oil.
3. **Ceramic piezoelectric generators** — Piezoelectric materials (with aligned domains) exhibit a change in surface charge under strain. If electrodes are applied to either side of the piezoelectric material this change in surface charge can be used to drive a current through a load, converting mechanical energy to electrical energy. The piezoelectric materials that exhibit the largest piezoelectric effect (the greatest change in surface charge) are piezoelectric ceramic materials.
4. **Polymeric piezoelectric generators** — These have the same working principles as piezoelectric ceramics. However, they are made of polymeric materials. Polymeric piezoelectric materials have lower performance, in terms of convertible energy density and efficiency, but have better material properties for wave energy applications.
5. **Triboelectric conversion technologies** — The triboelectric effect is when equal opposite surface charges occur when two different triboelectric materials are brought into contact. The triboelectric effect occurs in all materials to an extent, but materials further away from each other in the triboelectric series [34] result in larger

surface charges. If electrodes are connected to the back of the triboelectric materials, a current can be induced when the two layers of triboelectric material are separated, converting mechanical to electrical energy. Triboelectric materials used in triboelectric generators are typically polymers.

6. **Magnetostriction conversion technologies** — Magnetostriction materials are a group of ferromagnetic materials which change their magnetic flux density under applied strain. This varying flux density can induce a voltage in an induction coil (coil of wire), driving a current through a load. This enables the conversion of mechanical energy into electrical energy. Magnetostriction materials used in generators are ferrous alloys.

Chapter 4 presents a more detailed technical background on the working principles of these different technologies and their performance, and also reviews any previous applications in wave energy.

1.1.2 Innovation background

Given that wave energy innovation is one of the key themes of this thesis, this section gives a brief introduction to innovation and energy innovation. This starts by introducing the concept of innovation and how this is differentiated from invention. This is followed by a summary of how the innovation process has been characterised in the literature and how this has changed over time. Following this, the research, development, demonstration and diffusion paradigm for energy technologies is introduced, along with the concepts of incremental and radical innovation. Finally, the justifications for government support of innovation are summarised.

Defining innovation

Before innovation is discussed, it is important to define what the term innovation actually covers. A recent definition of business innovation comes from the OECD Oslo manual (a comprehensive set of guidelines for collecting and interpreting innovation data) [35]:

> *'An innovation is a new or improved product or process (or combination thereof) that differs significantly from the unit's previous products or processes and that has been made available to potential users (product) or brought into use by the unit (process)'*

An alternative, simpler definition of innovation is given by Fri [36]:

> *'Innovation is the process of introducing new scientific or engineering knowledge to serve market demand in new or better ways'*

While many other definitions of innovation are available, most highlight two key aspects of innovation found in the above definitions. The first aspect is that innovation is the product of new knowledge to, for example, a sector or firm (although often not new knowledge altogether). The second aspect is that innovation serves to meet demand through application. The second aspect is key in differentiating innovations from invention, as stated by the OECD [35]:

> *'The requirement for implementation differentiates innovation from other concepts such as invention, as an innovation must be implemented, i.e. put into use or made available for others to use.'*

Therefore, innovations are when new knowledge results in a technology or process that is put into practice. This means innovations are only successful when they couple together some form of novelty ('new scientific or engineering knowledge' [36]) with desirable characteristics that differentiate it to incumbents ('a new or improved product or process' [35]). In the case of renewable energy technologies this means development a technology that provides some kind of advantage for the needs of the energy system. In utility-scale applications these requirements can often be thought of in the context of the energy trilemma: secure, low-cost, low-carbon electricity.

Regarding this definition, it is clear that the wave energy sector has yet to produce a technology that could be called a successful innovation. While there has been development of a rather broad variety of concepts [37], none of these, to date, have resulted in an innovation with clear potential to serve the energy sector's objectives.

Study of the innovation process

The way in which the innovation process has been studied in the literature has developed significantly since its emergence in the early 20th century. In an effort to chart this development a concise review of the 'generations' of the innovation process was made by Rothwell in the mid 1990s [38] which is used as the basis of this section. This is summarised here, as it provides a useful framework to discuss the development of this body of research. It also introduces some key themes around innovation which are referred to throughout this thesis. Rothwell's view is that innovation models can be split into four *'generations'* which are covered below.

The first generation described by Rothwell lasted until the mid-1960s. Similar to the views of Schumpeter [39], the first generation model of innovation emphasised the importance of technology-push and basic science in the development of innovations. One of the most highly cited examples of this early linear model is the report 'Science: The endless frontier' [40]. This model, often referred to '*technology-push'* or the '*linear model*' of innovation in the literature, describes technology progress as a simple progression where scientific discovery is transferred through applied R&D to products and processes within a firm or organisation. This then leads to new or improved products in the marketplace, which simply absorbs the goods and services. The linear model's basic assertion therefore was that '*more R&D in equalled more innovation out'* [38]. An illustration of the linear model shown in Figure 1-10.

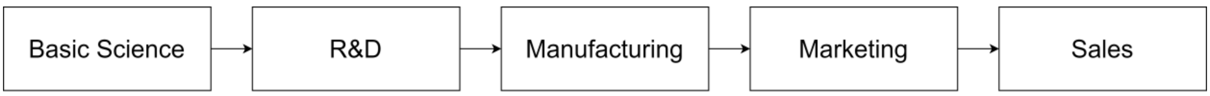

Figure 1-10. *The 'Technology-push' model, based on Rothwell* [38].

The second generation of models which emerged in the late 1960s placed a higher emphasis on demand as a driving force of innovation. Several prominent studies during this time attributed innovation in large part to latent demand for a product [41]. These explanations of innovation suggested that innovations were effectively *'called forth'* by the demand for a certain kind of '*need'* that innovations could fulfil [42]. This led to the emergence of another form of linear model. However, this time the model emphasised the role of the market, where innovations are pulled through by demand. In these models R&D is largely directed by market needs, rather than basic science. The demand-pull model of innovation is shown in Figure 1-11.

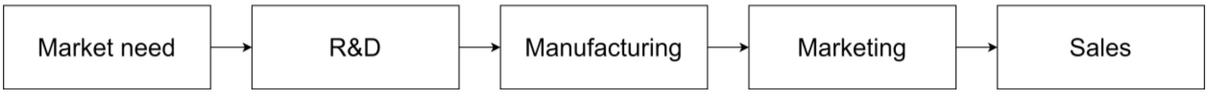

Figure 1-11. *The 'Demand-pull' model, based on Rothwell* [38].

During the 1970s critiques of both the technology-push and demand-pull linear models were made in a number of studies (see Mowrey and Rosenberg [42] for a critical review of earlier studies employing linear models of innovation). The third-generation models of innovation addressed the criticisms levelled at first and second-generation models, namely that they were overly simplified, and that extreme examples were often presented as evidence of technology-push or demand pull as the sole drivers of innovation. The third-generation models of innovation aimed to couple together the forces of technology-push and demand pull as both being key determinants of innovation, a view which effectively has gained universal acceptance in modern energy innovation literature [43]. While these models were still rather simplified (omitting many of the other 'innovation system' factors that play a role in innovation), they provided a better description of innovation being determined by both scientific opportunity and market forces. They also included information flows both forwards and backwards from R&D to production. These information flows are now described explicitly as feedforward or feedback effects [43], [44], [45, p. 8]. The coupled model of innovation is shown in Figure 1-12.

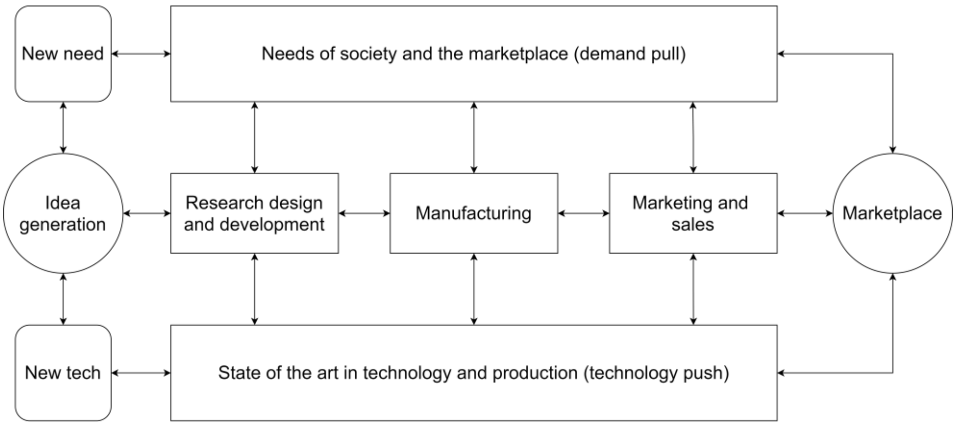

Figure 1-12. *The 'Coupled model' of innovation, based on Rothwell* [38].

Rothwell differentiated the fourth generation innovation models that came to prominence in the 1980s-90s from third-generation models by the emphasis they put on a parallel approach to innovation. The fourth-generation models present innovation as a less linear process than the preceding models. Two important aspects of these are that different phases of the development process overlap, and secondly an emphasis of knowledge transfer between different actors in the products supply chain [46]. This essentially resulted in additional emphasis put on the importance of feedback (from production and sales to R&D) and feedforward (from R&D to production and sales) in a firm's development process.

At the time Rothwell was writing about the stages of innovation in the mid 1990s, he suggested that a fifth generation of innovation was being entered. This effectively is an extension of the parallel fourth generation models. Rothwell's fifth-generation model highlights the importance of networking processes in enabling fast and efficient innovation, in an approach he coined, system integration and networking (SIN) [38]. Although Rothwell presents 26 factors that are important in SIN, they can be briefly summarised as: (1) increasingly close vertical relationships between firms and supply chains, (2) expansion of horizontal relationships (such as collaborative R&D consortia) between firms, (3) the importance of learning by doing and consumer feedback, and (4) other elements of lean innovation such as fast prototyping (through computer aided design) and increased agency of managers at lower levels. Rothwell also put strong emphasis on the role of IT technology advancements in enabling these processes, especially knowledge transfer in intra-firm communication and speed of product design and prototyping.

The 'generations' described by Rothwell show how the study of innovation has become increasingly intricate. The linear models that initially focused on the R&D processes of individual firms in the 1950s have expanded over time and become increasingly outward-looking [47]. It can be seen that over the 'generations', along with R&D, there is an acknowledgement of the importance of demand, internal knowledge transfer and knowledge transfer both within a firm's supply chain and throughout the sector, as drivers of the innovation process. Additionally, it has been widely acknowledged that innovation is not a process internal to individual sectors. Along with advances in economy-wide basic science at the supply side (as described by the linear model), the diffusion of innovations in other fields can create a spillover effect, where these existing innovations are adapted for a new application [36].

Since the work of Rothwell, innovation literature has been characterised by an increasingly broad view of technology change that considers more factors that determine the success of an 'innovation system' [48]. Some of the influential 'innovation systems' approaches include: National Innovation Systems [49] which focuses on assessing and improving the flows of knowledge within 'knowledge based economies'; the Multi-Level Perspective [50] which focuses on the importance of technology market niches; and Technology Innovation Systems [51], [52] which studies the interplay of actors, knowledge networks and institutions in innovation. As this PhD focuses on techno-economic aspects of wave energy, these system-level analysis methods have not been applied, and are not reviewed in this section. It should, however, be noted that the Technology Innovation Systems approach has been used to assess the wave energy sector in previous studies. Examples of this cover the UK wave energy [13], [47] European marine energy [53], [54] and Swedish wave energy [55] sectors.

Energy innovation: the RDD&D paradigm

As highlighted earlier in this section, many different models describing the innovation process exist.

Within the energy technology innovation literature, a common thread is the Research, Development, Demonstration and Deployment (RDD&D) paradigm, combining supply side (technology-push) and demand side (market-pull) drivers of innovation [36]. As highlighted earlier in this section, the innovation process is not linear, and therefore the RDD&D process does not describe a linear progression from basic research to deployment. Rather the RDD&D process contains feedback loops where knowledge is gained though technology development, deployment and end use. This means that continual improvements are made to the technology throughout the innovation process, e.g. learning from the application of the technology in the diffusion stage can feed back into the development of the next generation of a technology [56]. Additionally, knowledge spillovers also play a role in innovation, where developments in one sector or technology find new applications in a different sector or technology [43], [45]. As a renewable energy technology develops, different effects drive technology progress. In a nascent stage, progress is mainly driven through research and development (R&D) and knowledge transfer [56]. As the technology develops, feedback effects through deployment also become key drivers of performance improvement [56]. Wilson and Grubler [45, p. 8] describe the process of energy technology innovation though the RDD&D paradigm, as shown in Figure 1-13. It should be noted that this process shares similarities to the coupled model of innovation described by Rothwell in Figure 1-12.

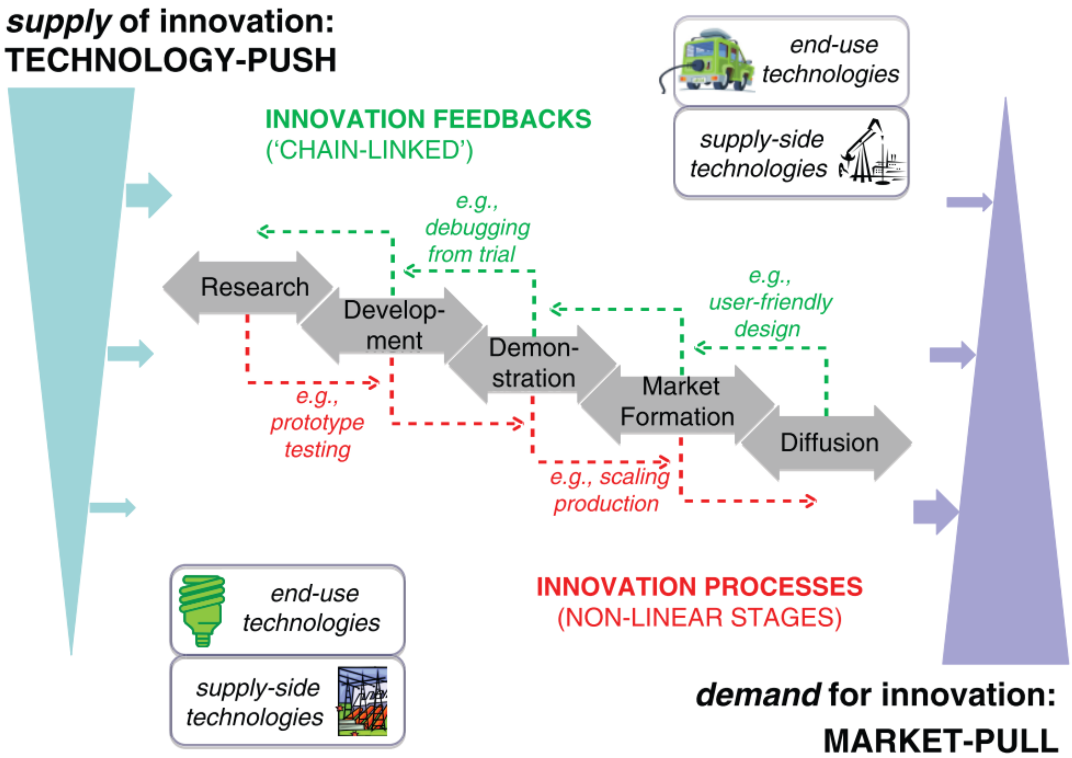

Figure 1-13. *The 'Innovation chain' reproduced from Wilson and Grubler* [45, p. 8].

The individual stages shown in the RDD&D innovation chain are described below. These are based on definitions from Wilson and Grubler [45, p. 7] and the OECD [57, p. 45]:

- **Research and development (R&D)** — Knowledge generation by directed activities aimed at developing new knowledge, improving on existing knowledge, or applying existing knowledge in a novel way. R&D can be split into three subcategories [57]:
    - *Basic research* — Experimental or theoretical work to acquire new knowledge of the underlying foundations of phenomena and observations without a particular application or use.
    - *Applied research* — An original investigation to acquire new knowledge directed primarily towards a specific practical aim or objective.
    - *Experimental development* — Systematic work drawing on knowledge from research and producing additional knowledge which is directed at the production of new, or improving exiting, products or processes.
- **Demonstration** — Construction of prototypes or pilots to test and demonstrate technological feasibility and/or commercial viability. These prototypes may be tested at a number of scales during the innovation process.
- **Market formation** — This is the creation, enhancement or exploitation of niche markets for the technology and early commercialisation of the technology in wider markets. These niche markets describe a limited market setting where the technology has a relative performance advantage (or is supported by targeted public policy) and is generally shielded from full market competition. This could be, for example, the use solar PV in off-grid applications to power lights and sensors prior to utility-scale applications [58].
- **Diffusion** — The widespread uptake of the technology throughout the market of potential adopters. This represents full commercialisation of the technology.

If wave energy technology is considered within the RDD&D paradigm the sector, it currently straddles the R&D and demonstration phases. The most mature WEC devices are currently undergoing full-scale prototype testing, while a development on more novel WEC concepts are still in the R&D phases. Market formation and diffusion is yet to take place. It should be noted that other measures of technology development used for renewables such as the TRL scale [59] fit within the innovation process. However, the TRL scale, for instance, does not capture all the steps of the innovation process. This is because it does not consider basic research that may feed into the innovation process, or the diffusion of a technology once it has been demonstrated at full-scale in an operational environment.

As can be seen in Figure 1-13, there are drivers of the energy technology innovation process from both supply side, known as technology-push, and demand side, known as market-pull. These are described by Wilson and Grubler [45, p. 7]:

- **Technology-push (or supply-push)** — Forces driving the generation of innovations (e.g. by reducing innovation development costs).
- **Market-pull (or demand-pull)** — Forces driving the market provision of innovations (e.g. by increasing innovation payoffs).

As discussed later in this section, policies can be introduced by government that support both technology-push or market-pull drivers of innovation, for instance R&D tax credits or feed-in tariffs respectively. As shown in Figure 1-13, technology-push is considered as a more relevant driver of innovation in the early stages of a technology's development, while market-pull is more relevant as the technology becomes more mature.

Alongside technology-push and market-pull, other factors help enable technology innovation within the wider innovation system. These include factors such as knowledge transfer between different actors in the innovation system (for example through workforce mobility). These innovation system factors are covered in the system-level innovation studies for the wave energy sector referenced earlier in this section. A review of these other drivers is not covered in this thesis as they are not directly related to the work that was carried out on technoeconomic assessment.

Energy innovation: incremental and radical innovation

Energy technology innovation can be thought of in two categories, radical and incremental innovation. These are described below based on Wilson and Grubler [45, p. 7]:

- **Radical innovation** (or step-change innovation) — A novel technology that strongly deviates from incumbents. This often entails a disruptive change over existing commercial technologies and associated institutions.
- **Incremental innovation** — An incremental improvement in, for example, the performance, cost, reliability or design of an existing commercial technology.

Winskel et al. [26] note that the development of other forms of energy supply technology have shown a pattern of radical (or step-change) innovation occurring in the early stages of technology development, while more mature technologies largely derive their cost reductions from incremental learning effects. This is to be expected as structural factors create a bias towards path dependence (or lock-in) to existing technologies, as opposed to radical alternatives, as an energy technology sector matures [60]. Three factors that create this path dependence in regards to innovation are described by Aghion et al. [61]. Firstly, scientists are attracted to areas that are already well funded and where other good scientists work: this creates a path dependence related to *knowledge generation*. Secondly, the *deployment* of innovations is path dependent. This is because the incentives to deploy innovations that leverage existing infrastructure are much higher. A prime example of this is that selling electric cars is more difficult in certain markets than petrol or diesel cars, due to the existing refuelling infrastructure. This is also clear in electricity supply where existing electricity transmission infrastructure generally was constructed to service large-scale, concentrated generation close to urban areas, rather than the more distributed, often more remote, renewable energy sources. Finally, incentives for technology adoption create path dependence. This is where the benefits of using a product benefit from others utilising the product, and unilaterally switching to a technology may be unattractive. This can be thought of as a kind of first mover disadvantage. A prime example of this in the renewable energy sector is concept of technology learning, which describes how increased commercial deployment of certain technologies results in incremental cost reductions (or incremental innovation). This technology learning creates a bias to incumbent forms of technology in more mature technologies and sectors that have already benefitted from cost reductions through many years of deployment. This technology learning has been notably demonstrated in the solar PV and onshore wind sectors. Figure 1-14, reproduced from Stern [62, p. 397], shows illustrative cost trajectories of a new technology and an established technology which has already benefitted from years of deployment cost reductions. When the new innovative technology is developed, may initially be higher-cost than the incumbent, even if it could become competitive over time. This therefore creates a barrier to the new innovative technology's uptake.

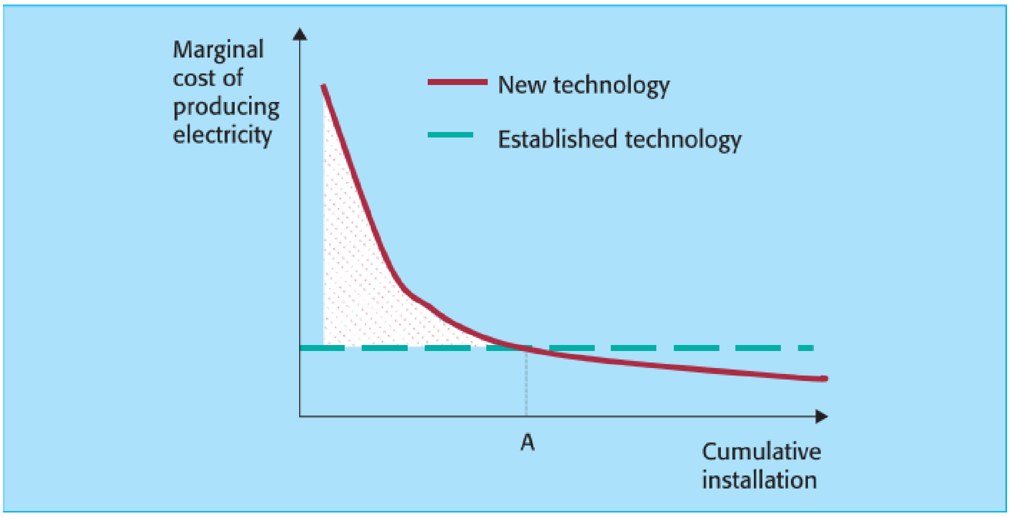

Figure 1-14. *Lock-in of established energy technologies, reproduced from Stern* [62, p. 397]. *Point A in shows the breakeven point between the new technology and the established technology.*

Together, these factors of path dependence show that there is strong inertia in a technology system that favours incumbents. This results in increased barriers to entry (or lock-out) of innovative nascent technologies [44], [62, p. 397]. To enable the development and commercial deployment of new innovative renewable energy technologies, government support is often required. This government support for energy innovation is discussed in the following section.

Government support for energy innovation

There are many different policies that government can adopt to support innovation in the energy sector. As with the drivers of innovation, these can broadly be defined as supply-side (technology-push) and demand-side (market-pull) measures:

- **Technology-push policy** — Policies that allow innovation to be carried out at a lower cost (or time). Examples include R&D grants, R&D tax credits or support for technology demonstration activities through publicly-funded test sites.
- **Market-pull policy** — Policies that reward the outcomes of successful innovation. Examples include revenue support, carbon taxation or innovation prizes.

The importance of government support for both technology-push and market-pull policy to support innovation can be explained by market failures. Some of these key market failures related to innovation in low-carbon technologies are outlined by Stern [62, p. 398] and Stavins [63], [64]:

- **Spillovers from R&D** — The public goods nature of knowledge means that once it is generated, it is effectively cost free to pass it on. This means that a company may not be able to capture the full benefits of its investment in R&D activities, even though it incurs the full costs of carrying out the R&D [63]. Therefore, the private value of R&D is lower than the societal value and individual companies will systematically underinvest in R&D in comparison to a socially optimal level. Policies that address this market failure include public grants or tax credits for R&D and the enforcement of intellectual property rights. International cooperation can also help address knowledge spillovers between borders where multiple countries may benefit from the same innovation programmes [62, p. 398]**.**
- **Uncertainty and long-term social returns on innovation** — Private companies focus on return on investment for shareholders and generally use higher discount rates than government. Additionally, R&D has long lead times and is inherently uncertain in nature [57, p. 28]**.** This can result in companies having an emphasis on short-term decision-making where profits are more certain, rather than investing in more speculative R&D that could lead to radical innovations [65, p. 140], [66]. Additionally, the learning phenomenon (as shown in Figure 1-14) and other factors outlined above favour lock-in to existing technologies which are lower-cost and less disruptive in the short term. Government technology-push support for more speculative early-stage R&D through innovation programmes (e.g. Horizon Europe) can address this failure.
- **Negative externalities** — If negative externalities (such as the production of CO_2) are not sufficiently accounted for in the price of electricity, there will be a lower level of demand for low-carbon energy sources than is socially optimal. Subsequently, this would create a reduced incentive to develop low-carbon innovations as the market size, and therefore payoffs, for successful innovation are lower [63]. Government market-pull support, either through carbon pricing or subsidising low-carbon power generation, can address this market failure. Additionally, due to the long lead times of R&D, organisations must have a level of clarity over any future carbon prices or subsidies to make present-day investments in R&D. For this reason, making future commitments to stable market-pull mechanisms is seen as a driver of long-term innovation investments for the private sector.

These market failures make it clear that public support is required to support innovation, both in terms of technology-push policy to reduce the costs of carrying out innovation, and market-pull to increase the payoffs for successful innovations. This is especially true for the support of radical innovation which has long lead times, often more uncertain payoffs — and as outlined in the previous section — faces barriers related to sectoral lock-in to incumbent technologies.

Wene and the OECD/IEA note that publicly-funded R&D programmes and public-private partnerships are particularly important in providing the building blocks for future radical innovations that are commercialised in the private sector [44], [56], [67]. Market pull policies can then create market formation opportunities for these new technologies, which then may benefit from learning effects (incremental innovation) as they are deployed at scale [68, p.

28]. The roles of government support in the energy innovation process can be summarised by a simplified process based on Wene[3] [67]:

1. Government support is often needed for high-risk R&D efforts to find radically new solutions.
    a. Demonstration projects or targeted government R&D grants can help knowledge gained in public R&D to be transferred to industry, where the technology can be deployed at scale and benefit from learning effects.

2. After the demonstration, the new technology is often too expensive to compete in the market, therefore:
    a. It will then need market-pull support to enable large-scale deployment and achieve learning related cost reductions.
    b. Subsidisation of private R&D (for example R&D tax credits) may complement this process (due to the private sector's tendency to underinvest in energy R&D).

To conclude this section, a brief example is given of the balance between technology-push and market-pull policy in the European Union. In recent years EU policy support for renewable energy (both R&D and deployment subsidies) has been increasingly heavily weighted to deployment subsidies. Between 2014 and the end of 2019, the total public funding within EU countries was on average approximately 1.36 billion EUR_{2020} per year for renewable energy R&D[4] [69] and 76.7 billion EUR_{2020} per year on renewable energy deployment subsidies [70]. This means that, during the period from 2014-2019, for every Euro spent on renewable energy R&D almost 55 Euros was spent on deployment subsidies. It has been highlighted in the literature that this high ratio of deployment subsidy to R&D investment for renewable energy technology may not be optimal, and that investing more heavily in R&D may offset subsequent deployment subsidies [71]. While there is little consensus on an optimal ratio of deployment subsidy compared to R&D, Albrecht et al. [71], [72] suggests a ratio of around 20:1 may be appropriate, based on the R&D intensity of other engineering sectors.

[3] This process is reproduced from Kerr et al [74].
[4] This is the domestic renewable energy R&D from the EU28 (this data is from before the UK exited the EU) and the EU programs; Horizon 2020, Horizon Europe and the Innovation fund. Data was not available for all countries in some years, or for the following EU countries in any years: Bulgaria, Croatia, Cyprus, Latvia, Malta, Romania or Slovenia. It should also be noted that the budget for EU programs includes contributions from associated countries such as Norway and Switzerland which are not part of the EU.

1.2 Research questions, aims and objectives

This section presents the research questions for this thesis and the supporting aims and objectives. This starts by introducing the overall research question and the three supporting research questions. Following this, the aims and objectives are presented for each research question.

1.2.1 Research questions

The overall question that this thesis attempts to answer is:

> *Could direct conversion be an enabling technology in achieving cost-competitive wave energy?*

This is supported by three further research questions that seek to explore if an innovative class of technologies, namely direct conversion, could enable efficient cost reduction in wave energy; thus allowing wave energy to be competitive with other sources of renewable electricity generation:

> ***Q1*** *What level of learning investment may be required to achieve cost-competitive wave energy through incremental, deployment-related cost reductions? And what effect could developments of radical innovation have on this learning investment?*

> ***Q2*** *Does direct conversion offer an innovation opportunity for the wave energy sector? And how can the potential of different direct conversion technologies for wave energy applications be consistently assessed in a repeatable manner?*

> ***Q3*** *What development barriers currently exist for the most promising direct conversion technologies for wave energy applications? And what actions could be taken to overcome these barriers?*

The three parts (A, B and C) of this thesis attempt to answer these three questions in turn. The aims and objectives corresponding to each of the research questions are laid out below.

1.2.2 Aims and objectives

Aims and objectives for research question 1

The first research question is re-stated below:

> ***Q1*** *What level of learning investment may be required to achieve cost-competitive wave energy through incremental, deployment-related cost reductions? And what effect could developments of radical technology innovations have on this learning investment?*

Aims for research question 1

The levelised cost of energy (LCoE) of wave energy must be reduced to become a viable source of utility-scale electricity supply. Public investment in both technology-push (supporting radical innovation) and market-pull (supporting incremental cost reductions) can reduce the LCoE of wave energy. The aim of this the work in Part A is to estimate the level of investment associated with reducing the LCoE of wave energy to a competitive level through either incremental deployment cost reductions, or radical innovation cost reductions. This will be investigated by evaluating the learning investment associated with deployment scenarios for the wave energy sector, both with and without innovation-related cost reductions, using an experience curve approach. This allows an estimation of the effect innovation could have on the total learning investment required for wave energy to reach a competitive LCoE.

Objectives for research question 1

- Develop a model which can estimate the learning investment associated with cost and deployment scenarios for the wave energy sector.
- Develop a baseline deployment and cost reduction scenario for the wave energy sector using the experience curve approach (representing incremental deployment cost reductions).
- Develop a set of alternative deployment and cost reduction scenarios for the wave energy sector that include various levels of radical innovation related cost reduction.
- Use the learning investment model to evaluate the learning investment associated with both the baseline incremental cost reduction scenario and the innovation cost reduction scenarios.
- Discuss the impact of radical innovation on the level of investment required to bring the LCoE of wave energy to a viable level for utility-scale generation and the implications on support policy for the wave energy sector.

Aims and objectives for research question 2

The second research question is re-stated below:

> ***Q2*** *Does direct conversion offer an innovation opportunity for the wave energy sector? And how can the potential of different direct conversion technologies for wave energy applications be consistently assessed in a repeatable manner?*

Aims for research question 2

Direct conversion technologies (DCTs) have several attractive attributes for WECs and could potentially enable radical innovations in WEC design, such as a power take-off that is integrated and distributed within the wave energy converter’s structure [30]. However, several of these DCTs exist, with a variety of operating principles, physical properties and mechanical properties. Currently, there is not an established approach for comparing and assessing the viability of these DCTs in wave energy applications. The aim of the work in Part B was to develop a set of parameters and a repeatable process that can be used to assess the potential viability of a DCT for wave energy applications. This process would be WEC design-agnostic and based on publicly available data. Once developed, the process would be tested on a selection of DCTs.

Objectives for research question 2

- Review existing wave energy assessment literature to determine which WEC performance areas could be impacted (in a way that is quantifiable) by the use of a direct conversion technology.
- Identify a set of measurable, design-agnostic parameters for a direct conversion technology that indicate performance in these WEC performance areas.
- Develop a repeatable assessment process based on these parameters which can evaluate the potential of a direct conversion technology for use in a wave energy application.
- Run a selection of direct conversion technologies through the assessment process.
- Discussion of the potential future attractiveness of these technologies and the value that that the process has in directing future research into direct conversion for wave energy applications.

Aims and objectives for research question 3

The third research question is re-stated below:

> ***Q3*** *What development barriers currently exist for the most promising direct conversion technologies for wave energy applications? And what actions could be taken to overcome these barriers?*

Aims for research question 3

For the more promising direct conversion technologies (as identified through research question 2), barriers may still need to be addressed to enable adoption in wave energy applications. Understanding what these barriers are and what actions are needed to address these is vital information for potential R&D funders. The aim of Part C of the research is to determine the key barriers which need to be addressed to develop the most promising DCT (dielectric elastomer generators) that was identified during Part B of the research. Part C of the research will also establish the degree of difficulty associated with these actions and if a logical order exists in which the barriers should be addressed. To do this, an initial identification of barriers to dielectric elastomer generator (DEG) WEC development will be carried out through a literature review. Then this will be built upon by carrying out a series of semi-structured interviews with experts in the field of DEGs and their applications in wave energy.

Objectives for research question 3

- Review the literature on barriers to the development of DEGs for wave energy applications.
- Prepare an interview framework and identify a range of DEG and wave energy experts to interview.
- Carry out semi-structured interviews with experts in the field to gather expert opinion on:
    - The key barriers to developing DEGs for wave energy applications (to supplement the areas identified from the literature).
    - The actions that could be taken to address these barriers.
    - The degree of difficulty in carrying out these actions.
    - Establishing a priority order to address the barriers.
- Summarise the findings of the literature and semi-structured interviews, presenting a list of key barriers, actions to address these barriers, difficulty in carrying out these actions and prioritisation in addressing the key barriers.
- Discussion of the barriers to using DEGs in wave energy and the actions that could be taken to address these barriers. Discussion of the implications this has on future R&D for DEG WECs.

1.3 Thesis outline

The main chapters of the thesis are collected into three parts corresponding to the research question that they are addressing. Each of these parts contains a literature review on previous work relevant to the research question, along with the original analysis that was conducted during this PhD. In each part, this original analysis is comprised of a methodology, results and discussion section. Part B of the thesis also contains a chapter covering a detailed technical background for the direct conversion technologies that were evaluated in this thesis. The structure of the thesis parts and chapters is shown in Figure 1-15.

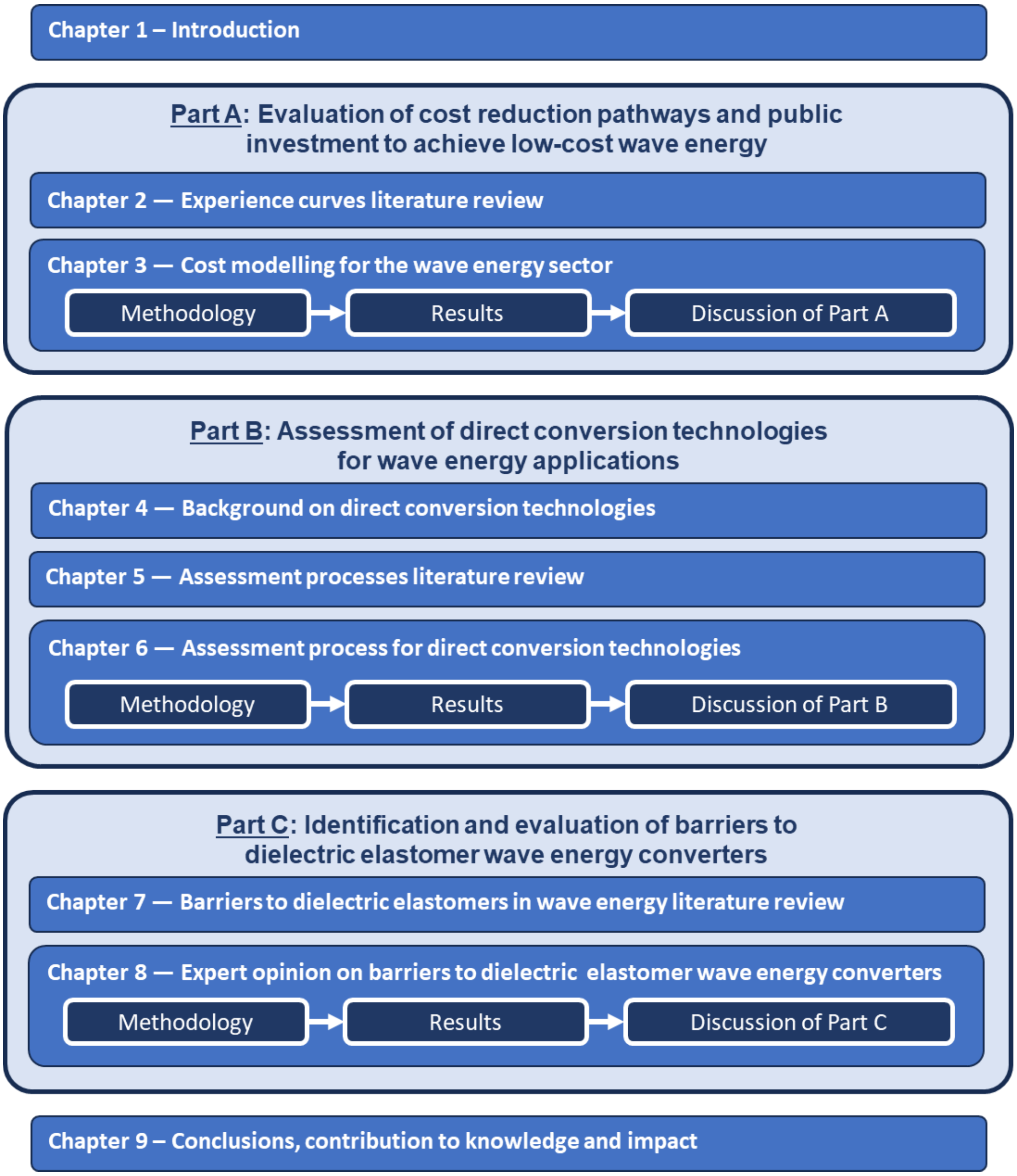

Figure 1-15. *Overall thesis structure.*

Throughout the thesis the level one headings are referred to as chapters, while any level two or three headings are referred to as sections. The content of the chapters that make up the thesis are summarised below.

Chapter 1 — Introduction
This is the current chapter. This chapter presents a background on wave energy, energy innovation and direct conversion technologies. It then presents the research questions, aims and objectives.

Part A: Evaluation of cost reduction pathways and public investment to achieve low-cost wave energy

Chapter 2 — Experience curves literature review
This chapter reviews the literature on experience curves. This chapter is split into two main sections. The first of these sections covers experience curve analysis for renewable energy in general. The second main section covers studies of particular relevance to research question Q2. These are studies that specifically consider the application of experience curves in wave energy and the treatment of radical innovation in experience curve analysis.

Chapter 3 — Cost modelling for the wave energy sector
In this chapter, long-term cost reduction trajectories are modelled for the wave energy sector using an experience curve approach. This considers the effects of two types of cost reduction; (1) incremental cost reductions, brought about by an aggregation of incremental technology innovations and other learning effects, that improve the performance or cost of an existing technology, and (2) radical or step-change cost reductions, which are brought about by a radical (or step-change) technology innovation that strongly deviates from existing technologies or processes.

Part B: Assessment of direct conversion technologies for wave energy applications

Chapter 4 — Background on direct conversion technologies
The first chapter in Part B provides a technical background of the working principles and previous applications in wave energy for the direct conversion technologies that were assessed during the thesis. This covers dielectric elastomer generators (DEGs), dielectric fluid generators (DFGs), ceramic piezoelectric generators, polymeric piezoelectric generators, triboelectric conversion technologies and magnetostriction conversion technologies.

Chapter 5 — Assessment processes literature review
This chapter reviews existing assessment processes and metrics used in (a) the wave energy sector, and (b) for the assessment of direct conversion technologies. This chapter is split into two main sections. The first section covers assessment processes and metrics that are used in the wave energy sector in general. The second section covers any assessment processes and metrics that have previously been used to evaluate direct conversion technologies for wave energy applications.

Chapter 6 — Assessment process for direct conversion technologies
In this chapter, a screening process was developed to assess the potential viability of a direct conversion technology (DCT) in wave energy applications. This screening process was designed to remove non-viable options, therefore identifying DCTs that merited further investigation for wave energy applications. To do this, a set of metrics was identified which could be used to assess the fundamental viability of a DCT in a way that was agnostic to its specific application in a wave energy converter.

Part C: Identification and evaluation of barriers and development actions for dielectric elastomer wave energy converters

Chapter 7 —Barriers to dielectric elastomers in wave energy literature review
In Part B of the thesis dielectric elastomer generators (DEGs) were found to be a technology which has potential viability in wave energy generation applications. For this reason, the barriers and actions to develop DEGs for large-sale wave energy applications was the focus of Part C of the thesis. In this chapter, a review was carried out of the previous DEG WEC literature and the barriers that were identified to the development of DEG WECs. These barriers were grouped into categories of (1) DEG performance barriers, (2) manufacturing at scale barriers, (3) system integration barriers, (4) environmental barriers and (5) other barriers.

Chapter 8 — Expert opinion on barriers to dielectric elastomer wave energy converters

For this chapter, a series of semi-structured interviews were conducted with DEG WEC experts to elicit expert opinion on the key barriers that existed to DEG WEC development and the actions that are required to overcome these barriers. Additionally, expert opinion was gathered on the perceived difficulty of carrying out these actions and the prioritisation with which each of the experts thought the barriers should be addressed. This builds on the literature review, by identifying any additional barriers or details about the barriers, and also outlining the actions that could be taken to address these.

Chapter 9 — Thesis conclusions

This chapter revisits the research questions and covers how the research addresses each of these. It also presents the key contributions to knowledge from this research and highlights the wider impacts of this work.

Part A: Evaluation of cost reduction pathways and public investment to achieve low-cost wave energy

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It should be noted that the cost modelling presented in Part A of thesis uses a modelling method that was developed in partnership with Dr Donald R Noble. The development of this modelling methodology was as part of a collaborative effort for the DTOceanPlus project deliverable 8.3 [73] *which I (Paul Kerr) co-authored to and a journal article, for which I was first author* [74]*. Regarding areas of joint work, the modelling methodology developed for this work was a joint effort. MATLAB code to evaluate deployment-related cost reductions was developed by myself (Paul Kerr) and Donald R Noble in parallel, which was used to verify each other's work. The outputs of my own modelling are presented for the deployment cost modelling in this thesis (Section 3.1.1). Donald R Noble wrote the MATLAB code for the step-change innovation modelling that appears in Section 3.1.2, which was modified slightly for inclusion in this thesis.*

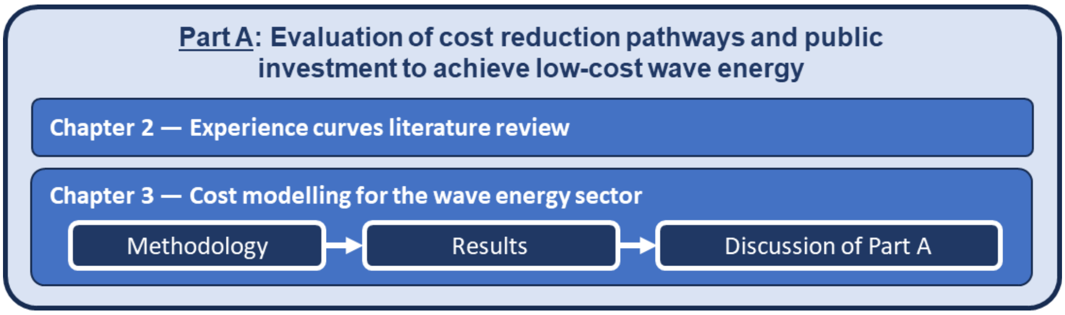
Research question for Part A:

> *What level of learning investment may be required to achieve cost-competitive wave energy through incremental, deployment-related cost reductions? And what effect could developments of radical innovation have on this learning investment?*

LCoE estimates for early commercial stage wave energy arrays are far higher than the cost of mature renewable or conventional energy sources. However, public investment in both technology-push and market-pull support may eventually reduce the LCoE of wave energy to the point that it is considered cost-competitive. In Part A of this thesis, long-term cost reduction trajectories are developed for the wave energy sector, with the aim of estimating the potential level of public investment required to achieve cost-competitive wave energy. This investigates both wave energy cost reductions derived from deployment and cost reductions derived from step-change technology innovation. Previous studies on this topic are found in non-academic literature. However, these provided limited scenarios and no information on their modelling methodologies. This research addresses both of these points.

The analysis carried out in Part A of the thesis develops a model to estimate deployment-based cost reductions for the wave energy sector using a single-factor experience curve. This was used to estimate future costs of wave energy alongside commercial deployment. As experience curves describe a relationship between the cost and cumulative deployment of a technology, this allows the level of deployment at which the wave energy sector achieves a target LCoE (cost-competitive level) to be estimated. From this, the total subsidy (or learning investment) associated with reaching this level of cumulative deployed capacity was estimated. The second part of the modelling evaluates the effect of 'radical' or 'step-change' innovation (these phrases are used interchangeably in this section) on this total learning investment. This was done by modelling scenarios where step-change wave energy technology innovations enabled a shift from the baseline cost reduction trajectory to a lower cost reduction trajectory. The total subsidy associated with these cost reduction trajectories, which included innovation, were then evaluated.

Part A of this thesis is split into two chapters, which is shown below.



Within Part A, Chapter 2 reviews the literature on experience curves for renewable energy and wave energy. Chapter 3 then presents the learning investment modelling that was carried out as part of this research. Chapter 3 covers the methodology used to develop the model, followed by presenting the results and concludes with a discussion of Part A of the thesis.

2 Experience curves literature review

This chapter presents a review of experience curves for renewable energy applications. It is split into two main sections.

Section 2.1 reviews experience curves for renewable energy technologies in general, covering the basic concepts of experience curves and learning investment, system boundaries for experience curve analysis, application in both mature and nascent renewable energy technologies and the limitations of experience curve analysis.

Section 2.2 covers, in additional detail, studies of particular relevance to this thesis. These are studies which consider the application of experience curves in wave energy cost estimation and the treatment of radical innovation in renewable energy experience curves.

2.1 Experience curves for renewable energy cost assessment

Learning curves and experience curves describe technology learning, where the unit cost of a technology declines through its production and use. For example, an experience curve could describe the falling average cost of solar PV panels as more units are manufactured. The terms ‘learning curve’ and ‘experience curve’ are often used interchangeably in the literature [75, p. 9]. However, in this work it is considered that learning curves describe firm-level or individual production line progress, while experience curves describe sector-level progress — for example Danish wind turbine costs. A similar distinction is made by Dutton and Thomas [76].

In a quantitative manner, the learning curve was initially documented in the late 19th century in the field of psychology, where a predictable improvement was observed in the time required to complete a memorised task with each subsequent repetition [68]. In applications describing technology improvement, the first use of learning curves is attributed to Wright in the 1930s where he observed learning curves in aircraft manufacturing [77]. Wright observed a correlation between per unit labour costs and units of aircraft production. This was attributed to improvements in worker proficiency due to practice and greater usage of tooling as production quantity increases. When plotted on logarithmic x and y axis, Wright observed a linear relationship between labour costs per unit and cumulative manufactured units. This relationship is described by the learning rate or progress ratio in modern experience curve analysis. Since these initial applications, learning behaviour has been demonstrated in a large number of manufacturing industries (see studies such as McDonald and Schrattemholzer [78] and Argote and Epple [79]).

The experience curve was popularised by the Boston Consulting Group [80] in the late 1960s, gaining prominence in renewable energy cost assessment in the late 1990s and early 2000s. In the following years, the experience curve effect has been well documented in multiple forms of more mature renewable energy technology, notably in onshore wind and solar PV [81]–[83]. In general, learning curves have more of a role in business and firm strategy, while experience curves, which describe entire sectors, are of more interest for economic modelling with respect to policy makers. The focus of this literature review will therefore be on the experience curve, as this is more relevant to the modelling carried out in this thesis.

2.1.1 The experience curve and learning investment concepts

The most ubiquitous form of experience curve is the single-factor experience curve (SFEC) [84] which uses a single independent and dependent variable. In renewable energy technology applications, SFECs describe technology cost as a function of experience. These costs are usually capital costs or energy costs, while experience is usually measured as cumulative deployed or produced capacity [44], [85]. It should also be noted that, due to sector-level data availability, the experience curve often uses price data as a proxy for costs [44], [68], [86]. This relationship between costs (Cost) and output (X) is described by Equation 2-1. Cost_q is an initial unit cost at cumulative output X_q. $Cost_t$ is the unit cost at time t and X_t is the corresponding cumulative output at time t. The b value is related to the learning rate by Equation 2-2.

$$\mathrm{Cost}_t = \mathrm{Cost}_q \left(\frac{X_t}{X_q}\right)^b$$

Equation 2-1. *Single-factor experience curve.*

The learning rate (LR) shown in Equation 2-2 describes the percentage decrease in technology cost for every doubling of cumulative output. Progress ratio (PR in Equation 2-2) is also used to describe the rate of cost reduction in the literature, simply defined as 100% minus the learning rate. Therefore, a learning rate of 20% is equivalent to a progress ratio of 80%. A higher learning rate, or lower progress ratio, describes a faster rate of cost reduction alongside deployment.

$$LR = 1 - 2^b$$

$$PR = 1 - LR$$

Equation 2-2. *Learning rate and progress ratio for single-factor experience curve.*

Equation 2-2 can be re-written as a linear logarithmic equation, as shown in Equation 2-3. This describes the linear experience curve when plotted on a double logarithmic axis (see the lower panel of Figure 2-1).

$$\log(Cost_t) = \log\,(\mathrm{Cost}_q) + b\left(\log\left(\frac{X_t}{X_q}\right)\right)$$

Equation 2-3. *Log-linear single-factor experience curve.*

A generic experience curve is plotted in Figure 2-1, on both linear and logarithmic axes. Due to the consistent proportional reduction in cost for every doubling in quantity (the learning rate), the rate of cost reduction is much higher in the early stages of deployment. Also shown in Figure 2-1, the experience curve can be used to extrapolate an observed experience curve (solid black line) to estimate future cost reductions (the dashed line) alongside deployment. Therefore, learning curves allow comparison and projection of technology's future costs at different stages of development. This does, of course, rely on the assumption that the learning rate remains constant, which is discussed in Section 2.1.5.

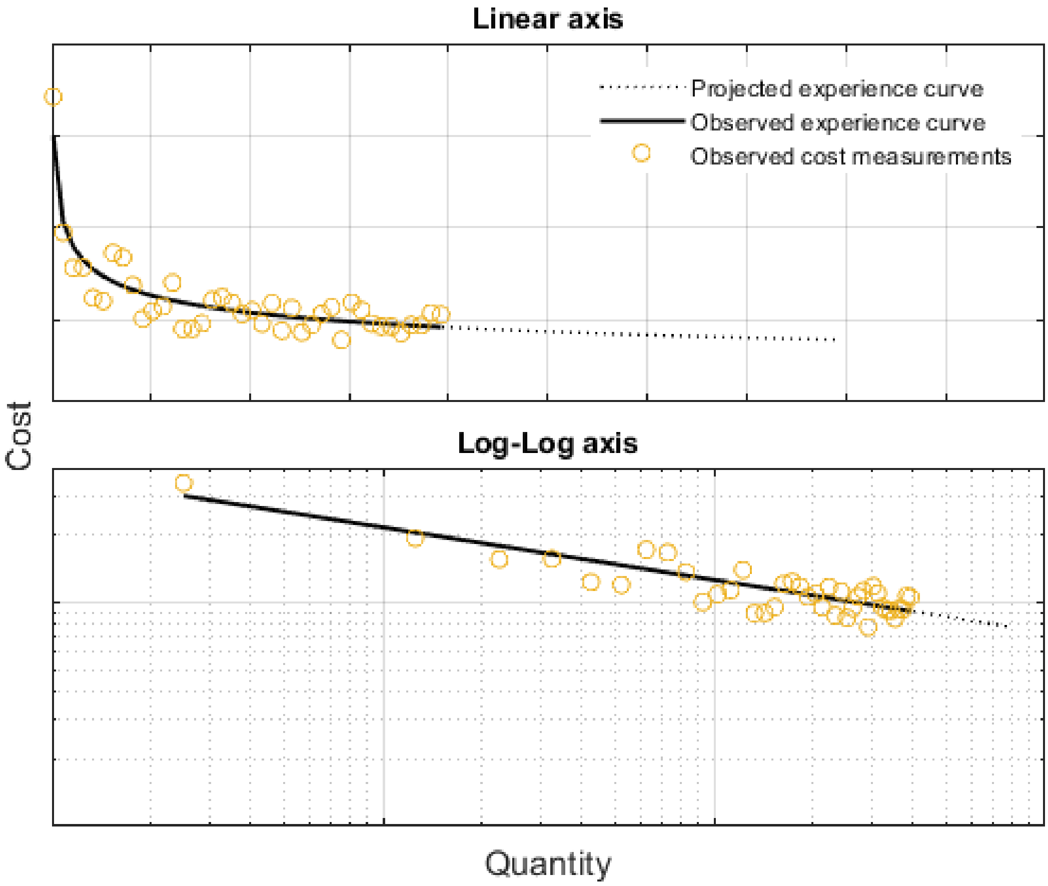


Figure 2-1. *Generic experience curve relationships (using dummy data). Shown on linear and logarithmic axis, the axis ranges are the same in both tiles.*

In an ideal experience curve the starting quantity (Q_q) could be thought of as corresponding to the very first unit of production. However, in practice, it often is more appropriate to consider an early starting capacity and cost that does not correspond to the very first unit of production [87]. This is because there is often a decoupling of prices (which are commonly used as a proxy for costs in experience curve analysis) and costs in early stages of a sector's development which can mask potential learning effects. This price-cost decoupling is discussed in references [44], [80], [86]. Additionally, the CAPEX or energy costs of early-stage demonstrations of technologies (such as wave energy) may not be representative of commercial-scale CAPEX or energy costs [88]. Therefore, the starting quantity (Q_q) can be thought of as an early, but not initial, level of cumulative deployment, and Cost_q as the corresponding unit cost.

Learning investment

Another important parameter related to experience curves is learning investment. Initial deployment of renewable energy technologies often happens at costs far higher than incumbent generation technology. Experience curves can be extrapolated to estimate the level of deployment at which the new technology reaches cost parity with a cheaper incumbent technology (assuming the learning rate remains consistent). The additional investment associated with this deployment is known as learning investment [87]. This makes learning investment an important strategic decision-making tool for policymakers when assessing the future costs of supporting renewable energy technology deployment. This learning investment is shown in Figure 2-2 as the shaded area between the extrapolated cost curve and the level of cost parity with an incumbent technology's current costs. Figure 2-2 also shows that the point at which cost parity with the fossil fuel incumbent is achieved depends on the learning rate (or progress ratio in Figure 2-2).

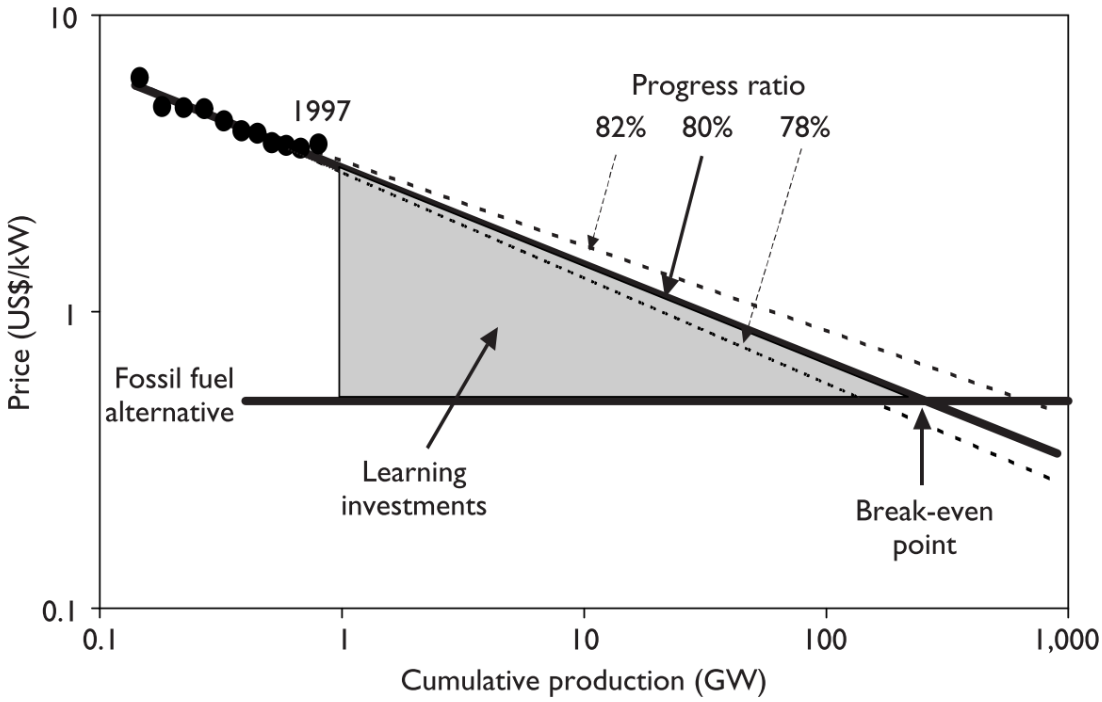


Figure 2-2. *Learning investment for solar PV to reach cost parity with a fossil fuel alternative, reproduced from the IEA* [44]*. Shown on log-log axis.*

To determine the learning investment required for a renewable energy technology to achieve cost parity with an incumbent technology, several parameters are required. Firstly, the parameters to determine the SFEC shown in Equation 2-1 are required to determine the experience curve for the renewable energy technology. In addition to this, the cost of the incumbent technology which is used for comparison (fossil fuel alternative in Figure 2-2) is required. Studies such as [74], [87], [89] have highlighted the extreme sensitivity that these parameters have on the total learning investment to achieve cost parity. Due to this sensitivity, it is important to exercise caution when using learning investment analysis to estimate potential future costs of subsidy. Presenting a reasonable sensitivity range in the experience curve parameters is an important step to highlight a range of results based on reasonable inputs. For the learning rate this sensitivity range could be based on the confidence intervals of a regression analysis (see Louwen and Lacerda [68, p. 25]). Use of sensitivity analysis is especially important for nascent technologies, such as wave energy, where limited data exists to derive experience curve parameters [90].

Sources of cost reduction

A single-factor experience curve aggregates all sources of cost reduction. This can include changes in production (e.g. learning by doing, upscaling, process innovation), changes to the product (e.g. product innovation) and changes to input costs (e.g. raw material and finance costs) [91]. These different sources of cost reduction for a renewable energy technology are categorised by Elia [92] as:

- Learning by deployment (LBD), which can be disaggregated into:
  - Learning by doing — cost reductions due to experience gained in production.
  - Learning by using — improvements due to users during operation.
  - Learning by interacting — cost reductions due to knowledge exchange between actors in the technology's value chain.
- Economies of scale — both device upscaling and manufacturing scale.
- Learning by research (LBR) where cost reductions are derived from research activities.
- Market effects, such as changes in the costs of raw materials, capital and labour costs.

It is important to note that single-factor learning rates only measure a correlation between independent and dependent variables, cumulative production and cost respectively [93]. For this reason, the SFEC has been described as a 'black box' in the literature [44], where the underlying mechanisms of cost reduction are somewhat unclear. Trying to determine the contribution from these multiple sources of cost reduction has been the driver behind the development of multi-factor experience curves (MFECs) which are covered in Section 2.1.3.

2.1.2 System boundaries of an experience curve

Different metrics exist that can be used to measure output (independent variable) and costs (dependent variable) in experience curve analysis. Four key types of SFEC using different combinations of independent and dependent variable were identified by Junginger [86] for wind energy experience curves, as shown in Table 2-1. In Table 2-1 CoE refers to cost of energy.

Table *2-1.* *Different types of single-factor experience curve for wind energy identified by Junginger at al* [86].

Type	Independent variable	Dependent variable
1	Cumulative capacity installed or manufactured* (MW)	Price of capacity (EUR/MW)
2	Cumulative energy units produced (MWh)	Cost or price of electricity (EUR/MWh)
3	Cumulative capacity installed or manufactured* (MW)	Cost or price of electricity (EUR/MWh)
4	Cumulative number of turbines installed or manufactured*	Cost or price of electricity (EUR/MWh)

* This originally appeared at 'produced' in Junginger et al.

The choice of independent and dependent variables is important, as they determine the boundaries of a learning system, and therefore what sources of cost reduction are included in the experience curve [44], [86], [91], [94]. Depending on these system boundaries, cost reductions can be related to the upfront cost of the renewable energy technology, or the way in which it performs throughout its lifetime. For example, simply considering the manufacturing cost of renewable energy technology as the dependent variable (approximated by unit prices) will result in the learning rate reflecting improvements in the costs of manufacturing (such as labour and material costs). However, in experience curves that consider energy costs as the dependent variable, the learning rate reflects many other sources of cost reduction, such as financing costs, operations and maintenance (O&M), installation, annual energy production (AEP) and lifetime. [95]. In renewable energy technology sectors such as wind and solar, learning rates observed for levelised energy costs have been higher than for capital costs [81], [91], [95], [96]. This is because LCoE experience curves include more sources of learning (i.e. both improvements in lifetime costs and lifetime energy production) [87], [91]. The effect of measuring different dependent variables on the system boundaries and the sources of cost reduction a wave energy converter (WEC) or WEC farm are shown in Figure 2-3.

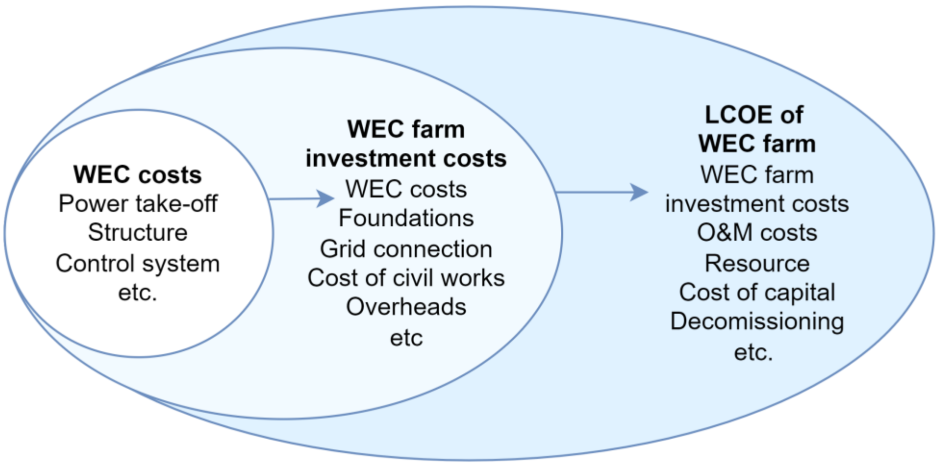


Figure 2-3. *Sources of cost changes for wave energy with different learning system boundaries, based on Junginger et al.* [86].

This poses the question of what dependent variable is most appropriate for renewable energy technology experience curve analysis. It is recognised that experience curves should measure a cost which includes '*all of the cost elements which may have a trade-off against each other*' [80]. For a renewable energy technology, there exist multiple trade-offs between, for example, capital costs, reliability, and energy production. It is therefore unlikely that renewable energy projects are simply focused on reducing capital costs, as capital costs are only one of multiple factors included in energy price. The overall objective is more likely to optimise these parameters to minimise LCoE. For this reason, Bolinger et al. suggest LCoE experience curves provide a more complete view of technology advancements in comparison to other dependent variables such as CAPEX [95]. Unlike the dependent variable, the vast majority of experience curve analysis uses cumulative capacity in MW (either produced or installed) as the independent variable (for a recent review of renewable energy experience curves see supplementary information of Malhotra and Schmidt [83]).

The choice of geographic scope over which these variables are measured is also important. At an early stage of development, a technology may exist in a number of insulated niche markets (for instance in different countries), where limited experience in one market spills over into the learning system of the other [94]. However, as the technology becomes more widespread, supply chains typically become increasingly globalised, and the learning system also bridges between individual countries [94] (see Figure 2-4).

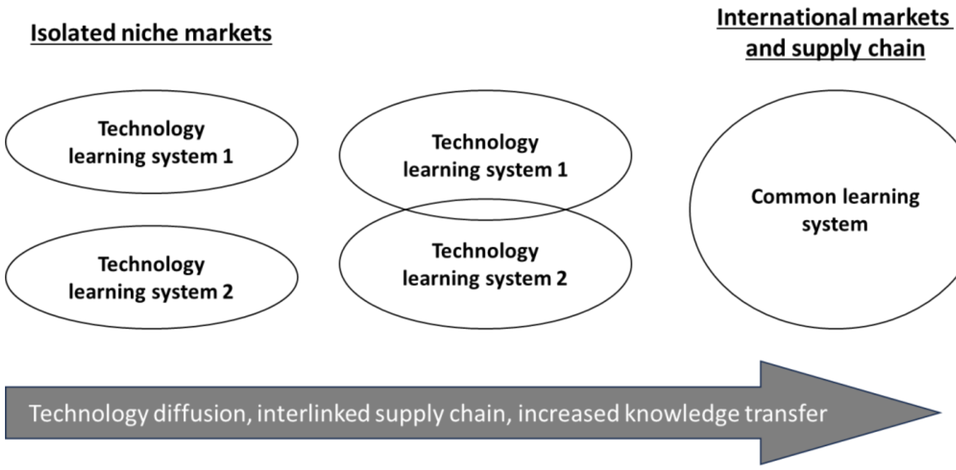


Figure 2-4. *Learning system boundaries, based on Martinsen* [94].

Because of this, using national deployment data for a technology that has a global market could potentially lead to distorted learning rates [86]. A clear example of this would be that over a period of time the price of buying a solar PV panel would fall in a country even if it did not deploy any PV arrays, due to technology learning occurring outside of its borders. However, the arguments made in favour of national or regional experience curves include the greater consistency in data type and data quality and reduced impact of regional non-learning factors such as policy and regulation [75, p. 36].

A final important point is that cost reduction will not follow a perfectly smooth trajectory. Therefore the cost and quantity parameters should be measured over a sufficiently long time (and deployment) period to estimate the underlying experience curve effects [91]. Ferioli et al. [87] suggest that at least two orders of magnitude (or around seven doublings of the independent variable) is required to properly assess an experience curve trajectory.

2.1.3 Other kinds of experience curve

While SFECs are the most ubiquitous form of experience curve, two other forms of experience curve for renewable energy applications are commonly referred to in the renewable energy literature. These are multi-factor and component-based experience curves which are summarised in this section.

Multi-factor experience curves

While it is acknowledged that multiple learning effects drive cost reduction, their individual contributions to cost reduction are not explicitly quantified in SFECs. Essentially, the SFEC is a black box providing little insight about the mechanisms resulting in cost reductions [68, p. 13] which has drawn criticism from several authors [85], [97]. This is because it does not quantify the effects of variables other than cumulative deployment that also effect learning.

Multi-factor experience curves (MFECs) attempt to unpick the black box of learning by separating the effects of different independent variables that effect learning. This takes the form of an additional term (or terms) in the experience curve equation. While many models exist (including independent variables such as R&D expenditure, time, patents, knowledge spillovers or raw material costs), the most common form is a two-factor experience curve that considers installed capacity or production and a parameter that estimates R&D stock [84], [85], [98]. An example of a MFEC with deployment and R&D stock as the independent variables is shown in Equation 2-4. Here the experience curve equation (Equation 2-1) has an additional term to account explicitly for learning by research. There are now two b coefficients, b_{LBD} which accounts for learning associated with capacity additions and b_{LBR} which accounts for learning associated with cumulative R&D expenditure or knowledge stock (KS). The definition of the parameter KS varies within the literature. However, common measures are time-lagged public R&D expenditure or patents [98], sometimes with an assumed level of knowledge depreciation [84]. The other symbols have the same meaning as those in Equation 2-1.

$$\log(Cost_t) = \log(\mathrm{Cost}_q) + b_{LBD}\left(\log\left(\frac{X_t}{X_q}\right)\right) + b_{LBR}\left(\log\left(\frac{KS_t}{KS_q}\right)\right)$$

Equation 2-4. *Multi-factor experience curve.*

In theory, MFECs provide a valuable way to analyse the rates of cost reduction attributable to different independent variables. For example Jamasb used a two-factor experience curve to assess the relative impact on cost reduction, and levels of substitution elasticity between R&D expenditure and capacity additions in several renewable energy technologies [85]. Jamasb's study showed the relative importance of R&D in cost reduction for several energy technologies and a limited substitution elasticity between R&D and deployment. However, MFEC approaches face two major categories of methodological challenges. Firstly, the data requirements are much larger, and may require more processing, than the independent variables for traditional experience curve analysis [68]. Additional data such as R&D spending, especially in the private sector, can be less available than deployment data [97], [98]. The second issue is the potential for high levels of co-linearity between input variables [97]. MFEC assumes that deployment and R&D expenditure are independent, however in reality this may not be the case [98]. It would be logical to assume that increased revenue associated with increased production is likely to stimulate increased private sector R&D. Similarly, increased investment in R&D may lead to price decreases stimulating deployment (both of these effects were observed by Watanabe et al. in their assessment of the Japanese solar PV sector [99]). In practice, this can make it very difficult to tease apart the effects of capacity additions and R&D expenditure on cost reduction [84]. Additionally, different forms of R&D (such as blue-skies or applied) may have different goals and time horizons, and may be more aligned with very different innovation outcomes [67], [98]. Therefore, aggregating different forms of R&D expenditure may provide unclear guidance for policymakers [97]. Similar issues are applicable to upscaling technologies. While this is a separate source of cost reduction from learning by deployment, attempting to fast-track upscaling through bypassing incremental upscaling alongside deployment has produced disappointing results in other renewable energy sectors [100].

Rubin et al. carried out an extensive review of renewable energy technology experience curves, concluding that that multi-factor learning rates offer at best a qualitative understanding of the effects of R&D and capacity additions on cost reduction, and do not offer significant advantages in accuracy over traditional single-factor experience curves [84]. Multi-factor experience curves therefore highlight the importance of factors other than deployment, such as R&D, in achieving renewable energy technology cost reductions. However, they require larger amounts of input data, more effort in data processing, and have issues about potential independent variable collinearity. These issues are especially pertinent for immature technologies where there is often insufficient data for costs, deployment and other independent variables (e.g. R&D spending or patents) to determine experience curve parameters. For this reason, MFECs are generally not used to analyse cost trajectories of early-stage renewable energy technologies [93].

Component-based experience curves

Another type of experience curve is the component-based experience curve (CBEC), where separate learning rates are applied to different constituent components of a technology. The theory behind this approach is that different components within a technology have different levels of accumulated experience and may also have different learning rates. Essentially, utilising a component-based approach can take into account that 'off the shelf' components may have a higher base level of experience, and therefore slower cost reductions than more novel components [87]. In addition, the CBEC approach can be used to estimate the learning rate of components within a nascent technology by basing the component's learning rates on similar components in other technologies [84]. The basic formulation of CBECs is shown in Equation 2-5 [87] where $Cost_t$ is the total technology cost in time period t, $CCost$ is a component's cost, and i refers to the i^{th} component making up the overall technology comprised of n components. The other symbols have the same meaning as in Equation 2-1.

$$Cost_t = \sum_{i=1}^{n} CCost_{qi} \left(\frac{X_{ti}}{X_{qi}}\right)^{-bi}$$
$$= CCost_{q1} \left(\frac{X_{t1}}{X_{q1}}\right)^{-b1} + CCost_{q2} \left(\frac{X_{t2}}{X_{q2}}\right)^{-b2} + \cdots + CCost_{qn} \left(\frac{X_{tn}}{X_{qn}}\right)^{-bn}$$

Equation 2-5. *Component-based experience curve.*

While a component-based approach may seem more methodologically satisfying, it is still subject to many of the same constraints as MFECs, namely additional data requirements for each component's experience curve. Additionally a 'similar component' may need to be specified as the basis of the learning rate for any components without established experience curves [84]. Trade-offs are also made between component costs, reliability and energy production in a renewable energy technology to reduce overall LCoE rather than simply reduce the cost of each component. The presence of these trade-offs may bring into question the theoretical grounding of the CBEC approach, which assumes each component follows an independent experience curve.

2.1.4 Use of experience curves for renewable energy technologies

This section covers the use of experience curves for renewable energy technologies. This is split into two, first covering mature forms of renewable energy technology such as onshore wind and solar PV, and then covering nascent renewable energy technologies such as wave energy.

Experience curves for mature renewable energy technologies

The development of experience curves for mature renewable energy technologies generally follows three steps [91]:

1. Data acquisition and verification
2. Data processing
3. Interpretation of results

In the data acquisition and verification stage, data on production and cost are gathered and verified for a sufficiently long period of time to construct an experience curve. This data will need to be brought into a common currency and adjusted for inflation [68, p. 17], [91]. The additional step may also be taken to adjust cost data for non-learning influences, such as raw material costs, labour costs or macroeconomic changes to the weighted average cost of capital (WACC) [95]. Following this, a regression analysis is carried out on the data to determine the learning rate and fit accuracy of the experience curve (see Lowen and Lacerda [68, p. 20]). A segmented regression may also be carried out to identify if there are any significant breaks in the experience curve, where different learning rates are observed [95]. In the final step the experience curve is analysed. This can help interpret the technology's progress compared to other sources of energy technology, evaluate learning investment and assess the uncertainties in cost projections.

This general process has been applied to many forms of more mature renewable energy technology (comparisons of experience curves for different renewable energy technologies can be found in [81]–[83]). The most frequently studied technologies are onshore wind and solar PV. Malhotra and Schmidt carried out a large review of the capital cost[5] learning rates at both regional and global levels for wind and solar PV, finding the mean learning rate to be around 10% for wind and 20% for solar PV [83]. For both wind and solar PV, consistently higher learning rates have been observed for LCoE-based learning rates than those for capital costs [81], [91], [95]. Considering commercial-scale (>5 MW) US wind and solar PV projects, Bolinger et al. found an LCoE learning rate of 15% for wind energy between 1982-2020 and 24% for solar PV between 2007-2020 [95], when the effects of non-learning parameters had been corrected for. Similarly, an earlier study by Neij estimated the LCoE learning rate for

[5] The study considered CAPEX costs, turbine prices and investment costs for onshore wind and module costs, module prices and investment costs for PV.

wind turbines producers in Denmark as 18% between 1981-2000, while the learning rate for the turbine price over the same period was only 8%. IRENA also compiled learning rates for several renewable energy technologies (including onshore wind and solar PV) between 2010-2021, showing significantly higher learning rates for LCoE in comparison to CAPEX [81]. As covered in Section 2.1.2, this may be due to the additional potential sources of learning in LCoE-based experience curves compared to capital cost-based experience curves.

Regarding the difference in observed learning rate between these different classes of energy technology, some recent studies have attempted to better understand the characteristics of energy technologies that influence the learning rate. Recent work by Wilson et al. [101] has attempted to explain the difference of learning rates with respect to unit size, highlighting that smaller unit size technologies have historically enjoyed higher learning rates. A recent review of experience curves for energy technologies carried out by Malhotra and Schmidt furthered this form of analysis by classifying energy technologies on two axes, their design complexity and need for customisation [83]. They found that more standardised, lower complexity energy technologies tended to experience higher learning rates than complex technologies that required higher levels of customisation for their application. The typology of different energy technologies developed by Malhotra and Schmidt is reproduced in Figure 2-5.

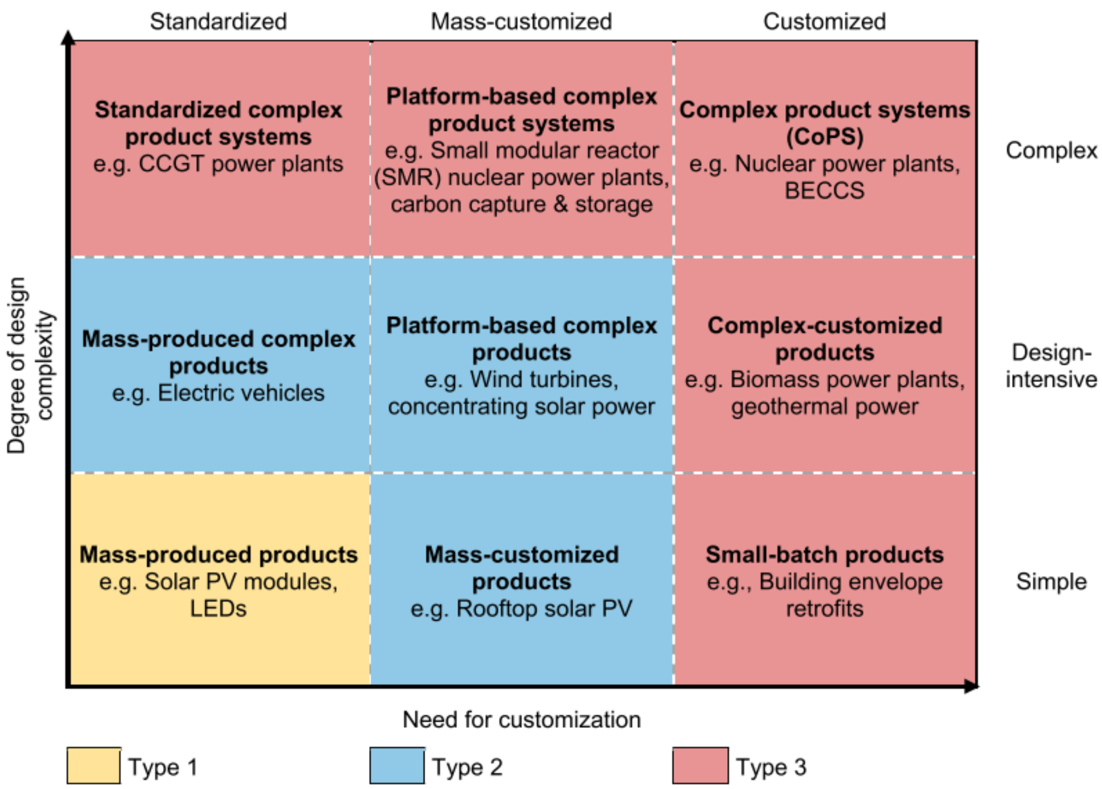


Figure 2-5. *The complexity/customisation typology for energy technologies, reproduced from Malhotra and Schmidt* [83]. *In Malhotra and Schmidt's analysis, the simple & standardised (Type 1) technologies had the highest learning rates, while complex & customised (Type 3) technologies had the lowest learning rates.*

Experience curves for nascent renewable energy technologies

For immature technologies, a sufficiently large deployment series of technology costs may not exist to derive a learning rate using regression analysis. This is certainly the case in wave energy, as deployment has largely been limited to single (or very small arrays of) prototype devices. To address this lack of cost-deployment data for immature technologies, two main approaches exist to select an appropriate learning rate.

The first approach is basing learning rates on experience curves seen in other similar renewable energy sectors [44]. This approach is the least challenging to implement. Using energy technology typologies (such as presented in Figure 2-5) may be useful to determine a reasonable learning rate based on analogous technologies. However, defining what constitutes an analogous technology, in terms of learning effects, still involves significant uncertainties.

A second approach used for estimating learning rates for early-stage technologies is a bottom-up, component-based method [93], [102] — where separate learning rates are applied to different constituent components of a renewable energy technology (see Section 2.1.3). The theory behind this approach is that analogous components exist in other technologies, to which the learning rates can be approximated. A component-based approach was used by the Carbon Trust [28] to estimate learning rates for both wave and tidal energy shown in Table 2-2. Rubin [102] used a component-based approach to estimate experience curves for CCGT with CCS plants, a system with many shared components with a conventional CCS plant. Similarly Mukora [90] argues that many components seen in marine energy devices are currently 'off the shelf' which may support this approach for developing learning rate estimates for wave energy technologies.

Table 2-2. *Component-based learning rates for wave energy device subsystem CAPEX. Data from the Carbon Trust* [28].

Subsystem	**Learning rate**
Structure and Prime mover	9%
Power take-off	7%
Foundations and mooring	12%
Connection	1%
Installation	8%
O&M	12%

However, as covered in Section 2.1.3, CBECs are still subjected to many of the constraints of the first approach, namely what constitutes a 'similar component' [84]. Additionally, there are far more requirements for data gathering for the CBEC approach and trade-offs may exist between components (this is discussed in Section 2.1.3).

An additional uncertainty in experience curves for nascent technologies is establishing the start point in terms of cost and capacity for the experience curve. As covered in Section 2.1.1, the experience curve is unlikely to be reliably defined from the first unit of production. Grubler [103] notes that the cost of solar PV reduced by a factor of three through R&D before most deployment-based experience curves for solar PV were established. Therefore, the costs used to determine the start point in experience curves for nascent technologies may include an assumed level of cost reduction between the technology's current costs, and its entry costs for early commercial projects. For example, most cost estimates for wave energy technologies consider the LCoE for early commercial arrays [28], [88], [104], [105], while even the most mature WEC technologies are currently at single device demonstration. Significant assumptions about device lifetime, CAPEX for mass production and OPEX will therefore be factored into these LCoE estimates, which are used to determine the experience curve's starting point.

Ultimately, defining experience curve parameters for nascent forms of renewable energy technology is prone to high levels of uncertainty whichever approach is taken. For this reason, when constructing scenarios, carrying out a thorough sensitivity analysis can be used to cover a range of likely scenarios.

2.1.5 Limitations of experience curves

This section covers some of the main critiques and limitations of experience curves presented in the literature. For a more detailed description of the limitations of experience curves, see Louwen and Lacerda [68, p. 27] and Yeh and Rubin [97].

Lack of causation

Single-factor experience curves are an abstracted way of looking at technology progress that inform an analyst of a cost reduction outcome rather than the underlying process. Attributing cost reductions to specific effects in experience curve analysis is difficult (see MFECs in Section 2.1.3). This means that, while a strong correlation may exist between capacity additions and cost reductions, a mechanism of causation is not proved by the experience curve [90], [93]. Indeed, a large range of learning rates have been shown for different forms of energy supply technology, with only relatively high-level explanations for this disparity (see Section 2.1.4). Along with feedback effects (technology learning), where increased deployment results in cost reductions, elasticity of demand results in cost reductions leading to greater deployment [62, p. 411], [85]. Elasticity of demand is not accounted for in single-factor experience curve analysis, meaning that it is unclear if deployment is driving cost reductions or cost reduction driving deployment [85]. However, recent work by Lafond et al. [106] examined a scenario where demand was not primarily determined by price - weapons production during WW2. They concluded that cumulative demand does play a significant role in price decline, supporting the experience curve hypothesis.

In addition, greater experience does not automatically lead to increased learning, rather it leads to more learning opportunities [76], [91]. If the correct incentives to encourage exploitation of these learning opportunities are not in place (such as sufficient competition or knowledge transfer), the experience gained through deployment may not be as successfully translated into cost reductions. Finally, as single-factor learning curves are usually not time dependent, they omit many sources of cost reduction related to general improvements in basic science that bring economy-wide performance improvements and spillovers from other sectors [107]. On the other hand, there is also the potential for 'institutional forgetting' [97] (alternatively referred to as 'forgetting by not doing' [107]). This is where unit costs of a technology increase following a significant reduction in the rate of production. A factor cited by Yeh and Rubin [97] that may contribute to this ‘institutional forgetting’ is that when a sector contracts, experienced workers may exit the sector’s work force, resulting the loss of the experience gained by these workers. This ‘institutional forgetting’ may be relevant to the wave energy sector, which has seen relatively sporadic deployment to date (see Figure 1-2).

The combination of these factors suggests some limitations in using the experience curve as a justification to accelerate renewable energy cost reductions through an increase in deployment rate. As the relationship between deployment and cost reduction in historic experience curves is often not well understood, attempting to accelerate a renewable energy technology’s cost reductions through simply increasing deployment rates may lead to disappointing results [62, p. 411]. For this reason, an understanding of the non-deployment factors that allow efficient technology learning to occur is essential to good policy design. These factors are addressed in MFEC studies (see Section 2.1.3) and also the study of technology innovations systems more broadly (for studies on wave energy technology innovation systems see [13], [55]).

Variable learning rates and drivers of cost reduction

An assumption when using experience curves to predict future renewable energy technology costs is that the learning rate remains constant. However, the importance of different learning effects in driving cost reduction are likely to vary as a renewable energy technology matures. The IEA [56] highlight the prominence of learning by research and knowledge exchange in early stages of renewable energy technology development, where learning by doing opportunities are limited [75]. As technologies mature, they derive their cost reductions increasingly from both unit scale, manufacturing scale and learning by deployment. The IEA [66] highlights how, between 1980 and 2001, cost reductions in PV were mainly driven by learning by research, while in the period 2001 to 2012, cost reductions were mainly driven by economies of scale. Similarly, Elia et al. [108] carried out bottom-up cost modelling of Vestas wind turbines between 2005 and 2017 (a good example of a more mature renewable energy technology sector), finding the most important factor in CAPEX reduction was learning by deployment. This variation in cost drivers at different periods of a technology’s development may suggest the use of different learning rates over different time periods. Indeed, the analysis of experience curves for LCoE of both solar PV and onshore wind have seen significant increases in learning rate over the last decade [81], [95]. This was true even when costs were corrected for several non-learning factors such as raw material costs [95]. The variability seen in the learning rates for wind and solar PV highlights the potential uncertainties in carrying out long-term cost extrapolations using experience curves.

Cost floors

The generalised single-factor experience curve describes cost reductions that continue indefinitely with increased levels of production [80]. However, limits to cost reduction will clearly exist for renewable energy technologies. These include raw material costs, labour costs or physical limits (such as the Betz limit for wind turbines). Due to these limits, cost floors are commonly used in combination with experience curves in integrated assessment models [109]. For this reason, it has been suggested in the literature that technology experience curves will not follow a constant log-linear cost capacity relationship indefinitely, but rather level off as these physical limits are approached [87], [103]. Ferioli and Schoots [87] suggest that in early stages of a technology's diffusion, costs are dominated by innovative components where significant cost reduction potential exists. As the costs of these innovative components reduces, a larger proportion of costs are made up of non-learning factors such as raw materials which impose a floor on cost reductions, resulting in a slowing of learning rates. Eventually, as the product reaches market saturation or constraints in natural resources, the learning effects may cease altogether. This is presented as a three-stage process by Ferioli and Schoots [87]: (1) linear learning, where the log linear experience curve relationship holds true; (2) maturity, where the rate of cost reduction begins to fall behind the experience curve relationship; and (3) senescence, where a level of cost stability occurs. This is shown qualitatively in Figure 2-6.

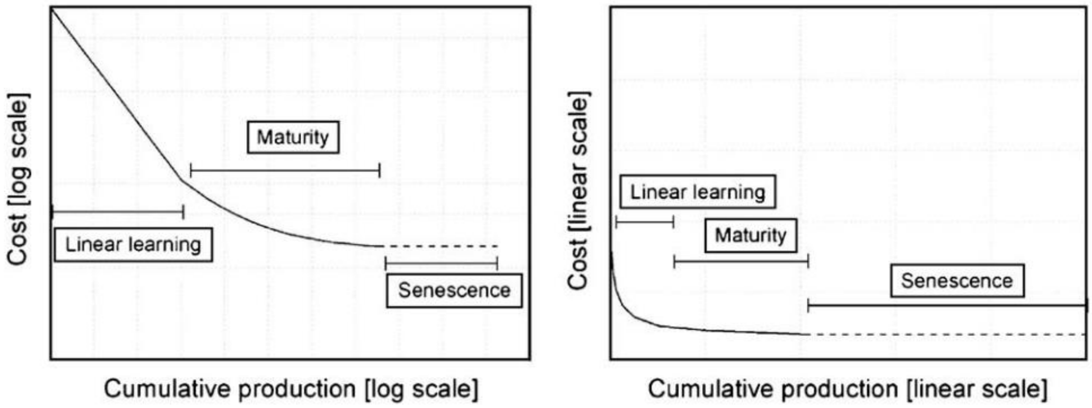


Figure 2-6. *Illustrative stages of learning process with technology maturity, reproduced from Ferioli and Schoots* [87].

While theoretical floors are likely to exist, the selection of their level for modelling is unclear. As discussed in Way et al. [109], the historic cost floors applied in integrated assessment modelling by the IEA and IPCC have significantly underestimated the actual rate of cost reduction for renewable energy technologies. Indeed, as described earlier in this section, the learning rates for onshore wind and solar PV LCoE have both accelerated over the last decade, rather than slowed.

As wave energy is still an immature energy technology, it is likely to be far from its theoretical cost floor. However, it is also a very long way from cost competitiveness. Therefore, when considering extrapolating cost reductions through learning effects of almost an order of magnitude it would not be surprising for a slowing of learning effects to occur. This is clearly another source of uncertainty in long-term cost extrapolations for expensive nascent technologies such as wave energy.

Radical innovation

The SFEC in theory describes predictable incremental cost reductions that occur as a function of cumulative production. Therefore, it cannot account for future (or past) radical innovations that lead to a step-change in technology costs [68, p. 28]. A radical innovation may cause a pronounced break in the experience curve relationship [44], [68, p. 28], [89]–[91]. This is where costs fall rapidly as a result of, for example, a new design, material, or manufacturing process, that may in turn allow some existing limiting factor on technology performance to be overcome [90], [110]. As this process of radical innovation is not part of the ongoing process of incremental innovation, it may call for a new experience curve to be established [91]. In the literature these step-changes are often presented graphically as shifts between experience curves, as shown in Figure 2-7.

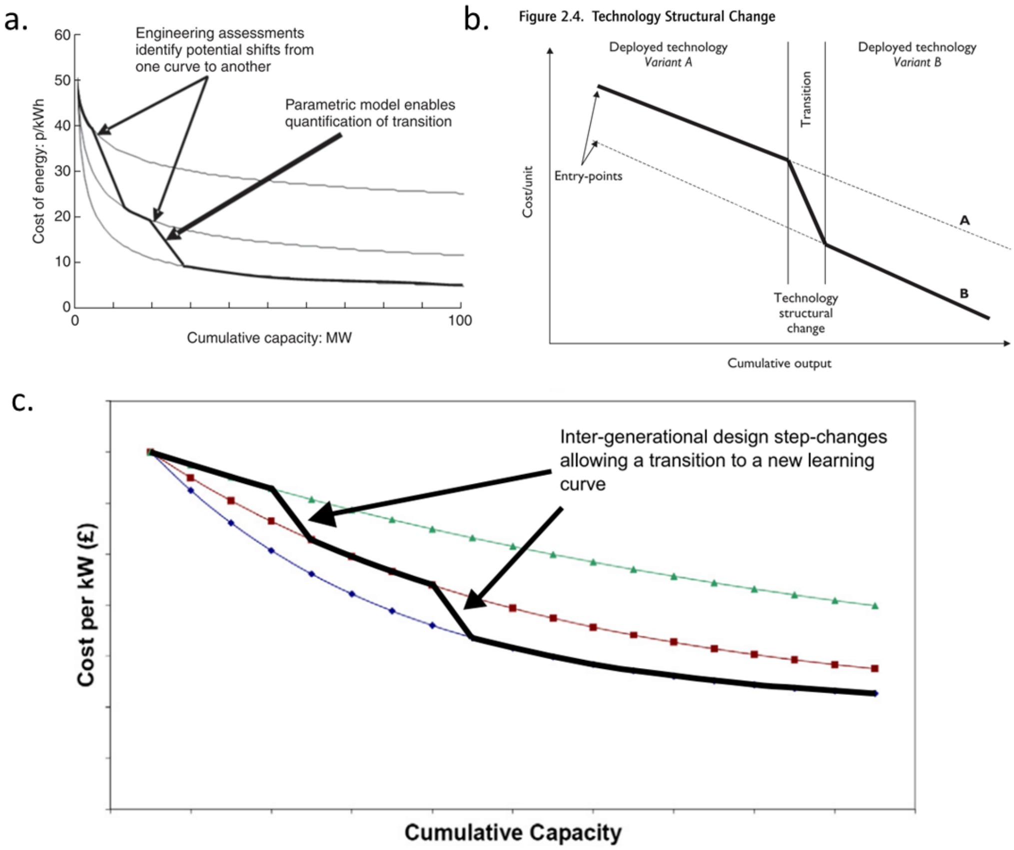


Figure 2-7. *Illustrative effects of radical innovation on experience curve cost trajectories, reproduced from a. Mukora* [90]*, b. IEA (log-log axis)* [44]*, c. MacGillivray* [89]*. These illustrate that radical innovation could cause a break from consistent incremental cost reductions.*

With sufficient data, these breaks can be identified in historic experience curves [44], [68, p. 28]. However, as a SFEC cost reduction is based only on one parameter (e.g. deployment) it can, by definition, not account for future innovations that lead to step-changes in technology costs [68, p. 28]. As discussed in Section 2.1.1 the total learning investment to reach a given cost is highly sensitive to starting costs. Therefore, radical innovation that results in a transition to a lower experience curve has the potential to drastically reduce the learning investment for an immature renewable energy technology to meet cost parity (as shown in Figure 2-8).

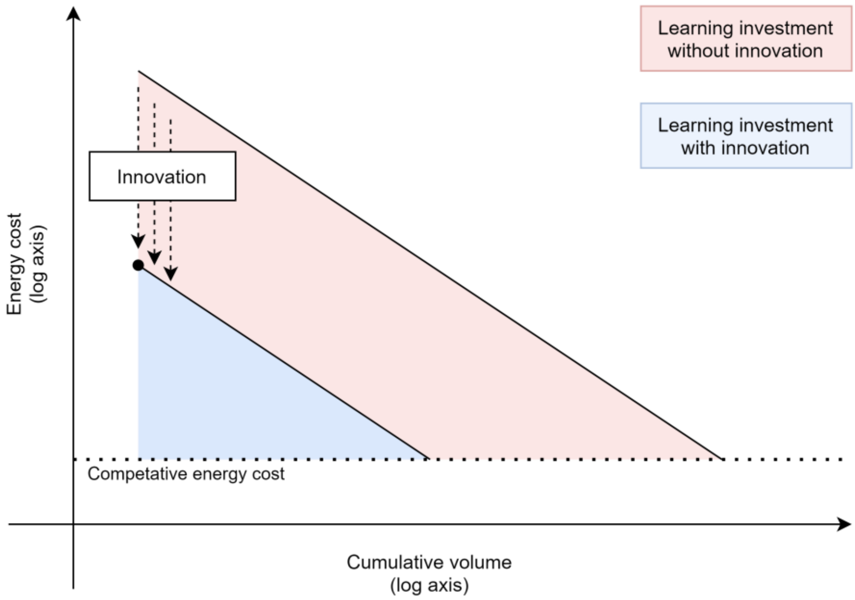


Figure 2-8. *The effects of innovation on learning investment causing a shift from a higher cost experience curve down to a lower cost experience curve (shown on log-log axis).*

2.2 Experience curves for wave energy and radical innovation in experience curve analysis

Two areas of literature with particular relevance to this thesis are the application of experience curve analysis to the wave energy sector and the treatment of radical innovation in experience curves. For this reason, these two areas are covered in additional detail in this section.

2.2.1 Experience curves and learning investment for wave energy

A number of studies have used experience curves to estimate the future costs of wave energy. The learning rates used in a selection of literature studies for wave energy experience curves are shown in Figure 2-9. As covered in Section 2.1.4, estimation of the experience curve parameters for wave energy cannot readily be done using data gathering and regression analysis due to an insufficient time series of cost and deployment data. Therefore, the estimation of experience curve parameters in wave energy cost projection studies have relied largely upon comparison with analogous technologies or engineering judgement. The estimates for the learning rates in Figure 2-9 are briefly described below.

In the SI Ocean report, a 12% learning rate for wave energy CAPEX was assumed, which was then compared to engineering judgment based on an aggregation of component level learning rates [111]. The 2011 Carbon Trust report used learning rates between 1-12% for the CAPEX of individual WEC components (see Table 2-2) [28]. A weighted average of these learning rates resulted in a device CAPEX learning rate of ~8%. The 2006 Carbon Trust report suggested a range of between 10-15% for wave energy LCoE learning rate [88]. Both Carbon Trust reports based their learning rates on engineering judgement, and, in the case of the 2006 report, the rate of cost reduction seen in other industries. The 2018 JRC report used a central learning rate of 10% for wave energy CAPEX, with high and low scenarios of 15% and 7% respectively [112]. This was based on a literature review of experience curve studies for ocean energy technology (both wave and tidal). The 2019 JRC report used a 12% learning rate for wave energy LCoE [113], but does not disclose the reason for assuming this learning rate. Finally, the learning rate presented in the 2015 OES-IEA study fits an experience curve to WEC developer LCoE estimates of future wave energy projects at different levels of deployed capacity [104]. This resulted in a learning rate of 17%. From the comparison with other reference studies in Figure 2-9, it can be seen that WEC developers implicitly anticipate higher learning rates than most figures presented in the literature. Additionally, Figure 2-9 shows that the learning rates used in wave energy studies for LCoE are generally higher than those for CAPEX (this is consistent with the general experience curve literature, see Section 2.1.2).

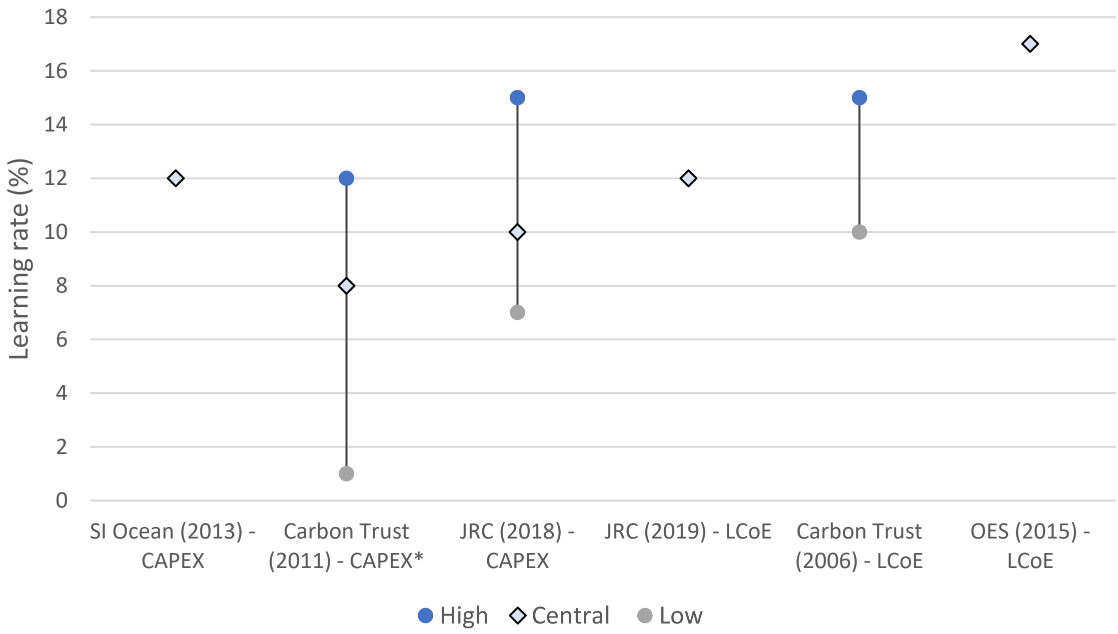


Figure 2-9. *Learning rate used in the literature for wave energy cost modelling, denoted for either LCoE or CAPEX learning rates. CAPEX data from* [28], [111], [112] *LCoE data from* [88], [104], [113]
**for Carbon Trust 2011 the high and low values are for individual component learning rates, central value is estimated total LR weighted by subsystem CAPEX contribution (the average of the component CAPEX weightings from Figure 6-4 were used).*

A smaller number of studies consider learning investment for the wave energy sector. The 2006 Carbon Trust study [88] evaluates the learning investment to achieve cost parity with CCGT generation in a selection of wave energy deployment scenarios. This study is reviewed in more detail in Section 2.2.2. In a 2013 study [89] and later in his PhD thesis [114], MacGillivray carried out a sensitivity analysis for marine energy learning investment. Both the 2013 study and 2016 thesis considered the reductions in the capital costs of marine energy (rather than disaggregating this into tidal and wave energy). The learning investment in this work was also calculated with respect to offshore wind as a 'cost parity' target for marine energy. Due to the relative immaturity and high cost of offshore wind at the time MacGillivray published these works, the second of these points results in a significantly lower learning investment when compared to studies which use conventional generation as the 'cost parity' benchmark[6]. An aspect of MacGillivray's work which deviates from the experience curve literature was the introduction of a parameter, CSCR, that describes the level of capacity deployed before sustained cost reduction occurs. In MacGillivray's work this was treated independently to the starting LCoE. Most other experience curve studies (including the work in this thesis) simply consider the cost and deployment to be a pair, with the cost of a technology considered at a certain level of deployment. MacGillivray concluded that the variation between the plausible scenarios he explored (with different learning rates and starting costs at different levels of deployed capacity) had the potential to 'make or break' the marine energy sector's ability to successfully commercialise. To this end, in the 2013 study, MacGillivray goes on to make several recommendations for the marine energy sector's innovation strategy based on lessons learned from other sectors, such as gradual upscaling, the importance of knowledge sharing, and technology transfer and innovation [89].

2.2.2 Radical innovation in experience curve analysis

A select number of studies have addressed the impacts of radical innovation on experience curve analysis. The work of Mukora [75], [90], MacGillivray [89], [114], Linton and Walsh [110], the IEA [44] and Wene [67] all present graphical representations and explanations of the effects of radical innovation in experience curve analysis, some of which are reproduced in Figure 2-7 (see Section 2.1.5). However, they give little in the way of numerical quantification of the effects of radical innovation on learning investment. Three studies were reviewed that, to an extent, estimated the effects on renewable energy experience curve cost reduction with and without radical innovation. However, only the study by Shayegh et al. [98] was published in a peer-reviewed academic journal.

A 2006 report by the Carbon Trust [88] presented scenarios for wave energy sector learning investment analysis where step-change innovations are integrating into experience curves. These scenarios include a 10% learning rate, 15% learning rate and a 10% learning rate with a step-change in costs due to innovation. This step-change reduced the initial LCoE from 250 £/MWh to 100 £/MWh at 50 MW of cumulative deployed capacity. The scenarios used by the Carbon Trust for an experience curve with a 10% learning rate, both with and without step-change cost reductions, are shown in Figure 2-10.

[6] In the 2013 study the cost of offshore wind was represented as a moving baseline (which is unconventional for learning investment analysis). However, in the 2016 thesis this was revised to be a static baseline value of £2800/kW.

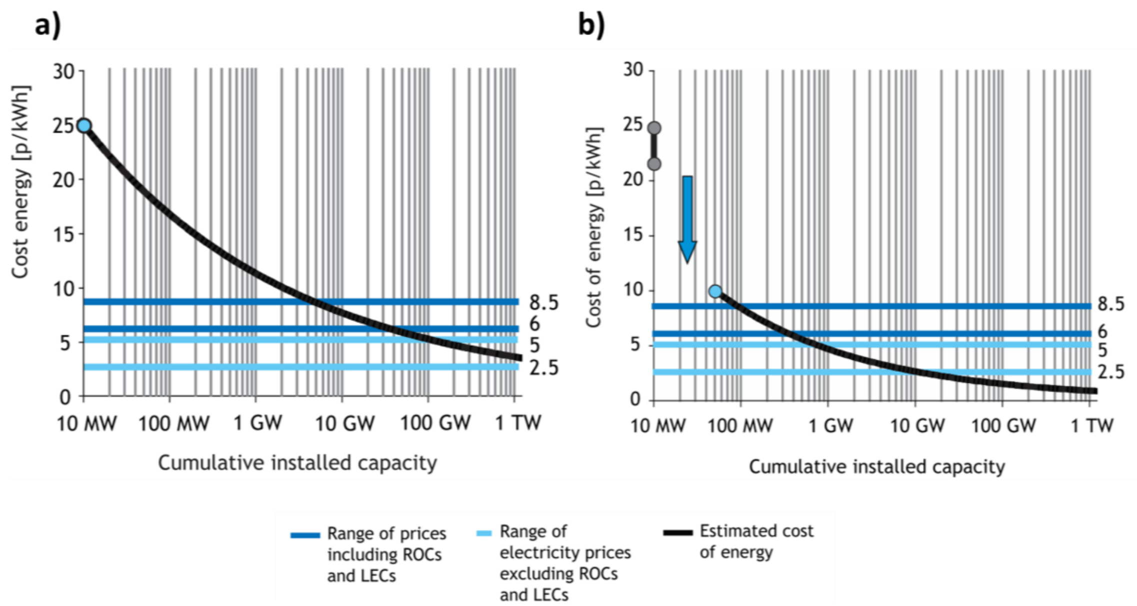


Figure 2-10. *Step-change cost reduction and experience curve, adapted from Carbon Trust* [88]*. Panel a) shows a 10% learning rate only, Panel b) shows a 10% learning rate with a step-change cost reduction caused by innovation.*

The Carbon Trust used these experience curves to estimate the learning investment required to reach cost parity with CCGT (shown as the dark blue lines in Figure 2-10). The required learning investment in these scenarios ranged from hundreds of millions of GBP (for the faster learning and innovation scenarios), to tens of billions of GBP for the low learning and no innovation scenario. The overall conclusion of the 2006 Carbon Trust study was that the wave energy sector would need either significant innovation paired with learning rates of >10%, or a higher learning rate of 15% to achieve competitiveness with CCGT within several gigawatts of deployment.

A similar analysis was carried out in a 2011 report from the Carbon Trust [28]. This report analysed device innovation cost reductions from the Marine Energy Accelerator programme run by the Carbon Trust from 2007-2010 (the individual cost reductions from these innovations is covered in [28]). These innovation cost reductions were then combined with learning rates to form cost reduction curves. These essentially presented a pure 'learning by doing' curve (representing incremental experience effects) and then an accelerated cost reduction pathway, where the innovations from the Marine Energy Accelerator are included. The results from this modelling were that without innovation the wave energy sector may only reach an LCoE of ~150 GBP/MWh after >40 GW of global deployment, while with the innovations from the Marine Energy Accelerator, similar LCoE values may be reached before 1 GW of global deployment. The report did not explicitly evaluate the learning investment required, but suggested that *'moving to a scaled- up manufacturing process is not going to reduce costs sufficiently for marine energy to be competitive unless many MW of capacity are installed at costs of energy above 20p/kWh [200 GBP/MWh]. Installing hundreds of MW at these high costs is simply not feasible'*. The report concluded that a focus of the marine energy sector must be continued technology innovation to accelerate cost reductions at early stages.

Although not considering marine renewables, a study by Shayegh et al. [98] aimed to evaluate the effect on total learning investment from R&D that either accelerated incremental innovation, or R&D that shifted an energy technology to a lower experience curve. In this study it was assumed R&D could have two different effects on experience curves. Firstly, curve-following R&D produced incremental cost reductions that generate information that might have been gained through additional deployment. Shayegh et al. considered this to be representative of many of the R&D investments carried out in the private sector, which generally are small, incremental improvements to existing products (this is explored in references [60], [62], [65], [115]). The other kind of R&D considered by Shayegh et al. was 'curve-shifting' R&D. This shifts a renewable energy technology onto a lower experience curve with the same slope. Shayegh et al. suggest that this is representative of transformative R&D such as the use of entirely new materials, or energy capture mechanisms that would not occur as a product of incremental innovation during production. A schematic showing the effects of both kinds of R&D on learning investment compared to a no-R&D scenario is presented in Figure 2-11. It should be noted that the curve-shifting learning investment in Figure 2-11 is significantly lower than the curve-following learning investment, but this is obscured by the logarithmic axis.

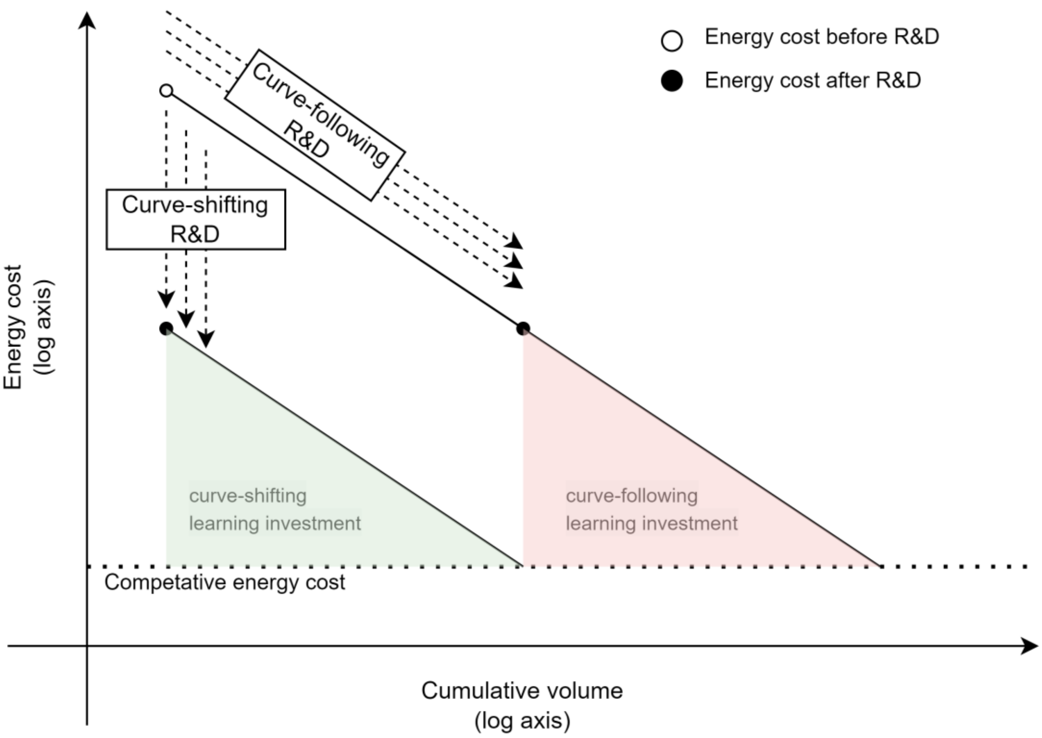


Figure 2-11. *The effects of curve-shifting and curve-following R&D on learning investment based on Shayegh et al.* [98] *(shown on log-log axis).*

The study evaluated the effects of curve-following and curve-shifting R&D on learning investment for different energy technologies. Shayegh et al. found that curve-shifting R&D is particularly important in reducing learning investment for technologies that are far from a competitive cost of energy, and/or have low learning rates. The conclusion of this work highlights the importance of innovation policies promoting more transformative (or radical) innovation to reduce subsequent deployment subsidies, especially in high-cost, slow-learning technology sectors.

2.3 Summary of wave energy experience curve literature and knowledge gaps

To summarise, experience curve analysis is a frequently used way to evaluate historical cost reductions of renewable energy technologies, estimate their future costs and evaluate the levels of subsidy associated with their deployment. Experience curve analysis has been used extensively for mature renewable energy technologies, notably onshore wind and solar PV. It has also been used as a way to develop cost reduction scenarios for nascent renewable energy technologies such as wave energy. Whilst the most ubiquitous form of experience curve is the single-factor experience curve (SFEC), other forms of experience curve such as multi-factor (MFEC) and component-based experience curves (CBEC) have been developed in an attempt to address the shortcomings of SFEC analysis. The applicability of these other approaches to nascent renewable energy technologies such as wave energy may be limited due to additional data gathering requirements. There are also several criticisms of the SFEC approach in the literature, including a lack of explicit causation between deployment and cost reduction, variability in learning rates over different time periods, cost floors for renewable energy technologies and accounting for non-incremental innovation.

Several studies have already considered wave energy and radical innovation in experience curve and learning investment analysis. However, knowledge gaps exist, which the work in this thesis aims to address. While several other studies have presented experience curve estimates for the marine energy sector, they often utilise initial costs (at only a few MW of cumulative deployment) that are now significantly lower than current sector estimates [88], [89], [104], [116]. Using these assumptions may result in underestimates in the magnitude of learning investment associated with cost reductions in the wave energy sector. The work in the thesis addresses this by presenting what the author believes to be a more reasonable set of baseline assumptions, along with an in-depth sensitivity analysis, to better understand the effects of deviations from this baseline.

The second knowledge gap addressed is the integration of radical innovation in learning investment estimation for wave energy. This has been touched upon by the Carbon Trust in previous studies for the wave energy sector [28], [88]. These highlighted how innovation may greatly improve the wave energy sector's prospects of being commercially successful. However, these provided little detail about the approach taken, or sensitivities involved with the various assumptions. The analysis in this thesis addresses these issues by presenting a detailed methodology to integrate radical innovation into experience curve analysis, and presents a range of scenarios and sensitivities to better explore the value of successful innovation and the uncertainties involved in this kind of analysis.

3 Cost modelling for the wave energy sector

In this chapter, long-term cost reduction trajectories are modelled for the wave energy sector. This chapter is split into three sections, first covering the methodology of this cost modelling, then the results and finally a discussion. In the modelling presented in this chapter two types of cost reduction are considered:

1. **Incremental cost reductions**, that are brought about from an aggregation of incremental technology innovations and other learning effects that improve the performance or cost of an existing technology.
2. **Radical/step-change cost reductions,** where a step-change (or radical) innovation is developed that strongly deviates from existing technologies or processes.

The methodology and results sections within this chapter are split into two sections, first covering the modelling of deployment cost reductions and then the addition of step-change (or radical) innovation cost reductions.

To model the incremental cost reductions, the single-factor experience curve method was used. This projects incremental cost reductions alongside future wave energy commercial deployment. These incremental cost reductions are referred to as 'deployment cost reductions' in this section. This was used to create a baseline cost reduction trajectory for the wave energy sector, based on current estimates of the costs of early commercial wave energy arrays and plausible learning rates from the literature. This baseline experience curve allows an estimation of the level of cumulative deployed capacity at which wave energy achieves a cost-competitive LCoE (the LCoE target). The total subsidy above the cost of an incumbent technology associated with this deployment – the learning investment – was calculated. This gives an estimate of the investment in deployment subsidies required to achieve cost-competitive wave energy. It should be noted that throughout this section the phrases 'total subsidy' or 'total deployment subsidy' have the same meaning as learning investment.

Radical or step-change innovation was then modelled as discontinuities between experience curves. These cost reductions are referred to as 'step-change innovation cost reductions' in this section. This step-change innovation represents the development of a new wave energy technology on a lower cost trajectory (a lower experience curve) than the baseline cost trajectory. The inclusion of this step-change innovation in the modelling results in less deployment subsidy, as the LCoE target is met at a lower level of cumulative deployment. This difference in the total investment (learning investment and the cost of the innovation programmes) between scenarios with and without step-change innovation was the focus of the modelling methodology presented in Section 3.1.2.

Following this, Section 3.2 presents the results from both the incremental cost reduction modelling and the step-change innovation cost reduction modelling. Finally, Section 3.3 presents a discussion of Part A.

3.1 Method for wave energy cost modelling

The methodology is split into two sections, first covering the modelling of deployment cost reductions (Section 3.1.1) and then the addition of step-change (or radical) innovation cost reductions (Section 3.1.2). The methodology in this section is the same as that presented in the journal article published alongside this research [74].

3.1.1 Deployment cost reduction modelling

This section covers the formulas and input data that were used to model the deployment cost reductions for the wave energy sector that were developed in this part of the thesis. These formulae and data were implemented in MATLAB to generate the results. This section starts by covering the selection and formulation of the experience curve that was assumed for the wave energy sector in the model. It then describes how learning investment was modelled based on this experience curve. Finally, the base case data inputs are described for the deployment cost reduction modelling, and any additional modelling assumptions are covered.

Experience curve and learning investment formulation

Experience curve and deployment schedule

Experience curves describe technology cost reductions alongside deployment and allow estimation of future costs (see Section 2.1). To model these cost reductions, a single-factor experience curve (SFEC) was developed to describe a series of wave energy deployment scenarios. The reason for selecting the SFEC is that the parameters to define the SFEC can be more readily estimated for the wave energy sector than for either a multi-factor experience curve (MFEC) or component-based experience curve (CBEC) approach. Additionally, the MFEC and CBEC have other limitations which make them less suitable for early-stage technologies (this is discussed in Section 2.1.3).

Regarding the selection of dependent and independent variables for the SFEC, it was decided that cumulative deployed capacity would be used as the independent variable and levelised cost of electricity (LCoE) as the dependent variable. Cumulative deployed capacity was selected as the independent variable as this is standard in the experience curve literature, and time series of cumulative deployed capacity are readily available for wave energy and other forms of renewable energy technology. LCoE was selected as the dependent variable for the SFEC as trade-offs between the different cost and energy production factors in renewable energy technologies are largely made to minimise LCoE. Therefore, it is a better measure of renewable energy technology progress than, for example, CAPEX (see Section 2.1.2 for a detailed discussion of SFEC variables). As this study considers the total learning investment required to reduce the cost of wave energy, the system boundaries are global. Therefore, the cumulative deployment represents total global deployment of wave energy and LCoE represents a global average for wave energy.

A SFEC of this type for wave energy is described by Equation 3-1. In this work, the experience curve starts at a level of cumulative deployed capacity where reasonable LCoE estimates can be made for the wave energy sector. It was decided that this would correspond to initial commercial wave energy arrays (see Table 3-2). Therefore, in Equation 3-1, $LCoE_c$ represents LCoE estimates for early commercial wave energy arrays in EUR/MWh, while CDC_c is the corresponding level of global wave energy cumulative deployed capacity in MW. In Equation 3-1, $LCoE$ is the levelised cost of electricity for a wave energy array at time t and CDC is the corresponding global level of wave energy cumulative deployed capacity at time t. The learning rate (LR) describes the percentage cost reduction seen per doubling of cumulative deployed capacity. For this work it was assumed that the base case values for the experience curve starting LCoE and cumulative deployment would be CDC_c = 100 MW and $LCoE_c$ = 400 EUR/MWh (see Table 3-1). Wave energy is not yet at a stage where it has achieved early commercial arrays, and only around 35 MW of cumulative capacity has been deployed to date worldwide (see Table 3-1). Therefore, the initial level of cumulative deployment (before the experience curve relationship is established) is defined as CDC_0. For the deployment between CDC_0 and CDC_c the LCoE is considered to be uncertain, and not able to be estimated using the experience curve relationship. For this reason, a conditional clause is added to Equation 3-1, where it is assumed that $LCoE = LCoE_c$ for any deployment before CDC_c is reached. This is discussed further below and shown graphically in Figure 3-2.

$$LCoE = \begin{cases} LCoE_c & if\ CDC < CDC_c \\ LCoE_c \left(\frac{CDC}{CDC_c}\right)^b & if\ CDC \geq CDC_c \end{cases}$$

$$LR = 1 - 2^b$$

Equation 3-1. *Single-factor LCoE experience curve used to estimate wave energy incremental cost reductions.*

If the natural logarithm of the learning rate equation is taken, the b value can be defined in terms of the learning rate, as shown in Equation 3-2.

$$b = \frac{\ln(1 - LR)}{\ln(2)}$$

Equation 3-2. *The experience curve b value as a function of the learning rate.*

Next, the deployment schedule is defined. This allows an LCoE trajectory to be modelled for our wave energy sector scenarios in terms of time and deployment. A deployment schedule is considered in this work where the level of cumulative deployed capacity increases exponentially with time. This deployment schedule is described in Equation 3-3, where RCI is the annual rate of capacity increase and t is the time after the initial deployment in years (t=0 at CDC_0). All other symbols have the same meanings as in Equation 3-1.

$$CDC = CDC_0(1 + RCI)^t$$

Equation 3-3. *Cumulative wave energy deployed capacity as a function of time.*

Combining the experience curve relationship with the deployment schedule gives an LCoE that varies with both time and deployment within the model. An example of this LCoE varying with both time and cumulative deployed capacity is shown in Figure 3-1, for a generic experience curve and deployment schedule.

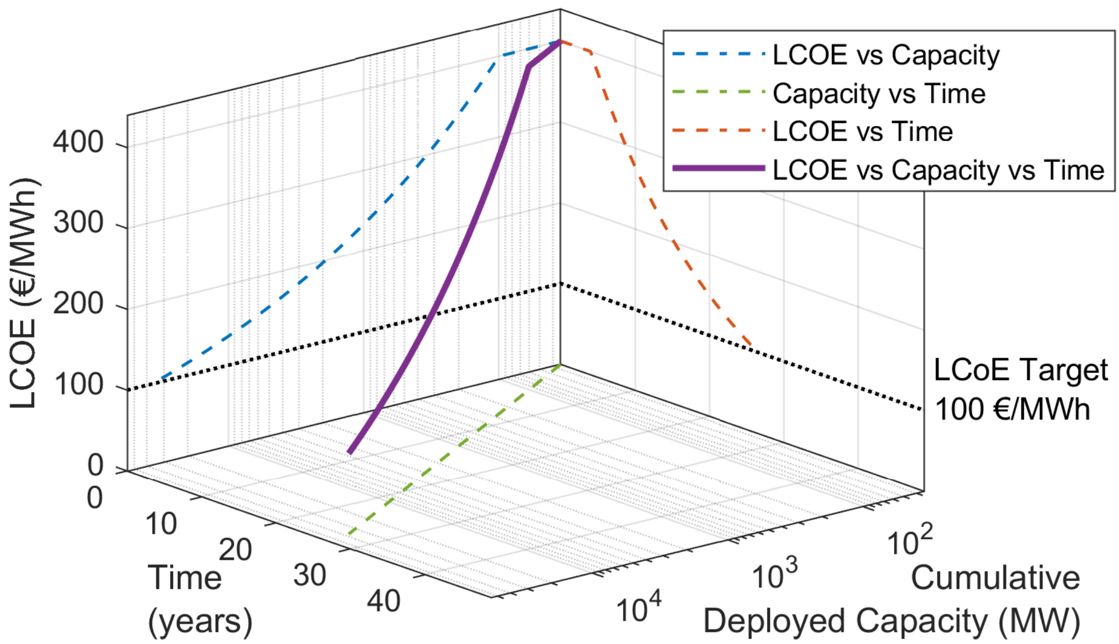


Figure 3-1. *Illustration of LCoE varying with cumulative deployed capacity and time within the cost model. This shows LCoE vs Capacity, Capacity vs Time, LCoE vs Time and the combined curve (LCoE vs Capacity vs Time).*

Learning investment

A nascent renewable energy technology like wave energy is often deployed at a significantly higher LCoE than incumbent energy technologies. The experience curve relationship can be extrapolated to estimate the capacity at which the nascent technology (wave energy in this case) achieves cost parity with an incumbent technology due to deployment-related cost reductions. As discussed in Section 2.1.1, learning investment describes the additional investment required to reach this point of cost parity. On a per unit energy basis, this additional investment can be thought of as a deployment subsidy, which subsidises the additional energy cost of the nascent technology above the costs of an incumbent. The learning investment can therefore be thought of as the total deployment subsidy required to reach cost parity with an incumbent technology. Figure 3-2 shows the learning investment above the LCoE target (representing the cost of an incumbent technology) and the key parameters required to evaluate learning investment. The learning investment above the incumbent is shown in the shaded areas. The key parameters to determine learning investment are:

- Starting point $(CDC_c, LCoE_c)$ — the starting LCoE at a given level of cumulative deployed capacity from which the learning curve is extrapolated.
- LCoE target — the LCoE target represents the cost of an incumbent technology. When the experience curve reaches this LCoE the learning investment calculation is complete. The level of subsidy or learning investment on a unit energy basis is the differential between the LCoE of wave energy (as defined by the experience curve) and the LCoE target.
- Learning rate (LR) — the percentage reduction in LCoE for every doubling in cumulative deployed capacity.

The starting point of the experience curve ($CDC_c, LCoE_c$) in Figure 3-2 represents a level of deployed capacity at which reliable LCoE estimates can first be made for the wave energy sector. For the work presented in this section, $LCoE_c$ corresponds to LCoE estimates for early commercial wave energy arrays and CDC_c is the corresponding level of global cumulative deployed capacity. Before CDC_c is reached, the LCoE is considered to be uncertain. Consequently, either A or A + C (see Figure 6) could be considered as the learning investment required to reach ($CDC_c, LCoE_c$). Due to the high level of uncertainty in LCoE estimates, and unreliability of experience curve relationships in early stages of technology development, the learning investment prior to the starting point is assumed to be defined by A only for the analysis in this section. This is described by the conditional clauses of the experience curve in Equation 3-1. Preliminary modelling also suggested that considering A or A + C as the learning investment before the start of the experience curve has very little effect on the overall learning investment in the scenarios considered in this work.

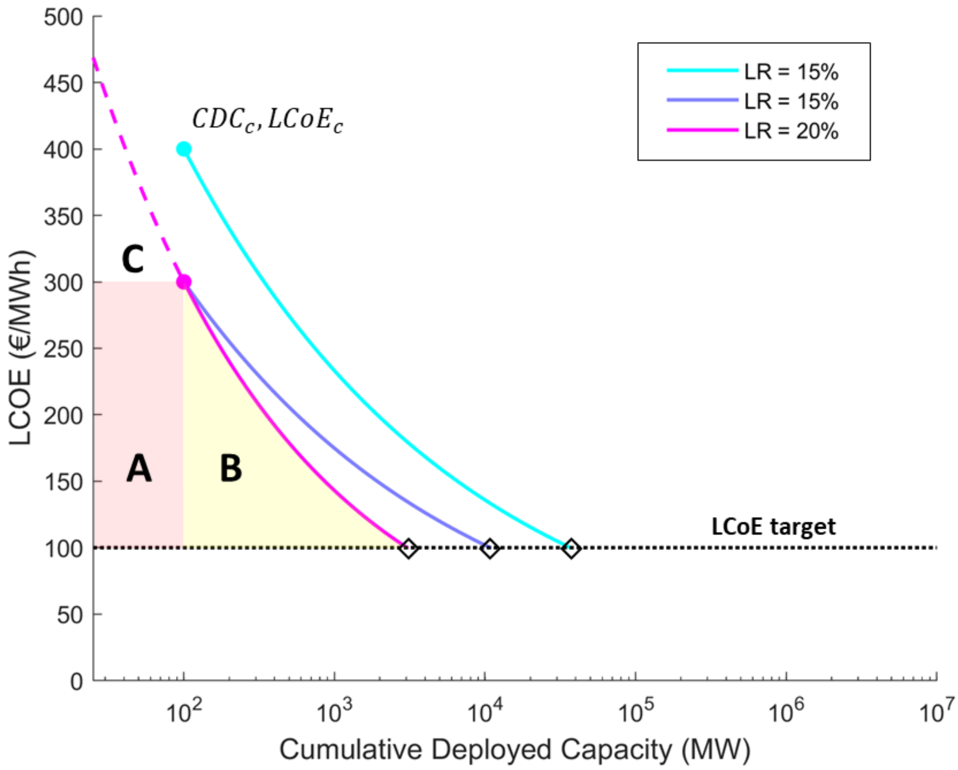


Figure 3-2. *Key parameters and learning investment in the incremental cost reduction model. Circles indicate starting points of the experience curves, and black diamonds indicate when the LCoE target is achieved. Shaded areas A and B are proportional to learning investment (subsidy above the LCoE target). For the pink experience curve, the pink dashed line represents extrapolation of the experience curve backwards before CDC_0.*

To calculate the learning investment associated with an experience curve and deployment scenario, a model was developed that calculates outputs in discrete time steps (Δt). For the work presented in this section, monthly time steps were used ($\Delta t = 1/12$) as they represent a reasonable level of granularity for sector-wide deployment. The deployments in the learning investment model are staggered with respect to time as defined by the deployment schedule (Equation 3-3). If this is combined with an assumed capacity factor (cf) and a fixed revenue support duration (T_{SP}), a matrix of subsidised generation hours can be specified as shown in Equation 3-4. In the generation matrix ($Gen_{i,j}$), subscript i refers to generation in specific time steps and j refers to generation from a specific deployment. For instance, $Gen_{20,10}$ would refer to the generation in the 20th time step from a deployment that was made in the 10th time step of the model. The subsidised generation in each cell of the generation matrix is a function of the capacity deployed in the deployment step (defined as $dep_j = CDC_j - CDC_{j-1}$), the number of hours in the time step ($\Delta t \times 8766$) and the capacity factor (cf). The conditional clauses in Equation 3-4 account for the lack of subsidised generation before a deployment is made ($i < j$) or after the duration of the subsidy ($j + \frac{T_{SP}}{\Delta t}$).

$$Gen_{i,j} = \begin{cases} 0 & if\ i < j \\ 0 & if\ i \geq j + \dfrac{T_{SP}}{\Delta t} \\ dep_j \times \Delta t \times cf \times 8766 & otherwise \end{cases}$$

Equation 3-4. *Subsidised generation matrix.*

The investment ($Inv_{i,j}$) associated with the subsidised deployment from each cell of the subsidised generation matrix can then be calculated by multiplying the generation matrix ($Gen_{i,j}$) by the differential cost between the LCoE in the deployment step and the LCoE target. This is shown in Equation 3-5. It should be noted that, as the experience curve describes LCoE varying with the cumulative deployed capacity, it is assumed that LCoE reductions happen following each deployment.

$$Inv_{i,j} = Gen_{i,j} \times (LCoE_j - LCoE_{target})$$

Equation 3-5. *Subsidised investment matrix.*

Finally, a time series of the investment ($CumInv_i$) can be calculated by summing the investment in the columns of the investment matrix (this is shown in Equation 3-6). The total learning investment ($CumInv_{total}$) required to meet the target LCoE is calculated by summing the entire investment matrix (this is shown in Equation 3-7).

$$CumInv_i = \sum_j Inv_{i,j}$$

Equation 3-6. *Investment time series.*

$$CumInv_{total} = \sum_i \sum_j Inv_{i,j}$$

Equation 3-7. *Total investment (or total learning investment).*

Data inputs and assumptions for incremental cost reduction model

The base case data inputs for the deployment-related cost reduction model are described in Table 3-1. Following this a more detailed justification is given for the selection of these base case values. Finally, some important assumptions are listed for the model. It should be noted that the numbers in Table 3-1 vary slightly from those used in the published journal article [74] and technical report [73] due to updated wave energy deployment figures, changes in macroeconomic conditions and to ensure consistency between the sections in this thesis.

__Table 3-1.__ Base case data assumptions for wave energy incremental cost reduction model.

Variable	Symbol	Base case	Unit	Description
Learning rate	LR	15	%	The LCoE learning rate for the wave energy experience curve after CDC_c is reached
Initial capacity	CDC_0	35	MW	Cumulative global wave energy capacity at start of model
Capacity at experience curve start	CDC_c	100	MW	Level of global cumulative deployed wave energy capacity assumed for early commercial wave energy arrays (cumulative deployment at start of experience curve)
LCoE at experience curve start	$LCoE_c$	400	EUR_{2020} /MWh	The estimated LCoE of wave energy for early commercial wave energy arrays (LCoE at start of experience curve)
LCoE target	$LCoE_{target}$	100	EUR_{2020} /MWh	LCoE target representing the cost of the incumbent energy generation
Subsidy duration	T_{SP}	20	Years	Duration of production subsidy for each deployment in the model, assumed to be the same as each WEC farm's lifetime
Rate of capacity increase	RCI	30	%/Year	Rate of annual cumulative deployed capacity increase
Capacity factor	cf	30	%	Average power/rated power of the wave energy deployments
Time step	Δt	1/12	Years	Time step used in the model
Social discount rate	dr_s	3	%	European Union social discount rate used for any cost discounting

First, the parameters are defined for the deployment schedule (Equation 3-3). The initial capacity CDC_0 is the level of wave energy cumulatively deployed at the start of the model. Using data from IRENA and OEE, the cumulative level of globally deployed wave energy between the start of 2004 at the end of 2021 was around 31 MW[7] [6], [7]. Based on this, a value of 35 MW was selected as the initial capacity CDC_0 in the model. In the model it is assumed that the rate of cumulative deployed capacity increase (RCI) is 30% per year in the base case. This is based on the annual rate of cumulative deployed capacity increase for the onshore wind and solar PV sectors observed between 2007 and 2017 using REN21 data [117]. The annual rates of deployment for onshore wind and Solar PV are shown in Figure 11-1 in Appendix A.1 — Wind and solar PV deployment rates.

Next, the parameters for the wave energy experience curve are defined (Equation 3-1 and Equation 3-2). Firstly, the starting point of the experience curve (CDC_c, $LCoE_c$) is determined. A review was carried out on LCoE values for early-stage wave energy arrays, which is presented in Table 3-2. This shows both the assumptions for LCoE estimates (converted into 2020 EUR) and the corresponding project and/or sector maturity in these studies. The process

[7] As this is cumulative deployment this includes subsequently decommissioned capacity.

used to deal with inflation and currency conversion of the LCoE values is detailed in Appendix A.2 — Currency conversion. It should be noted that these values do not represent the current state of the wave energy sector (which has only achieved large-scale demonstration to date), but rather are estimates of the future LCoE of wave energy once early commercial wave energy arrays are deployed.

Table 3-2. *Wave Energy LCoE estimates for early commercial arrays with supporting assumptions. Data converted into 2020 Euro values* [15], [28], [88], [104], [105], [111], [118], [119].

Source	**Project / sector maturity**	**LCoE (EUR_{2020}/MWh)**		
		Low	**Central**	**High**
Carbon Trust (2006)	10 MW initial wave arrays	184		673
Ernst & Young (2010)	10 MW wave array, 160 MW of cumulative global deployment	242	293	346
Carbon Trust (2011)	10 MW initial wave arrays	498		629
SI Ocean (2013)	10 MW wave array*	348	490	659
OES (2015)	Early commercial arrays (literature review)	268		459
OES (2015)	Early commercial arrays (projections from wave energy developers)	115		268
Jenne, Yu & Neary (2015)	10 MW array of RM3 wave energy converters		937	
BEIS (2020)	9 MW wave energy array in 2025	225	342	452
Baca et al. (2022)	Expert opinion survey, approximate LCoE at 100 MW of cumulative deployment*	263		438

* Values estimated from graphs in the respective reports.

These studies were chosen to reflect the estimated LCoE of wave energy if it were deployed as a small-scale early commercial wave farm (many sources assume a farm size of ~10 MW). Based on the values given in Table 3-2, an LCoE of 400 EUR_{2020}/MWh was selected to represent the base case $LCoE_c$ in the model. A corresponding level of global cumulative deployed capacity (CDC_c) for these early commercial arrays was set as 100 MW for the base case. This aligned well with the studies in Table 3-2, where a level of cumulative deployed capacity was included. The end point of the experience curve in our modelling is where the wave energy LCoE meets the LCoE target. This $LCoE_{target}$ is meant to represent the cost of an incumbent energy generation technology. The $LCoE_{target}$ was selected as 100 EUR_{2020}/MWh for this modelling. This is similar to the LCoE of the most expensive conventional non-dispatchable low-carbon generation (nuclear) using BEIS electricity generation costs methodology [15], [120]. This is also similar to projections made in 2022 of long-term average EU and UK wholesale market electricity prices, which are predicted to remain above 100 EUR/MWh throughout the 2020s [121], [122]. The final parameter to define the experience curve is the learning rate (LR). From the literature that was reviewed in Section 2.1.4, LCoE learning rate values for wave energy were between 10-17% (see Figure 2-9). Additionally, long-term historic LCoE learning rates for wind energy (which could be considered as an analogous technology to wave energy) have been around 15% (see Section 2.1.4). The base case LCoE learning rate (LR) was therefore set as 15%.

Finally, the base case values for the remaining parameters required to define the subsidised generation matrix (Equation 3-4) and investment matrix (Equation 3-5) are discussed. For the capacity factor (cf), values of ~20-40% were found in the literature for wave energy converters [15], [104], [123]. A value of 30% is used as the base case in the modelling as it represents a reasonable midpoint value. The duration of subsidy (T_{SP}) for each wave energy deployment in the model was selected to be 20 years. This is similar to the lifetime of WECs commonly quoted in the literature [15], [28], [123], [124]. For any discounting calculations the European Union social discount rate of 3% was used, although it should be noted that a wide range of social discount rate values are used in different countries or regions [125].

Finally, some important additional assumptions are listed for the incremental cost reduction model:

- Capacity additions — as mentioned above, these occur in monthly time steps ($\Delta t = 1/12$) following an exponential growth in cumulative deployed capacity until the wave energy LCoE reaches the target LCoE. Capacity additions after this point are considered un-subsidised and are excluded from the learning investment calculation. As covered above, these capacity additions are assumed to occur at a fixed rate of 30%. In reality, a different deployment trajectory could be expected during earlier stages of deployment (as can be seen for wind and solar PV in Figure 11-1). Although the methodology laid out in this section could accommodate a non-exponential deployment schedule, it was not considered in this work.
- Variations in learning rate — variations have been observed in the learning rates for technologies such as onshore wind and solar PV (see Section 2.1.5). Additionally, some kind of cost floor may exist below which wave energy will not fall (see Section 2.1.5). However, as there is little consensus on how to deal with these in long-term experience curve extrapolations, variations in learning rate over time have not been considered.
- Target LCoE value — in this work it was assumed that the target LCoE is a single value that remains constant. In reality, the LCoE of incumbent technologies will vary both spatially and temporally. However, this was considered too uncertain to model, and therefore a constant value of 100 EUR/MWh was used.
- Capacity factor — trends from other renewable energy sectors have shown that capacity factors may vary over time. Although the modelling methodology outlined in this section could accommodate this, variation in capacity factor is considered too uncertain to include for wave energy.
- Subsidy tracks LCoE — for this work it is assumed that the subsidy (or learning investment on a per unit energy basis) is simply the difference between the LCoE of each wave energy deployment and the LCoE target (representing incumbent technology costs). In reality, the level of subsidy is unlikely to perfectly track LCoE, and a stability between price and cost may not be achieved in early stages of deployment [44], [80], [86]. Therefore, the model is likely to underestimate the total learning investment required. Additionally, it is likely that in early stages of deployment, wave energy will rely on other forms of public support such as grants or investment subsidies alongside revenue support [43], [126]. However, this was not

modelled. The design of this early-stage support would be an important consideration for policymakers.

3.1.2 Step-change innovation cost reduction modelling

Step-change innovation implementation in cost model

The second aspect of the learning investment modelling investigates the effect of step-change (or radical) innovation on the wave energy cost reduction trajectories developed using the deployment cost reduction model in Section 3.1.1. This step-change innovation represents the development of a new wave energy converter or subsystem technology that is a major technological breakthrough, with a lower LCoE that the baseline wave energy technology. These breakthroughs cannot be accounted for by extrapolation of a SFEC, as the SFEC considers consistent incremental technology improvements (see Section 2.1.5). The development of this lower-cost technology results in a change in the technology paradigm, where the incumbent technology is replaced by the new technology [44]. This section describes how the modelling presented in Section 3.1.1. was extended to model cost reduction scenarios for the wave energy sector, where step-change innovation is included.

To integrate step-change innovation into experience curve analysis for the wave energy sector, the development of a step-change innovation has been represented as a discontinuity in the wave energy sector's experience curve (see Section 2.1.5 and 2.2.2 for discussion of discontinuities in experience curves). This is where a transition happens from the baseline wave energy experience curve down to a lower-cost experience curve, representing the step-change innovation. Figure 3-3 shows an illustration of the baseline wave energy technology (experience curve A) and a lower-cost new wave energy technology which represents a step-change technology innovation (experience curve B). Modelling these different cost reduction trajectories allows the time, level of deployed capacity and learning investment to reach the LCoE target to be estimated both with and without step-change innovation.

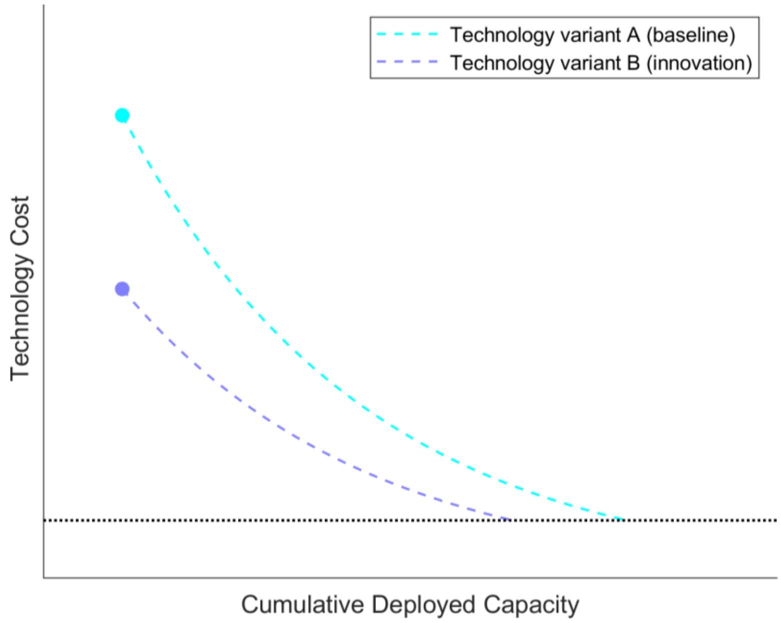


Figure 3-3. *Illustration of a baseline experience curve (technology variant A) and a lower-cost experience curve representing a technology innovation (technology variant B).*

To implement step-change innovation into the deployment cost model, scenarios are modelled where the SFEC from Section 3.1.1 represents a baseline (curve A in Figure 3-3). This represents incremental deployment cost reductions only. Following this, different scenarios were modelled where step-change innovation results in a transition from the baseline experience curve down to a lower LCoE experience curve (curve B in Figure 3-3). For this work it was assumed that the learning rate (LR) of the step-change innovation experience curve (curve B) is the same as the baseline experience curve (curve A). Additionally, it was assumed that any experience accrued by the baseline wave energy technology can be transferred to the new technology (assumption considered by the IEA [44]). This means that the new step-change innovation experience curve assumes the same level of experience in the independent variable as the baseline experience curve. These assumptions mean the transition from the baseline experience curve to the step-change innovation experience curve can be modelled at any point in the deployment trajectory as a transition between similar experience curves with different starting points ($CDC_c, LCoE_c$).

To integrate step-change innovation in the cost modelling, a publicly-funded innovation programme is considered that brings about a wave energy technology innovation. For scenarios where step-change innovation is included in the cost modelling, four variables are considered. These are based on the time, investment and cost reduction associated with running an innovation programme to develop a step-change innovation (this is discussed in the data and assumptions section):

- Innovation cost reduction (RE_{LCoE}) — this is the level of cost reduction in the step-change innovation experience curve in comparison to the baseline experience curve. For instance, a step-change innovation that gave a 25% reduction in LCoE would mean that the experience curve for the step-change innovation started at an $LCoE_c$ that was 25% lower than the baseline experience curve $LCoE_c$.

- Innovation development time (T_I) — this is the time to develop the step-change innovation, based on the estimated time required to develop novel wave energy subsystems and devices.
- Transition time (T_{TR}) — once the step-change innovation has been developed it is assumed that a period of time is required for the innovation to diffuse into the wave energy sector. This is the transition time (T_{TR}). The transition time is the time taken to transition between the baseline and the step-change innovation experience curves.
- Innovation investment (Inv_I) — this is the level of public investment to develop the step-change innovation, based on the estimated cost of developing novel wave energy subsystems and devices.

When integrating scenarios with step-change innovation into the baseline experience curve modelling, two sets of scenarios were considered:

a) Delayed deployment — the deployment of wave energy, and therefore initiation of the experience curve, is delayed by the time it takes to complete the step-change innovation plus the transition time ($T_I + T_{TR}$). The cost reduction trajectory in this scenario is essentially the baseline experience curve described in Section 3.1.1 with a lower $LCoE_c$ and a start time that is delayed by duration $T_I + T_{TR}$.

b) Parallel deployment — the deployment of wave energy, and therefore deployment-related cost reductions, occur in parallel to the development of the step-change innovation. In these scenarios a transition is modelled from the baseline experience curve to the step-change innovation experience curve, after the time to develop the innovation has passed T_I. A simple linear interpolation (with respect to time) was considered as the average LCoE during the transition period (T_{TR}).

The delayed deployment (a) and parallel deployment (b) scenarios are illustrated in Figure 3-4. The baseline experience curve (from Section 3.1.1) is also shown, which represents deployment cost reductions only. The LCoE vs time scenarios use a deployment schedule that increases exponentially with time.

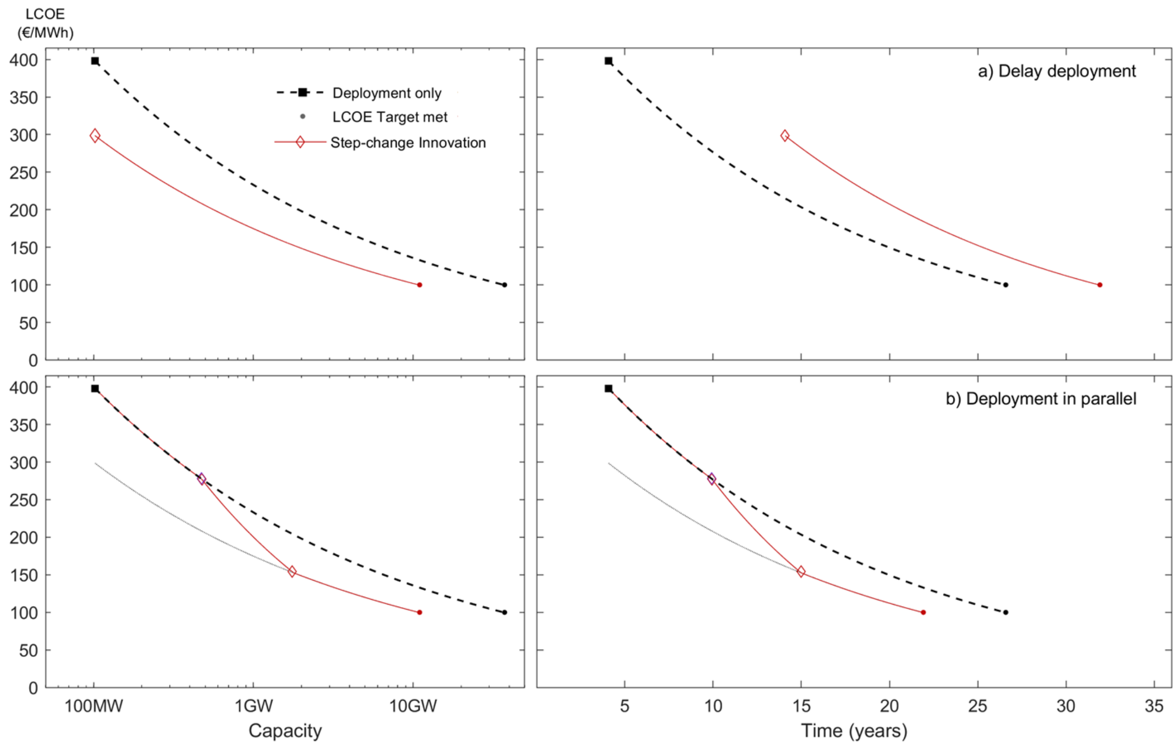


Figure 3-4. *Illustrative LCoE vs cumulative deployed capacity and LCoE vs time for the wave energy sector with and without step-change innovation. Top panels show scenarios where deployment is delayed until after the innovation has been developed. Bottom panels show scenarios where deployment is carried out in parallel with the innovation. Black dotted line shows baseline experience curve representing deployment cost reduction only. Red line represents scenario which also includes step-change innovation cost reductions.*

To integrate these step-change innovation scenarios into the modelling, the following steps were carried out:

1. The total investment ($CumInv_{total}$) is increased by the investment required to develop the step-change innovation (Inv_I).
2. No reduction in LCoE of the baseline experience curve is observed until the step-change innovation is complete (after T_I). The two sets of scenarios (a & b) above were considered for how the step-change innovation is implemented into the experience curve:
    a. Delayed deployment — in these scenarios no deployment occurs until the step-change innovation development time and transition time ($T_I + T_{TR}$) has elapsed. At this point, an experience curve with a lower starting $LCoE_c$ (reduced by $\mathrm{R_{LCoE}}$) is established.
    b. Parallel deployment — deployment happens in parallel to the development of the step-change innovation. The LCoE in this scenario follows the baseline experience curve until the innovation development time (T_I) has elapsed. At this point a transition occurs to an experience curve with a proportionally lower starting LCoE (reduced by RE_{LCoE}). In this case it is assumed that the experience accrued by in the baseline experience curve is transferred to the step-change innovation experience curve. The LCoE during the transition

period is modelled as a simple linear interpolation (with respect to time) between the two experience curves over a time period of T_I.

3. Using the new cost trajectories which include step-change innovation, the time, deployment and learning investment to reach the cost target then can be calculated using Equation 3-4 - Equation 3-7.

The next section will cover the data inputs for the step-change innovation model (R_{LCoE}, T_{TI} , T_{TR} and Inv_I) and any additional important assumptions.

Data inputs and assumptions for step-change cost reduction model

This section starts by introducing the base case assumptions for the step-change innovation modelling. Following this a more detailed justification is given for the selection of these base case values. Finally, some important assumptions are listed regarding the implementation of step-change innovation in the modelling.

For the step-change innovation modelling, a set of plausible scenarios were developed for the wave energy sector as part of the DTOceanPlus project deliverable 8.3 [73] in conjunction with the work carried out for this thesis. This work considered the time, investment and potential LCoE reduction associated with developing innovative wave energy converter subsystems through publicly-funded innovation programmes. The work in DTOceanPlus 8.3 deliverable considered this time and investment to develop a novel subsystem from a small-scale concept (TRL 1-3) to a commercial-scale subsystem (TRL 7-8), and then integration of the subsystems within a single commercial-scale wave energy converter demonstrator [73]. The investments after the single commercial-scale demonstration were considered to be funded by deployment subsidy, rather than additional investment in step-change innovation programmes and were therefore not included as investment for the step-change innovation. Additionally, work before TRL 1-3 was considered basic research and was not included due to uncertainty about the required time and cost to carry this out. Based on this work, the data inputs in Table 3-3 were used as the base case for the step-change innovation scenarios in the cost modelling. As with the assumptions made in DTOceanPlus 8.3, the values in Table 3-3 correspond to developing a novel WEC subsystem from a small-scale concept (TRL 1-3) to a commercial-scale subsystem (TRL 7-8) and then integrating this within a single commercial-scale wave energy converter demonstrator.

Table 3-3. Base case assumptions for the step-change innovation cost reduction model.

Variable	Symbol	Base case	Unit	Description
Innovation cost reduction	RE_{LCoE}	25	%	Percentage reduction in LCoE brought about by the step-change innovation compared to the baseline experience curve.
Innovation development time	T_I	10	Years	The time to develop and demonstrate the step-change innovation at a commercial scale.
Transition time	T_{TR}	5	Years	The time taken for the transition between the baseline experience curve and the step-change innovation experience curve.
Innovation investment	Inv_I	50	mEUR	The level of investment to carry out the step-change innovation development and demonstrate the step-change innovation at a commercial scale.

The cost reduction, innovation development time, and innovation investment used in the DTOceanPlus modelling were based on the development investment, time, and attrition rates from the Wave Energy Scotland subsystem programmes, and the investment, time, and estimated LCoE reduction from wave energy projects recorded in the CORDIS database. The data used to develop these scenarios is presented in Appendix A.3 — CORDIS and WES funding data. These values, along with an assumed value for the transition time, were then validated by ocean energy project developers who were part of the DTOceanPlus consortium. It should be noted that the work in DTOceanPlus highlighted that there is a large variation in the parameters used in the step-change innovation model from different sources. Therefore, a wide sensitivity range is used in the results section. Additionally, it should be noted the modelling assumes that the innovation programmes are successful. Many innovation programmes may not produce a step-change innovation but will still incur investment and development time. Additionally, due to significant variation of resource in different sites, wave energy may not converge on one successful device concept. This means that an innovation may not be able to be adopted by the whole wave energy sector. Therefore, several innovation programmes may need to be run to achieve a cost reduction for the wave energy sector. It would be reasonable to assume that this may happen in parallel, and therefore does not affect the timing (T_I or T_{TR}). However, running multiple innovation programmes would directly multiply the innovation investment. The wide range for innovation programme costs in the sensitivity analysis addresses this.

Finally, some important additional assumptions are listed for the step-change innovation cost reductions:

- Perfect experience transfer — for the modelling of step-change innovation, the experience accrued by the incumbent technology (baseline experience curve) is assumed to be transferred to the lower LCoE step-change innovation experience curve. This assumes that the experience accrued by deployments and cost reduction that occurred prior to the development of the step-change innovation are transferred. An alternative approach would be assuming that none of the experience is transferred, and the step-change innovation experience curve has to start from scratch. However, this would suggest an unrealistic lack of knowledge transfer between the incumbent wave energy technology (baseline experience curve) and the new wave energy technology variant (step-change innovation experience curve). In reality, a middle ground between these assumptions is likely. However, this was not modelled in this work. Therefore, the step-change innovation scenarios presented in this work, where innovation and deployment happen in parallel, are likely to overestimate the achieved cost reduction and underestimate the total learning investment.

- Consistent learning rates — it is assumed that the learning rate for the baseline experience curve and the step-change innovation experience curve are the same. In reality, if the step-change innovation varies dramatically to the baseline wave energy technology, they may have different learning rates. However, determining a value for this different learning rate was considered too uncertain to model in this work.
- Step-change innovation parameters — as mentioned above, the parameters to estimate the time and investment to develop a step-change innovation for the wave energy sector and the LCoE reduction that a step-change innovation could bring about is highly uncertain. Therefore, the base case values for the step-change innovation in Table 3-3 are meant to represent plausible values that can show the potential benefits of innovation to the wave energy sector, rather than a prediction of future wave energy sector development. A wide sensitivity analysis on the step-change innovation parameters was also carried out to address this.
- Success rate — it is assumed in the modelling that if an innovation programme for the wave energy sector is carried out, a successful step-change innovation will occur. In reality, due to the uncertainties associated with carrying out R&D, many of these programmes may fail, and no step-change innovation will occur. As discussed above, allowing for a sensitivity analysis on the innovation investment (Inv_I) allows for the fact that many innovation programmes may need to be run to develop a step-change innovation.

3.2 Results from learning investment modelling

The results from the cost modelling are split into two sections. Section 3.2.1 covers the results from the deployment-only cost reductions. Section 3.2.2 covers the results from modelling where step-change innovation was included.

3.2.1 Deployment cost reduction results

If not otherwise stated, the base case assumptions from Table 3-1 are used to generate the results in this section. These base case assumptions are reproduced below.

Variable	Symbol	Base case
Learning rate	LR	15%
Initial capacity	CDC_0	35 MW
Capacity at experience curve start	CDC_c	100 MW
LCoE at experience curve start	$LCoE_c$	400 EUR_{2020}/MWh
LCoE target	$LCoE_{target}$	100 EUR_{2020}/MWh
Subsidy duration	T_{SP}	20 Years
Rate of capacity increase	RCI	30%/Year
Capacity factor	cf	30%
Time step	Δt	1/12 Years
Social discount rate	dr_s	3%

Cost reduction trajectories for deployment cost reduction

Figure 3-7 shows the wave energy experience curves (LCoE vs cumulative deployment) modelled for different values of LCoE for early commercial wave energy arrays ($LCoE_c$). In Figure 3-7, dashed lines show 25 EUR/MWh increments in $LCoE_c$. It should be noted that the x-axis starts at 100 MW of cumulative deployed capacity. This has been overlaid with estimates of the total European and Global wave energy resource (as estimated by Gunn and Stock-Williams [5]). In the base case scenario (shown by the dark blue experience curve) the LCoE target of 100 EUR/MWh is met at 37.4 GW of cumulative deployed wave energy capacity. This analysis shows that wave energy's potential to reach the LCoE target of 100 EUR/MWh could be constrained by the available wave energy resource if it is commercialised at a very high initial LCoE. For instance, a starting LCoE of 500 EUR/MWh results in a deployment of almost 96 GW of cumulative deployed wave energy capacity before the LCoE target is met. This is especially true given that the base case 15% learning rate is relatively optimistic compared to the reference studies. Of course, even after reaching this capacity limit, wave arrays could be repowered as devices are retired at the end of their life cycle. However, this would result in a much-diminished rate of deployment (and therefore reduced production rate of wave energy devices). This could result in 'forgetting by not doing'. This is a phenomenon that has been observed in other technologies where unit costs increase following drastic production cuts [107].

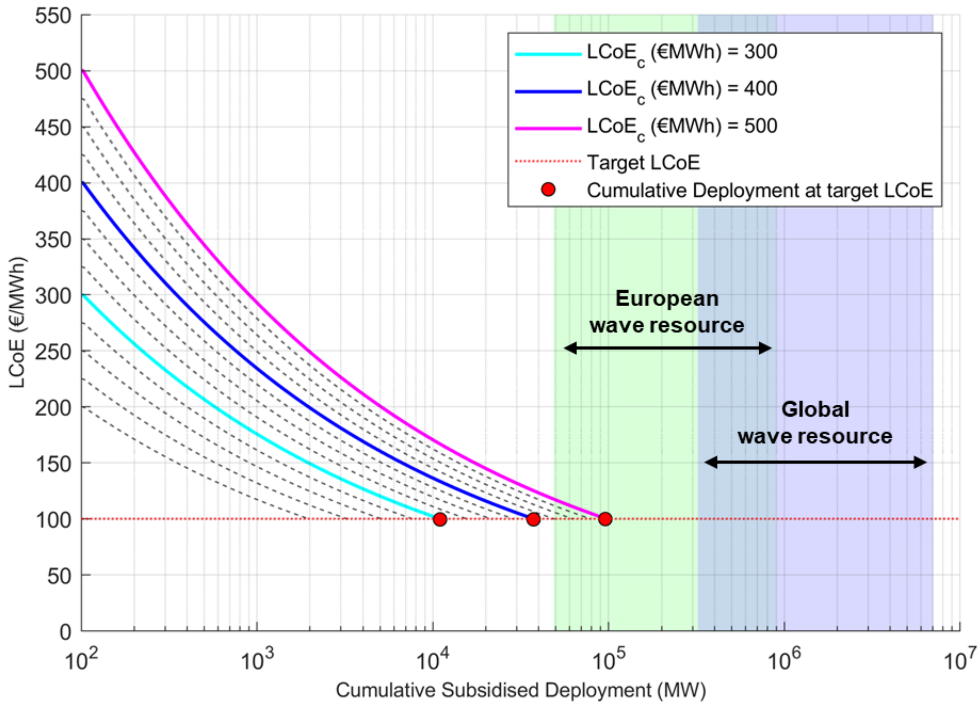


Figure 3-5. *Cumulative deployed capacity required to achieve the LCoE target through deployment-related cost reductions. Grey lines show 25 EUR/MWh increments in* $LCoE_c$*. Resource ranges are between extractable resource (based on arrays of Pelamis P2 devices) and theoretical wave resource (based on estimated global incident coastal wave power resource) data from Gunn and Stock-Williams* [5]*. Both estimates assume a 30% capacity factor, see Appendix A.4 — Global wave energy resource.*

LCoE vs deployment is plotted for variations in the learning rate in Figure 3-6, where dashed lines show 1% learning rate increments. The base case experience curve is shown in dark blue. This highlights that scenarios with low learning rates may also reach capacity constraints before the LCoE target is met. In the lowest learning rate scenario of 10%, over 930 GW of cumulative deployed wave energy capacity is required to reach the LCoE target. These concerns will be especially pertinent if only a small number of countries deploy wave energy technology.

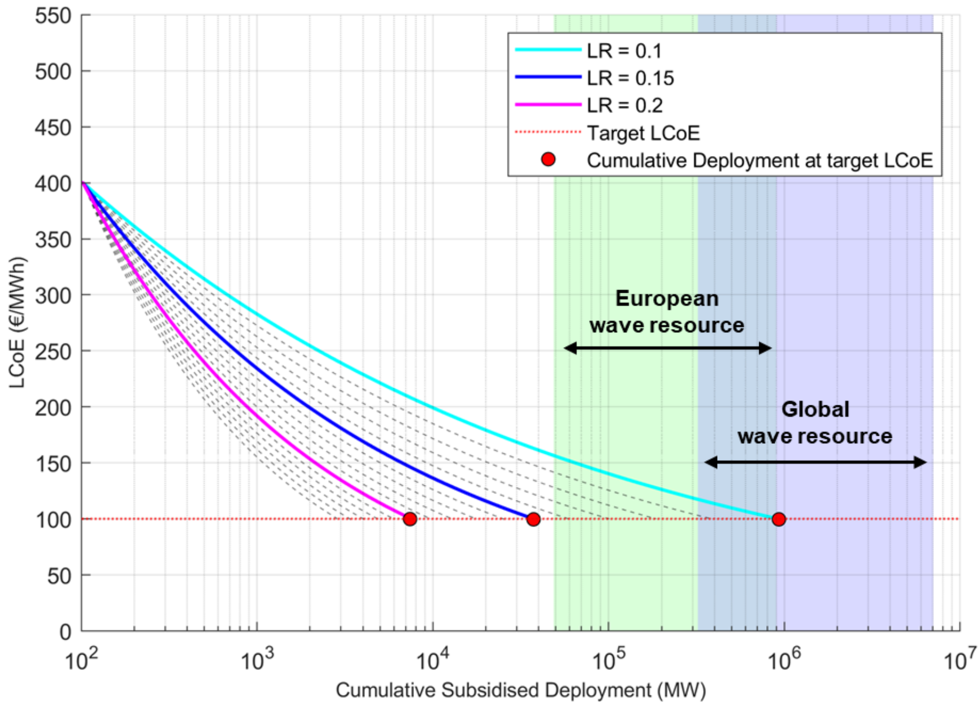


Figure 3-6. *Cumulative deployed capacity required to achieve the LCoE target through deployment-related cost reductions. Dashed grey lines show 1% increments in LR. Same wave energy resource ranges as Figure 3-5.*

Learning investment and sensitivity analysis

These results explore the relationship between learning investment and the initial LCoE ($LCoE_c$) and learning rate (LR). As $LCoE_c$ is the levelised cost of energy for the wave energy sector at a specified level of cumulative deployed capacity (CDC_c), these two parameters are not considered independent. Therefore, a sensitivity analysis was carried out on $LCoE_c$ but not CDC_c. The assumed subsidy duration (T_{SP}) and capacity factor (cf) are directly proportional to the total learning investment, as they directly increase the hours of subsidised generation over a wave energy deployment's lifetime. However, as neither subsidy duration or capacity factor affects the level of deployment required to reach the LCoE target within the model, sensitivity analysis was not carried out on these parameters. Finally, sensitivity analysis was also not applied to the deployment rate as it only effects the distribution of the learning investment, not the total value.

Figure 3-7 shows the total learning investment to reach the LCoE target of 100 EUR/MWh with respect to the initial LCoE ($LCoE_c$) and learning rate (LR). Different starting LCoE values are plotted at 25 EUR/MWh increments, and different learning rates are plotted with 1% increments. Both undiscounted values and the present value (PV) of the investment are shown using the European Union 3% discount rate (using the approach taken by the Low Carbon Innovation Coordination Group [116]). Figure 3-7, which is plotted on a logarithmic y-axis, highlights the highly nonlinear relationship between total learning investment and both the initial LCoE and learning rate. For instance, the undiscounted learning investment is over 10 times higher at a learning rate of 10% compared to a learning rate of 15%.

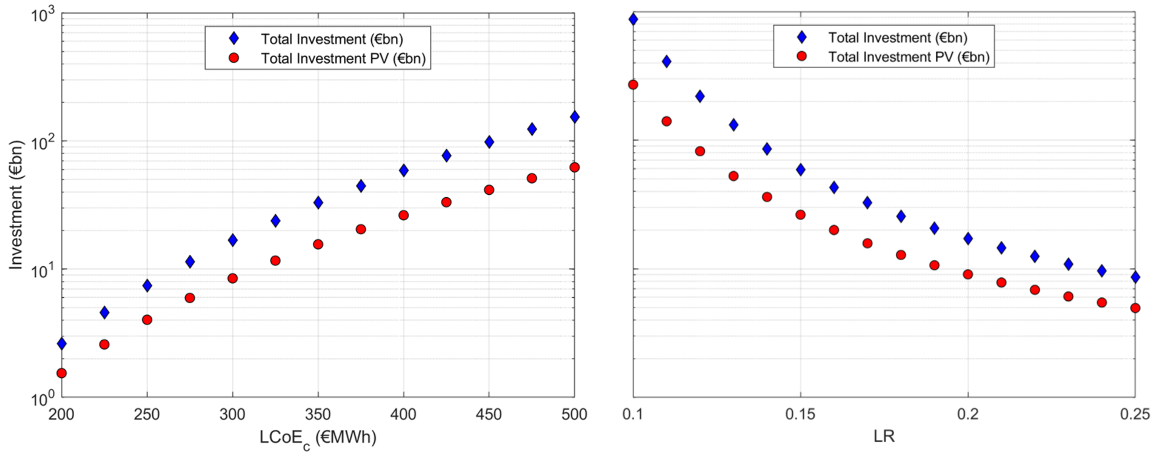


Figure 3-7. *Sensitivity of total learning investment to starting LCoE (left panel) and learning rate (right panel), learning investment (y-axis). Shown on a logarithmic scale.*

The total learning investment for combinations of $LCoE_c$ and LR is shown in Figure 3-8. This figure illustrates what combinations of these two parameters result in a feasible level of learning investment for the wave energy sector. The base case scenario, where $LCoE_c$ = 400 EUR/MWh and LR = 15%, is highlighted in Figure 3-8. This results in a total undiscounted learning investment of 59 billion EUR (26.3 billion EUR when discounted at 3%). Small changes to $LCoE_c$ and LR can result in large changes to the total learning investment required to reach the LCoE target. Given the range of potential learning rates (Figure 2-9) and LCoE estimates (see Table 3-2) for the wave energy sector, the viability of these different scenarios varies significantly. Wave energy could reach a competitive LCoE in as little as tens of billions of EUR learning investment under the more optimistic assumptions identified in the literature (e.g. $LCoE_c$ = 300 EUR/MWh and LR = 17%), or multiple thousands of billions of EUR under more pessimistic assumptions (e.g. $LCoE_c$ = 500 EUR/MWh and LR = 10%). These plots highlight the importance of both commercialising wave at a relatively low LCoE and achieving a high learning rate during commercial deployment.

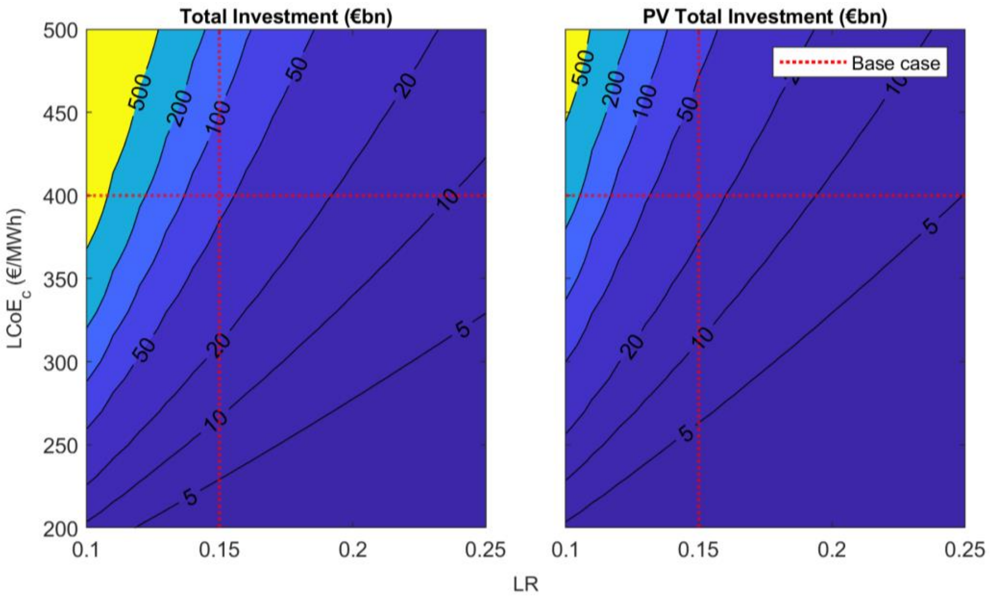


Figure 3-8. *Total learning investment plotted against starting LCoE ($LCoE_c$) and learning rate (LR). Left panel shows undiscounted values and right panel shows present value at 3% discount rate. Moving down the plot represents a reduction in $LCoE_c$, for example, from pre-deployment innovation. Moving right is an increase in LR. Either of these changes reduce the total learning investment.*

Annual investment for deployment cost reduction

Finally, the annual subsidy investment is plotted against time for a range of starting LCoE values in Figure 3-9. A faster rate of deployment (R_{CI} = 60 %/Year) is shown with the dotted grey lines. As can be seen in Figure 3-9, the learning investment is highly backloaded in our base case deployment scenario (dark blue line), with the peak annual subsidy of 2.8 billion EUR only occurring in year 27 of the time series. The faster deployment scenarios represent the same total learning investment, compressed over a shorter time period.

For context (although not direct comparison[8]) the total subsidy for renewable energy sources (including biomass) within the European Union was 79 billion EUR_{2020} in 2020, and is estimated to have been 76 billion EUR_{2020} in 2021 [70]. It should be noted that the learning investment numbers for wave energy in this section are also at a global scale.

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[8] It should be noted that, as most of these EU subsidies are feed-in tariffs, the subsidy is dependent on the difference between the wholesale market price and FiT price. For instance, the average wholesale market price in Germany was 30.5 EUR/MWh in 2020, 96.9 EUR/MWh in 2021 and 235.4 EUR/MWh in 2022 [290], [291]. This wholesale price is essentially the LCoE target considered in the modelling in this section. For this reason, the 2021 figures for the EU are likely to be more comparable to the learning investment for wave energy, as the wholesale price (for the EU) and the LCoE target are at similar levels. Overall, this means that the learning investment in this work is not exactly equivalent to the subsidy seen for other forms of renewable energy, as the reference cost of energy that the subsidy is calculated from is different. However, it still makes for an interesting reference point regarding the order of magnitude of investment.

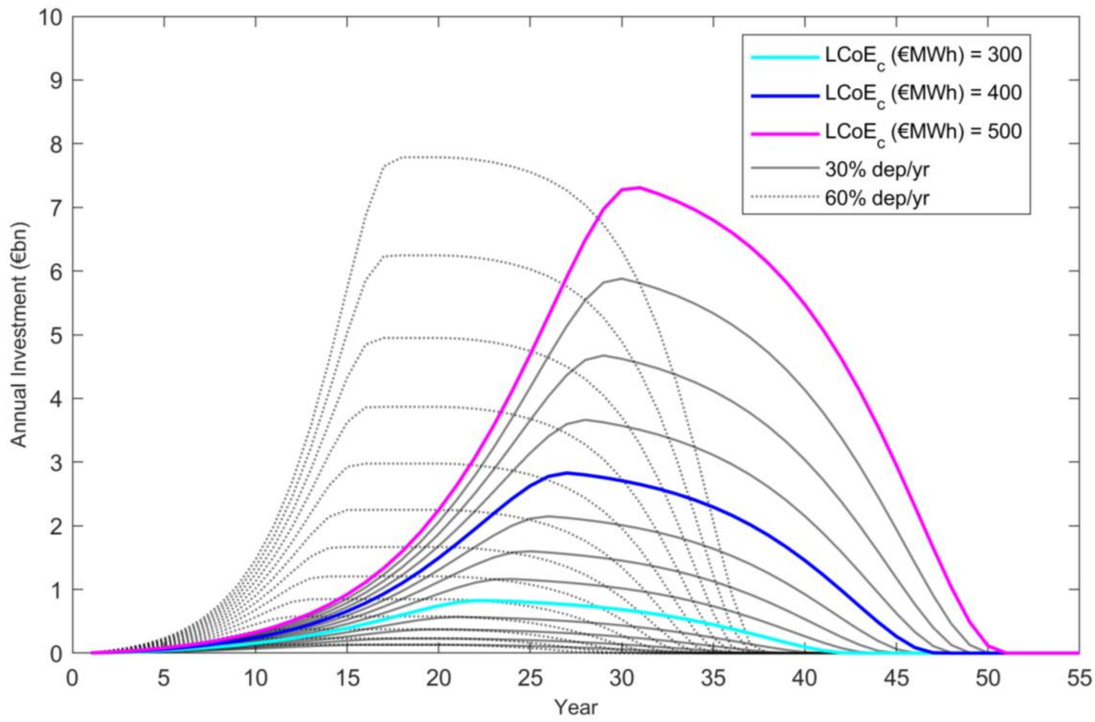


Figure 3-9. *Annual investment for a range of $LCoE_c$. Grey lines show 25 EUR/MWh increments in $LCoE_c$. An accelerated deployment rate where R_{CI} = 60 % per year is shown by the dotted lines.*

3.2.2 Step-change innovation cost reduction results

This section presents the results from the modelling, where step-change or radical innovation was included. The deployment-only cost reduction scenarios utilise the same base case assumptions (see Table 3-1) that were used to generate the results presented in Section 3.2.1. The base case for the step-change innovation scenarios in Table 3-3 are used in this section if not specified otherwise. These base case assumptions are reproduced below.

Variable	Symbol	Base case
Innovation cost reduction	RE_{LCoE}	25%
Innovation development time	T_I	10 Years
Transition time	T_{TR}	5 Years
Innovation investment	Inv_I	50 mEUR

In this section, the deployment-only cost reduction scenarios are referred to as 'pathway 1'. The scenarios with a step-change innovation, where deployment is delayed until the innovation has been completed, are referred to as 'pathway 2a', and the scenarios where deployment and innovation development happen in parallel are referred to as 'pathway 2b'.

Cost reduction trajectories with step-change innovation

LCoE variation with respect to deployment and time for the three cost reduction pathways are shown in Figure 3-10 with different levels of innovation cost reduction (RE_{LCoE}). In all panels the dashed black line shows the pathway 1 scenario, which is the baseline deployment-only cost reduction experience curve. The top two panels show 2a pathways for the step-change innovation, where deployment is delayed until the innovation is completed. The bottom two panels show 2b pathways where innovation development and deployment happen in parallel. The left-hand panels show LCoE as a function of cumulative deployed capacity, while the right-hand panels show LCoE as a function of time. The cost reduction curves all stop when the LCoE target of 100 EUR/MWh is met. Additionally, the experience curve is only plotted after CDC_c (100 MW) in Figure 3-10.

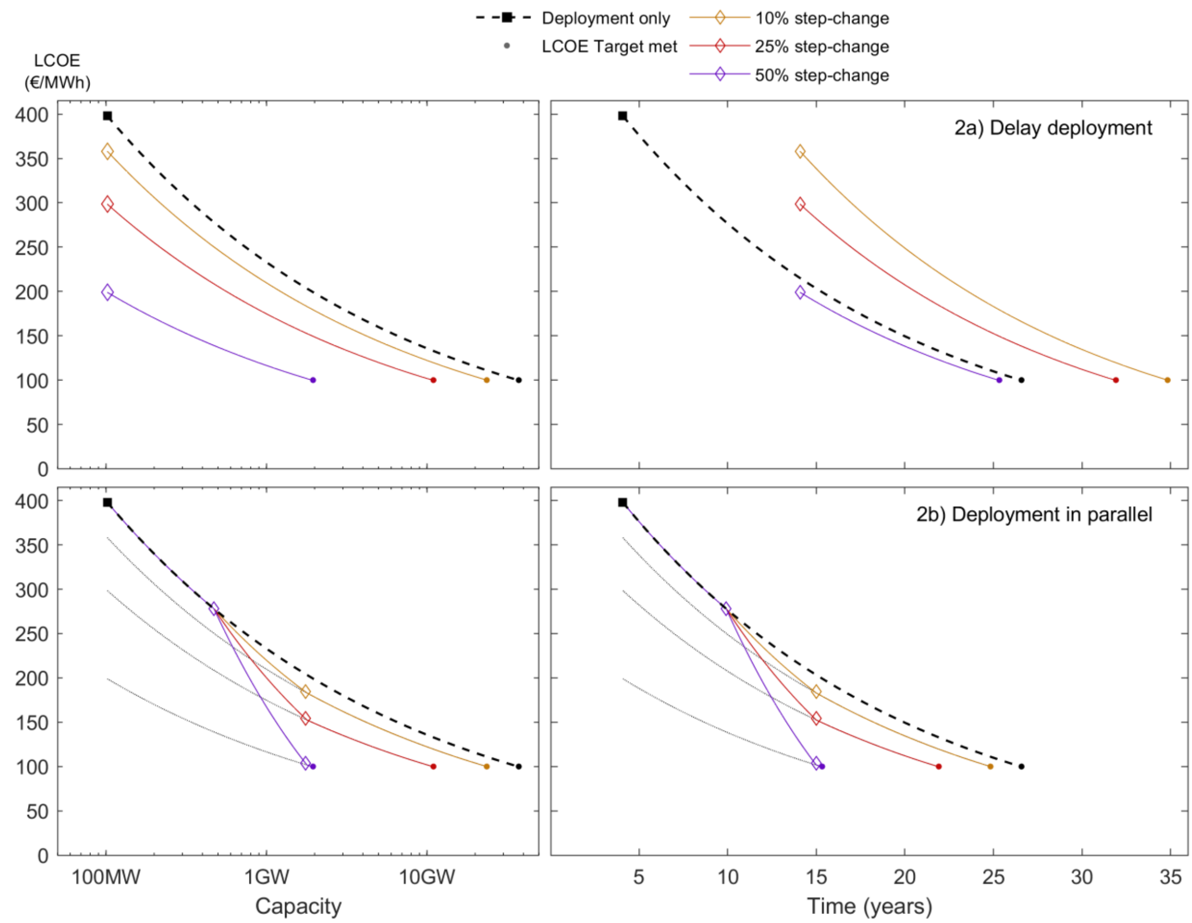


Figure 3-10. *Trajectories of LCoE vs Cumulative deployed capacity (left) and LCoE vs Time (right) from the step-change innovation modelling. Top panels show scenarios where deployment is delayed until after the innovation has been developed. Bottom panels show scenarios where deployment is carried out in parallel with the innovation. An innovation development time (T_I) of 10 years and a transition time (T_R) of years 5 are used in all scenarios.*

In Figure 3-10 it can be seen that, under the base case assumptions, it takes longer to reach the LCoE target in the 2a pathways than the deployment-only pathway in all scenarios except the 50% innovation cost reduction. In the pathway 2b scenarios, where deployment is subsidised in parallel with running the innovation programme, the time taken to reach the LCoE target is reduced (provided it is assumed that experience can be transferred, see Section 3.1.1). However, the investment is slightly higher than in the 2a pathways as deployment is subsidised at a higher level before the transition to the innovation experience curve has occurred.

Total investment with step-change innovation

The difference in total investment (both to subsidise deployment and carry out the innovation programme) are shown in Figure 3-11 for the different cost reduction pathways. This shows the first pathway (deployment-only) compared to pathway 2a — delayed deployment step-change innovation, and pathway 2b — parallel deployment and step-change innovation. An innovation programme length of both 10 years (the base case) and 5 years are shown for the 2b pathways. As can be seen the total investment is highly dependent on the level of innovation cost reduction (RE_{LCoE}). A 25% innovation cost reduction will reduce the total investment by around 2/3 (or 40 billion EUR) under the base case assumptions.

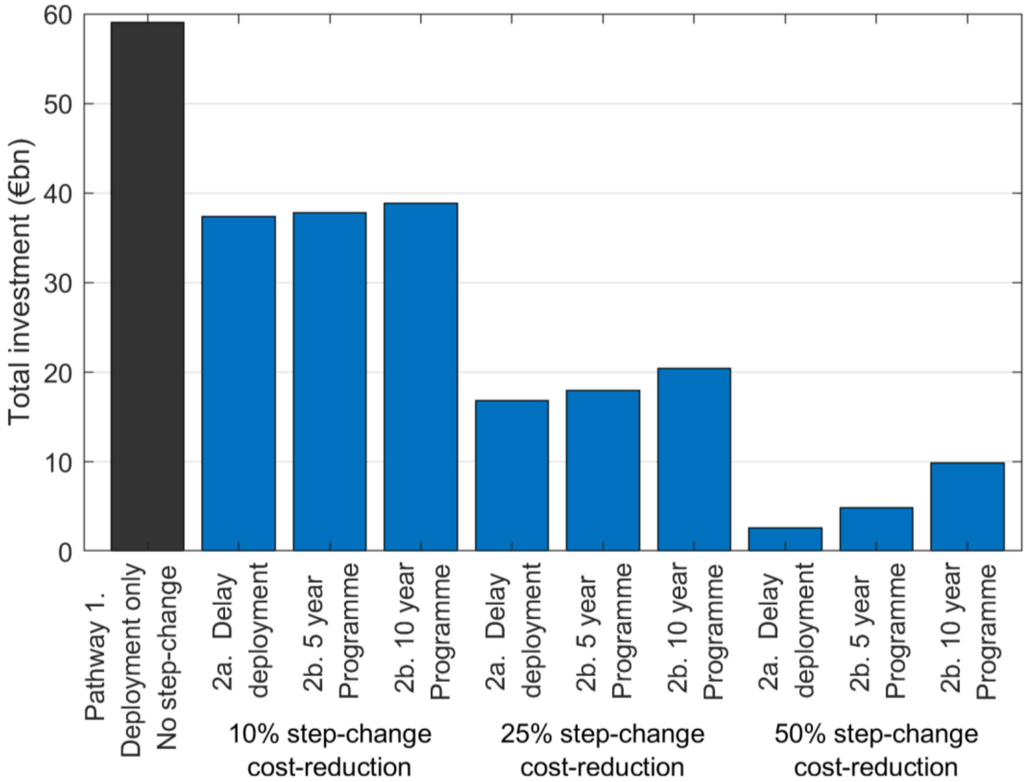


Figure 3-11. *The total investment for the base case deployment-only cost reductions and selected scenarios including step-change innovation.*

As discussed above, the pathway 2b scenarios incur slightly higher total investment than the pathway 2a scenarios, as deployment is subsidised at a higher LCoE before the transition to the step-change innovation experience curve. These differences become more pronounced for scenarios with a larger innovation cost reduction, as there is a larger difference between the step-change innovation experience curve and the deployment-only experience curve. Additionally, for pathway 2b scenarios, if the accumulated learning is not fully transferrable (which may be the case in reality, see Section 3.1.2) the increase in total investment from deployment in parallel (pathway 2b) compared to delaying deployment (pathway 2a) would be greater than the modelling in this section suggests.

Total investment sensitivity analysis

Figure 3-12 shows the sensitivity of the total investment (deployment subsidy plus innovation programme investment) to the innovation investment, innovation development time and transition time for the 2b pathway scenarios. The pathway 2a scenarios are not shown, as the total investment is not affected by timing of the step-change. The three coloured lines in Figure 3-12 correspond to scenarios with a 10%, 25% or 50% step-change cost reduction. Sensitivity is then shown to variations in the innovation investment, development time and transition time. For all the different scenarios of step-change cost reduction, the relative investment value of 1 corresponds to the baseline innovation investment (50 million EUR), innovation development time (10 years) and transition time (5 years). It should be noted that the maximum innovation development time and maximum transition time scenarios are not shown for the 50% step-change, as the LCoE target is achieved before the end of the transition time.

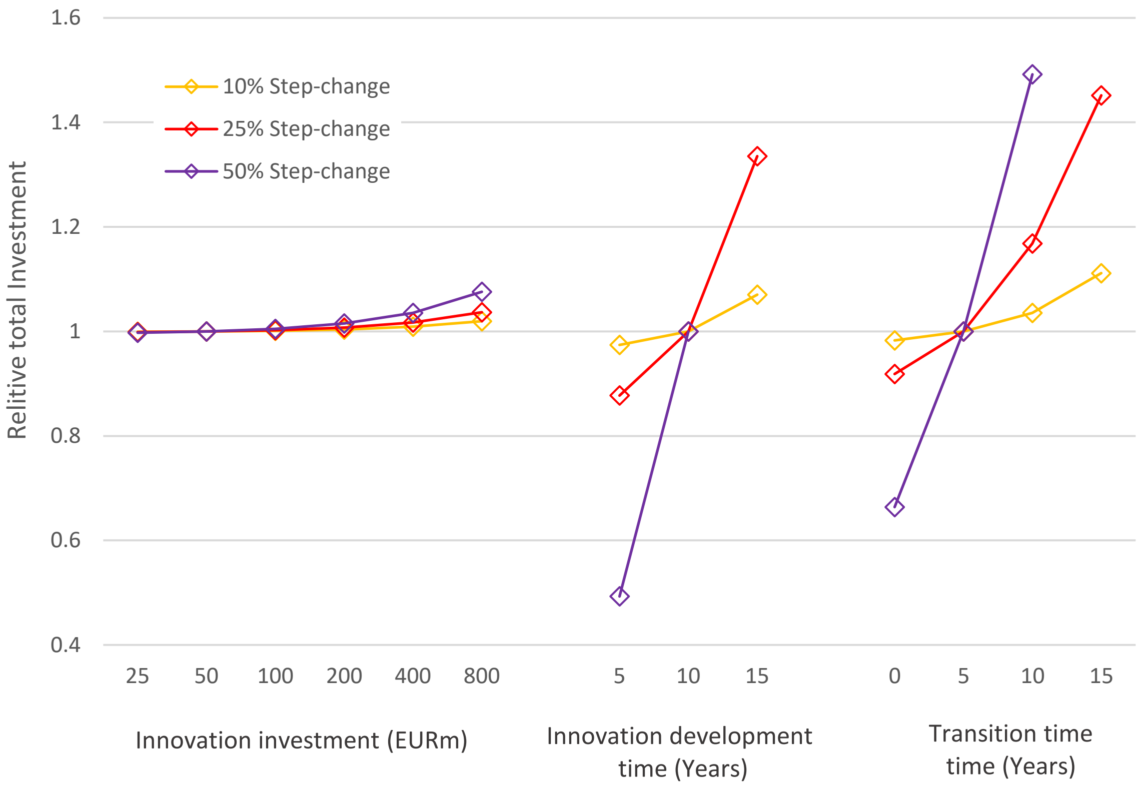


Figure 3-12. *Sensitivity analysis on the innovation investment, development time and transition time for scenarios with a 10%, 25% or 50% step-change innovation cost reduction. Y-axis shows total investment relative to the baseline innovation investment, development time and transition time. It should be noted that the maximum innovation development time and maximum transition time have been removed for the 50% step-change scenarios as the LCoE target is achieved before the end of the transition time.*

It can be seen in Figure 3-12 that scenarios with a larger step-change cost reduction are more sensitive to variation in the sensitivity parameters. This is because the total investment is lower in these scenarios, and therefore any additional investment has a larger relative impact on the investment compared to the base case. The sensitivity analysis shows that, within the sensitivity range, the innovation development time and the transition time have the largest impact on relative total investment. As can be seen, innovation investment has little impact on the relative total investment within the sensitivity range. This indicates that a low individual programme success rate, corresponding to the need for multiple innovation programmes, would still result in an acceptable level of learning investment in many scenarios.

3.3 Discussion of Part A

The discussion starts with Section 3.3.1, which presents the key results from the cost modelling from Part A and compares these results to the findings of similar studies in the literature. Section 3.3.2 then discusses what implications can be drawn from these results regarding the importance of supporting radical innovation to enable the development of cost-competitive wave energy. The discussion of Part A concludes with Section 3.3.3 which covers limitations of the research in Part A and presents recommendations of potential future work that could build on this.

3.3.1 Key findings from Part A

In this work, the target LCoE for the wave energy sector was set at 100 EUR/MWh. The learning investment is calculated based on the subsidy that is required above the level of 100 EUR/MWh. For the deployment-related cost reductions using the base case assumptions for the wave energy sector (see Table 3-1), a learning investment of 59 billion EUR was required to achieve the LCoE target of 100 EUR/MWh. It should be noted that this is a total global learning investment, which differs from the national-level renewable energy subsidies shown in Table 3-4. In the base case exponential deployment scenario (with an annual increase in cumulative deployed capacity of 30%/Year), this learning investment was highly back-loaded with a peak of around 2.8 billion EUR per year of subsidy in year 27 of the base case deployment scenario. These figures are of the same order of magnitude to the subsidy invested by individual European countries in the large-scale deployment of other forms of renewable energy technology, as shown in Table 3-4. However, it should be noted that there are several generous assumptions in the deployment cost model, primarily that subsidy perfectly tracks LCoE. For this reason, 59 billion EUR should be seen as a lower limit of the learning investment for the base case scenario. Additionally, it should be noted that the figures for the wave energy sector presented in this work are based on an LCoE target (against which the subsidy is calculated) of 100 EUR/MWh. The cumulative renewable energy subsidies presented in Table 3-4 are based on subsidising the renewable energy technologies above wholesale electricity prices. Over the 2000-2018 period in which the subsidy is calculated, the wholesale electricity prices may have been significantly lower than the 100 EUR/MWh target used in this work. For this reason, these figures are not directly equivalent to the learning investment calculated in this research (this is covered in Footnote 8 on p.74). However, they do make for an interesting reference point regarding the order of magnitude of investment.

Table 3-4. *Total deployment subsidy, cumulative deployed capacity and LCoE for German Solar PV, German onshore wind, Japanese solar PV and Danish wind between 2000 and 2018, reproduced from Noble et al.* [73].

	Total Deployment Subsidy* (Billions EUR)	**Cumulative deployed Capacity (GW)**		**LCoE* (EUR/MWh)**	
	2000-2018	**2000**	**2018**	**2000**	**2018**
German Solar PV	94.9	0.1	45.2	280	90
German onshore wind	74.5	6.1	52.4	130	60
Japanese Solar PV	69.3	0.3	56.1	600	150
Danish wind (Onshore & offshore)	5.3	2.4	6.1	110	40

*It was not indicated in Noble et al. [73] what year the deployment subsidy or LCoE values are quoted, and therefore they have been reproduced without adjusting for inflation.

The input assumptions for the modelling of the wave energy sector have large levels of uncertainty due to the absence of commercial deployment data for the wave energy sector. For this reason, a sensitivity analysis was carried out on the base case learning rate and starting LCoE. This sensitivity analysis showed that viable investment scenarios required a combination of a relatively low starting LCoE and high learning rate. Scenarios using values of LCoE and LR from the more pessimistic end of the estimates presented in the literature (see Figure 2-9 and Table 3-2 for learning rate and LCoE assumptions) could result in thousands of billions of EUR before the LCoE target was achieved. Additionally, if wave energy commercialises at a high LCoE or achieves a low learning rate, the modelling presented in Figure 3-5 and Figure 3-6 show that resource constraints could limit learning opportunities before the wave energy sector achieves the LCoE target of 100 EUR/MWh.

The key results from implementing the step-change innovation within the modelling are as follows. Firstly, even in the scenarios that considered a small relative LCoE reduction, a large reduction in total investment (learning investment plus cost of carrying out innovation programme) required to achieve the LCoE target was observed. Using the base case assumptions (see Table 3-1 and Table 3-3), a 10% relative reduction in LCoE through step-change innovation would reduce the total investment by around one third while the 25% step-change would reduce the total investment by around two thirds. Even if it is assumed that the success rate of the innovation programmes is low (thus requiring multiple innovation programmes to actually yield an LCoE reduction for the wave energy sector), the reduction in future learning investment offsets the cost of running the programmes in all the scenarios considered in this work. This is shown by the sensitivity analysis in Figure 3-12. When considering the step-change innovation, two pathways of timing scenarios were modelled. These considered a) subsidised deployment being delayed until the step-change innovation was complete and b) subsidised deployment and innovation development in parallel. The step-change innovation modelling found that the pathway a and pathway b scenarios incurred similar levels of learning investment in most scenarios, except when very long (15 year) innovation development or transition times are considered. However, the modelling assumed a full transfer of experience from the baseline technology to the step-change innovation, which in reality may not be the case. Therefore, the actual difference in investment between these scenarios may be higher than suggested by the modelling.

Comparison with previous work

Here the findings of this research are briefly compared to previous work (previous work is reviewed in detail in Section 2.2).

For the baseline deployment-only cost reduction scenario, the results can be compared to the other wave energy learning investment studies that were reviewed in Section 2.2. The results of these studies in comparison to this work are shown in Table 3-5 (values converted into EUR_{2020}). This shows a significantly higher learning investment modelled in this thesis in comparison with the literature. This is a function of the more conservative assumptions made in this work, especially around the start of the experience curve (CDC_c and $LCoE_c$). The values of learning investment presented as the base case in this thesis do, however, appear to be more in line with the actual levels of subsidy (tens to hundreds of billions of EUR) that have been required for the large-scale deployment and cost reduction of other forms of renewable energy technology (see Table 3-5).

Table 3-5. *Comparison of the learning investment for the wave energy sector in this study and previous work. All values converted into 2020 EUR* [88], [89].

Study	CDC_c (MW)	$LCoE_c$ (EUR/MWh)	LCoE target (EUR/MWh)	Learning rate (%)	Learning investment (EUR bn)
MacGillivray (2016) — base case	20	7291* (EUR/MW)	3402* (EUR/MW)	12	0.9
Carbon trust (2006) — pessimistic	10	381	130	10	28.3
Carbon trust (2006) — optimistic	10	331	130	15	1.2
This study	100	400	100	15	59

* MacGillivray used CAPEX rather than LCoE as the experience curve independent variable

A key difference between the work presented in the literature and the present research is that the cost reduction model developed during this research presented a method to calculate a time series of the learning investment. This allows annual learning investment to be evaluated along with present value calculations. This type of analysis was not presented in the other studies on wave energy learning investment.

Regarding the implementation of step-change innovation in experience curves, several other studies have presented graphical representations of a shift between experience curves enabled by step-change (or radical) innovation in experience curve analysis, such as Mukora [75], [90], MacGillivray [89], [114], Linton and Walsh [110], the IEA [44] and Wene [67]. However, only a small number of studies identified in the literature carried out analysis on the effect this step-change innovation could have on the learning investment required for a renewable energy technology to achieve an LCoE target (as reviewed in Section 2.2.2). Two Carbon Trust reports [28], [88] did specifically look at the impacts of innovation on the learning investment required to achieve cost-competitive wave energy. However, neither of these reports presented their methodology, and both only considered a small number of scenarios. Both of these issues were addressed in the present research. Additionally, the previous study which evaluated the effects of radical innovation on learning investment in the highest level of detail [98] did not consider wave energy, which was addressed by the present research.

While there are differences in the specific modelling and results between this work and previous studies, it should be noted that the overall conclusions of this work are consistent with previous work on step-change innovation and experience curves — that step-change innovation may be necessary for high-cost forms of renewable energy (like wave energy) to reach cost competitiveness at a viable level of public investment.

3.3.2 Sector implications from the results of Part A

The implications from the results of the work presented in Part A are summarised in this section.

The sensitivity analysis on learning investment with respect to starting LCoE and learning rate highlighted that both a low starting LCoE and high learning rate are required to achieve cost-competitive wave energy at a reasonable level of investment. However, as this modelling is based on estimates for LCoE and possible learning rates from the literature, there is a high level of uncertainty in the actual level of learning investment needed to achieve cost-competitive wave energy. Under the more optimistic assumptions, wave energy could reach the cost target within a few tens of billions of euros of learning investment. However, if the wave energy sector commercialises at a high LCoE or achieves a slow learning rate (still within the assumptions presented in Table 3-2 and Figure 2-9), it will require an unfeasible level of learning investment to achieve the LCoE target of 100 EUR/MWh. Additionally, the wave energy sector may face capacity constraints in scenarios with a high starting LCoE or low learning rate before the LCoE target is met.

This highlights that there is significant risk associated with attempting to commercialise wave energy at current LCoE estimates, as learning-related cost reductions alone may not provide a viable pathway to cost competitiveness. This emphasises the importance of wave energy funding bodies' updating learning investment models as actual cost and deployment data becomes available, to determine if the wave energy sector is on a trajectory that results in a reasonable level of learning investment and cumulative deployed capacity.

A second implication of this work is the large effect that successfully developed step-change (or radical) innovation could have on the subsequent learning investment required to achieve cost-competitive wave energy. Using the baseline assumptions in this modelling, even if these programmes had a very low success rate and multiple innovation programmes had to be run before a significant LCoE reduction was achieved, the benefits of successful innovation in terms of offsetting subsequent learning investment far outweigh the costs. This is true for both the scenarios where innovation is carried out before deployment or in parallel with deployment. Lowering the starting cost of wave energy through innovation would also enable cost-competitive wave energy to be achieved even if a lower learning rate is realised under the base case.

This emphasises the potential importance of innovation for wave energy to achieve a cost-competitive LCoE at a reasonable level of public investment. This is true even if a large number of innovation programmes are required to actually achieve a reduction in LCoE. As discussed in Section 1.1.2, public funding plays an important role in supporting innovation in the energy sector, especially radical innovation which could result in step-change reductions in cost.

The results of the modelling carried out in Part A therefore emphasise the importance of government support for policies that deliver both a low initial LCoE before or in the early stages of commercial deployment, and a high learning rate during commercial deployment. Some general points regarding government support for both a low initial LCoE and a high learning rate are outlined in the journal article that was published based on this research [74].

A final implication is related to the distribution of learning investment. In this work, which considers exponential deployment scenarios, the learning investment is highly back-loaded. This is due to the experience curve levelling off as it approaches the LCoE target. This would suggest that if wave energy, once commercialised, appears to be on a poor cost reduction trajectory, it may be beneficial to abandon deployment subsidies for the technology rather than attempt to buy it down the experience curve. This is true even if significant learning investments have already been made. This highlights the importance of monitoring the cost trajectory of the wave sector following commercialisation and continually updating learning investment estimates. Given the uncertainty in the key experience curve parameters at the early stages of renewable energy technology development (covered at the beginning of this section), this creates an argument for government supporting a large portfolio of more speculative technologies (both wave and other forms of renewable energy). If these innovations are developed in parallel, the technologies on poor cost reduction trajectories can have their subsidy removed, while keeping options available for other sources of low-carbon electricity generation.

3.3.3 Limitations and further work from Part A

There are several limitations inherent in any form of single-factor experience curve analysis. A review of these is provided in Section 2.1.5. Specifically, for this work the largest limitation is the uncertainty in using experience curves for the wave energy sector, due to the absence of commercial deployment data for wave energy. Therefore, an experience curve cannot be constructed using regression analysis of historic LCoE and deployment timeseries. Rather, the parameters for the experience curve have to be based on cost and learning rate estimates from the literature. In the wave energy literature, there is a wide range of assumptions used for the starting LCoE ($LCoE_c$) and potential learning rate (LR). As demonstrated by the sensitivity analysis carried out in Section 3.2.1, small changes in these parameters can have large effects on the total learning investment required to achieve the LCoE target. Therefore, as mentioned above, it is important that the assumptions for wave energy are updated as better data becomes available.

Limitations also exist in the implementation of step-change innovation in the modelling. Firstly, an assumption is made in the modelling that experience can be perfectly transferred from existing wave energy deployments to a new technology enabled by step-change innovation. As discussed in Section 3.1.2, it is unlikely all of this experience would be transferred in reality. Therefore, the modelling of innovation in parallel to deployment probably overstates the levels of cost reduction achieved. Secondly, the parameters used to construct the scenarios for step-change innovation have a high degree of uncertainty, again due to data availability. Additionally, for the step-change innovation scenarios, it is assumed that if a certain amount of investment and time are allocated to an innovation programme, a wave energy innovation will be developed. In reality, many innovation programmes do not yield successful technology innovations. Explicit consideration of the success rate of innovation programmes could be an interesting avenue of further work in this area. This would build on the sensitivity analysis presented in this work.

A final limitation is that learning investment analysis only considers technology costs and not benefits. Therefore, to properly evaluate the results, defining what a reasonable level of learning investment is to achieve cost-competitive wave energy would be beneficial. The development of other forms of renewable energy technology has required several hundreds of billions of EUR in deployment subsidy to achieve an LCoE similar to incumbent forms of electricity generation. Therefore, a learning investment in the range of tens to hundreds of billions of EUR may be considered reasonable for the wave energy sector's development. However, the case for subsidising present day wave energy may be less strong than, for example, the subsidisation of solar PV and onshore wind over the last four decades. An argument could be made that the availability of low-cost renewable energy alternatives at present and the limited wave energy resource (in comparison to technologies such as solar PV and wind) means that a lower level of total learning investment should be considered for the wave energy sector's development. Alternatively, the present need for a more rapid decarbonisation of our electricity supply could be an argument in favour of developing a larger portfolio of renewable energy technologies, such as wave energy, at a higher overall cost (incurring more learning investment). For this reason, identifying what constitutes a viable level of learning investment to bring about cost-competitive wave energy would be valuable to put these learning investment estimates into more context. Further work in this area could combine a high-level assessment of the total benefits (such as energy system and environmental benefits) of wave energy deployment in a certain region, with a learning investment analysis. This would allow a form of cost benefit analysis to determine the level of learning investment that is considered viable to enable low-cost wave energy.

Part B: Assessment of direct conversion technologies for wave energy applications

Research question for Part B:

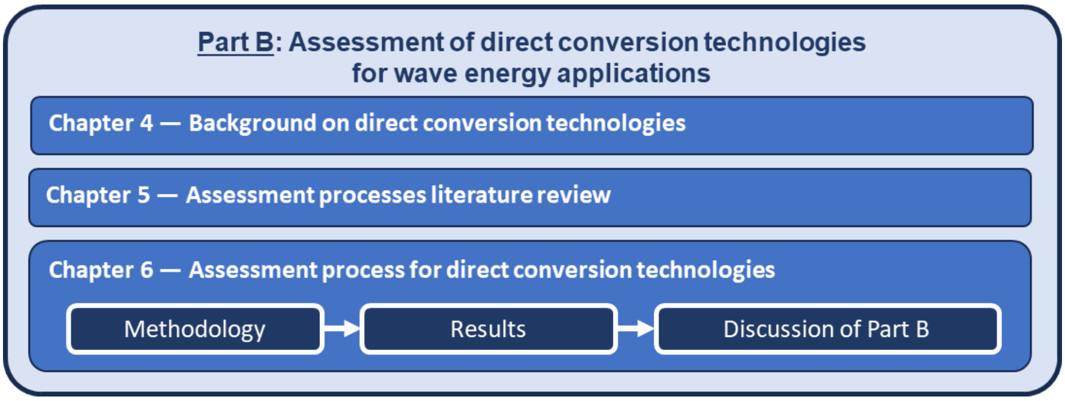
> *Does direct conversion offer an innovation opportunity for the wave energy sector? And how can the potential of different direct conversion technologies for wave energy applications be consistently assessed in a repeatable manner?*

Part A of this thesis highlight the large potential benefits of radical innovation for the wave energy sector. The results from Part A of the thesis showed that even relatively modest cost reductions through radical innovation had the potential to dramatically reduce the total learning investment associated with achieving cost-competitive wave energy. The modelling in Part A highlighted that innovation programmes can be considered good value as they offset their costs, through reducing subsequent learning investment. This is true even if individual innovation programmes have low success rates and therefore multiple programs have to be run to yield a successful innovation. Part B of this thesis follows on from this to explore a specific class of technology (direct conversion) which could potentially enable radical innovation in wave energy converter design.

Direct conversion technologies are a class of materials which can directly convert mechanical to other forms of energy. The use of these technologies in a wave energy application may have some potential benefits, including redundancy (through distributed power take-off), use in combination with flexible, low-cost structural materials and the reduction/removal of moving PTO parts that are most susceptible to failure [33]. Several direct conversion technologies (DCTs) have been developed to varying degrees of maturity in wave energy applications, including dielectric elastomer generators [32], triboelectric generators [127]–[129], piezoelectric generators [130] and magnetostriction generators [131]. However, there has been little work published which aims to develop a process to assess the underlying viability of different direct conversion technologies for wave energy applications. Only one (non-academic) study was identified which attempted to develop such a process [132]. This work builds upon this previous study and addresses several of its limitations (see Section 5.2).

The aims for Part B are to develop a repeatable process that can be used to assess the potential viability of one or more direct conversion technologies for wave energy applications. This process is designed to assess conversion technologies, rather than WEC concepts, it has therefore been designed to be WEC design-agnostic. Given that the main aim of this process is to remove non-viable options, a screening process was selected as the method of assessment. The screening process is based on a set of parameters where minimum acceptable levels of performance could be identified for a DCT, when considering its requirements in a wave energy application. The screening process developed in this research was then used to evaluate the viability of six DCTs for wave energy applications: dielectric elastomer generators (DEG); dielectric fluid generators (DFG); piezoelectric polymer generators; piezoelectric ceramic generators; triboelectric generators; and magnetostriction generators.

The structure of Part B of the thesis is shown below, with its three constituent chapters.



In Part B, Chapter 4 gives a brief review of the working principles of the technologies that were evaluated using the screening process. This chapter also briefly outlines the research that has been carried out in applying these technologies in wave energy applications to date. Following this, Chapter 5 presents a literature review of assessment processes for both wave energy (in general) and the assessment of DCTs for wave energy applications. This outlines key performance metrics and processes for wave energy, and previous work that has assessed DCTs for wave energy applications. Finally, Chapter 6 develops a screening process that builds on the metrics and assessment processes from Chapter 5. This covers the methodology of the screening process, describing the selection of assessment parameters and structure of the screening process. The results section then presents the outcomes of applying the screening process to a selection of DCTs. Chapter 5 concludes with a discussion of Part B, and recommendations based on the results from this chapter.

4 Background on direct conversion technologies

This chapter presents an overview of six direct conversion technologies (in four groupings) that were considered for the assessment process, along with their previous applications in wave energy. These technologies were identified through a scoping study commissioned by Wave Energy Scotland [132], with the addition of dielectric fluid generators, which were identified as a promising technology during the course of the research. The technologies that are assessed in this section are:

1. Dielectric conversion technologies:
    a. Dielectric elastomer generators
    b. Dielectric fluid generators
2. Piezoelectric conversion technologies:
    a. Ceramic piezoelectric generators
    b. Polymeric piezoelectric generators
3. Triboelectric conversion technologies
4. Magnetostriction conversion technologies

The first four sections of this chapter give a general background on each DCT, the operating principles, how the DCT is used in generators, and finally an overview of the common materials used for each DCT. The performance of the technologies is covered in Section 6.2. This structure is the same for each of the conversion technologies. The final section (4.5) gives a brief overview of research that has applied these technologies in wave energy applications.

4.1 Dielectric generation background

This section reviews both dielectric elastomer generators (DEGs) and less mature dielectric fluid generators (DFGs).

Dielectric elastomer actuators have been under development since the early 1990s [133]. However, their first reported application as generators was recorded in 2001 [134]. Dielectric fluid generators have seen far less research than dielectric elastomer generators, with only one study published in 2017 [135], known to the author. Dielectric actuation systems (such as HASEL actuators) have some early-stage commercial applications, notably in soft robotics.

4.1.1 Dielectric technologies operating principles

Dielectric elastomer generators (DEGs)

DEGs consist of a deformable dielectric material (the DE) sandwiched between compliant electrodes. Together, these form a variable capacitor [136]. The variable capacitance of a DEG is explained by the formula for capacitance of infinite parallel plates. This is shown in Equation 4-1, where C is the capacitance of the system, ε is the permittivity of the dielectric material between the electrodes, A is the surface area of the electrodes and h is the distance between the electrodes (note this equation is only accurate for high values of A/h).

$$C = \frac{\varepsilon A}{h}$$

Equation 4-1. *Capacitance of parallel plates.*

As the DEG is deformed, both the surface area (A) and distance between the electrodes (h) varies. This gives rise to the variable capacitance of the system. An equiaxial tensile stretch case for a disc of DEG is shown in Figure 4-1, where $h1$ and $A1$ represent the distance between electrodes and electrode surface area when the disc is un-stretched, and $h2$ and $A2$ represent the distance between electrodes and electrode surface area when the disc is stretched. Considering this case of equiaxial stretch, the DEG has the highest ratio of surface area (A) to distance between the electrodes (h) when it is in a stretched state (due to conservation of volume), hence the capacitance (C) is at a maximum.

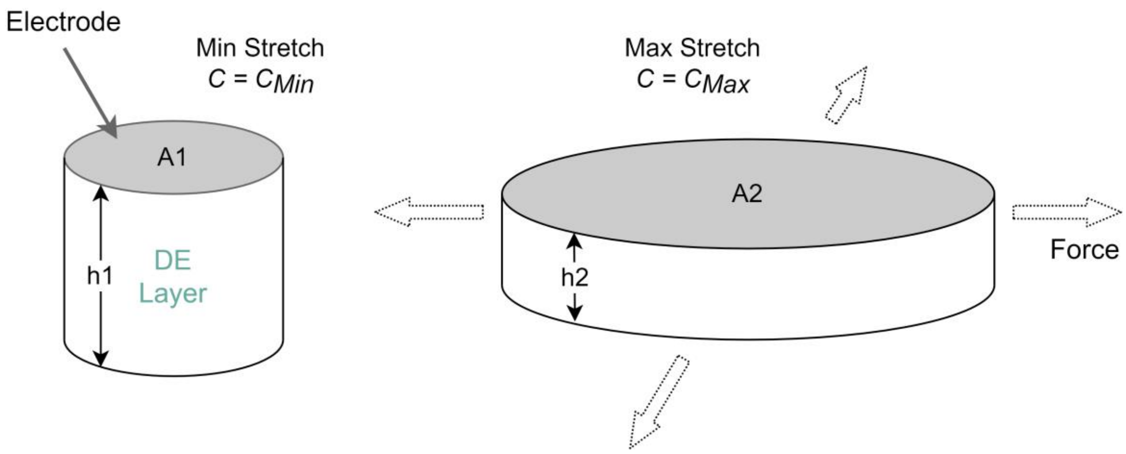


Figure 4-1. *Variable capacitance of dielectric elastomer, showing low capacitance in relaxed state and high capacitance in stretched state.*

To convert mechanical to electrical energy using a DEG, electrical charges must be deposited on the surface of the DE layer (on compliant electrodes) while it is in a stretched state. When the DEG is allowed to relax, the capacitance of the DE layer falls and the voltage is boosted between the electrodes, as shown in Equation 4-2, where V is voltage and Q is charge.

$$V = \frac{Q}{C}$$

Equation 4-2. *Voltage charge capacitance relationship.*

If most of the charge deposited on the electrodes is conserved through the process, then this increases the stored energy, enabling a net electrical energy output from the cycle [134].

Dielectric fluid generators (DFGs)

DFGs have the same basic operating principle of variable capacitance as DEGs. For DFGs however, one of the layers of dielectric material is a variable volume of dielectric fluid. For the DFG, a low capacitance configuration is obtained by pumping dielectric fluid between the electrodes, while a high capacitance state is obtained by removing this liquid. This is shown for an example DFG in Figure 4-2.

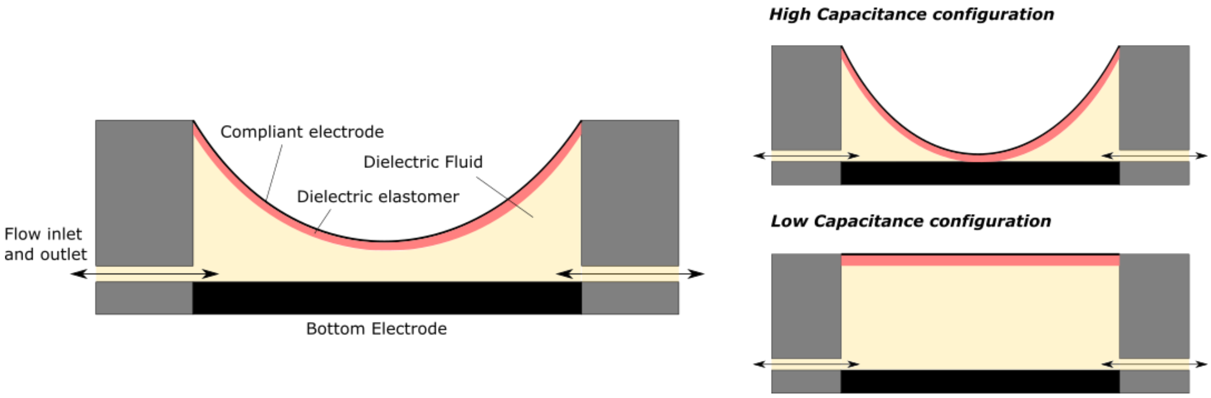


Figure 4-2. *Example dielectric fluid variable capacitor, based on Duranti et al.* [135].

Several architectures are possible for DFGs. They all have the following common properties [135]:

- Two or more electrodes, at least one of which is deformable (flexibility is required, but unlike DEGs, certain configurations do not require these electrodes to be stretchable).
- One or more layers of dielectric fluid.
- At least one non-conductive dielectric layer between the electrodes (to ensure there is not a short circuit in the high capacitance configuration). Again, flexibility is required, but in some configurations stretchability would not be required.

If the shape of the deformed membrane is known (top membrane in Figure 4-2) the total capacitance (C_{total}) of the stack of dielectric solid (DS) and dielectric fluid (DF) can be estimated by integrating over the flat electrode's surface (S) [135], as shown in Equation 4-3.

$$C_{total} = \int \frac{1}{\frac{h_{solid}}{\varepsilon_{solid}} + \frac{h_{fluid}}{\varepsilon_{fluid}}} dS$$

Equation 4-3. *Capacitance of dielectric fluid and elastomer stack.*

In in Equation 4-3, h is the thickness of the respective fluid or elastomer layer and ε is the permittivity of the respective fluid or elastomer. The term associated with the fluid layer ($\frac{h_{liquid}}{\varepsilon_{fluid}}$) will approach zero as the dielectric fluid is removed from the system. This means that the capacitance in the high capacitance configuration is almost entirely defined by the dielectric elastomer layer (provided the dielectric fluid is effectively removed).

4.1.2 Dielectric generators

Dielectric elastomer generators

An example of a DEG operating cycle is presented in Figure 4-3. This shows a cylindrical DEG being stretched in an equiaxial fashion. A constant charge control system is considered here, but other configurations are possible [136][137]. Four states (a, b, c, d) are shown in Figure 4-3 with transitions (T1, T2, T3, T4) between the states. The cycle can be described in terms of these four transitions:

- T1 (stretching) At State a, the DEG is at its minimum stretch position with no charge on the electrodes, and the capacitance is at its minimum value. Mechanical energy is then input to deform the DEG to a maximum stretch at State b, where the capacitance is at its maximum value.
- T2 (charging) During this stage, charge is deposited on the electrodes of the DEG while it is held in its maximum stretch. Once fully charged, the DEG is at State c.
- T3 (relaxing) The DEG is then allowed to relax while still charged. This reduces the DEG's capacitance, boosting the voltage between the electrodes. Once fully relaxed, the DEG is at State d.
- T4 (discharging) Charge is off-taken through an external circuit at a higher voltage than when it was deposited on the DEG (during P2). This then returns the DEG to State a.

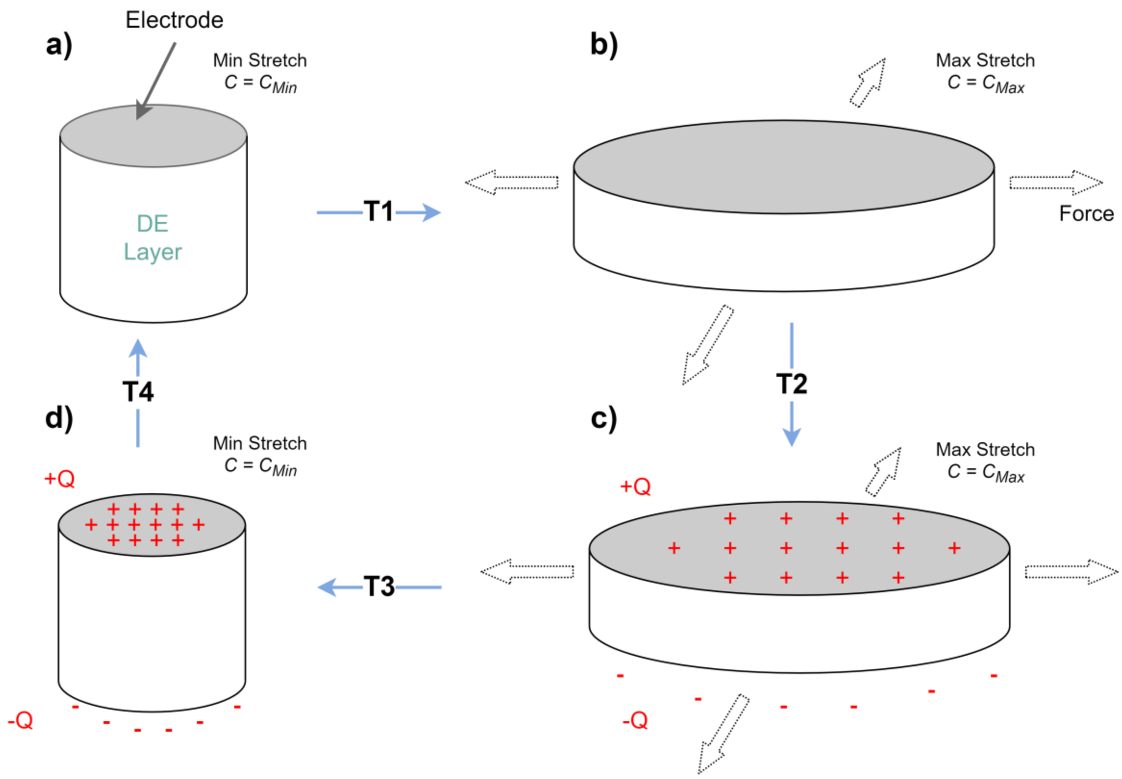


Figure 4-3. *Illustrative DEG working cycle based on Moretti et al.* [136]. *This shows a) relaxed uncharged DEG b) stretched uncharged DEG c) stretched charged DEG d) relaxed charged DEG.*

For this cycle, the net electrical energy output is the difference between the energy used to deposit the charge on the electrode during T2 and the energy taken off during T4. The net mechanical energy input is the difference between the mechanical energy used to stretch the DEG (T1), and the mechanical energy output as the DEG relaxes (T3) (assuming the elastic energy can be recovered). Not all the charge that is deposited on the electrodes will be extracted from the DEG during T4. Electrical losses occur as the DE layer has finite resistivity and the electrodes have finite conductivity. If the charge losses are sufficiently large, the electrical input will exceed the electrical output and the DEG will not generate a net energy output [138]. Mechanical hysteresis losses also occur as the DEG is stretched and relaxed. These loss mechanisms are addressed thoroughly in the literature [32], [136], [139].

The maximum energy density of DEGs is explored in several studies. Shian et al. [137] provide a good explanation of the boundary conditions to DEG energy density. Moretti et al. [136] present three simplifications which allow a quick estimation of the maximum theoretical energy density of different dielectric materials:

1. The distribution of stretches on the DE membranes is uniform.
2. The DEG is deformed between two limit stretches (its minimum and maximum stretch) without being affected by any electromechanical instabilities.
3. The breakdown electric field for the DE is constant and does not vary with stretch.

Given these assumptions, the maximum electrical energy (E_e) that can be generated in a cycle is defined by Equation 4-4 and Equation 4-5 — where ε is the dielectric permittivity of the DE layer, Ω is the volume of the DE layer, E_{BD} is the breakdown electric field strength of the DE layer, and f_g is a parameter dependent on the ratio of stretch on the DEG between in its maximum and minimum stretch configurations. In Equation 4-5, λ_1 is the stretch along the first stretch axis and λ_2 is the stretch in the orthogonal axis (multiplied together they give area strain). It should be noted that these equations describe an idealised charging and discharging cycle. The energy outputs for other charging cycles (which are more realistic for real world implementation) are given in Moretti et al. [136].

$$E_e = \Omega \varepsilon E_{BD}^2 f_g$$

Equation 4-4. *Maximum energy output from DEG generation cycle.*

$$f_g = \ln \frac{(\lambda_1 \lambda_2)_{Max}}{(\lambda_1 \lambda_2)_{Min}}$$

Equation 4-5. *Geometric parameter describing DEG strain.*

From these equations it can be seen that there are several parameters that should be maximised (while minimising electromechanical losses) in order to maximise energy density per cycle. Electrical breakdown strength is the parameter that energy density is most sensitive to, while permittivity is directly proportional to energy density. In terms of geometric considerations, configurations that give the greatest stretch in both x and y planes result in the largest capacitance change, and therefore the highest energy density per cycle. An overview of these geometric considerations for DEG energy generation cycles is given in Moretti et al. [136].

Dielectric fluid generators

In the same way as a DEG, a DFG energy harvesting cycle can be described as a four-stage process [135]. This harvesting cycle considers an elastic DE membrane, although flexible non-elastic materials could also be used in DFGs. The four-stage cycle is shown with four states (a, b, c, d) and four transitions (T1, T2, T3, T4) in Figure 4-4 and is described below:

- T1 (deflating) At State a, the DFG has the maximum dielectric fluid between the electrodes, and the capacitance is at its minimum value. Mechanical energy is then input to remove the fluid from between the layers. The DFG then reaches State b, where the minimum fluid is between the layers and the capacitance is at its maximum value.
- T2 (charging) During this stage charge is deposited on the electrodes of the DFG while the capacitance is at its maximum value.
- T3 (inflating) Mechanical work is then used to pump dielectric fluid between the electrodes. This decreases the capacitance of the stack between the electrodes, boosting the voltage and electrical energy stored in the DFG.
- T4 (discharging) The charge is then harvested from the electrodes at a higher voltage, resulting in an electrical energy gain.

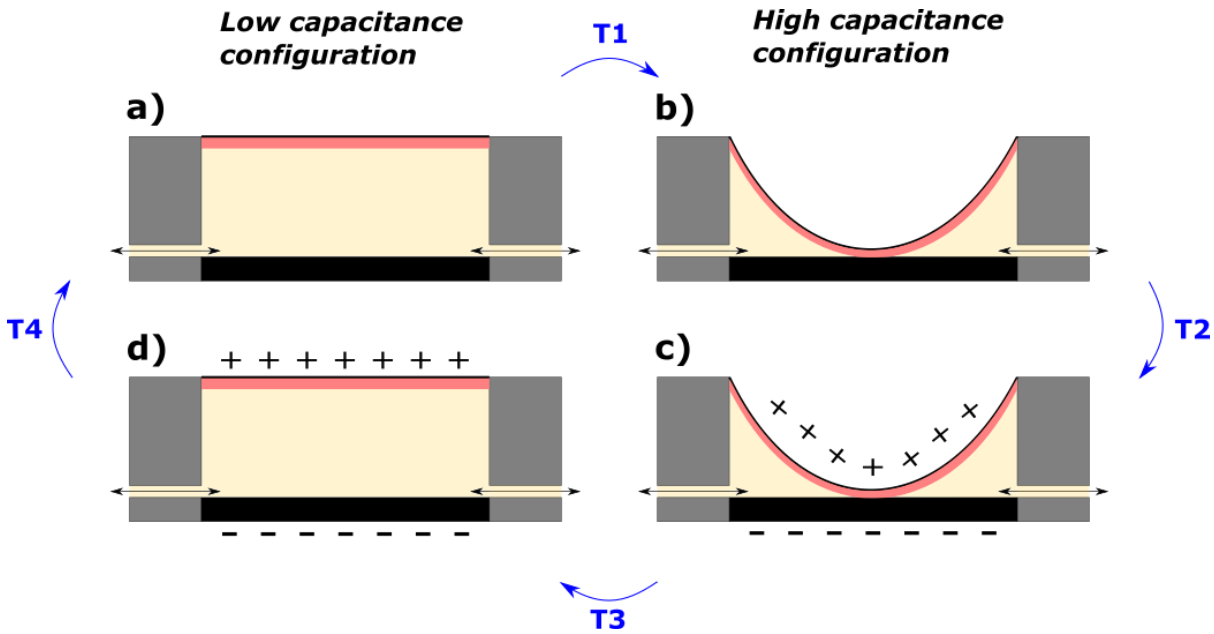


Figure 4-4. *Illustrative working cycle for a dielectric fluid generator based on Duranti et al.* [135]. *This shows a) high fluid volume uncharged DFG b) low fluid volume uncharged DFG c) low fluid volume charged DFG d) high fluid volume charged DFG.*

Mechanical energy is input in both the inflation (T3) and deflation (T1) parts of the cycle. The net electrical output is the electrical energy output during T4 minus the electrical energy input in T2. As with DEGs, electrical losses occur due to the finite resistivity of the DS and DF layers (resulting in charge leakage) and conductivity of the electrodes. In addition to mechanical losses (viscous or viscoelastic) in the dielectric solid, viscous mechanical losses also occur in the dielectric fluid as it flows in and out of the chamber. Some of these loss mechanisms are considered in Duranti et al. [135].

The energy output of a DFG system is estimated in Duranti et al. [135]. It should be noted that Duranti et al. assumed that the dielectric fluid layer is stressed more than the elastomer layer (owing to typically lower permittivity) and has a lower E_{BD}. Therefore, the fluid is considered the limiting factor in terms of operating electric field. Recent work in dielectric fluid actuators has suggested that this approach may significantly underestimate the electric field limit, and therefore the energy density of DFGs[9]. If it is assumed the cycle is operated at a constant voltage, the energy harvested in a cycle (E_e) in the absence of losses is a function of the capacitances at State c ($C3$) and State d ($C4$), and the voltage (V) at which the cycle is operated. This is described in Equation 4-6.

$$E_e = (C_3 - C_4)\frac{V^2}{2}$$

Equation 4-6. *Maximum energy output of DFG generation cycle operated at constant voltage.*

Assuming the capacitance in State d ($C4$) is negligible compared to the capacitance in State c ($C3$), the following upper limit[10] can be defined for the system's electrical energy output. This is shown in Equation 4-7.

$$E_e = \frac{(\varepsilon_{fluid} \times E_{BDfluid})^2}{2\varepsilon_{solid}}\ \Omega_{solid}$$

Equation 4-7. *Maximum energy output of DFG generation cycle (assuming negligible capacitance in State c).*

Where Ω_{solid} is the total volume of dielectric elastomer, E_{BD} is the breakdown strength of the respective material and ε is the permittivity of the respective material. This gives a similar set of parameters to DEGs that need to be optimised for a maximum energy harvesting cycle, namely increasing the permittivity and E_{BD} of the DF and DE.

4.1.3 Dielectric generator materials

Dielectric elastomer generators

In general, for DEGs three classes of polymeric material have seen use in the literature: Acrylic elastomers; Silicone elastomers; and natural rubbers. The use of styrene-based rubbers has been proposed [140], but these appear to be largely untested. The majority of DEG experimentation to date has utilised acrylic DE layers [136]. Acrylic DE has several properties that are less suitable for use in low frequency DEG systems than natural rubber or silicone

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[9] There is now some experimental evidence that there is a shielding effect when a dielectric polymer is placed between the electrodes and the dielectric liquid. This can allow the liquid to survive electric fields significantly above their quoted E_{BD} [149]. As the energy density is proportional to the stack's E_{BD}^2, this means that the theoretical energy density of DFGs could be significantly higher if it is not limited by the E_{BD} of the liquid (this limit is assumed in Equation 4-7). Personal communication with an expert in dielectric generators/actuators suggested that, due to this shielding effect, the true theoretical energy density of DFGs could be as high, or higher than that of DEGs, depending on the employed materials [292].

[10] Note that the electrical breakdown limit is probably conservative - see footnote 9.

elastomers[11]. The literature suggests that acrylic is more suited to laboratory and prototype experiments, while large-scale commercial energy harvesting applications are more likely to utilise either silicone elastomers or natural rubber [141], [142]. A comparison of acrylic to natural rubbers is made in Kaltesis et al. [142], which finds that natural rubbers can give theoretical energy densities almost three times greater than acrylic elastomers. However, silicone has benefits including, lower stiffness, lower mechanical hysteresis and availability of commercially manufactured films specifically for dielectric elastomer applications. Table 4-1 presents the key characteristics of these materials (adapted from Moretti et al. [136]).

Table 4-1. *Material properties for common dielectric materials. Adapted from Moretti et al.* [136] *with additional data from* [141], [143]–[148].

Properties	Units	Acrylic (VHB 4905)	Natural rubber (Oppo Band)	Silicone (Elastosil)
εE_{BD}^2	J/cm^3	0.2-1.2	0.2-2.2	0.1-1
Relative permittivity	$\varepsilon/\varepsilon_0$	4.14	2.74	2.85
E_{BD}***	kV/mm	70-180	100-300	75-195
Conductivity	pS/m	1-5	0.1-0.4	0.0005-0.05
Mechanical loss ****	%	12-17	4-23	2-4
Density	kg/m^3	960	930*	~1000**
Shear modulus	GPa	17	620	308
Tensile strength	Mpa	0.69	31	10.3
Elongation at break	%	820	510	550

*Average density for unvulcanised natural rubber from MatWeb (accessed 06/09/2021).
**Typical value for synthetic rubbers.
***Ranges account for varying stretches or voltage wave-forms during the tests [136], [141].
****Ranges account for varying strain ranges and strain rates during testing [136], [141].

Dielectric fluid generators

The dielectric solid materials that have been utilised to date in DFGs are the same as those used in DEGs. However, in theory, there is no requirement to use stretchable materials for certain DFG configurations. This opens up the potential to use several dielectric polymers with higher resistance to electrical breakdown, for instance BOPP has an E_{BD} of ~700 kV/mm and has already been demonstrated in dielectric fluid actuators [149]. Utilisation of these materials in DFGs may significantly improve achievable energy densities of DFG systems. The selection of the fluid, however, is also important for the system's performance. The research in DFGs is at an early stage, and is yet to converge on a commonly used set of DF or DS materials (although ester has been used successfully with both PDMS [150] and BOPP [149]

[11] It has a lower breakdown strength than natural rubber, experiences higher hysteresis losses, and is more conductive (resulting in higher electrical losses) than either natural rubber [142] or silicone elastomers [136]. The low RC time constant (effectively a measure of how quickly the DE will discharge due to its capacitance and internal resistance) in acrylic elastomers results in high charge losses at low frequency operations in comparison to natural rubber or silicone elastomers [141].

in dielectric fluid actuators). In general, fluids with high breakdown strengths and permittivity are desirable to maximise the electrical energy output, while low viscosity fluids will reduce viscous losses. The solid dielectric layer should have the same electrical properties that are favourable in a dielectric elastomer generator, although in some potential DFG configurations they are not required to be stretchable. The compatibility of the fluid with elastomer dielectrics (or the electrodes) is also important, as they will be in direct contact in a DFG system. Table 4-2 (which is adapted from Duranti et al. [135]) shows the properties of dielectric fluids that may have potential use in DFG systems.

Table 4-2. *Properties of dielectric fluids. Adapted from* [135] *with additional density data from* [151], [152] *and data from actuation experiments from* [149], [150].

Properties	Units	Silicone oil	Mineral oil	Ester
Density*	Kg/l	960	880	970
Relative permittivity	ε/ε0	2.7	2.2	3.2
E_{BD}	kV/mm	30-45	39	45
$\varepsilon_{fluid} E^2_{BDfluid}$	kV/mm	81-121	86	144
Conductivity	pS/m	0.1	10	300
Compatibility	Compatible solid dielectric materials	Synthetic rubber, Natural rubber, Silicone elastomer, Acrylic elastomer	Acrylic elastomer (possibly)	Silicone elastomer, Acrylic elastomer (possibly) BOPP [149] PDMS [150]

*At 25°C.

4.2 Piezoelectric generation background

The piezoelectric effect was discovered in the 1880s by the Curie brothers [153]. Currently, piezoelectric materials have a variety of commercial applications in the consumer electronics, medical imaging, industrial and military sectors [154]. Substantial research has been carried out into energy harvesting using piezoelectric generators, largely at the sub-watt scale [155], although at present commercial energy harvesting applications seem to be limited.

4.2.1 Piezoelectric operating principles

Piezoelectric materials are materials which exhibit a coupling between surface charge and mechanical strain.

The piezoelectric effect is shown in Figure 4-5. In a) the piezoelectric crystal is in an undisturbed state. In this state, the overall centres of the positive and negative charges for the molecule coincide, resulting in an electrically neutral molecule [153, p. 200]. Due to the arrangement of the atoms in the molecule, when it is strained the centres of positive and negative charge are separated (in the diagram, the centre of negative charge is shifted to the right, and centre of positive charge shifted to the left). This results in the molecule developing dipoles in response to strain [153, p. 199] which is shown in b) in Figure 4-5. Neighbouring molecules in a piezoelectric material form local areas of alignment called domains[12]. If these domains are aligned (through poling), the bulk piezoelectric material will exhibit the piezoelectric effect, as shown in c) of Figure 4-5 [156, p. 41]. The magnitude of the surface charge density resulting from the piezoelectric effect is known as the piezoelectric polarisation (P). The change in this surface charge with respect to change in material strain (induced by mechanical stress) can be utilised in a piezoelectric generator if electrodes are connected to the piezoelectric material's surface [153, p. 203]. The piezoelectric effect can also work in reverse, as an applied electrical field (E) induces a strain in a piezoelectric element (inverse piezoelectric effect) [156, p. 41].

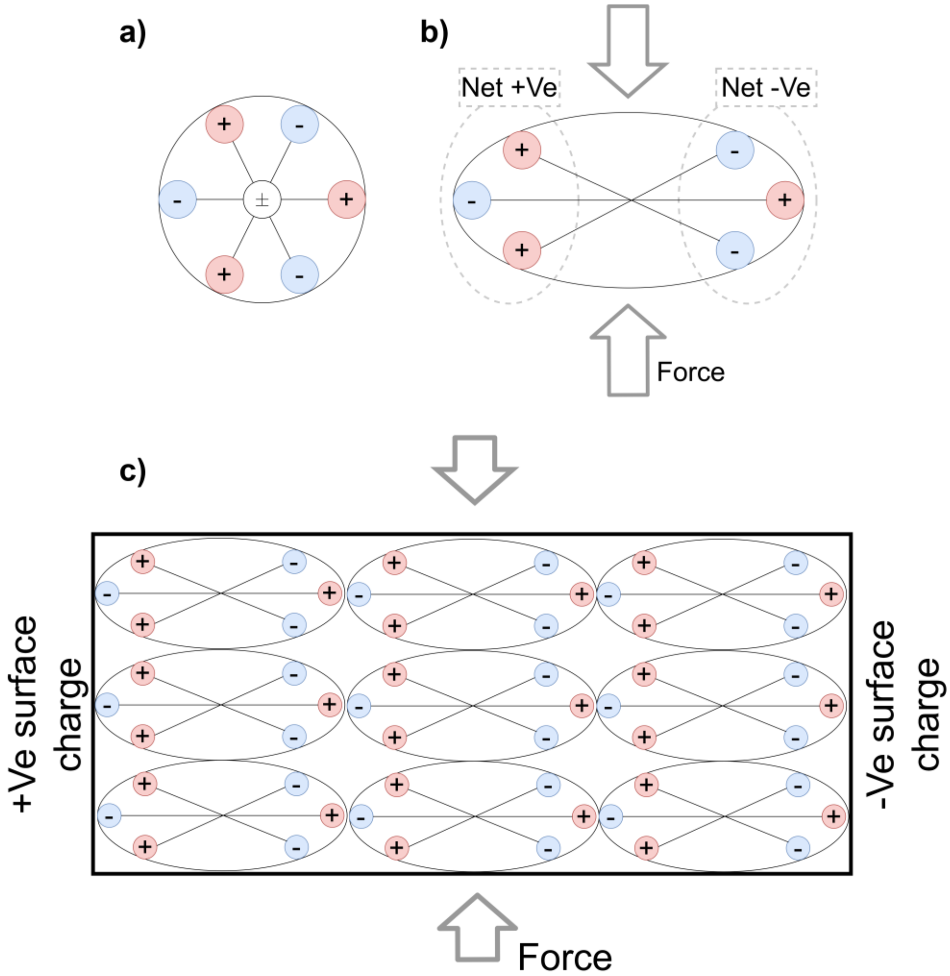

Figure 4-5. *Piezoelectric effect, based on Dahiya and Valle* [153, p. 199]*. This figure shows a) an undisturbed molecule without any piezoelectric polarisation b) piezoelectric polarisation when an individual molecule is subjected to an external force c) the effect of this polarising effect on the surface of a bulk piezoelectric material.*

[12] These domains are usually randomly orientated in a bulk material, resulting in a negligible overall piezoelectric effect [241]. However, they can be aligned through a process called poling, where a strong electric field is applied to the material [293]. This allows the material to develop a net polarisation when strained. A good diagram of the poling process is presented in [130].

In a simplified form (without directional notation) the following equations[13] can be written that describe the relationship between mechanical and electrical behaviour in a piezoelectric material, accounting for both the direct and inverse piezoelectric effects [156, p. 42].

$$\lambda = T/Y + dE$$
$$D = \varepsilon E + dT$$

Equation 4-8. *Piezoelectric electrical and mechanical coupling (without directional notation).*

In Equation 4-8, E is electrical field strength, D is dielectric displacement, T is mechanical stress, λ is mechanical strain, Y is young's modulus, ε is dielectric permittivity and d is the piezoelectric strain constant. The piezoelectric strain constant describes the degree of polarisation that occurs per unit stress applied to the piezoelectric material [153, p. 203]. A key parameter that can be derived from these equations is the coupling coefficient. The coupling coefficient (k^2) describes the effectiveness with which the piezoelectric material converts mechanical strain energy into electrical energy without losses [157]. This can be thought of as the maximum conversion efficiency of a piezoelectric material when operated far from resonance (see Crossley and Kar-Narayan [157]). Equation 4-9 defines the coupling coefficient (without directional aspects) [156, p. 46].

$$k^2 = \frac{Yd^2}{\varepsilon}$$

Equation 4-9. *Piezoelectric coupling coefficient (without directional notation).*

As mentioned above, the piezoelectric element is poled in a certain direction. This means that their response favours a certain direction. Discussion regarding the directional components of the piezoelectric generator in a wave energy context is covered in Jbaily and Yeung [130].

4.2.2 Piezoelectric generators

To utilise the change in this surface charge, electrodes can be attached to either side of the piezoelectric element which are in turn connected in a circuit. A simple piezoelectric generator is shown in Figure 4-6.

[13] The nomenclature for mechanical stress and strain has been changed to be consistent with the other equations in this section.

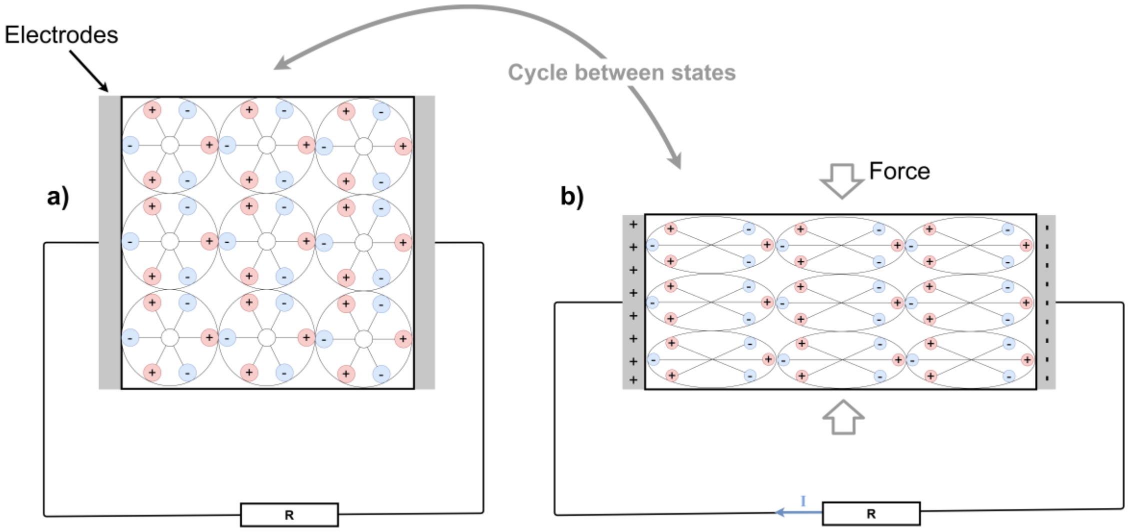

Figure 4-6. *Simplified piezoelectric generator. Based on Dahiya and Valle* [153, p. 199]*. This figure shows a) unstrained piezoelectric element with neutral surface charge b) strained piezoelectric element with surface charges (current flows through circuit to the electrodes to balance these surface charges).*

When the piezoelectric material is in State a, it is unpolarised, and there is no charge on the electrodes. When the piezoelectric element is strained, it moves to State b, where the material becomes polarised creating a surface charge density on the surfaces that are in contact with the electrodes. A current will then flow through the external load (R), extracting electrical energy, to neutralise these surface charges [153]. Cycling between these two states therefore creates a simple generator. A more detailed description of piezoelectric generation cycles, including the use of switching between open and closed circuits to maximise energy output per cycle, is given by Crossley and Kar-Narayan [157]. Losses will occur due to mechanical hysteresis and leakage currents, but it is noted by Crossley and Kar-Narayan [157] that there appears to be little quantitative data on these loss mechanisms in the literature. Excluding loss mechanisms, the maximum electrical output of a piezoelectric element can be simplified into the following equation [156, p. 45].

$$E_e = \frac{k^2 {T_y}^2}{2Y} \Omega$$

Equation 4-10. *Maximum energy output from piezoelectric generation cycle.*

In Equation 4-10, Ω is the volume of piezoelectric material, E_e is electrical energy, T_y is yield stress and the other symbols have the same meanings as in Equation 4-8 and Equation 4-9. From Equation 4-10, the parameters that determine the energy density of a piezoelectric generator are the piezoelectric materials' coupling coefficient, the mechanical stress that is applied, and the material stiffness. This applied stress is limited by the yield stress of the material, which cannot be exceeded.

4.2.3 Piezoelectric generator materials

A large number of materials exhibit some form of piezoelectricity [158]. However, in energy harvesting applications the most commonly used materials are either piezoelectric ceramics (notably PZT) and polymers (notably PVDF) [155]. Several other classes of piezoelectric material exist, including composites where ceramic piezoelectric material is embedded in a passive polymer matrix and single crystal piezoelectric materials.

In general, ceramic piezoelectric materials have higher coupling coefficients and energy densities than polymeric piezoelectric materials. However, piezoelectric polymers have better material properties for energy harvesting, such as higher tensile strength and flexibility compared to the weak and brittle ceramics. Composite piezoelectric materials present a middle ground between the higher performance ceramic piezoelectric materials and better material properties of polymer piezoelectric materials. Single crystal piezoelectric materials can give higher energy densities than PZT (by a factor of around 10). However, these are highly expensive and can only be produced in very small sizes [156, p. 54]. The two most commonly used ceramic and polymeric piezoelectric materials for generator applications are summarised in Table 4-3. In Table 4-3 the directional components for the piezoelectric strain coefficient and piezoelectric coupling coefficient are denoted by the subscripts. For an explanation of directional notation for piezoelectric materials see Jbaily and Yeung [130].

Table 4-3. *Summary of piezoelectric materials, data from* [156, p. 53], [159]–[161].

Properties	Units	PZT (ceramic)	PVDF (polymer)
k_{33}	CV/Nm	0.75	0.16
Maximum electrical energy density (theoretical)	J/kg	7.4	0.035
Density	kg/m^3	7600	~1700
Elastic modulus	GPa	50	3
Tensile strength	MPa	20*	52
Elongation at break	%	<1	135**

*Compressive strength, tensile strength extremely low for ceramics.
**Average from MatWeb for PVDF (accessed 06/09/2021).

4.3 Triboelectric generation background

While the triboelectric effect has been observed for over 2000 years, the first triboelectric series (that ranks the triboelectric effect in different materials) was produced in the mid-18th century [162]. Triboelectric generators are, however, still at a very early stage in their development, having only been demonstrated in 2012 [163], and still without commercial applications.

4.3.1 Triboelectric operating principles

The triboelectric effect is when equal opposite static surface charges occur at the interface between two different triboelectric materials that are brought together in friction (this can be two solids or a liquid and a solid). Any two materials exhibit the triboelectric effect when brought into contact [34]. Materials that are further apart on the triboelectric series have a higher tendency to gain/lose electrons when brought into contact, creating a greater surface charge density. Material processes that increase the contact area, or pairing a solid triboelectric material with a liquid triboelectric, also effect the level of surface charge separation that occurs between the two materials [164]. However, while triboelectricity can be measured, the underlying mechanism is still not fully understood [164], [165], and a standardised quantitative way of defining the triboelectric series has only recently been proposed [34].

Once two materials have been brought into contact, they can then be separated using mechanical work. The basic principle of triboelectricity is shown in Figure 4-7 (surface charge density denoted as σ).

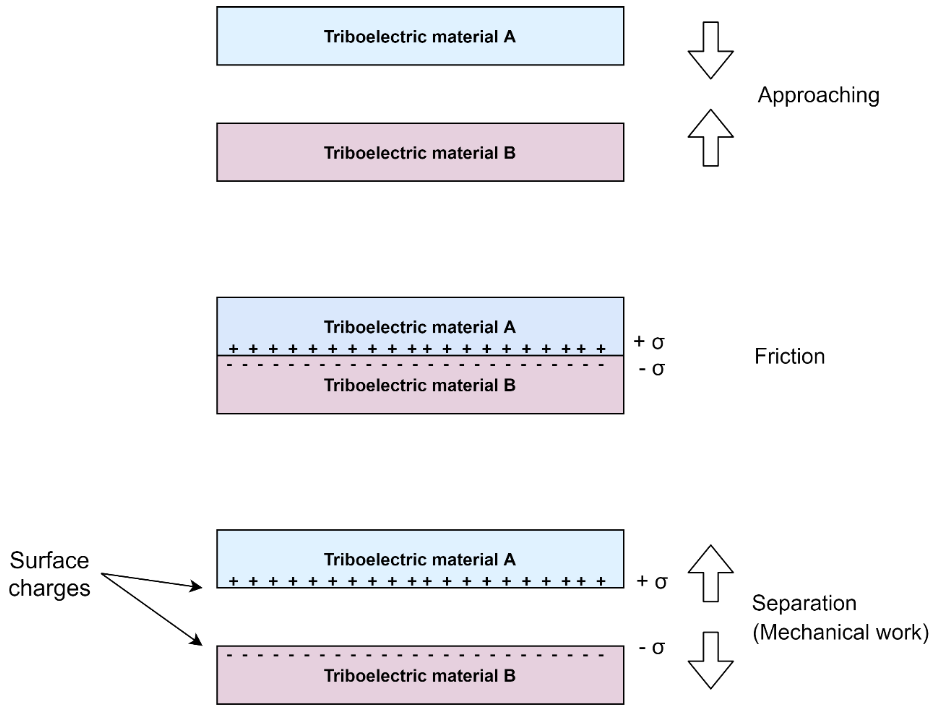

Figure 4-7. *The triboelectric effect. Contact between materials separated in the triboelectric series results in equal and opposite surface charges.*

The capacitances of the dielectric layers in a triboelectric generator are shown in Figure 4-8, where C_1 and C_2 are the capacitances of the triboelectric layers and C_3 is the capacitance of the air gap. The open circuit voltage between the two triboelectric layers is increased during separation due to the decrease in capacitance of the air gap between the charged triboelectric surfaces (see Equation 4-2 - note that the dielectric layer is air in this case).

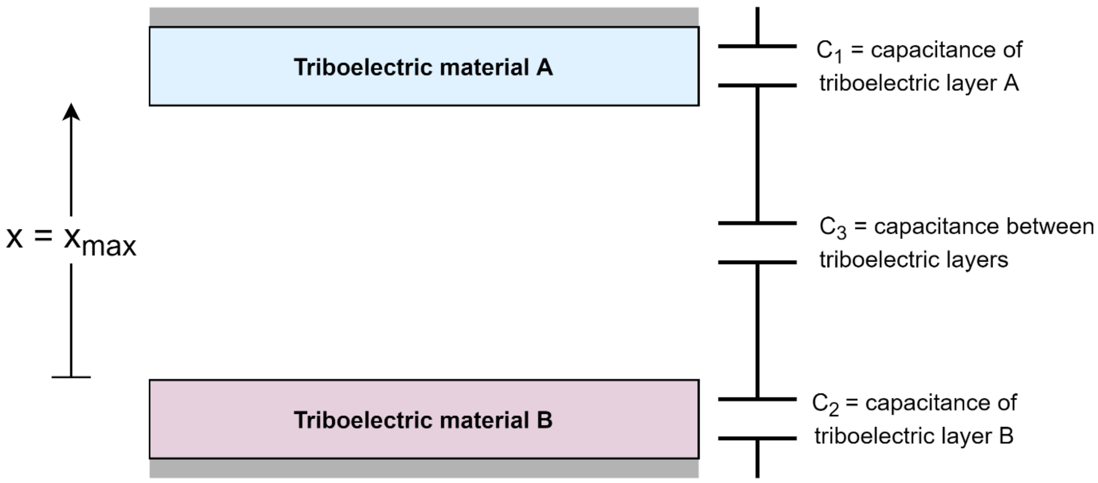

Figure 4-8. *Capacitances of triboelectric layers and air gap between layers, based on Zi et al.* [166].

The working principles of triboelectric generators share similarities with dielectric generators, as they both utilise variable capacitance to increase the electric potential of surface charges. As the air gap (x) is the varying dielectric layer in a contact separation triboelectric generator (see Figure 4-8), this means the operating electric field strength and dielectric permittivity is lower compared to DEG or DFGs[14]. While their theoretical energy density is difficult to define (as Section 4.3.2 explains), the difference in breakdown strength and permittivity would suggest that it is highly unlikely that configurations where air is the dielectric layer would have comparable maximum energy densities to DEG or DFGs.

4.3.2 Triboelectric generators

To use the triboelectric effect to generate electricity, the back sides of the triboelectric layers need to be connected to an electrode and a circuit. As all materials show a degree of triboelectricity when brought together, one of the electrodes can also serve as half or the triboelectric pairing if there is at least one layer of dielectric material between the electrodes during contact. This circuit allows charges to flow between the two electrodes when induced by the potential difference generated by the separation of the surface charges on the triboelectric layers. Triboelectric generators therefore work by combining the triboelectric effect and electrostatic induction [163]. In this section the figures describe a contact separation system architecture for a triboelectric generator. It should be noted that four fundamental modes of triboelectric generator have been identified [167]. For further explanation of the operation of these four modes of triboelectric generator, the reader is directed to Wang et al. [167], and for an analysis of the relative performance of different modes of triboelectric generator see Zi et al. [166].

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[14] The E_{BD} of air is ~3 kV/mm compared to >100 kV/mm for dielectric elastomers, relative permittivity of DE's ≥2.7. This is less applicable to LS or contact mode FS triboelectric generators as the triboelectric layers are in direct contact. However, the maximum theoretical energy densities of these modes of triboelectric have also been shown to be low (see Appendix B.1 — Energy density of triboelectric generators).

A simple energy harvesting cycle for a contact-separation type triboelectric nanogenerator is shown in Figure 4-9.

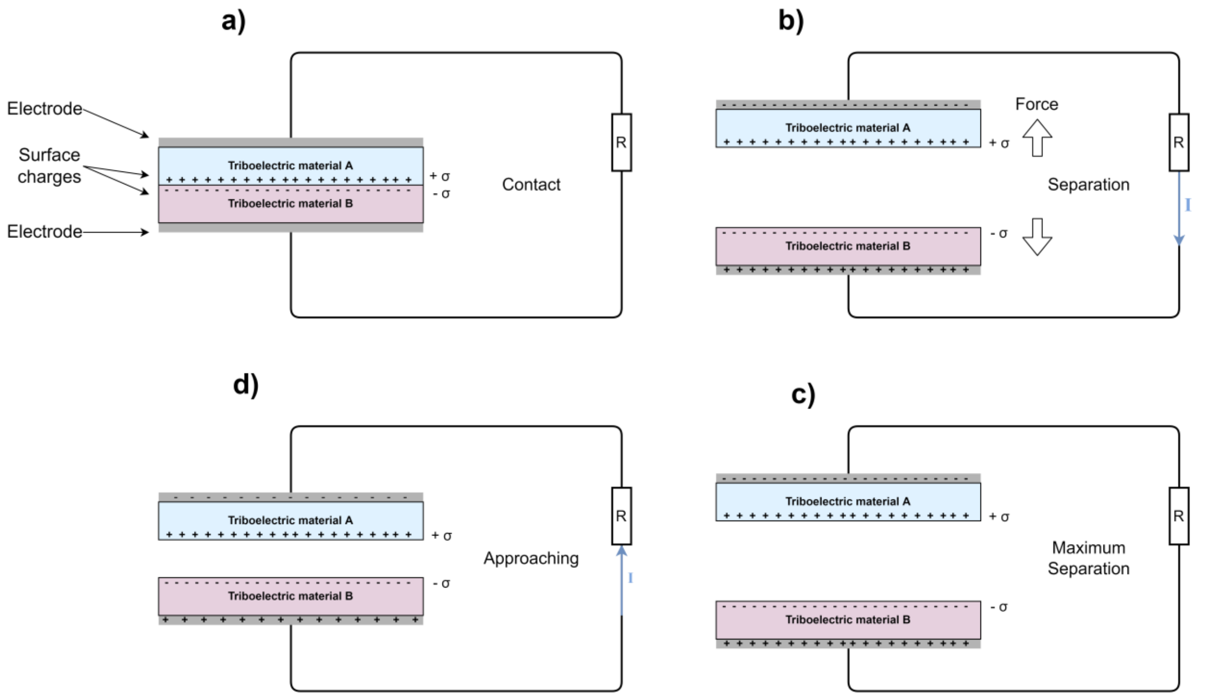

Figure 4-9. *Triboelectric generator, based on Zhu et al.* [168]*. This figure shows a) triboelectric layers are brought into contact, resulting in surface charge separation b) the triboelectric layers are brought apart from one another, inducing a current to flow to the electrodes though the circuit c) the triboelectric layers have reached maximum separation, and the maximum charge is held on the electrodes d) the triboelectric layers are brought back together, and the charge on the electrodes falls, with a current flowing in the opposite direction through the circuit.*

First, the two triboelectric materials are brought into contact. Surface charges appear on the two triboelectric materials due to the triboelectric effect, shown as State a in Figure 4-9. In State b, mechanical work is used to separate the two layers. This increased separation induces a voltage between the triboelectric layers, which induces a current flow between the electrodes [167] through the load (R), extracting electrical energy. At State c, the triboelectric plates have reached maximum separation, and the maximum charge is on the electrodes. As the plates are brought back together — State d — the voltage between the two triboelectric materials falls, and the current flows back through the load (R) in the opposite direction. In the literature there is little analysis of specific loss mechanisms during triboelectric generation. However, these will include mechanical losses through friction and electrical losses due to charge leakage across the triboelectric materials, and resistance of the electrodes.

Zi et al. [169] describe the maximum energy harvesting cycle for a triboelectric generator. The maximum theoretical energy output of a triboelectric generator is limited by three parameters which are discussed in detail in Zi et al. [169]:

- The maximum open circuit voltage $\left(V_{OC_{Max}}\right)$ - this is the maximum open circuit voltage achieved between the triboelectric layers (i.e. the voltage at maximum separation with an open circuit).
- The maximum short circuit transferred charge $(Q_{sc_{Max}})$ - this is the maximum charge that could be transferred between the electrodes with a closed circuit (i.e. at maximum separation with a closed circuit).
- The maximum achievable absolute voltage (V'_{Max}) - this is the maximum voltage between the electrodes when the charge is at $Q_{sc_{Max}}$ (i.e. at minimum separation with an open circuit).

The equation governing maximum theoretical electrical energy output of a triboelectric generator is shown in Equation 4-11. Note that this is maximum energy output rather than density.

$$E_{e_{max}} = \frac{1}{2} Q_{sc_{Max}} (V_{OC_{Max}} + V'_{Max})$$

Equation 4-11. *Maximum energy output from triboelectric generation cycle.*

The values of $Q_{sc_{Max}}$, $V_{OC_{Max}}$ and V'_{Max} vary based on triboelectric generators' geometry, maximum separation of the triboelectric layers, the mode of operation (e.g. contact separation), capacitance of the triboelectric layers and the level of triboelectric effect between the layers. Zi et al. [166], [169] describe these parameters for different triboelectric generator modes. However, all three of the parameters in Equation 4-11 are proportional to the surface charge density (σ), and therefore the total energy harvested is proportional to σ^2 [169]. For this reason, utilising materials that are far from each other on the triboelectric series will increase energy output. Ultimately, the maximum energy density of a contact-separation type triboelectric generator will be limited by the E_{BD} of the air gap [170] (which, as discussed earlier, is significantly lower than the dielectric materials used in DEs or DFGs). The maximum energy density of various configurations of triboelectric generator are modelled by Fu et al. [170] and also discussed in Appendix B.1 — Energy density of triboelectric generators.

4.3.3 Triboelectric generator materials

Any two materials will produce a degree of triboelectric charge separation when brought together in friction. As described above, the maximum energy harvested from a triboelectric generator is a function of the surface charge density. For this reason, selecting materials that are far apart in the triboelectric series is advantageous for the design of triboelectric generators.

The commonly used materials are polymers that display high triboelectric charge separation. Such commonly used materials include Kapton, PTFE, Nylon, FEP, PET, PDMS and silicone [127], [165], [171], [172]. Depending on the mode of operation, one of these materials is either paired with a second dielectric triboelectric layer (ideally far apart on the triboelectric series) or an electrode (commonly copper or aluminium [169], [173], [174]). Classes of solid/liquid triboelectric generators have been trialled using a liquid metal (Gallium or Galinstan were used in Zi et al. [169]) that served as the second electrode and triboelectric layer. In these experiments, the solid/liquid triboelectric materials demonstrated significantly higher charge separation than the equivalent materials in a solid state [169]. However, as most experiments are conducted using solid-solid triboelectric layers, these are considered in the table of common material properties.

Table 4-4. *Material properties for common triboelectric materials, data from* [34], [175]–[178].

Properties	Units	Kapton	PTFE	FEP	PDMS
Maximum electrical energy density (theoretical)	J/kg	Dependent on configuration			
Standardised triboelectric effect*	μC/m^2	-93	-113	N/A	-102
Density	kg/m^3	1460	2150	2040	970
Elastic modulus	GPa	4.8	2.8	0.42	0.36-0.87
Tensile strength	Mpa	310	22	24	2.24
Elongation at break	%	55	220	330	/

* as defined by Zou et al. [34], where mercury is used as the second triboelectric material.

4.4 Magnetostriction generation background

The magnetostriction effect has been known about for over 100 years and has several commercial applications in sensor and actuator technologies [179]. However, the technology seems to have had limited applications in power generation.

4.4.1 Magnetostriction generation operating principles

Magnetostriction materials are a group of ferromagnetic materials which have coupled mechanical and magnetic properties. This means that, through the magnetostriction effect, the material will change dimensions when a magnetic field is applied to it, and through the inverse magnetostriction effect (Villari effect) it will change its magnetic field when strained.

To model this process, magnetostriction materials are approximated as a collection of non-interacting magnetic domains [180]. The bulk magnetisation of the material is determined by the orientation of these domains. To align the domains when applied stress is low, permanent magnets are used to create a bias field, resulting in the maximum bulk magnetisation. The maximum bulk magnetisation is shown in State c of Figure 4-10. When compressed, the domains within the magnetostriction material begin to align in a perpendicular direction to the applied stress, reducing the material's bulk magnetisation. The bulk magnetisation reaches zero at stress-induced saturation, shown in State a of Figure 4-10 [180].

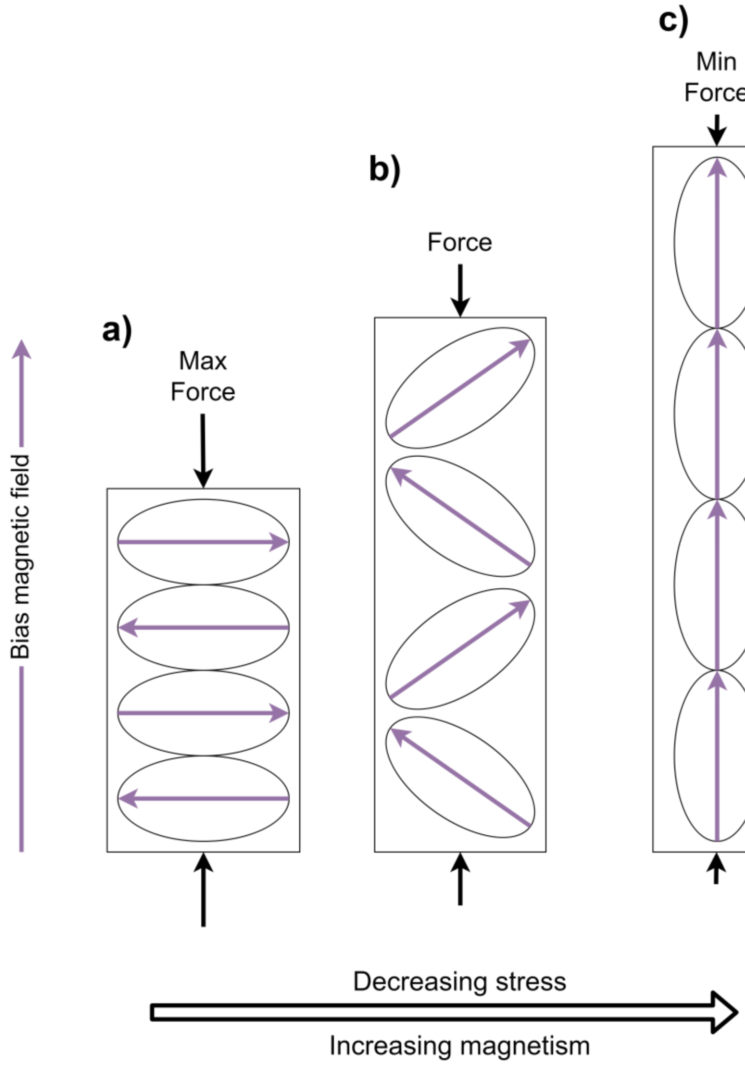

Figure 4-10. *Changing magnetic field with strain in a magnetostriction material based on Deng and Dapino* [180]. *This shows a) perpendicular magnetic domains resulting in zero bulk magnetisation when compression dominates b) domains beginning to align with the bias magnetic field as the compressive force is removed c) aligned domains resulting in maximum bulk magnetisation when the bias magnetic field dominates.*

For small stresses this coupling can be described using the following equations[15] [180]:

$$\Delta B = a\Delta T + \mu^H \Delta H$$
$$\Delta\lambda = \Delta T / Y^H + a\Delta H$$

Equation 4-12. *Magnetostriction mechanical magnetic coupling (without directional notation).*

Here a is the piezomagnetic constant, H is magnetic field strength, B is magnetic flux density, T is mechanical stress, λ is mechanical strain, Y is young's modulus, μ^H is magnetic permeability and superscript H indicates values determined at a constant magnetic field (H = constant). This shows that, at a constant external magnetic field (which is the case for most magnetostriction generators), the change in magnetic flux density is directly proportional to the change in applied stress. The strength of this response is determined by

[15] The equations have been rearranged to use young's modulus instead of compliance and the nomenclature for mechanical stress and strain have been changed to be consistent with the other conversion technologies.

the piezomagnetic constant (a). Similarly to piezoelectric materials, a coupling coefficient (k_m^2) describes the effectiveness with which the magnetostriction material converts mechanical strain energy into magnetic energy without losses. Equation 4-13 is the definition of coupling coefficient [181].

$$k_m^2 = \frac{a^2 Y^H}{\mu^T}$$

Equation 4-13. *Magnetostriction coupling coefficient.*

4.4.2 Magnetostriction generators

To use the magnetostriction effect to harvest electrical energy, an induction coil is wound around a magnetostriction material as shown in Figure 4-11. Common architectures for magnetostriction generators include axial (shown) and cantilever arrangements [182]. Permanent magnets are placed at either end of the magnetostriction material to generate a bias field. These magnets are not shown in Figure 4-11. In State a, force is applied to the magnetostriction material, compressing it and causing its bulk magnetic flux density to fall. In State b, the force is reduced, allowing the magnetic domains to align and increase the magnetic flux density. The variation in flux density during the change between States a and b induces a voltage on the induction coil [180]. This means that the system only generates a voltage on the induction coil — and therefore electrical energy — when the strain applied to the magnetostriction material is varying.

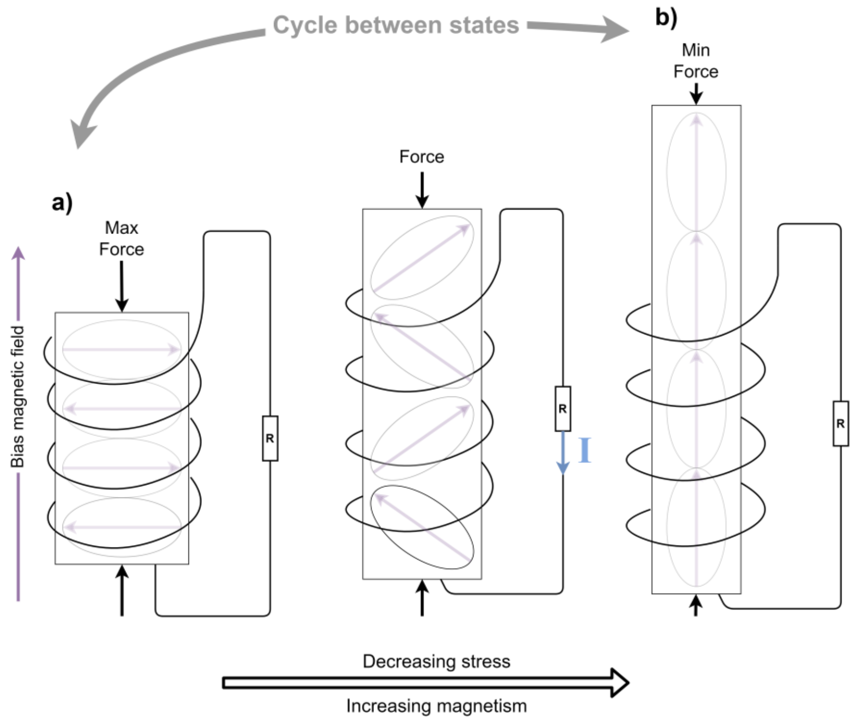

Figure 4-11. *Operating principle of an axial-type magnetostriction generator, where an induction coil is wound around a magnetostriction bar, based on Mohanty et al.* [182]. *This shows a) zero bulk magnetisation when compression dominates b) maximum bulk magnetisation when the bias magnetic field dominates. Cycling between these two states varies the magnetic field strength through the induction coils, inducing current flow.*

In the author's survey of the literature there was not a readily available equation that could be used to estimate the theoretical energy density of magnetostriction materials. As with triboelectric and piezoelectric generators, specific loss mechanisms are also not usually quantified for magnetostriction generators in the literature; rather, an aggregate conversion efficiency is measured. Along with mechanical losses (such as mechanical hysteresis), losses will occur when converting mechanical to magnetic energy (such as magnetic hysteresis), with additional losses converting this magnetic energy to electrical energy (such as eddy currents in the magnetostriction material) [182]. When considering a magnetostriction generator's electrical energy density, the magnetic energy density can be considered an upper bound to the electrical energy density for magnetostriction generators, as the actual electrical energy density that can be delivered will be lower than this (due to losses in the magnetic-to-electrical energy conversion). Some commercial magnetostriction material suppliers and literature sources present magnetic energy densities which can be used as an approximation of the electrical energy density of a magnetostriction generator (these are shown in Table 6-13).

4.4.3 Magnetostriction generator materials

The two most common materials used in magnetostriction energy harvesters are Galfenol and Terfenol-D as they present the strongest magnetostriction effects [183]. Galfenol and Terfenol-D are both brittle ferrous alloys, some of their key material properties are shown in Table 4-5

Table 4-5. *Material properties of common magnetostriction materials, data from* [183]–[185].

Properties	Units	Terfenol-D	Galfenol
a	10^{-12} m/A	6000-10000	20000-30000
k_m	CV/Nm	0.7-0.8	0.6-0.7
Maximum magnetic energy density	J/kg	2.7	0.138* 0.077
Density	kg/m^3	9200-9300	7800
Elastic modulus	GPa	50-90	60-80
Tensile strength	Mpa	28-40**	350
Elongation at break	%	<1	<1

*Experimentally obtained magnetic energy density from Yoo et al. [186], the other energy density value for Galfenol is from supplier datasheet.
**Compressive strength 300-880MPa.

4.5 Direct conversion technology applications in wave energy

This section gives a brief overview of the research activities in wave energy applications for the four categories of direct conversion that were assessed in this project (dielectric, piezoelectric, triboelectric and magnetostriction). Whilst this is intended to give an overview of the status of research in these areas, it does not directly feed into the assessment carried out in Section 6. This is because the assessment is meant to be device-agnostic and based on the technology's capabilities rather than the performance of existing small-scale devices (which are at varying maturity levels). The number of publications identified through a search of the Web of Science database is shown in Table 4-6. The search root was used to identify general wave and ocean energy journal articles in the database, which had wave energy related terms in their title, abstract or key words. These were then filtered using the search terms, which found subsets of these articles with direct conversion technology-related terms in their title abstract or key words. Following this, a manual check was performed to remove non-relevant articles. This database search found that most research was published recently, with over 75% of identified publications from the 5 years prior to the search date (Appendix B.2 — Direct conversion technology publication data).

Table 4-6. *Search terms used in Web of Science database, articles and filtered articles. Search carried out on 17/08/2021.*

	Search terms (title, abstract and key words)	Filtered articles
Dielectric Elastomer	"dielectric elastomer" OR "DEG" OR "electroactive polymer" OR "EAP"	28
Triboelectric	triboelec*	90
Magnetostriction	magnetostrict*	0
Piezoelectric	piezoelec*	55
Search root	(ocean* AND wave*) OR (ocean* AND power) OR (ocean* AND energy) OR (sea AND wave*) OR (sea AND power) OR (sea AND energy) OR (marine AND wave*) OR (marine AND power) OR (marine AND energy) OR "wave energy conver*" OR "wave energy harvest*" OR "WEC"	

The remainder of this section provides a brief overview of the status of research into each conversion technology in wave energy applications.

4.5.1 Dielectric elastomer wave energy converters

Close to 30 publications in the area of dielectric elastomer-based wave energy converters were identified by the author in the database search. No applications of dielectric fluid generators in wave energy devices were identified.

The research carried out into DEG based WECs has already yielded promising results. Several proposals for DEG WEC have been identified (as highlighted in two recent review articles [32], [187]). The most advanced research into dielectric elastomer WECs is largely associated with two key projects, the PolyWEC project and the SBM S3 WEC. The PolyWEC project was a

Horizon 2020 research project to design, test and assess dielectric elastomer-based wave energy conversion. During this project both a submerged pressure differential and an oscillating water column (OWC) type WEC were designed and then experimentally validated in lab tests. Additionally, the OWC type PolyWEC had is mechanical response demonstrated in real sea tests. Results from the PolyWEC project have shown (in optimal wave regimes) average power outputs of ~4 W (corresponding to 300-600 kW at full-scale) and energy densities within the DE of 190 J/kg [136]. Additionally, resonant behaviour at wave frequencies have been demonstrated and wave-to-wire conversion efficiencies of ~20% were achieved [188]. Although the project concluded in 2017, several of the researchers involved in the project have continued to publish work in the area of DEGs and dielectric elastomer WECs (e.g. [32], [136]). Tank testing of a PolyWEC prototype is shown in Figure 4-12.

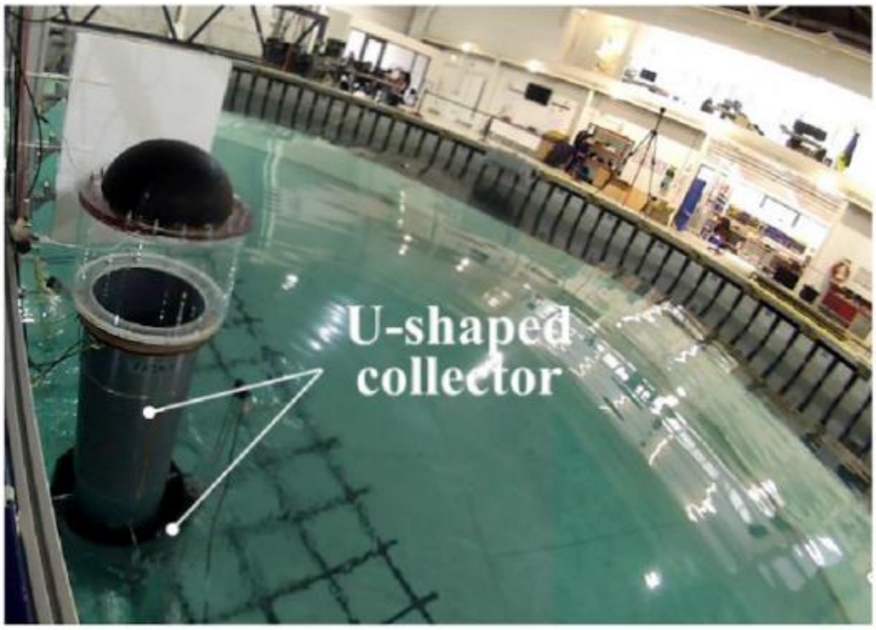

Figure 4-12. *PolyWEC OWC WEC during wave tank testing, reproduced from Moretti et al.* [32].

The second of the projects (the SBM S3) is a bulge wave type wave energy converter that has been in development since 2009 by SBM Offshore. There is less publicly available data about the SBM device compared to the PolyWEC device. Results from a 2010 test of an early-stage prototype of 10m in length showed a maximum power output of 1.2 W (although the paper suggests that around 100 W could have been achieved by running the experiment at a higher electric field) [189]. Additionally, in 2017, numerical modelling was carried out for the S3 device, suggesting a capture width of 5m would be achieved for a 100m long S3 device [190]. Tank testing of a prototype S3 device is shown in Figure 4-13.

Figure 4-13. SBM S3 bulge wave WEC during wave tank testing, reproduced from SBM Offshore [191].

Research into the S3 device is ongoing, with a pilot demonstrator under development. In addition to these projects, Bombora, in collaboration with Sant'Anna School of Advanced Studies, carried out tests on a dielectric elastomer-based version of their submerged pressure differential WEC in 2022 (the 'emWave') as part of the first stage of the Europe Wave project. However, publicly available data on this work is not available at the time of writing.

4.5.2 Piezoelectric wave energy converters

In the database search, 55 articles considering piezoelectric wave energy converters were identified. While papers published as far back as the 1980s have been identified [192], around two thirds of the articles have been published over the last four years. Unlike dielectric and triboelectric WEC research, where research is clustered around a few key organisations and projects, the research in piezoelectric wave energy converters appears to be more dispersed.

So far, prototype piezoelectric WEC devices have been small-scale, in the order of µW-mW; while devices in the watt scale have been numerically modelled [130], [193]. Early-stage sea trials have also been carried out, again at very small scales (power output in the order of single W/m^3 of active material) [194]. Sea trials of a small-scale piezoelectric sheet generator attached to a raft and ocean buoy are shown in Figure 4-14.

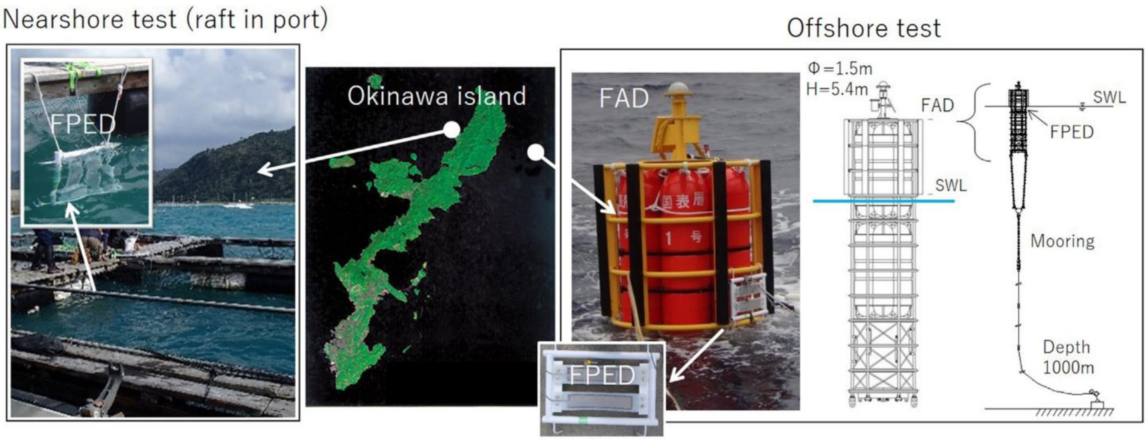

Figure 4-14. Sea trials of prototype flexible piezoelectric sheet generator attached to a raft and ocean buoy, reproduced from Mutsuda et al. [194].

The most comprehensive review of piezoelectric wave energy converters was carried out by Jbaily and Yeung [130] in 2015[16]. The power outputs of the piezoelectric devices identified in Jbaily and Yeung's study were in the µW-W scale (these being the result of both experimental testing and modelling), with power densities of ≤15 W/m^2. The conclusion drawn by Jbaily and Yeung was that piezoelectric-based wave energy converters at the time were not suitable for scaling up to grid energy applications, but may serve a purpose in powering sensors and other electronics. While a systematic review of the piezoelectric wave energy literature was not carried out during this work, no evidence in the literature published since 2015 was found (for experimentally-validated devices) that contradicted the conclusions of Jbaily and Yeung.

4.5.3 Triboelectric wave energy converters

There is significant research interest in triboelectric wave energy converters, with 90 articles identified in the database search. Whilst the first publication applying triboelectric generations in WECs was made in 2013 (a year after the development of triboelectric generators), the vast majority of the research has been published in the last 4 years.

So far, these devices have been demonstrated at small scales, with the highest peak power output in the order of tens of mW [127]–[129]. Small-scale tank testing of a triboelectric wave energy converter is shown in Figure 4-15.

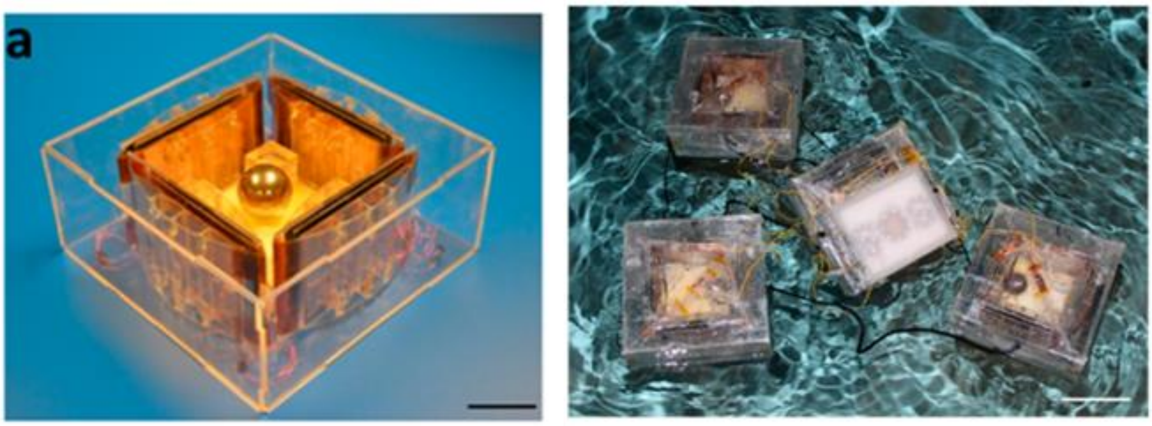

Figure 4-15. *Single triboelectric wave energy converter (left figure), and small network of triboelectric wave energy converters (right figure) undergoing wave tank testing, reproduced from Chen et al.* [195]. *The ball bearing activates contact separation triboelectric generators when it impacts cube walls.*

Three review articles that have been published since 2020 assessing advances in triboelectric-based WECs [127]–[129]. A large number of highly novel device types have been developed (as reviewed in Shen et al. [129]). The power densities of these devices spanned several orders of magnitude, however are low in general, with the highest peak power performances being in the order of single W/m^2 and ~200 of W/m^3 [127]–[129]. However, care must be taken when interpreting these results. The review studies largely present peak power outputs, which for triboelectric generators are unlikely to represent the power output of the device

[16] Two less comprehensive review articles on piezoelectric WECs have been published since 2015 [294], [295].

operating over a sustained period (triboelectric generators are characterised by generating very high peak powers in comparison to average power — see, for example, [172]). Several highly cited articles presenting some of the most promising peak power outputs do not include average power outputs alongside these peak values [196], [197], which makes it hard to interpret the actual performance of the devices. Additionally, the excitation frequency in many of the best performing studies is ~2 Hz [128], [129], [195], [197], [198]. This is approximately an order of magnitude higher than ocean wave frequencies. As the power output of triboelectric generators is directly proportional to contact frequency [174], this may bring into question the replicability of these power densities in 'real world' wave energy applications where the average cycling frequency may be significantly lower.

Given the current performance of triboelectric-based WECs, two of the three recently published review papers [128], [129] concluded that their applications would currently be best suited to powering sensors and other electronics, rather than grid-scale energy generation.

4.5.4 Magnetostriction wave energy converters

In contrast to the other technologies surveyed, there is very little publicly available research around magnetostriction-based wave energy converters. No research articles were identified by the author in the database search, and only one project was identified by the author — the Oscilla Power magnetostriction wave energy converter (M-WEC). A schematic of this device is shown in Figure 4-16.

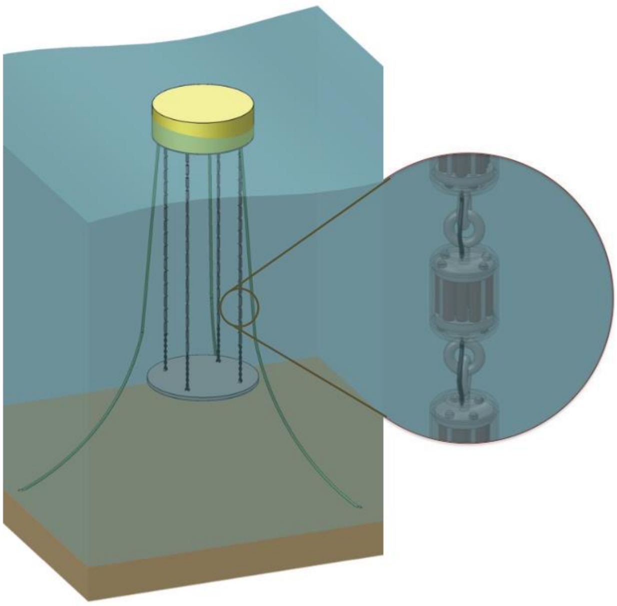

Figure 4-16. *Schematic of Oscilla Power M-WEC point absorber WEC highlighting magnetostriction generator, reproduced from Mundon and Nair* [131].

Little publicly-available information exists about the technical parameters of this project, with the most detail (to the author's knowledge) given in a 2014 conference proceedings [131]. This described the hydrodynamic response of the WEC and the basic operation and architecture of the magnetostriction PTO. The conference proceedings claim a generator rated power of 12 kW and the potential to stack these generators into a device rated at 100’s of kW. However, there were no experimental or modelled performance results presented for the generator system. The M-WEC was demonstrated in a sea trial in 2015 and performed ‘as expected’ [199]. However, it appears no performance data was made available from the tests, and the M-WEC project seems to have been abandoned shortly after this.

5 Assessment processes literature review

This chapter reviews assessment processes and metrics both for wave energy and direct conversion technologies for wave energy applications. This is split into two sections.

First, Section 5.1 covers prominent assessment processes and metrics that have been for wave energy in general. This sets the context for the overall requirements for a successful wave energy converter.

Section 5.2 then reviews other studies that have attempted to assess direct conversion technologies in wave energy applications. The processes and metrics reviewed in this section were used as the basis for the assessment parameters that were developed for the screening process presented in Chapter 6.

5.1 General assessment processes and metrics for wave energy conversion

At a high level, utility-scale wave energy should be aligned with the energy trilemma - low cost, low-carbon, and secure energy supply. However, many assessment metrics exist for wave energy converters which may cover one or more of these areas at different levels of granularity. For example, these metrics can cover wave energy arrays (e.g. LCoE or TPL), device-specific metrics (e.g. ACE or capture width), and subsystem specific metrics (e.g. conversion efficiency). It should be noted that many of the device and subsystem-specific metrics are components of the array-level metrics or assessment processes (e.g. conversion efficiency is included in TPL and the IEA-OES framework).

In an attempt to bring together a somewhat disparate landscape of assessment metrics, the IEA-OES published *An International Evaluation and Guidance Framework for Ocean Energy Technology* in 2021 [29]. The Technology Performance Level (TPL) metric developed by NREL similarly aims to evaluate all the stakeholder requirements for a successful wave energy device. This section will start by reviewing the most comprehensive evaluation methods for wave energy — the IEA-OES evaluation framework and Technology Performance Level (TPL). Although it is included in both the IEA-OES framework and TPL, levelised cost of electricity (LCoE) is also reviewed in a separate section due to its ubiquity in energy technology assessment. A short review of lifecycle assessment (LCA) is then presented, due to the importance of environmental performance metrics such as carbon emissions per unit energy output for energy technologies. Finally, some less comprehensive wave energy assessment metrics are briefly reviewed at the end of this section. For further review of wave energy assessment processes and metrics, see Sandia National Laboratories [200] and the review of metrics for wave energy structured innovation presented by Roberts [201, pp. 33–44].

5.1.1 IEA-OES - An International Evaluation and Guidance Framework for Ocean Energy Technology

As covered in the introduction, the development of the IEA-OES evaluation and guidance was an attempt to unite existing technical specifications, guidance and standards for ocean energy. The main aim of the IEA-OES assessment guidance was to build consensus and to support decision-making for ocean energy evaluation, guide activities though the technology development process, support knowledge sharing and collaboration, and support funding allocation decisions.

The IEA-OES guidance comprises three main components: firstly, the evaluation areas that were used to assess ocean energy technologies (see Table 5-1) and how these feed into the overall affordability of the electricity generated; secondly, the evaluation criteria that can be used to measure the performance in each of the evaluation areas (for instance reliability is measured using mean time to failure and failure rate); thirdly, recommended engineering activities, arranged by the evaluation areas, that should be carried out during an ocean energy technology's development. These activities are outlined for five different levels of WEC maturity, based on the TRL scale.

The evaluation areas used in the IEA-OES framework are described in Table 5-1. These were developed through a series of workshops carried out with ocean energy stakeholders, including investors and technology developers.

Table 5-1. *Evaluation areas used by the IEA-OES* [29].

Evaluation Area	Definition
Power Capture	Power Capture is the process of extracting energy from the natural resource by the interaction with a device and making it available as an input to a power take-off (PTO).
Power Conversion	Power Conversion represents the second step in the power conversion chain, whereby the mechanical power captured by the device is converted to electricity.
Controllability	Controllability is defined as the ability for control systems to be implemented to a subsystem or device and incorporates evaluation of the benefits control can deliver and the reliance of a subsystem or device on it.
Reliability	Reliability is defined as the 'probability that an item can perform a necessary function under given conditions for a given time interval'.
Survivability	Survivability is a measure of the ability of a subsystem or device to experience an event ('Survival Event') outside the expected design conditions, and not sustain damage or loss of functionality beyond an acceptable level, allowing a return to an acceptable level of operation after the event has passed.
Maintainability	Maintainability is defined as the 'ability to be retained in, or restored to, a state to perform as required, under given conditions of use and maintenance'.
Install-ability	Install-ability is defined as the ease with which a component, subsystem or device can be prepared, deployed at the operational open-water site and commissioned, resulting in a condition of operational readiness. Install-ability

Evaluation Area	Definition
	also includes the ease with which the component, subsystem or device can be recovered.
Manufacturability	Manufacturability is defined as the ability for the technology to be manufactured quickly, cheaply and with minimum waste, and therefore its compatibility with the supply chain's capability, readiness and maturity.
Affordability	Evaluation of Affordability relates to the cost of electricity generated from the wave or tidal stream resource.

These evaluation areas all ultimately feed into the affordability of the ocean energy device/array of devices which is shown in Figure 5-1.

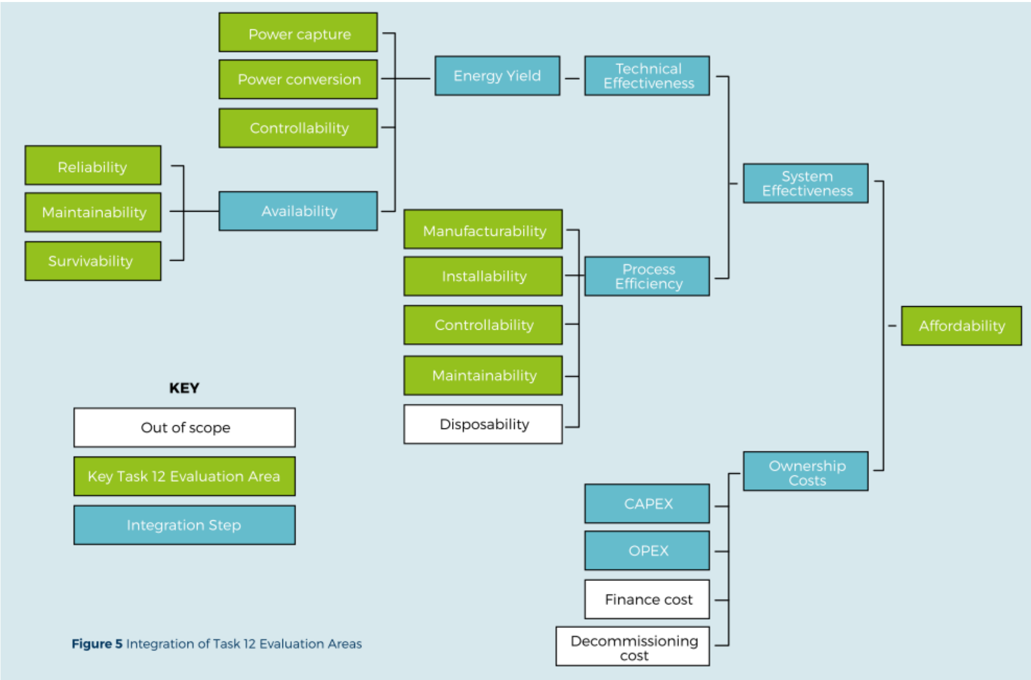

Figure 5-1. Evaluation areas of the IEA-OES guidance feeding into overall device affordability [29]

Several evaluation areas were considered out of scope of the IEA-OES process, including environmental impacts, disposability, financing costs and social impacts (see p.23 of the report [29]).

The remainder of the IEA-OES assessment and guidance lays out the evaluation criteria that can be used as indicators in the evaluation areas (Table 5-1). It then outlines the engineering activities that should be carried out at different stages to estimate/demonstrate performance against the evaluation criteria. The evaluation criteria under each evaluation area are shown in full in Appendix B.3 — Evaluation of IEA-OES T12 and TPL in Table 11-8. The evaluation and guidance framework uses six stages of maturity covering:

1. Concept creation (TRL 1)
2. Concept development (TRL 2-3)
3. Design optimisation (TRL 4)
4. Scaled demonstration (TRL 5-6)
5. Commercial-scale single device demonstration (TRL 7-8), and
6. Commercial-scale array demonstration (TRL 9)

The activities covered in each stage include increasingly high-fidelity modelling and testing in more relevant environments as the technology progresses. Finally, some guidance is given on basic LCoE evaluation for incomplete ocean energy devices, including the impact of developing a new WEC subsystem on overall WEC LCoE. The IEA-OES framework recommends setting up a baseline LCoE model and breakdown of subsystem costs, from which the affordability impact of individual subsystem innovations can be evaluated. A similar approach to this was used in the assessment process methodology described in Chapter 6, where a fixed breakdown between some of the subsystem costs was assumed when evaluating the viability of the direct conversion technologies.

The IEA-OES evaluation and guidance framework clearly highlights important areas of assessment related to the affordability of a WEC and the activities required to evaluate these areas at different stages of project maturity. Regarding its relevance to conversion technology assessment, clearly some of the evaluation areas are more applicable than others. For example, conversion efficiency and CAPEX are clearly relevant and at least partially measurable for the conversion technology, while power capture is more related to the overall device hydrodynamics. Therefore, adaptation will be required to apply these evaluation areas to the issue of conversion technology assessment. The relevance of the assessment areas of the IEA-OES guidance framework to the evaluation of DCTs for wave energy is covered in detail in Appendix B.3 — Evaluation of IEA-OES T12 and TPL.

Limitations of the IEA-OES guidance include its sole focus on affordability, which neglects important factors such as sustainability [202] (although it is stated in the IEA-OES framework that future updates will cover performance aspects outside affordability). Additionally, it has been highlighted that the IEA-OES framework does not include any thresholds to assess an ocean energy converter against the evaluation criteria [203]. This may make it difficult to use the IEA-OES framework to track the development of an early-stage ocean energy project, and evaluate if it is on track to achieve a competitive LCoE.

5.1.2 Technology Performance Level (TPL)

Technology performance level (TPL) is a system engineering approach to WEC assessment. It was originally developed to assess the economic performance of a wave energy array at different stages of development. TPL was envisioned as a compliment to the technology readiness level approach (TRL), as it was considered that for utility wave energy applications TRL is too focused on commercial readiness, rather than the economic viability require for market entry [204]. The aim of using TPL and TRL in parallel is to ensure that the techno-economic performance (TPL) of a WEC keeps pace with the device readiness (TRL) [205]. This approach, in theory, should reduce design changes at late stages of WEC development, which are more costly and time consuming to carry out (more explanation of TRL-TPL development trajectories is giving in by Weber [205]).

Detailed guidance for the TPL process has been developed by Sandia Laboratories [204]. This lays out a set of capabilities for a wave energy array (shown in Table 5-2) which were based on an extensive stakeholder consultation [206]. In addition to these first-level sub-capabilities, there are several second-level sub-capabilities outlined in Babarit et al. [206].

Table 5-2. Technology Performance Level (TPL) capabilities and sub-capabilities [204].

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

The TPL assessment is essentially a multi-criteria analysis, relying on aggregation of performance ratings across multiple areas. The TPL assessment rates a WEC as high, medium or low against the sub-capabilities, based on scales provided in Bull et al. [204]. The ratings of high, medium and low are defined for a WEC at three maturity levels: TRL 1-2; TRL 3-4; and TRL 5 — with greater data fidelity required at higher TRL levels. These high, medium and low ratings are turned into a score from 1-9. Following this rating, the scores are aggregated across all the different categories and sub-categories (using weightings and both geometric and additive aggregation). The calculations to carry out this aggregation are shown in Chapter 4 of the Sandia guidance. Overall, the TPL puts the highest weighting on the capabilities that fall under the economics category in Table 5-2, which accounts for 70% of the overall TPL score.

The TPL process provides a comprehensive list of criteria for a wave energy farm, which is valuable for assessors such as public sector funders who have to consider the effects of supporting a technology from multiple socioeconomic perspectives. This covers all the areas of the trilemma, which is a potential limitation of the IEA-OES evaluation criteria. As with the IEA-OES approach, only a subset of the sub-capabilities are relevant to assessing a conversion technology (this is explored in Appendix B.3 — Evaluation of IEA-OES T12 and TPL). However, there are also some limitations to the TPL approach. Firstly, in order to carry out the TPL assessment, a large amount of information is required. A WEC's performance at early stages in some of these areas may not be immediately clear. For instance, as Roberts [201] highlights, it may be difficult to score a WEC's benefit to local communities (criteria C4.2) at TRL 1-2. The scoring and weighting used in TPL is also an area that could be questioned. Additive aggregation of economic, societal and environmental performance suggests that these can be directly traded off against one another, which may not be realistic. Additionally, the use of complex scoring, weighting and aggregation processes (such as used in TPL) are brought into question more generally in the assessment literature [207], as these processes reduce the transparency required to make informed decisions.

5.1.3 Levelised Cost of Electricity (LCoE)

LCoE is probably the single most used cost-based assessment metric for renewable energy projects. While LCoE is part of both TPL and the IEA-OES framework, it was considered appropriate to also review it separately. LCoE provides an indication of the unit energy costs over the life of a project, including capital (CAPEX) operational (OPEX) decommissioning (DECEX) and financing costs [208]. It does this, in general terms, by summing the lifetime costs of the energy producing system (e.g. a wave or wind farm) and then divides this by the lifetime energy production, to give a value in terms of cost per unit energy [208]. Many wide-ranging estimates have been made of the LCoE of future wave energy arrays, as reviewed by Roberts [201, p. 38].

There are multiple ways to calculate LCoE. Two main approaches are reviewed by Aldersey-Williams and Rubert [208] — one suggested by the UK Government's Department for Business, Energy and Industrial Strategy[17] (BEIS), and one suggested by the US National Renewable Energy Laboratory (NREL). These are both discussed in this section. Additionally, the costs and discount rate in an LCoE calculation can be either treated in real terms (negating the effects of inflation on the discount rate and costs) or in nominal terms (where an estimation of the inflation rate is included in the discount rate and costs). This section (and the thesis broadly) considers LCoE calculated using the methodology set out by BEIS [15], using a discounted cash flow method where real costs and discount rates are used.

The definition of LCoE given by BEIS is '*the discounted lifetime cost of building and operating a generation asset, expressed as a cost per unit of electricity generated'.* This is the sum of the net present value (NPV) of the expected costs of the plant during its lifetime, divided by the NPV of expected electricity generation during the plant's lifetime. This is essentially the constant energy price (in real terms) required to deliver a break-even NPV for the entire project [208]. Equation 5-1[18] is the definition of LCoE used by BEIS.

[17] In 2023 BEIS was split into four new departments, with the energy and climate remit now covered by the Department for Energy Security and Net Zero.

[18] It should be noted that there appears to be a typo in the formula used for LCoE in the BEIS 2020 electricity generation costs. Therefore, this equation is representative of the 2016 version of this report.

$$LCoE = \frac{NPV_{costs}}{NPE} = \frac{\sum_{y=1}^{n} \frac{CAPEX_y + OPEX_y}{(1+dr)^y}}{\sum_{y=1}^{n} \frac{E_{e_y}}{(1+dr)^y}}$$

Equation 5-1. *LCoE formula used by BEIS.*

Where NPE is the discounted sum of electricity production, NPV_{costs} is the discounted sum of the costs, $CAPEX_y$ is the capital cost in year y, $OPEX_y$ is the operational cost in year y (including decommissioning costs), E_{e_y} is the electrical energy output in time year y, n is the project lifetime in years (including both pre-operation and decommissioning time) and dr is the discount rate in real terms. As mentioned above, the costs and the discount rate are expressed in real terms (the values are not adjusted based on inflation expectations). Additionally, BEIS recommend that, for most technologies (including wave), the scrappage value should cover decommissioning costs.

The approach taken by NREL [209] differs from the BEIS LCoE calculation, as it calculates the costs and energy production on an annual basis[19], where the CAPEX is adjusted by a Fixed Charge Rate (FCR). The FCR is defined as the amount of revenue per dollar investment that must be collected annually to cover the carrying charges on an investment (such as return on debt and equity, insurance and tax). The FCR is discussed in more detail in Short et al. [210, p. 22]. The LCoE formula used by NREL is shown in Equation 5-2, where FCR is the fixed charge rate, $CAPEX$ is the total capital cost, $OPEX_{fixed}$ is the fixed annual operational costs, $OPEX_{variable}$ is the variable annual operational costs on a per unit energy output basis, and AEP is the annual energy production.

$$LCoE = \frac{(FCR \times CAPEX) + OPEX_{fixed}}{AEP} + OPEX_{variable}$$

Equation 5-2. *LCoE formula used by NREL.*

As the NREL LCoE calculation is carried out on an annual basis, it assumes that the OPEX and AEP are the same in every year of the project's operational lifetime, that there are no decommissioning costs, and that the construction CAPEX all occurs in year 1. If these assumptions are made (and also assuming that the FCR is equal to the capital recovery factor — therefore negating tax and insurance, see Short et al. [210, p. 22]) the BEIS and NREL LCoE calculations return the same value. Aldersey-Williams and Rubert suggest that neither the NREL or BEIS approach is necessarily right or wrong, but the discounted cash flow method used by BEIS is more standard [208].

LCoE therefore gives a simple but sophisticated way to evaluate the lifetime costs of electricity generation technologies [208]. Additionally, the high level of acceptance of LCoE means that it is estimated by a large number of organisations (such as the IEA, IRENA and government agencies) for a wide variety of energy technologies, facilitating comparison of different classes of energy technology. However, there are several criticisms of LCoE. Firstly, it does not capture wider system benefits or costs, such as timing of generation, dispatchability, or the impact on power networks [15]. For this reason, lower LCoE technologies, when integrated

[19] However, it is also noted that NREL use the discounted cash flow method in some of their modelling.

into an energy system, may not necessarily deliver lower total system costs. In terms of calculating LCoE, there are issues around selection of appropriate discount rates, the treatment of inflation [208], and uncertainty in many of the parameters required to define the total costs and electricity generation. The choice of discount rate has a significant effect on the LCoE of a generation plant, especially CAPEX intensive renewable energy projects such as wave energy. However, for a technology like wave energy, the discount rate used in LCoE calculations for future arrays is simply an educated guess, as no full-scale projects have been developed. Regarding the inclusion of inflation, it is noted by Aldersey-Williams and Rubert [208] that incorporating inflation results in divergent LCoE values in different energy generation technologies (using BEIS methodology), due to their different patterns of expenditure. Aldersey-Williams and Rubert found that higher inflation expectations had a greater effect on the LCoE of technologies with significant operational costs, e.g. Combined Cycle Gas Turbine. Finally, for wave energy LCoE estimation, many of the parameters required to define the costs and electricity generation are highly uncertain due to lack of operational experience for the sector. Therefore, it is common for some values to be taken as baseline estimates in wave energy LCoE studies (e.g. OPEX estimated as a percentage of CAPEX per year). This introduces additional uncertainty which could be obscured by the overall LCoE value.

5.1.4 Life cycle assessment (LCA)

Life cycle assessment (LCA) is the assessment of lifecycle environmental impact of a product, from raw material extraction to end-of-life disposal within a defined system boundary. For energy generation technologies, this is essentially an environmental performance metric, usually measured on a unit energy output basis. For energy generation technologies, the lifetime impacts within this boundary are normally separated into four stages [211]:

- Materials and manufacturing
- Assembly and installation
- Operations and maintenance
- Decommissioning and disposal

Using inventory analysis (accounting for the environmental impacts associated with all the materials and energy use in the four stages above), an LCA analysis presents environmental impacts in different categories, normalised by estimated lifetime electricity generation. Commonly used environmental impact categories include lifecycle global warming potential (CO_{2e}), energy payback time (years), and other forms of pollution, waste and depletion [211]. Unlike LCoE, neither numerator nor denominator are discounted. In a similar way to LCoE, this facilitates the comparison of the lifecycle environmental impact of different energy sources [19] on a per unit energy output basis. Several studies have carried out LCA studies on a variety of wave energy converters [16]–[18].

Potential issues with LCA studies are the consistency of system boundaries used. It is recommended by Raventós et al. that this boundary is drawn at the transformer station which connects to the national grid for energy generation stations [211]. However, as noted by Raventós et al. these boundaries have not been consistent in previous marine energy studies. LCA studies also need large amounts of data input [212]. Similarly to LCoE, some of these data inputs, for example estimated lifetime energy production and O&M related emissions, may not be well defined for early-stage technologies like wave energy, due to lack of operational experience.

5.1.5 Other metrics and assessment processes

Some of the other metrics and assessment processes for wave energy which are covered in the literature are briefly reviewed below.

The Average Climate Capture Width per Characteristic Capital Expenditure (ACE) is a proxy metric for LCoE designed to evaluate WECs at low TRL levels. The ACE metric was developed for the Wave Energy Prize [213]. ACE is the ratio of estimated structural costs (including foundations) of a wave energy converter, divided by the WEC's capture width, averaged over a number of wave climates (six wave energy climates were used in the Wave Energy Prize). ACE was used as part of the assessment in Chapter 6. The formula and a few estimates of ACE values for different devices are shown in Section 6.1.3 on the cut-off value for parameter 1.1. The main criticism of ACE is that it includes subjective cost parameters in the estimation of the structural costs and that it places greater importance on CAPEX, as operational costs are not included [201, p. 42]. Additionally, as ACE is a measure of cost per unit absorbed energy, it does not consider the conversion efficiency of absorbed wave energy into usable electrical energy in the PTO (or indeed the capital costs of the PTO).

Several hydrodynamic performance metrics for wave energy converters are described in Dallman et al. [200] and Babarit et al. [214]. These include annual absorbed energy per unit characteristic mass, annual absorbed energy per wetted surface area, capture width ratio and absorbed energy per unit RMS PTO force. The modelling by Babarit et al. [214], and test results from the Wave Energy Prize [215], showed varying rankings of performance in these different metrics for different devices, indicating their limitations (when not combined with a cost estimation) to evaluate overall WEC economic viability.

Other metrics for wave energy assessment are noted in a review of ocean energy performance metrics carried out by Sandia National Laboratories [200]. However, these were either included in the IEA-OES assessment guidance and/or TPL, or were not considered relevant to this study.

5.2 Assessment processes and metrics for direct conversion in wave energy applications

Several studies have reviewed or compared direct conversion for a variety of, often small-scale, energy harvesting applications [160], [183], [216]. These highlight metrics which are useful for comparing technologies (e.g. energy density and conversion efficiency). However, the requirements in these applications are very different to those for wave energy (often delivering power outputs in the order of Watts, with lower sensitivity to cost). Therefore, these studies are not reviewed in this section.

Only one study was found that developed an assessment process to compare and assess direct conversion technologies for wave energy applications. This was a technical report that was commissioned by Wave Energy Scotland (WES) and carried out by the Frazer-Nash consultancy in 2018, with the aim of identifying and analysing alternative generation technologies which could potentially reduce the cost of wave energy [132]. The main objectives of this study were to identify alternative conversion technologies, assess their characteristics, identify which technologies could offer a cost reduction opportunity for wave energy and outline the development challenges for the technologies. The main part of this work was an economic analysis of four alternative conversion technologies that Frazer Nash considered to have the highest potential in wave energy applications.

The Frazer Nash study starts by defining the assessment criteria that will be used to evaluate the conversion technologies. This comprised a set of 10 assessment criteria, defined by Frazer Nash and wave energy stakeholders, which could be scored either low, medium or high for each technology. These criteria covered scalability, operation in a marine environment, durability, controllability, CAPEX, OPEX, conversion efficiency, power density, and maturity. Following this, an initial identification and review of the working principles of energy conversion technologies was carried out. The technologies were separated into their level of maturity in wave energy applications, where TRL 7+ was classified as 'mature' and TRL 1-6 'alternative'. An initial screening of the alternative technologies was carried out by Frazer Nash and WES (details of the criteria used are not available). This resulted in several technologies being removed on the basis of low power density or efficiency. The results of the screening are shown in Table 5-3.

Table 5-3. *Technology readiness level and the down selected 'alternative' conversion technologies reproduced from Frazer Nash* [132].

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

Following this screening, an economic analysis was carried out for the selected 'alternative' technologies; piezoelectric, magnetostriction, dielectric elastomer and triboelectric generators. This economic analysis established a baseline CAPEX, OPEX and conversion efficiency for a conventional WEC. This baseline was both for a conventional WEC's generator and for the WEC's other subsystems (the Balance of Plant, BoP). The effects on the overall CAPEX and OPEX of the WEC were then estimated, based on replacing just the generator with an alternative conversion technology. To do this, Frazer Nash estimated the CAPEX of the DCT-based generator, by sizing it based on the experimentally demonstrated power density of DCTs. The OPEX of each DCT generator was estimated, largely based on expert judgement from Frazer Nash. The efficiency of each DCT was then used to evaluate the WEC's energy output, relative to a baseline generator.

Two scenarios were considered by Frazer Nash to make these estimates. The first scenario was based on the current efficiency and costs of the alternative conversion technologies. The second scenario was based on the predicted future costs and efficiency over the next 25 years. The future costs and efficiency were then compared to the baseline to assess the potential cost reduction offered by the alternative conversion technologies against the current state of the art. The data used for CAPEX and efficiency values were sourced from a combination of academic studies, conversations with experts, and material supplier websites. The OPEX values (with the exception of DEGs) seem to be based on the judgment of Frazer Nash.

The results of the economic analysis are summarised in Table 5-4. The main conclusions were that none of the technologies, when used to replace a WEC's generator, offered a step-change cost reduction opportunity in wave energy applications. This was true even considering the future values for cost and efficiency, which assumed performance improvements as the alternative technologies matured. The main driver of this was considered to be low conversion efficiencies of the alternative generation technologies in comparison to the baseline conventional generator. However, the report highlights high levels of uncertainty in the results due to the limited availability of data and the time scale over which the technology was considered (25 years). Frazer Nash also note that DEGs may be able to replace the entire PTO (as opposed to just the generator), which could offer benefits in terms of overall WEC CAPEX reduction. However, this was not investigated as part of the study. The study concludes with a section explaining the development challenges for each of the down selected alternative conversion technologies, outlining priority areas of performance and design improvement.

Table 5-4. Summary of results from Frazer Nash economic analysis of 'alternative' conversion for wave energy applications [132].

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

* Future predictions are based on technology development activities achieving the assumed improvements for each technology as described in Section 7.6.
† The baseline considers a complete rotary generator, rather than just the key generation material (used to cost alternative technologies).
‡ The future development of the baseline generator has not been considered. It has also been assumed that future development of conventional generation will be not be led by the wave energy industry.
** This value considers DEG used as a replacement for the baseline Electrical Generation Subsystem. Further considerations around DEG OPEX are highlighted in 7.6.3.

While the Frazer Nash study identifies some of the key drivers of performance for alternative conversion technologies, there are several limitations in the study's approach and execution. The first and most important limitation is that the study only considers generator replacement. This is not an application where alternative generation is likely to have a significant beneficial effect on WEC economics, as there is limited scope for CAPEX reduction and efficiency improvement in conventional generators. The Frazer Nash study assumes the baseline generator contributes 10% to the overall WEC CAPEX, 10% to the overall WEC OPEX and has a conversion efficiency of 95%. Using the Frazer Nash methodology, this means that if the alternative conversion technology that replaced the generator was free (zero CAPEX), required no maintenance over 20 years (zero OPEX), and was lossless (100% conversion efficiency), the total reduction in through-life costs compared to the baseline would only be 14.5%. It is therefore hard to imagine that any realistic technology would provide a 'step-change' in wave energy costs when limiting the assessment to generator replacement (as done in the Frazer Nash report). This highlights a second limitation of the Frazer Nash study. The study uses power density as the metric which drives the volume of alternative conversion technology that is required to achieve a rated power output. This is an issue, as the power density of a conversion technology demonstrated in an experiment is not intrinsic to the technology. Rather, it is a product of both the technology and the conditions under which it is tested. For instance, both DEGs and Triboelectric have power densities that are, at least in theory, approximately proportional to the frequency of loading [32], [174]. As the different conversion technologies have been tested under very different loading frequencies in the literature, the use of power density (without normalising by frequency) has limited merit as a metric of comparison. Additionally, some of the technologies have very low energy outputs per cycle. Therefore, they need to be cycled at very high frequencies to give reasonable power densities (e.g. Magnetostriction), while others (e.g. DEGs) have high energy densities. However, it is assumed in the study that only the generator is replaced (see Figure 6-3) and that all other Non-DCT subsystems components remain consistent in cost between technologies. A third issue is that the study does not consider important aspects of conversion technologies, such as environmental effects (e.g. embodied carbon), or their ability to survive extreme loads. A conversion technology with extremely high embodied emissions in its raw materials, or low tolerance to extreme loading, is unlikely to be suitable for wave energy applications.

A final issue with the study is the sourcing of data. Some of the data is gathered from scientific studies, while other data is gathered from experts without experimental evidence (for example the efficiency of DEGs is based on a 'potential' value of 50-90% from [217]). This makes it hard to verify the data used in the study. The data on costs is also potentially misleading. Some of the costs are based on material costs (for instance triboelectric and magnetostriction), while others are based on manufactured costs (e.g. DEGs). This may not be a valid comparison, as the manufactured cost of early-stage technologies may be significantly higher than the material costs, due to small manufacturing volumes. In the Frazer Nash study, there are also speculative estimates for both the OPEX and the future costs and future efficiency. The current OPEX values (with the exception of DEGs) are based on Frazer Nash assumptions, without supporting references. In addition, all the future values (for OPEX, CAPEX and efficiency), which are the basis of the through-life cost calculations, are largely based on Frazer Nash assumptions, again with limited justification.

The work presented in Chapter 6 aims to address these issues. Firstly, the application of the DCT in a wave energy converter is considered as replacing at a minimum the entire PTO, rather than just the generator. This is a more sensible application of the DCT to consider, as it does offer the potential for significant cost reduction. Secondly, some different assessment parameters are used to address the issues around power density, lifetime, and environmental impact. Finally, the screening process relies (where possible) on quantitative data, rather than the assumptions of the assessor, in order to improve the repeatability and transparency of the assessment process outcomes.

6 Assessment process for direct conversion technologies

To assess the potential viability of direct conversion technologies (DCT's) for wave energy applications, a screening process was developed, which is the subject of this chapter. This screening process was developed based on a set of parameters where a minimum level of performance was deemed fundamental for the potential viability of a DCT in a wave energy application. The process was then used to screen the six DCTs that were introduced in Chapter 4.

The first section in this chapter (Section 6.1) presents the methodology used to develop the screening process. This covers the overall design of the screening process, the parameters that were used to evaluate the DCTs, and the key assumptions that were required to develop the screening process. Following this, Section 6.2 presents the results from applying the process to the six DCTs. The chapter then concludes with a discussion of these results in Section 6.3. This covers the key points from the screening process, compares the process and results to previous work, covers the key implications of the work, discusses the screening processes limitations and finally makes recommendations based on these results.

6.1 Method for screening direct conversion technologies

6.1.1 Design of screening process

Screening for direct conversion technology selection

As noted in the introduction to Part B of the thesis, before assessing any of the technologies' development requirements (in Part C), it is logical to determine which direct conversion technologies may be viable in wave energy applications. Therefore, the question that is essentially being asked is, *is there sufficient evidence to reject a DCT for wave energy applications?* This aligns with the role of a screening process, which is to remove options that cannot meet certain essential (or desired) requirements. Indeed, it is proposed in the literature that a properly designed formal screening process for technology selection can reduce the effort expended by assessors by removing bad options at an early stage, whilst enabling the same conclusions to be reached as a more detailed assessment [207], [218]. For these reasons, screening processes are a commonplace procedure in the early stages of both technology selection [219], [220] and materials selection [221], [222]. They have been already been applied in wave energy contexts for materials selection [223], [224].

The structure of screening processes can vary considerably, with some processes opting for a qualitative assessment from a panel of assessors, while others use more structured scoring methods. Given the significant number of both interdependent and essential criteria for a conversion technology used in a wave energy converter, a more formalised screening process was utilised, as described in the remainder of this section. The use of a formalised screening process, using pre-defined assessment parameters and cut-off values, also ensures a level of repeatability in the assessment process, which may be lacking in a more qualitative assessment.

Multi-stage screening

For the screening process, it was decided that two sequential filters would be used (multi stage filters have been used in several other technology assessment processes [207], [218], [225]). The first filter deals with the DCT's peak performance (either theoretically or experimentally demonstrated). Passing this filter means that the DCT's upfront cost is not prohibitively expensive, and efficiency is not prohibitively low. This filter covers the areas of conversion performance and capital cost, and only considers peak performance, not aspects of through-life performance such as lifetime. Cut-offs in Filter 1 are set on the basis that the technology survives for the WEC's full lifetime (20 years in the base case — see Table 6-4). Therefore, technologies that demonstrate that they cannot meet the cut-off values will clearly be unsuitable to move forwards in the screening process. Additionally, the first filter deals with information that is generally well reported in the literature for conversion technologies.

The second filter deals with the through-life aspects of the conversion technology. This covers the cost and embodied carbon emissions on a unit lifetime energy output basis and the durability of the conversion technology. This aims to assess the potential lifetime performance of the technologies, rather than just their peak performance. Due to the more laborious nature of producing lifetime data for conversion technologies, the information for Filter 2 is generally less well reported in the literature. The benefits of arranging the filters sequentially include:

- If a technology is rejected by Filter 1, information does not have to be gathered for the subsequent filter, which saves time and effort (e.g. if a technology is unfeasibly expensive, even assuming a long lifetime, the assessor does not have to expend time gathering fatigue life data).
- The filters are ordered so that the critical and highly available data is gathered first. This means technologies that cannot meet the primary requirement of converting significant amounts of mechanical energy into electrical energy are rejected at an early stage (for instance, there is little point in gathering data on embodied carbon, durability, or lifetime, before knowing if the technology can convert useful amounts of mechanical to electrical energy).

The structure of the screening process is shown in Figure 6-1. Both filters include several parameters that are used to indicate the technology's performance. Cut-offs will be set, where applicable, that indicate minimum acceptable performance levels in these parameters (the value of these cut-offs is shown in Table 6-6 on p.139). If a technology demonstrates that it cannot meet these cut-offs, it may not pass through the filter. These are shown as the rejected technologies in Figure 6-1.

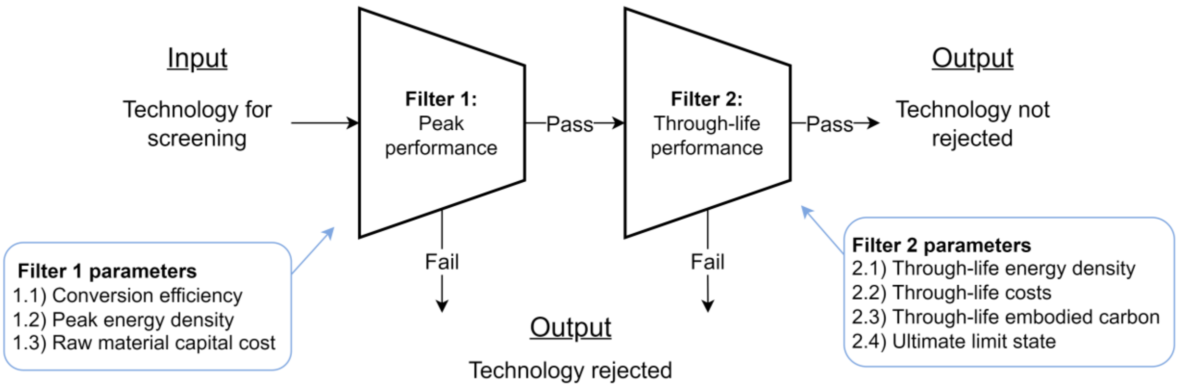

Figure 6-1. *Screening process and filter parameters for direct conversion technology assessment.*

To ensure technologies are not pre-emptively rejected, a recommendation made by Shehabuddeen et al. [207] is adopted, where the technology may still proceed to the next stage if a relatively minor improvement is needed to meet the cut-off and it is likely a change, or adaptation exists that could bring about this improvement. This is facilitated by carrying out a review before a technology is rejected. This also applies to any technology where significant uncertainty exists in a parameter which means it cannot be confidently assessed.

It should also be noted that the technologies assessed in this project are all early-stage in applications for large-scale generation (TRL 1-5) and may see significant performance improvements in the future. While not in the scope of this project, if a technology is discarded it may be re-assessed using the same screening process if a breakthrough occurs (for instance if a material science breakthrough increases the technology's energy density). The data for the different technologies can be updated periodically by re-running saved searches in databases or search engines.

Stages in screening process

Before the screening process is carried out, the cut-offs for each parameter should be determined. The cut-off values for the parameters used in this study are discussed later in this section and are presented in Table 6-6. To carry out the screening, each DCT is assessed against parameters that make up the filter, being awarded:

- *Pass* — the technology exceeds the filter cut-off for this parameter.
- *Fail* — the technology does not meet the filter cut-off in for this parameter.
- *Borderline* — there is too much uncertainty to evaluate if the technology meets the cut-off in this parameter. This could be because the performance is close to the borderline between passing and failing and/or there is significant uncertainty in the technology's performance. The reason for a borderline assessment should be noted.
- *N/A* — no data is available to assess the technology in this parameter.

The pass and fail criteria will be based on pre-determined cut-off values (where applicable). These indicate a 'deal breaker' for the technology if not met. These cut-off values are meant to be absolute minimum requirements, not necessarily a good performance. The cut-off values used for this assessment are shown in Table 6-6. An example parameter assessment table for the conversion efficiency cut-off is shown in Table 6-1.

Table 6-1. *Example assessment of the conversion efficiency parameter (cut-off = 35%).*

	Best conversion efficiency experimentally demonstrated (%)	**Typical resonance frequency**	**Parameter evaluation**
Technology 1	50 (ref)	Low (< 1Hz)	Pass
Technology 2	20 (ref)	High (typically >100Hz)	Fail
Technology 3	90 (ref)	N/A	Pass
Technology 4	10 (ref)	N/A	Fail
Technology 5	85 (ref)	Low (< 1 Hz)	Pass

Following the evaluation against these cut-offs, the assessor(s) should have a table for each parameter that evaluates the technologies against the cut-offs. The parameter evaluations are then combined to form the initial assessment table (shown in the bottom half of Figure 6-2).

Parameter table

	Best conversion efficiency experimentally demonstrated (%)	**Typical resonance frequency**	**Parameter evaluation**
Technology 1	50 (ref)	Low (< 1Hz)	Pass
Technology 2	20 (ref)	High (typically >100Hz)	Fail
Technology 3	90 (ref)	N/A	Pass
Technology 4	10 (ref)	N/A	Fail
Technology 5	85 (ref)	Low (< 1 Hz)	Pass

Initial assessment table

	Raw material cost per unit rated power	**Conversion efficiency**	**Energy/power density***	**Initial assessment**
Technology 1	Pass	Pass	No cut-off	*Pass (PP)*
Technology 2	Pass	Fail		*Fail (PF)*
Technology 3	Borderline	Pass		*Borderline (BP)*
Technology 4	Fail	Fail		*Fail (FF)*
Technology 5	N/A	Pass		*Borderline (NP)*

* Energy density does not have a specific cut-off value

Figure 6-2. *Combining the parameter assessment table into the initial assessment table.*

The initial assessment table will be used to initially sort technologies into pass, fail, or borderline, based around the technology's performance in the parameters. These initial assessment evaluations (final column in the initial assessment table) are given as follows:

- *Pass* — no fails, borderline, or not available N/A data (e.g. technology 1).
- *Fail* — one or more fails (e.g. technologies 2, 4 & 5).
- *Borderline* — mix of passes, borderline and/or not available (N/A) data (e.g. technology 3).

Following this initial evaluation, a review is conducted to finalise a decision for each technology. This essentially asks if the technology merits rejection from the process based on the available data. This final decision will fall into one of the three categories:

- *Straight pass* — the technology can demonstrate that it meets the cut-offs in all the parameters and is allowed to pass. Sufficient data exists for these all to be evaluated.
- *Considered pass* — the technology fails to meet the cut-offs in one or more parameters, or significant uncertainty exists in certain parameters. However, the technology is allowed to pass based on there being promising potential solutions, or a lack of data supporting the failure against a cut-off value.
- *Fail* — the technology demonstrates that it cannot meet the cut-offs in one or more parameters and no readily available solutions are identified in the literature.

Justifications are noted on the reasoning behind the final decision, especially if a different final decision is taken in relation to the initial assessment. This keeps a record of which technologies have additional risks attached to them — for instance if a technology is allowed to pass simply because insufficient data exists to reject it. The technologies that pass this stage then move on to the next filter in the screening process. An example of a final decision table is shown in Table 6-2.

Table 6-2. *Example final decision table for the peak performance filter.*

<table>
<tr><th>Technology</th><th>Initial assessment</th><th>Final decision</th></tr>
<tr><td>Technology 1</td><td>Pass (PP)</td><td>Straight Pass</td></tr>
<tr><td colspan="3">Technology passes the cut-off in all parameters.

Recommendations: Technology passes through to the next filter stage.</td></tr>
<tr><td>Technology 2</td><td>Fail (PF)</td><td>Considered Pass</td></tr>
<tr><td colspan="3">Technology currently fails conversion efficiency parameter. Efficiency may be improved by using existing solution (e.g. similar material with less hysteresis losses) — this should be noted going forwards.

Recommendations: Technology is allowed to pass to the next filter stage. Note that, whilst current conversion efficiency is insufficient, realistic options to significantly improve the conversion efficiency exist.</td></tr>
<tr><td>Technology 3</td><td>Borderline (PB)</td><td>Considered Pass</td></tr>
<tr><td colspan="3">Etc.</td></tr>
<tr><td>Technology 4</td><td>Fail (FF)</td><td>Fail</td></tr>
<tr><td colspan="3">Etc.</td></tr>
<tr><td>Technology 5</td><td>Fail (FF)</td><td>Considered Pass</td></tr>
<tr><td colspan="3">Etc.</td></tr>
</table>

6.1.2 Key considerations and assumptions for screening process

This section covers the key assumptions and simplifications which are required to determine the cut-off values described in Section 6.1.3.

Overall requirements for a DCT wave energy converter

To assess a direct conversion technology (DCT) for wave energy applications, an initial step is determining performance criteria for a successful wave energy converter, and how the utilisation of a DCT in a wave energy converter could affect these. Two of the most prominent processes that aim to address the requirements for a successful WEC are NREL's TPL assessment [204], [206]; and the IEA-OES evaluation framework for ocean energy [29]. These evaluation processes are for an entire device or array of devices, and therefore include many areas that are not readily applicable or quantifiable for early-stage conversion technologies (for example install-ability and social acceptance). Additionally, these assessment processes consider many areas of performance for a WEC, both essential areas of performance and 'nice-to-have' areas of performance. Areas where defining a required level of performance is unclear are not considered in the screening process, for example 'benefit to local community' [204], [206].

For these reasons, a subset of the performance criteria laid out in the NREL and IEA-OES documents were used as the basis of the screening process. These requirements were selected from the long list of requirements in the NREL and IEA-OES documents if they met the following criteria:

1. A definable level of performance (cut-off) in the parameter is critical for the success of a conversion technology in a wave energy application (for example an efficiency of over 50%), and
2. The parameter, or a suitable proxy, can be used to evaluate the conversion technology against the cut-off when the details of specific application to a future wave energy converter are not available.

The parameters used in the IEA-OES evaluation framework and the TPL assessment are tested against these two criteria in Appendix B.3 — Evaluation of IEA-OES T12 and TPL. Additionally, metrics that could not be assessed at early stages were not considered, for example manufacturing at scale. From this assessment of the metrics used by the IEA-OES and TPL, a set of requirements that will be used for the assessment of the conversion technologies can be defined. These fall into the following categories:

- Conversion efficiency — the DCT must be able to convert mechanical to electrical energy with limited losses.
- Lifetime — the durability of the DCT must be sufficient to not compromise the economic and environmental viability of a WEC.
- Cost — the cost of the DCT materials (on a power output basis) must be low enough to not compromise the economic viability of a WEC.

- Greenhouse gas (GHG) emissions — the GHG emissions embodied in the DCT materials (on a power output basis) must be low enough to not compromise the environmental viability of a WEC.

We can observe that these four areas relate to two overall metrics for a wave energy converter: LCoE and lifecycle embodied carbon. For an overall wave energy converter utilising these technologies, targets have been set for both these metrics, shown in Table 6-3. These overall targets are the basis of the cut-off values introduced later in Section 6.1.3.

Table 6-3. *Overall targets for a wave energy converter utilising a direct conversion technology.*

Metric	Units	Target	Justification
LCoE (real)	EUR_{2020}/MWh	100	Similar to the LCoE of the most expensive conventional non-dispatchable low-carbon generation (nuclear), using BEIS electricity generation costs methodology [15], [120]. This is also comparable to the forecasts made in 2022 of long-term wholesale market price of electricity in EU and UK [121], [122].
Lifecycle CO_{2e}	$KgCO_{2e}$/MWh	50	Similar to the highest-emissions conventional non-dispatchable low-carbon energy source (solar PV) in review from NREL [19]

It should be noted that unless specified otherwise, cost values are expressed in EUR_{2020} for the remainder of this chapter. Additionally, the LCoE values are in real terms (as described in the BEIS methodology, reviewed in Section 5.1) and pre-construction costs, such as consenting and surveys, are not included.

Application of conversion technologies in a wave energy converter

To make this evaluation, it is important to start by defining the potential role of a DCT within a wave energy converter. The basic elements of the energy conversion chain in a wave energy converter are shown in Figure 6-3.

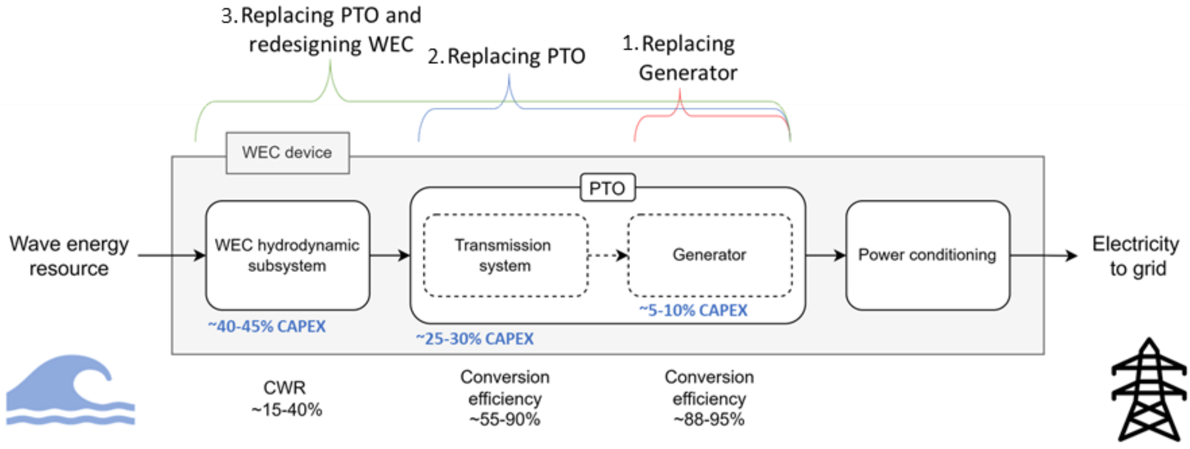

Figure 6-3. *Conversion chain for a conventional wave energy converter based on Pecher and Kofoed* [21, p. 20] *and Frazer Nash consultancy* [132] *and possible roles of a conversion technology within the wave energy conversion chain (power conditioning was not considered in this study).*

A DCT could fulfil different roles in this conversion chain, with three basic configurations:

1. Replacing the generator in a WEC. For this application, there is no requirement for the DCT to work well when cycled at a low frequency, as a transmission system can step up the frequency of the absorbed wave energy before it is delivered to the conversion technology.
2. Replacing the entire WEC PTO. This requires a DCT that can give high power outputs when it is delivered mechanical energy at an ocean wave like frequency, as there is no transmission stage.
3. A DCT that enables fundamentally different wave energy converter designs, for instance a power take-off that is integrated and distributed in the WEC's structure. This also requires a DCT that can give high power outputs when it is delivered mechanical energy at a low, ocean wave like, frequency.

Previous work in this area[20] has highlighted that there is minimal cost reduction benefit from only replacing the generator with a DCT. This is due to limited scope for CAPEX reduction or efficiency improvement (conventional generators typically contribute around 10% of a conventional WEC's CAPEX [132] and have efficiencies of over 90% [21], [132], [226]). For this reason, the technologies in this study are assessed on the basis that they would need to replace the entire PTO at a minimum (options 2 or 3 in Figure 6-3), to offer significant cost reduction potential to the wave energy sector. As this research is only concerned with technologies that could potentially enable radical innovation and step-change cost reductions, it is a prerequisite for the assessment process developed in Part B that a technology can operate well at low frequencies, as a transmission system would be absent.

[20] A study by Frazer Nash [132] highlighted that the effects on capital and operational cost of simply replacing a WEC's generator with a conversion technology is limited. Additionally, the findings of the PolyWEC project identified the need for more novel (low structural cost) structures, in combination with dielectric elastomer PTOs to reduce the overall WEC CAPEX to an acceptable level [262].

Impacts of direct conversion technology on wave energy converter performance

A challenge in making this assessment is that it needs to be design-agnostic — the architecture of a WEC utilising the DCT is unknown. For the purposes of assessing the impact of a DCT on a hypothetical WEC, two sets of subsystems can be considered:

- Direct conversion technology (DCT) subsystem — this is the mechanical-to-electrical energy conversion subsystem in the wave energy converter, based on the DCT technology.
- Non-DCT subsystems — this is all the non-DCT subsystems within the wave energy converter, including the non-DCT structural components.

For the DCT subsystem, the effects that the use of the conversion technology will have in terms of the cost of raw materials and embodied carbon can be directly estimated. These scale with the volume of DCT material required. The volume of DCT raw material can be calculated for each DCT on a per unit energy output basis (i.e. how much DCT material would be needed per unit energy output). Additionally, the lifetime costs of the DCT subsystem can be evaluated by estimating the number of replacements that will be required over the WEC's lifetime, according to the DCT's fatigue life.

To evaluate the effect of the DCT on the Non-DCT subsystems, an assumption is adopted from [132], the Non-DCT subsystems scale linearly with the absorbed power that is delivered to the DCT subsystem. This means the cost and embodied emissions of the non-DCT components scale with the wave power that is absorbed by the WEC (i.e. a proportionally larger device is needed to absorb more wave energy). It also follows that the cost and embodied emissions of the Non-DCT subsystems, on a unit energy output basis, scales with the conversion efficiency of the DCT. For example, if one DCT has a conversion efficiency that is half of another, twice as much mechanical energy will have to be delivered to the DCT subsystem (requiring twice the scale of Non-DCT subsystems) to achieve the same electrical energy output.

Baseline assumptions for DCT wave energy converter

To set cut-off values for the DCT assessment parameters, several assumptions need to be made about the overall hypothetical WEC performance. These are areas in which effect of utilising a DCT cannot be estimated, as they are related to the overall WEC design (such as capacity factor or WEC lifetime). Assumptions are needed in these areas to set cut-offs for the parameters used to assess the DCT in the screening process. A first set of general assumptions are shown in Table 6-4 (sensitivity is assessed to more, or less, optimistic assumptions in these metrics in Appendix B.4 — Cut-off value sensitivity analysis).

Table 6-4. Assumptions made for hypothetical WEC utilising direct conversion technology.

Metric	Unit	Baseline value	Justification
Build time	years	2	Same assumption as for offshore wind in [15] excludes pre-construction activities. CAPEX is split evenly between the two years.
OPEX	% CAPEX/yr	3	In the studies reviewed in [124] OPEX as a percentage of initial costs was 1.5-5% (although other studies, e.g. [27], have used up to 8%).
Capacity Factor	%	30	Ranges of ~20-40% found in the literature [15], [104], [123]. 30% used as a reasonable midline.
AEP_{perMW}	MWh/MW/y	2630	Capacity factor multiplied by hours per year.
Real discount rate	%	8.60	Discount rate in real terms used by BEIS for wave energy [15].
Operational WEC lifetime	years	20	Lifetime of WEC commonly quoted as 20 years in literature [15], [28], [123], [124].
DECEX	% CAPEX	0	Assumption that scrappage value covers DECEX [15].
ACE	$m/mEUR_{2020}$	25	Highest-performing devices in literature achieve ACE[21] values of 9-13 $m/mEUR_{2020}$ [27], [215], [227], [228]. Assumption that hypothetical WEC could achieve approximately double this value (25 $m/mEUR_{2020}$) due to the use of, for example, lower cost structural materials.
Average wave resource	kW/m	25	This represents a moderate resource value used in European wave energy studies [214], [215].

It should be noted that an OPEX towards the lower end of the range in the literature was used because the maintenance costs of direct conversion technologies are likely to be lower than conventional PTOs. The costs of replacing the entire DCT subsystem (if required) are not considered in this OPEX value.

Capital cost and life cycle carbon 'budgets' for DCT subsystem

The proportions of CAPEX dedicated to different subsystems within wave energy converters from a selection of studies are shown in Figure 6-4 (pre-construction activities such as consenting and surveys have been excluded). These are either for generic unspecified WEC types [27]–[29] or, in the case of the study from NREL, an array of point absorber WECs [229].

[21] ACE is the cost of the load bearing structure of a WEC (including foundations) per m of absorbed wave energy front [213]. This is essentially the economic efficiency of the WEC in terms of energy capture. ACE is discussed further in conversion efficiency (parameter 1.3) of section 6.1.3.

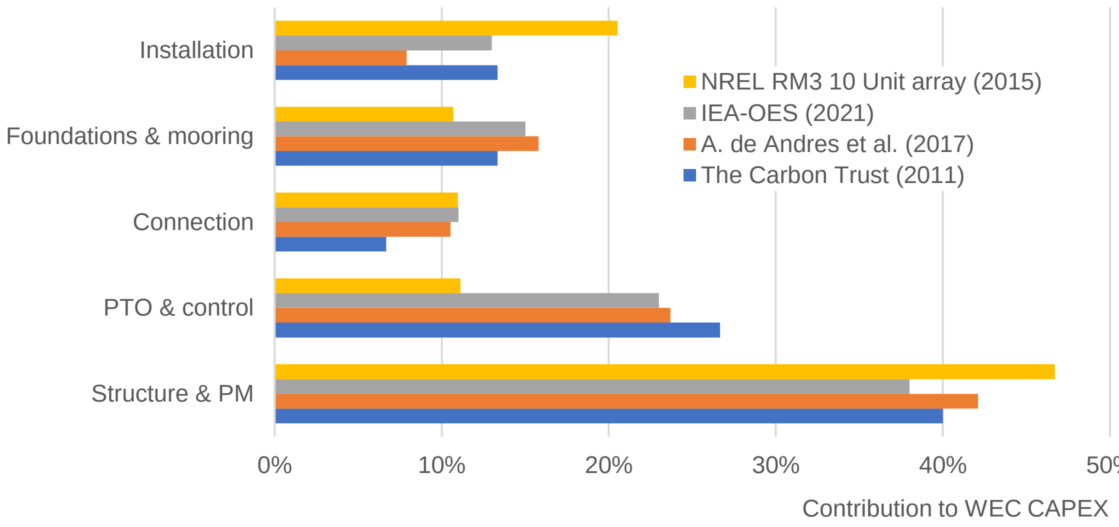

Figure 6-4. *Subsystem contribution to WEC CAPEX (excluding pre-construction costs). Data from* [27]–[29], [229].

To evaluate if a DCT subsystem would be too expensive to be used in a hypothetical WEC, a set of assumptions must be made about the DCT subsystem's relative contribution to the cost of an entire WEC. It is clear that the breakdown between subsystem cost centres may be different for a DCT-based WEC, compared with Figure 6-4. For example, if the DCT is distributed and embedded in the WEC's structure, the DCT technology could take up a significant part of the Structure & PM cost centre. However, if it is assumed that for the DCT based-WEC the proportion of the other subsystems remains consistent[22] a 'CAPEX budget' can be attributed to the DCT subsystems. The key assumptions which relate to the CAPEX breakdown are:

- 65% of the hypothetical DCT-WEC's CAPEX is attributed to the structure, PM and DCT subsystems (this is consistent with the reference WECs in Figure 6-4).
- 50% of the structure, PM and DCT subsystem's CAPEX (32.5 % of the total CAPEX) can be attributed to the DCT's raw materials (this is more generous than the ratios between PTO cost and Structure and PM cost observed in Figure 6-4, to account for the potentially greater role of the DCT subsystem compared to the PTO in a conventional WEC).
- 10% of the WEC's CAPEX is attributed to foundations and mooring.

Previous studies investigating the lifecycle CO_{2e} of WECs have found that the majority embodied of CO_{2e} (around 60-97%) is associated with the materials and manufacturing of the WEC and its moorings & foundations [16]–[18]. Uihlein [18] estimated the lifecycle CO_{2e} for over 100 WECs in the JRC database, and found that in most classes of WEC, the moorings were the single largest contributor to lifecycle carbon. However, structure and PTO were also significant in most device classes. The approximate range of contributions from different subsystems to the embodied carbon of the devices studies by Uihlein [18] are shown in Table 6-5.

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[22] To evaluate the impact on LCoE of replacing a subsystem within a WEC, the IEA-OES [29] suggest that at early stages a consistent cost breakdown between the WEC subsystems can be assumed.

Table 6-5. Contributions to lifecycle carbon for WECs in JRC database. Data from Uihlein [18].

Subsystem	Contribution to WEC CO_{2e} (%)
Moorings	~20-70
Structure	~10-50
PTO	~5-40
Electrical connection	<10

Due to the substantial variation in contribution to embodied carbon between classes of wave energy converter, some rather large assumptions must be made around lifecycle carbon. For embodied carbon, the same assumption is made as for CAPEX — the breakdown (in terms of contribution to lifecycle carbon emissions) between (1) the DCT subsystems + structure, and (2) the other subsystems, remains consistent. This allows a budget, in terms of lifecycle carbon, to be allocated to the DCT subsystem. The key assumptions are:

- 90% of the hypothetical WEC's lifecycle embodied carbon is associated with materials and manufacturing. This is within the range offered in the literature, and allocates a large proportion of the WEC's overall carbon 'budget' to this stage.
- Of the above 90%, 60% is attributed to the Structure, PM and DCT subsystems (54% of the total lifecycle embodied carbon), consistent with the range of results in [18].
- Within this 54% of the total lifecycle embodied carbon, 50% can be consumed by the DCT's raw materials (32% of the total lifecycle embodied carbon) — this is significantly higher than the ratio between PTO and structure & PM than the majority of WEC classes reviewed in [18].

There is clearly significant uncertainty in these cost and embodied carbon budgets. For this reason, a sensitivity analysis was carried out on the proportions of the CAPEX budget and embodied carbon budget that is allocated to the DCT in Appendix B.4 — Cut-off value sensitivity analysis. This shows the effect that using different assumed breakdowns of the CAPEX and embodied carbon budgets could have on the cut-offs for these parameters.

6.1.3 Screening parameters and cut-off values

This section discusses the parameters that are used in the filters that make up the screening process and the cut-off values. Most of the parameters used in the filters are combinations of several data points (e.g. specific cost and energy density to give the cost per unit energy). The parameters for each filter are shown in Table 6-6. A more detailed description of the data requirements for each parameter and the cut-off values is given in the rest of this section under the respective filter headings. These cut-offs are designed to be consistent with the targets of an LCoE of ≤ 100 EUR/MWh and a lifecycle embodied carbon of ≤ 50 $kgCO_{2e}$/MWh for an entire wave energy converter (see Table 6-3).

Table 6-6. The parameters and cut-off values used in the screening process.

Parameter	Unit	Suggested cut-off	Description
Filter 1 assessment parameters			
1.1) Conversion efficiency	%	≥35	Ratio of output electrical energy to input mechanical energy (coupling coefficient may also be used)
1.2) Energy density	J/kg	Dictated by Parameter 1.3	The maximum electrical energy that can be harvested per generation cycle per kg
1.3) Raw material cost per unit energy	EUR/J	≤0.12	Raw material cost divided by cycle maximum energy output
Filter 2 assessment parameters			
2.1) Through-life energy density	J/kg	Dictated by Parameters 2.2 and 2.3	Total energy per kg that can be harvested by the conversion technology before failure (over a maximum of 20 years)
2.2) Through-life energy costs	EUR/J	$\leq 3.2\times10^{-9}$	Raw material cost divided by through-life energy density
2.3) Through-life embodied carbon	$kgCO_{2eq}/J$	$\leq 4.2\times10^{-9}$	The embodied carbon of the conversion technology's raw materials divided by through-life energy density
2.4) Ultimate Limit State (ULS)	Technology specific	N/A - qualitative assessment	The resistance of the conversion technology to ultimate failure

It should be noted that some of these parameters could possibly be further combined, as trade-offs will exist between them. For instance, a high efficiency DCT would be able to have a slightly higher capital cost than a low efficiency one. However, the way in which these should be combined is not entirely clear, and this would further compound the uncertainties in each DCT's performance.

Filter 1 - Peak performance

The first filter assesses the DCT's maximum performance, without considering the through-life aspects of performance.

Parameter 1.1) Conversion efficiency

The conversion efficiency of the DCT is an important parameter that will affect the electrical power output of a WEC. The average conversion efficiencies for several types of WEC transmission are shown in Table 6-7 (weighted average conversion efficiency expected in wave energy operation, rather than efficiency at rated power or maximum efficiency).

Table 6-7. *Indicative average conversion efficiency for different generic PTO types.*

PTO type	Average transmission efficiency [21, p. 12]	Generator efficiency [230]	Combined average PTO efficiency
Direct	~95%	N/A	~95%
Air	~55%	~90%	~50%
Water	~85%		~77%
Hydraulic	~65%		~59%
Mechanical	~90%		~81%

To give the same power output a WEC with a lower average conversion efficiency would require a larger average power capture (either through better hydrodynamic efficiency (CWR), or a larger primary interface with the incoming waves), or to be placed at a location with a higher wave resource. The effect of conversion efficiency on a WEC's power output is shown in Equation 6-1, where P_e is the electrical power output from the PTO, P_m is the mechanical power absorbed by the WEC, and η is conversion efficiency.

$$P_e = P_m \times \eta$$

Equation 6-1. *WEC power output as a function of absorbed power and conversion efficiency.*

Conversion efficiency is effectively a measure of electrical energy output over mechanical energy input. However, it can be defined in several ways depending on what measure of mechanical energy is used and if losses are included[23]. Three common measures of conversion efficiency are presented for DCTs in the literature:

- *On-resonance efficiency* — this is the electrical energy that is output divided by the mechanical energy that is used by the system. This measurement of efficiency assumes that any mechanical energy that is stored in the material is recoverable. To achieve this efficiency, the conversion technology generator must operate at resonance.
- *Off-resonance efficiency* — this is the electrical energy that is output divided by the total mechanical energy input to the system. This measurement of efficiency assumes that none of the mechanical energy stored in the material is recoverable. This is representative of conversion material generators operating far from resonance.
- *Coupling coefficient* — the coupling coefficient is essentially the same as the off-resonance efficiency, except that electrical and mechanical losses are discounted. For this reason, the coupling coefficient is always higher than the off-resonance efficiency of a conversion technology generator. However, depending on the amount of stored mechanical energy, and the mechanical and electrical losses, the on-resonance efficiency may be either higher or lower than the coupling coefficient (for further explanation of coupling coefficient see Crossley and Kar-Narayan [157]).

This means that it is desirable for a DCT generator to have a low (wave-like) natural frequency and low electromechanical losses in order to achieve high conversion efficiencies in a wave

[23] A good explanation of these energy flows is given in Crossley and Kar-Narayan [157].

energy application. On-resonance conversion efficiencies that have been demonstrated at very high frequencies are unlikely to be representative of a DCT's performance in a wave energy application.

Cut-off value for Parameter 1.1

As explained above, a lower PTO conversion efficiency means that a WEC will need to capture and deliver more mechanical energy to the conversion subsystem to achieve a unit electrical power output. For the purposes of this work, a wave resource of 25 kW/m is assumed (see Table 6-4). This means that a WEC with a less efficient conversion subsystem requires a larger primary interface with the incoming waves or higher capture width ratio (more hydrodynamically efficient at absorbing incoming waves) to deliver a unit electrical output. To define a minimum acceptable conversion efficiency, an estimate of the cost of absorbing a unit of wave energy is therefore required. It should be noted at this stage that a lower conversion efficiency will also affect the lifecycle CO_{2e} of the WEC on a per kWh basis. However, there is not an established measure of embodied carbon per unit absorbed energy for wave energy devices. This has therefore not been considered when setting the cut-off for conversion efficiency.

The ACE metric developed by NREL [213] is a measure of the average capture width (i.e. the ratio of absorbed wave power (kW) to the energy in the wave resource (kW/m), measured in a set of climates), divided by the fabricated material costs[24] of a WEC's load-bearing components and its foundations. This is shown in Equation 6-2, where $\overline{ACCW}$ is the WEC's capture width averaged over a number of climates (six were used in the Wave Energy Prize) and CCE is the characteristic capital expenditure (a cost estimate of the load-bearing structure and foundations of the WEC).

$$ACE = \frac{\overline{ACCW}}{CCE}$$

Equation 6-2. *ACE metric formula* [213].

ACE, therefore, is an expression of the structural WEC costs associated with absorbing a metre of wave front in a set of wave energy climates. In the ACE Guidance documents [213], the characteristic capital expenditure does not include the mechanical-to-electrical conversion aspects of the PTO. However, as the DCT subsystem may also be part of the primary interface in our hypothetical WEC, it is included as part of the structural costs in the calculations presented in this section. Therefore, the assumption is being made that CCE in Equation 6-2 accounts for ~75% of total WEC CAPEX (based on the assumed breakdown of WEC CAPEX in Section 6.1.2). The findings in [215] show that the capture width for most WECs tested during the wave energy prize did not vary significantly in different sea states. For this reason, it seems valid to use the estimated ACE values in Table 6-8 (converted into EUR_{2020} values) for single sea states as a benchmark for the current state of the art.

[24] The fabricated cost values for several materials used in the wave energy prize to calculate ACE values are shown in [213, p. 33].

Table 6-8. ACE estimates for a selection of WECs. For calculation see Appendix B.5 — ACE value of other WECs.

Technology	Wave resource (kW/m)	ACE (m/million EUR_{2020})
CorPower Ocean 250 kW [27], [231]	26	13.3
Aquabuoy [227]	28	6.7
WEPTOS [228]	26	12.7
Aquaharmonics*	26	9

*Approximate ACE value from Dallman et al. [215] for Aquaharmonics in Yeu sea state (26 kW/m).

As shown in Table 6-8, high performing WECs in the literature can achieve ACE values of around 7-13 m/million EUR_{2020}. Given that our hypothetical WEC may have a very different architecture and utilise different materials compared to the current state of the art, it is a fair assumption that it may have a significantly higher ACE. For the purposes of this work, it is assumed that an ACE value of up to 25 m/million EUR_{2020} (around double the estimates for current state of the art) is achievable for a hypothetical DCT-based WEC.

Using the assumptions laid out in Table 6-4, the LCoE for a hypothetical DCT WEC at a given ACE value can be plotted against conversion efficiency (an example calculation is shown in Appendix B.5 — ACE value of other WECs). This can be used to illustrate the minimum required conversion efficiency (at a given ACE) to achieve the LCoE target of 100 EUR_{2020}/MWh. Figure 6-5 shows the variation in LCoE against conversion efficiency for the hypothetical WEC for two different values of ACE, representing the current state of the art (12 m/million EUR_{2020}) and the value that is assumed for the hypothetical WEC utilising a DCT (25 m/million EUR_{2020}).

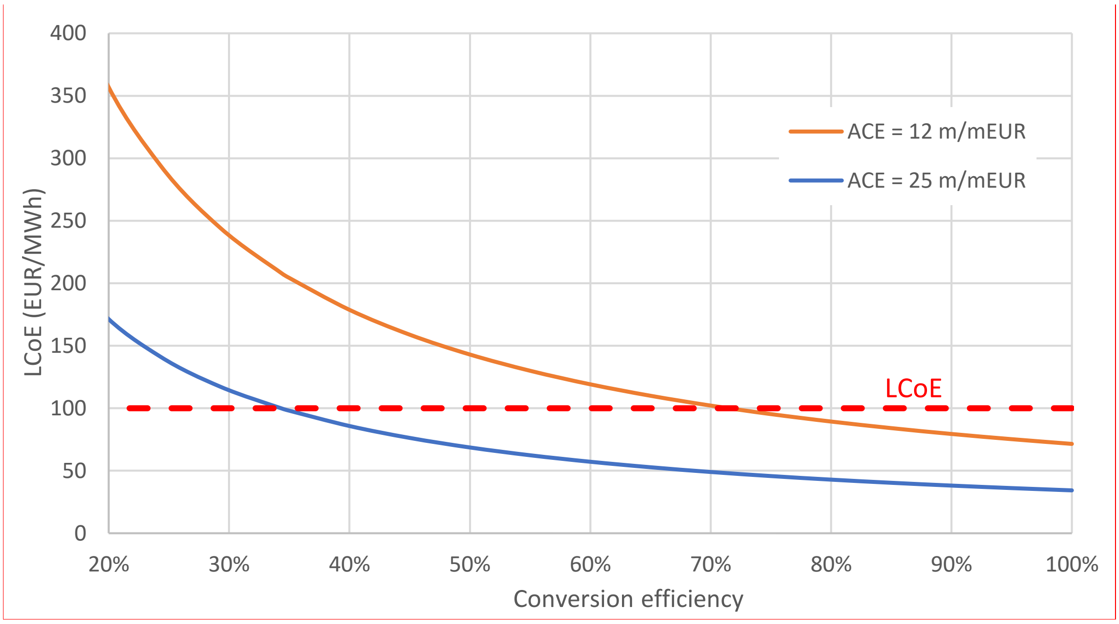


***Figure 6-5.** LCoE dependence on conversion efficiency at two different ACE levels (average wave resource of 25 kW/m).*

This shows that, in a wave resource of 25 kW/m, if the hypothetical WEC achieves an ACE similar to the estimates for current state of the art, a conversion efficiency of >70% would be required to meet the LCoE target of 100 EUR_{2020}/MWh. If the assumption is made that an ACE of around twice the level of the current state of the art is achievable by our hypothetical wave energy converter (orange line in Figure 6-5), a conversion efficiency of >35% would be required to meet the LCoE target of 100 EUR_{2020}/MWh. This assumption is based on the hypothetical wave energy converter having a lower structural cost or having a better hydrodynamic performance than current state of the art WECs. This improvement in ACE could come, for instance, though utilising lower cost structural components. The conversion efficiency cut-off value is set at 35%, corresponding to the more ambitious ACE value.

Parameter 1.2) Peak energy density

Energy density of the conversion technology is the driver of the mass of the conversion material required to give a unit rated power output in low-frequency operation. Essentially, lower energy density results in more of the active material required to deliver the same energy output per cycle. There are two data points that can be gathered for this:

- *Energy density* — the maximum electrical energy that can be output per cycle by the conversion technology. This can be defined per unit mass (J/kg), per unit volume (J/m^3), or per unit area (J/m^2). This figure may be either theoretical (based on what the technology can theoretically achieve), or experimentally demonstrated. Energy density is a useful metric as it is not frequency dependent and therefore can be more fairly compared between technologies.
- *Power density* — this is the electrical power output that the conversion technology can output either per unit mass (W/kg), per unit volume (W/m^3), or — in some cases — per unit area (W/m^2). An important aspect of power density is that it is dependent on the frequency at which the conversion technology generator is excited. Some technologies can achieve very high power densities, but only at very high frequencies (for example magnetostriction generators[25]). As the peak wave period for sea waves is typically in the order of ~0.1 Hz, power densities obtained at high excitation frequencies are unlikely to be a good representation of a technology's power density in a wave energy application.

Energy density affects the mass of conversion technology required to deliver a unit electrical power output. If it is assumed that the conversion technology delivers its full energy density twice per wave at rated power output, an appropriate relationship between rated power density and energy density can be written. This is shown in Equation 6-3, where it is also assumed that rated power is delivered at around the peak wave period T_p. Here, PD_{rated} is the rated power density of the conversion technology in W/kg, ED_{Max} is the energy density of the conversion technology in J/kg, and T_P is the assumed peak wave period in seconds.

$$PD_{rated} = \frac{ED_{Max}}{0.5T_P}$$

Equation 6-3. *Rated power density equation for conversion technology.*

In this thesis a peak wave period of 10s was assumed. This was based on the work of Bull and Dalman [232], who found that in the seven locations around the USA where they gathered

[25] Magnetostriction generators with high power densities of ~3000 W/kg have been demonstrated [239] however these high power outputs are all obtained with input mechanical energy sources at 100's to 1000's of Hz [180].

data, ≥60% of the annual wave energy resource was concentrated in sea states with peak energy periods (T_p) of around 10s (9.86-12.71s). By assuming that the conversion technology delivers its full energy density approximately every 5 seconds at rated power output (half of the 10 second peak wave period), a rough estimate of the unit rated power output per unit mass can be obtained, as shown in Equation 6-3.

Cut-off value for Parameter 1.2

A cut-off value is not specified for peak energy density — rather, this is driven by the material's capital cost. However, if extremely high masses of raw material are needed simply for the conversion technology, this could be considered a serious cause for concern. The mass of structural steel per unit rated power for several WECs were evaluated by [27]. These results are shown in Table 6-9, with the structural mass of an offshore wind turbine for comparison.

Table 6-9. *Structural mass of steel per unit rated power for a selection of wave energy converters* [27] *compared to wind turbine structural mass* [233].

Reference technology	Structure mass per unit rated power (tonnes/MW rated)
WEC — most common (7/11 assessed devices)	700-3000
WEC — best performers (3/11 assessed devices)	300-400
Large scale offshore wind turbines*	<150

*Mass of the tower, hub nacelle and blades for 5, 8 and 10 MW reference turbines

For example, an energy density of 10 J/kg would imply a mass of ~500 tonnes/MW is required, simply for the conversion technology's raw materials. Very low energy densities such as this are unlikely to be viable for wave energy applications.

Parameter 1.3) Raw material capital cost

Sufficiently low capital costs are a key requirement for a WEC. Therefore, evaluating the contribution of the conversion technology to a device's CAPEX is an important parameter to assess. The cost of the active raw materials was used as a proxy for the minimum capital cost of each DCT. This only considers the active materials' capital cost (that is, the material that converts mechanical to electrical energy). Therefore, it does not include the cost of the electrodes (unless they are part of the active material), any substrate the materials are bonded to, or additional parts of a generator such as the pickup coils or permanent magnets for a magnetostriction generator, or power electronics. Additionally, this did not consider the costs of manufacturing the generator from the raw material. Due to the exclusion of manufacturing costs as well as the costs of any other supporting systems (e.g. electrodes or electronics), this cost will be significantly lower than the actual cost of the assembled conversion technology in a generation application. Therefore, the raw material cost represents an absolute lower limit on the technology's contribution to the hypothetical WEC's CAPEX.

Raw material costs were chosen for three primary reasons. Firstly, for the purpose of filtering out unsuitable technologies, raw material costs give an absolute lower limit on the technology's cost and allow removal of technologies that are fundamentally unsuitable.

Secondly, current manufactured costs of generators may be misleading, or non-existent, at such an early stage. The technology may be manufactured in very small unit sizes or volumes and may only be manufactured for other applications (such as sensors or actuators). This could result in a cost that is far higher than might be seen in a large-scale generator application[26], and therefore is not a good basis for early-stage screening.

For this parameter, raw material cost for the conversion technology is divided by the energy density of the technology to give the cost per unit energy parameter. This gives a proxy of the lowest possible CAPEX for the DCT subsystem, and is therefore a good way to screen out clearly unviable technologies. This is shown in Equation 6-4, where EC is the cost per unit energy in EUR/J, CS is the specific cost in EUR/kg, and ED_{max} is the maximum energy density in J/kg.

$$EC = \frac{CS}{ED_{max}}$$

Equation 6-4. *Cost per unit energy of a conversion technology.*

Cut-off value for Parameter 1.3

Using the assumptions in Table 6-4, a limit for the overall CAPEX of the hypothetical WEC can be calculated to stay within the LCoE target of 100 EUR_{2020}/MWh. This LCoE was calculated in real terms, using the BEIS methodology (described in Section 5.2), and does not include pre-construction costs such as surveys and consenting. The corresponding CAPEX limit corresponding to 100 EUR_{2020}/MWh was found using goal seek in an Excel spreadsheet. Using these assumptions, a CAPEX of around 1.9 $mEUR_{2020}$/MW or less is permissible to stay within the LCoE target. In Section 6.1.2, it is assumed that the structure, prime mover and DCT subsystem account for around 65% of the WEC's total CAPEX (excluding pre-construction CAPEX) and that up to 50% of this can be allocated to the DCT subsystem's raw materials. Using this assumed contribution of the DCT subsystem to the overall WEC CAPEX, the overall CAPEX budget for the DCT subsystem raw materials is around 0.6 $mEUR_{2020}$/MW (or 0.6 EUR/W). This is shown in Table 6-10.

Table 6-10. *Assumed CAPEX budgets for hypothetical WEC subsystems.*

	Assumed contribution to overall WEC CAPEX (%)	**CAPEX budget ($mEUR_{2020}$/MW)**
Overall WEC CAPEX limit (excluding pre-construction costs)	100	1.9
Structure, prime mover and DCT subsystem	65	1.2
DCT subsystem raw materials	32.5	0.6

[26] For example, the raw material costs of the elastomers in DEGs is in the order of under ten Euro per kg [32], [245], [296], while the manufactured cost of high quality DE films is currently in the order of thousands of Euro per kg [32].

This CAPEX limit for the DCT raw materials can easily be converted into an energy density cut-off value by dividing the CAPEX cut-off by the assumed cycling period.

$$EC_{cut-off} = \frac{CS}{ED_{max}} = \frac{CAPEX_{target}}{0.5T_p}$$

Equation 6-5. *Energy cost cut-off.*

If the $CAPEX_{target}$ value of ~0.6 EUR/W and the T_p value of 10s (as defined for parameter 1.2) are substituted into Equation 6-5, we get a cost per unit energy density cut-off equal to 0.12 EUR/J.

Filter 2 – Through-life performance

While Filter 1 addresses the peak energy density of the conversion technology, it does not evaluate the through-life performance. Filter 2 aims to address this by taking into account the lifetime of the conversion technology.

Having a sufficiently high lifetime is essential for a WEC to be both economically and environmentally viable. A WEC will be cycled approximately once every 10 seconds while generating (equivalent to over 50 million fatigue cycles over a 20-year lifetime). Therefore, resistance to various forms of cyclic failure is important in evaluating the potential lifetime of a conversion technology in wave energy applications. Additionally, the ability to survive extreme events (e.g. high mechanical loads) is important to ensure a long technology lifetime.

Parameter 2.1) Through-life energy density

Through-life energy density is an important parameter for a conversion technology [234]. This is the estimated total electrical energy, in Joules, that can be output by the technology (in this case over the reference 20-year WEC lifetime) before it fails due to fatigue. The through-life-energy-density LED in J/kg is shown in Equation 6-6, where ED is the average energy density per cycle in J/kg and N is the number of cycles to failure.

$$LED = ED \times N$$

Equation 6-6. *Through-life energy density of a conversion technology.*

It should be noted that the energy density in this equation ED may not be equal to the maximum energy density (ED_{max}) used in Filter 1, as a compromise between maximum energy density and number of cycles to failure may be required to maximise LED.

Cut-off value for Parameter 2.1

The cut-off value for this parameter is defined by Parameter 2.2 (the technology's material costs) and Parameter 2.3 (embodied carbon).

Box 1: note on lifetime energy density.

It is important to note that lifetime energy density (LED) does not take account of the variability in energy output per cycle of the conversion technology. For this reason, as explained below, LED may overstate the performance of a DCT in a wave energy application. However, this is not considered an issue, as the screening process aims to set minimum performance cut-offs.

An optimum trade-off between cycles to failure and energy density may exist for a technology to maximise lifetime energy density (LED). If this optimum balance between energy density and fatigue life exists for a technology, then a maximum value of LED would be achieved when a technology is run at a constant energy output per cycle. The energy output per cycle when utilised in a wave energy converter is unlikely to be constant, due to the variability in wave energy resource (this is why rated power and average power outputs are different). For this reason, LED values from experiments run at constant energy outputs per cycle could overestimate LED compared to the values obtainable in wave energy applications. As the screening process is setting minimum performance cut-offs, this is not considered an issue. However, this should still be noted, as LED is factored into the cut-off values for Parameters 2.2 and 2.3.

Parameter 2.2) Through-life costs

The lifetime energy costs (LEC), in EUR/J, are calculated in the same way as the cost per unit energy in Filter 1, except the maximum energy density is replaced with the through-life energy-density (LED). This is shown in Equation 6-7. This provides an indication of the technology's through-life cost performance, which incorporates fatigue life. However, data collection is also more difficult, as it relies on combined energy density and lifetime data availability.

$$LEC = \frac{CS}{LED}$$

Equation 6-7. *Through-life cost of a conversion technology.*

It should be noted that this measure of through-life costs assumes that the total capital cost of any DCT subsystem replacements occurs during the WEC's construction period (i.e. the costs of replacements are not discounted).

Cut-off value for Parameter 2.2

To calculate the cut-off for the lifetime energy cost ($LEC_{cut-off}$) we start with the $CAPEX_{target}$ value for the conversion technology (see Section 6.1.3 on Parameter 1.3). This is a target in terms of cost per unit rated power output. To convert this cost per unit rated power target into a lifetime energy cost cut-off ($LEC_{cut-off}$), the $CAPEX_{target}$ is divided by the assumed hypothetical WEC's annual energy production (in joules) per MW rated capacity multiplied by the WEC's lifetime (for assumptions see Table 6-4). This gives the maximum capital cost of the DCT subsystem divided by its lifetime electrical energy output. This is shown in Equation 6-8, where LT_{WEC} is the WEC's lifetime in years and AEP_{perMW} is the annual energy production per MW of rated capacity.

$$LEC_{cut-off} = \frac{CAPEX_{target}}{LT_{WEC} \times AEP_{perMW}}$$

Equation 6-8. *Through-life energy costs cut-off.*

If the CAPEX target of ~0.6 EUR/W (see Parameter 1.3), a WEC lifetime of 20 years (see Table 6-4), and a capacity factor of 0.3, are substituted into Equation 6-8, the overall lifetime energy cost cut-off is equal to 3.2×10^{-9} EUR/J.

Parameter 2.3) Embodied carbon

Low lifecycle carbon emissions are a requirement for any energy generation technology (including wave energy), and will become increasingly critical as we further decarbonise our energy supply. Embodied carbon in the raw materials of the conversion technology can be used to assess the DCT subsystem's contribution to a WEC's lifecycle carbon emissions. The parameter used to evaluate lifecycle emissions is the embodied kg of CO_{2e} associated with the production of one kg of the active raw material (ECO_2). This can then be divided by the lifetime energy density (LED) to give the lifetime embodied carbon in $kgCO_{2e}$/J (LCO_2). This is shown in Equation 6-9.

$$LCO_2 = \frac{ECO_2}{LED}$$

Equation 6-9. *Through-life embodied carbon of a conversion technology.*

This is the same definition of the material used in the material cost parameter. This means that LCO_2 does not include any additional processing required to manufacture a generator from the raw material, nor does it include any of the supporting subsystems. This was chosen as a parameter for similar reasons to raw material costs: it sets an absolute lower limit on the CO_{2e} for the conversion technology generator, and it is a readily available parameter for many materials (reducing time requirements).

Whilst there are many other important environmental impacts, embodied CO_{2e} is one of the most widely used and readily available data points for materials (reducing data-gathering time), and has a good basis for determining a cut-off value.

Cut-off value for Parameter 2.3

As laid out in Table 6-3, the target for embodied carbon for the overall DCT WEC is <50 kgCO2e/MWh. The assumption from Section 6.1.2 is used, that 90% of the hypothetical WEC's lifecycle CO_{2e} emissions can be attributed to the materials and manufacturing. Of this 90%, around 60% (or 54% of the total) can be attributed to the structure, prime mover and DCT subsystem. Around 50% of this (or 27% of the total) can be allocated to the DCT raw materials. This means that the DCT subsystem's raw materials can account for a maximum of 13.5 $kgCO_{2eq}$/MWh, as shown in Table 6-11. This upper limit (cut-off) of 13.5 $kgCO_{2eq}$/MWh is equivalent to 3.75×10^{-9} $kgCO_{2eq}$/J.

Table 6-11. *Conversion technology carbon emission cut-offs.*

System/subsystem	Assumed contribution to WEC embodied CO_2 (%)	Emissions per MWh ($kgCO_{2eq}$/MWh)
WEC	100	50
WEC materials and manufacture	90	45
DCT subsystem + structure	54	27
DCT subsystem raw materials	27	13.5

Parameter 2.4) Ultimate limit state

While Parameters 2.1-2.3 all incorporate fatigue life, resistance to ultimate failure is another key characteristic that determines the lifetime of WEC components. Technologies that are more resistant to ultimate failure will reduce the probability of unscheduled maintenance/replacement of the conversion technology subsystem(s). If a technology is not resistant to ultimate failure, it would be too unreliable to use for energy conversion in a WEC.

As the operating conditions, and therefore failure modes, cannot be defined for the usage of the conversion technologies at this stage, a more qualitative judgement (that is still based on empirical data) will have to be made around the parameters that seem important for a specific technology. Some potential ultimate failure parameters could be:

- *Rupture strain/yield strain* — this defines the maximum extreme operation capability (in terms of strain) for a conversion technology. Additionally, conversion technologies with high strain ranges (hundreds of percent) can significantly change their shape under extreme loads, which may allow them to 'load shed' in storm conditions [224].
- *Ultimate/yield strength* — this indicates the maximum extreme operation capability (in terms of force) of a conversion technology.

As mentioned above this assessment will require a degree of qualitative judgement by the assessor(s). Additionally, good performance in some areas may negate the need for good performance in others (for example, having an extremely high rupture strain may mean that the strength of a material is less important, as load shedding can take place). However, this screening step will force the assessor(s) to think about the resistance of the material to ultimate failure at an early stage. This could be especially important for materials that have very poor properties (e.g. they are extremely brittle and weak) which could be considered unsuitable for WEC applications.

Cut-off value for Parameter 2.4

In the absence of a defined cut-off, this is a qualitative judgement based on the material's physical and mechanical properties.

6.2 Results from assessing direct conversion technologies

This section presents the results of the screening process when applied to the six direct conversion technologies. These results are grouped by filter. Section 6.2.1 shows only the parameter tables, initial assessment and review associated with Filter 1. This is then repeated in Section 6.2.2 for Filter 2.

6.2.1 Results for Filter 1

Filter 1 — Parameter assessments

Parameter 1.1) Conversion efficiency

The conversion efficiency of the DCTs is presented in Table 6-12. Given the cut-off value of 35%, one technology is given a *Fail* assessment as it clearly does not meet the cut-off value — polymeric piezoelectric generators. Dielectric fluid generators (DFGs) and magnetostriction are evaluated *Borderline.* For DFGs their performance is only slightly below the cut-off value. Additionally, the experiment that the DFG data is taken from was not optimised to achieve high conversion efficiencies, therefore it is likely that conversion efficiencies in line with the cut-off could be achieved utilising DFG technologies [135]. Magnetostriction generators have demonstrated conversion efficiencies close to the cut-off, with Galfenol generators having shown conversion efficiencies of up to 35%. However the lower cost, higher energy density, Terfanol-D based generators have only demonstrated conversion efficiencies of up to 25%. Additionally, magnetostriction generators typically have high resonance frequencies, owing to their large stiffness. This means that the results presented in Table 6-12 may overestimate the efficiency Magnetostriction generators could achieve in low-frequency wave energy applications.

All other technologies are given passes as they clearly exceed the cut-off.

Table 6-12. Highest demonstrated conversion efficiency.

Technology		Best conversion efficiency experimentally demonstrated (%)	Potential resonance frequency	Parameter evaluation
Dielectrics	DEG	40 [235] (Acrylic)	Low (< 1 Hz)	Pass
	DFG	~30 [135] (Acrylic + silicone oil)	N/A	Borderline
Triboelectric	Contact (LS mode)	50 [171] (PTFE + unspecified metal)	N/A	Pass
	Free standing	85 [173] (FEP + Al electrode)	N/A	
Piezoelectric	Ceramic (PZT)	78.5 [236] ~55 (coupling coefficient [156, p. 53])	High (typically >100 Hz)	Pass
	Polymer (PVDF)	12.5* (21.8* Maximum) (coupling coefficient) [237]	N/A	Fail
Magnetostriction		35 [238] ~35-50 (magnetic coupling coefficient [184]) (Galfenol) 25 [239] ~50-65 (magnetic coupling coefficient [185]) (Terfanol-D)	High (typically >100 Hz)	Borderline

*Coupling coefficient values experimentally obtained for PVDF nanowires. PVDF thin films have demonstrated significantly lower coupling coefficients of around 0.5–4% [237].

Parameter 1.2) Energy density

The potential energy output of a conversion technology per cycle can be described by its energy density (either in J/kg or J/m^3). This measure is independent of frequency, making it a good parameter for comparison of the different technologies. Table 6-13 shows that DEGs and DFGs have significantly higher energy densities than any of the other technologies assessed. The other technologies all have very low energy densities, translating into thousands of tonnes of raw material per MW rated power (when cycled at wave-like frequencies). Triboelectric generators are somewhat more uncertain, as a normalised power density was used for the demonstrated energy density, and there are significant uncertainties associated with the theoretical energy density (see Appendix B.1 — Energy density of triboelectric generators). However, the data available indicates, in general, low energy densities for triboelectric generators. Data for experimental demonstrations of piezoelectric and magnetostriction generators do not typically list maximum energy density. Therefore, some of these experimentally demonstrated maximum energy density values have been left blank in Table 6-13.

Table 6-13. Highest demonstrated and theoretical energy densities.

Technology		Electrical energy density per cycle (J/kg)	
		Demonstrated	**Theory**
Dielectrics	DEG	780 (Acrylic) [137]	1,200 [142]
		369 (NR) [142]	3,500 [142]
	DFG (Acrylic + silicone oil) **	47 [135]	184*** [135]
Triboelectric (PTFE)*		~0.5 [172]	~10 [240]
Piezoelectric	Ceramic (PZT)	N/A	≤ 7.4 [160]
	Polymer (PVDF)	N/A	≤ 0.035**** [160]
Magnetostriction*****		N/A (Terfanol-D)	2.7 [185]
		0.141 (Galfenol) [186]	0.079 [184]

*Values likely to be overestimates, see Appendix B.1 — Energy density of triboelectric generators.
**Combination of the mass of elastomer and fluid layers (derived from the energy density values in [135]), see Appendix B.6 — Energy density of DFG.
***Highest theoretical value based on the single experimental setup and assumptions presented in [135]. Significantly higher energy densities may be possible, see Appendix B.6 — Energy density of DFG.
****Jean et al. [160] used a coupling coefficient (k^2) of 2.3% to derive the energy density of PVDF. This is in line with thin film PVDF coupling coefficients but is lower than the maximum coupling coefficient demonstrated for PVDF nanowires (see Table 6-12).
*****Values are for magnetic energy density. In reality, electrical energy density would be lower due to losses in conversion from magnetic to electrical energy. Theoretical magnetic energy densities taken from product data sheets [184], [185]. The demonstrated magnetic energy density for Galfenol was measured as higher than the energy density specified in datasheet [186].

Box 2: note on power density.

An alternative parameter that could be assessed would be the maximal power density that was demonstrated for each technology from experimental testing. However, it is a less straightforward parameter to interpret than energy density. Some of the technologies (e.g. magnetostriction and triboelectric generators) have demonstrated very high power densities. However, this is largely a function of having been tested with a very high frequency mechanical input. This means that, while the power output is high, the energy output per cycle may be very low. Given that the number of cycles that will be performed per second are likely to be of a similar order of magnitude to the frequency of ocean waves, ~0.1 Hz in a wave energy converter (when a transmission system that increases the frequency of loading is omitted), the energy that can be converted per cycle is a better figure of merit to assess these technologies than power density. Some studies on energy harvesters have suggested that experimental power outputs could be normalised by frequency and/or acceleration of the mechanical input as a figure of merit for low-frequency applications [241]. However, this normalised power density is not consistently reported in the literature. For this reason, energy density was primarily used in this study. Where energy density is not available (either demonstrated or theoretical), normalised (or low-frequency) power density can be used (see, for example, the energy density values for triboelectric generators in Table 6-13 derived from normalised power density data). Demonstrated power densities and some notes of the associated conditions of mechanical input are shown in Table 6-14. This shows that significantly different results would be obtained using this figure of merit compared to energy density.

Table 6-14. Highest demonstrated power density for direct conversion technologies. Note these power densities are achieved at different frequencies.

Technology		Power density (demonstrated) W/kg	Notes
Dielectrics	DEG (Acrylic)	197 [188]	Diaphragm demonstrated at wave-like frequencies (0.7 Hz)
	DFG (Acrylic + silicone oil)	5.86 * [135]	Diaphragm demonstrated over a cycle period of ~10s*
Triboelectric (PTFE)		5,000 [171]	High-speed linear sliding contact
Piezoelectric	Ceramic (PZT)	147 [242]	Doubly fixed end beam, centre deflected a frequency of 1300 Hz
	Polymer (PVDF)	N/A	No data found in literature
Magnetostriction (Terfenol-D)**		2,950 [239]	Axial deformation at a frequency of 1000 Hz

*Derived by author, based on the average power output of 0.575 W and energy output of ~0.5 mJ/cycle.
**Power density derived based on Terfenol-D data sheet in [185].

Parameter 1.3) Capital cost

Approximate costs of the raw material for the active material in each technology are shown in Table 6-15. These values were converted into Euro per kilogram for each raw material. Where possible, these costs were taken as a range of the per kg costs presented on wholesaler websites or from the literature (although for some materials, e.g. Terfenol-D and Galfenol, only single sources of cost data could be identified by the author).

Table 6-15. Unit costs of active raw materials.

Technology		Active material	Raw material cost (EUR/kg)	Source
Dielectrics	DEG	Synthetic (e.g. acrylic)	5-15	Discussion with DEG experts suggested that cost estimate for general DE materials of 5-15 EUR/kg presented in [243] is appropriate Silicone quoted as ~6 EUR/kg in [244] Natural rubber quoted as <10 EUR/kg in multiple sources [32], [245]
	DEG	Silicone		
	DEG	Natural rubber	5-10	
	DFG	Silicone oil	8-20	Bulk (100-1000's kg) cost of Xamiter PMX 200, 50cs [246], [247]
	DFG	Ester*	8	Cargill Envirotemp FR3 transformer Fluid (1000 L drum) [248]
Piezoelectric	Ceramic	PZT	~75	Unprocessed material costs for bulk orders — search in various wholesale websites
	Polymer	PVDF	~15-25	
Triboelectric		Kapton	~15-45	
		PTFE	~5-20	
		FEP	~25-50	
Magnetostriction		Terfenol-D	13	Cost from only commercial supplier identified [249]
		Galfenol	4200-8400	

*Common dielectric fluid demonstrated in HASEL actuators [150].

To achieve the cut-off value for capital cost (0.12 EUR/J), a corresponding level of energy density must be achieved. This is calculated by substituting the capital cost cut-off and material costs into the cost per unit energy equation (Equation 6-4). Comparing these requirements to the energy density values for each technology in Table 6-13, it can be seen that the only technology that achieves an energy density that is consistent with meeting the capital cost cut-off of 0.12 EUR/J, both experimentally and theoretically, are DEGs[27]. DFGs were given a *Borderline* assessment. They would not meet the cut-off based on current experimental data (based on results from a single study [135]). Although, DFGs would surpass the cut-off value based on their theoretical energy density from the same study. In addition, significant improvements in DFG energy density (and therefore cost per unit energy) may be achieved using low-cost materials such as Kapton which have a high electrical breakdown

[27] Four of the six technologies would pass the cut-off of 600,000 EUR/MW if the highest demonstrated power density assumption is used. However (as discussed in Box 1), this is not representative of wave energy frequencies for many of the technologies.

strength. Piezoelectric, triboelectric and magnetostriction technologies[28] do not achieve high enough energy densities to meet the cut-off.

Table 6-16. Capital cost energy density requirements.

Technology		Material costs (EUR/kg)	Corresponding required energy density (J/kg)	Parameter evaluation
Dielectrics	DEG	5-15 (synthetic) 5-10 (NR)	42-125 42-83	Pass
	DFG (acrylic + silicone oil *)	7-19	58-158	Borderline
Triboelectric (PTFE)		5-20	42-167	Fail
Piezoelectric	Ceramic (PZT)	75	625	Fail
	Polymer (PVDF)	15-25	125-208	Fail
Magnetostriction (Terfenol-D)		13	108	Fail

*Combination of the mass of elastomer and fluid layers (derived from the energy density values in [135], see Appendix B.6 — Energy density of DFG).

Filter 1 — Initial assessment

The compiled parameter assessments are shown in Table 6-17. The only pass awarded from the initial assessment was DEGs (as it as the only technology to pass each parameter). DFGs were given a *Borderline* evaluation as they did not clearly pass or fail the assessed parameters in Filter 1. The other technologies each had at least one *Fail* against a parameter cut-off, and therefore they were awarded *Fail* assessments.

Table 6-17. Initial assessment table for Filter 1.

	Conversion efficiency	Maximum energy density*	Raw material cost per unit energy	Initial assessment
DEGS	Pass	No Cut-off	Pass	*Pass (PP)*
DFGs	Borderline		Borderline	*Borderline (BB)*
Piezo ceramics	Pass		Fail	*Fail (PF)*
Piezo polymers	Fail		Fail	*Fail (FF)*
Triboelectric	Pass		Fail	*Fail (PF)*
Magnetostriction	Borderline		Fail	*Fail (BF)*

*Energy density does not have a specific cut-off value

[28] Given that Galfenol's cost per kg is ~500 times higher than Terfano D, and energy density around 30 times lower, it was not included in Table 6-16.

Filter 1 — Review and final decision

A review was then carried out to determine the final decision for Filter 1. The results of this review are presented in Table 6-18.

Table 6-18. *Review and final decision for Filter 1.*

<table>
<tr><th>Technology</th><th>Initial assessment</th><th>Final decision</th></tr>
<tr><td>Dielectric Elastomer Generators</td><td>Pass (PP)</td><td>Straight pass</td></tr>
<tr><td colspan="3">DEGs met the cut-off values for each parameter in Filter 1.

Recommendations: DEGs pass to Filter 2.</td></tr>
<tr><td>Dielectric Fluid Generators</td><td>Borderline (BB)</td><td>Considered pass</td></tr>
<tr><td colspan="3">Uncertainty is high for DFGs due to the lack of identified research and data (only one paper was identified by the author with performance data).

Experimental data suggests that DFG performance is slightly below the cut-off for conversion efficiency and cost per unit maximum energy density. When considering the theoretical maximum energy density, the technology would meet the cost cut-off. It is likely that significant improvements in both conversion efficiency and energy density would be possible through more optimised experimental design (as noted in the single available study) and may be enhanced using different (already commercially available) materials which allow operation at higher electric field strengths.

Recommendations: DFGs progress to Filter 2, as the technology does not clearly fail any of the parameters in Filter 1. Additionally, the technology has large scope to improve energy density and conversion efficiency using currently available materials and optimising of experimental design.</td></tr>
<tr><td>Piezoelectric ceramics</td><td>Fail (PF)</td><td>Fail</td></tr>
<tr><td colspan="3">Piezoelectric ceramics have a low energy density, resulting in a large mass of the active materials being required per unit energy output. This, combined with raw material costs, resulted in the technology not meeting the cost per maximum unit energy cut-off.

Recommendations: Piezoelectric ceramics do not pass to the next stage of the filter process. Further investigation effort should be limited. A significant technology breakthrough in energy density would be required for the technology to be reconsidered.</td></tr>
<tr><td>Piezoelectric polymers</td><td>Fail (FF)</td><td>Fail</td></tr>
<tr><td colspan="3">Piezoelectric polymers have an extremely low energy density, resulting in a very large mass of the active materials being required per unit energy output. This, combined with raw material costs, resulted in the technology not meeting the cost per maximum unit energy cut-off.

Additionally, the conversion efficiency did not meet the cut-off.

Recommendations: Piezoelectric polymers do not pass to the next stage of the filter process. Further investigation effort should be limited. A significant technology breakthrough in energy density would be required for the technology to be reconsidered. Additionally, improvements in efficiency would be needed.</td></tr>
</table>

<table>
<tr><td>Triboelectric</td><td>Fail (PF)</td><td>Fail</td></tr>
<tr><td colspan="3">Based on the (optimistic) derivations made by the author (see Appendix B.1 — Energy density of triboelectric generators), the demonstrated normalised power density (as a proxy for energy density) and theoretical energy density of triboelectric is low (of the same order as the theoretical energy density of piezoelectric and magnetostriction generators). This would result in a large mass of the active materials being required per unit energy output. This, combined with raw material costs, would indicate that the technology could not meet the cost per maximum unit energy cost cut-off (although this is based on several assumptions). It should be noted that uncertainties exist about the maximal energy density of triboelectric generators, see Appendix B.1 — Energy density of triboelectric generators.

While triboelectric generators have demonstrated good conversion efficiencies, there is little discussion in the academic literature around energy losses or resonance frequency.

Recommendations: Triboelectric generators do not pass to the next stage of the filter process. It is recommended that the literature be occasionally reviewed for a better quantification of the energy density of triboelectric generators. Additionally, a significant volume of triboelectric generation wave energy related research is being carried out (see Appendix B.2 — Direct conversion technology publication data). Sources such as review articles should be monitored to identify any promising projects that may merit reassessment of the technology.</td></tr>
<tr><td>Magnetostriction</td><td>Fail (BF)</td><td>Fail</td></tr>
<tr><td colspan="3">Magnetostriction materials have a low magnetic energy density. Given that additional losses would be incurred converting this into electrical energy, a large mass of the active material would be required per unit energy output. This, combined with raw material costs, resulted in the technology not meeting the cost per maximum unit energy cost cut-off.

Additionally, magnetostriction generators were borderline with regards to the conversion efficiency cut-off.

Recommendations: Magnetostriction generators do not pass to the next stage of the filter process. Further investigation effort should be limited. A significant technology breakthrough in energy density would be required for the technology to be reconsidered. Additionally, it is likely improvements in efficiency would be needed.</td></tr>
</table>

6.2.2 Results for Filter 2

Filter 2 assesses the through-life performance of the technologies that passed Filter 1.

Filter 2 — Parameter assessments

This section will cover both DEGs and DFGs. In some parts of this section, they are covered separately rather than simultaneously (as indicated by underlining DEG or DFG in bold). This allows for more discussion of the uncertainties around the through-life performance of the two technologies.

Parameter 2.1) Through-life energy density

For DEGs, combined electromechanical fatigue testing is required to define both the energy output per cycle and number of cycles to failure (which, together, are used to estimate through-life energy density - see Equation 6-6). However, very few of these combined electromechanical fatigue tests have been reported in the literature for DEGs. While the fatigue life testing of DEGs is limited, some general points exist on the lifetimes of DEGs:

- To achieve long lifetimes, they have to be operated well below their electrical breakdown strength and rupture strains. This means that compromises have to be made between peak energy density and the lifetime of the DEG [234], [250], [251]. For this reason, the parameters from Filter 1 — based on theoretical maximum performance (where the DEG is operated up to its limit electric field and strain) — are unlikely to be representative of realistic DEG performance in long lifetime applications.
- Environmental conditions, such as humidity, can have a strong effect on a DEG's lifetime [250].
- The size of the sample and constraints applied to the DEG can have significant effects on its electrical fatigue life [189], [251], [252]. In general, large DEG samples fail at a lower number of cycles, due to a higher probability of a defect within the sample [189].

The results of a small number of studies that have quantified through-life energy density for DEGs (or provided the required data to estimate this) are presented in Table 6-19. These represent the highest levels of through-life energy density reported in the literature identified by the author. The work by Jiang [253] presents the highest through-life energy density of a DEG where a full experimental evaluation of the through-life energy density was carried out. The study carried out by Kornbluh [250] gave the test parameters (material, strain range, electric field and cycles to failure) for combined electro-mechanical fatigue testing of a DEG generator. The energy density estimate was derived using these parameters and the equations presented in Moretti et al. [136] (for details see Appendix B.7 — Through-life energy density of DEGs for details). This gave the highest through-life energy density based on real experimental electro-mechanical fatigue data (albeit estimating the energy density based on test parameters). Jean et al. [234] presents theoretical mechanical fatigue life estimates for different DEG materials and then estimates the total harvestable energy based on this. Importantly, this does not include electrical fatigue, so it is likely to be a significant overestimate of the DEG material's through-life energy density. As the relationship between lifetime and electromechanical fatigue is not well understood, a theoretical maximum through-life energy density has not been defined for any of the materials.

Table 6-19. Through-life energy density of DEGs from experiments and theoretically derived data.

Study	Material	Fatigue type	Experimental results	Maximum through-life energy density (MJ/kg)
Jiang et al. (2022) [253]	PVMS SiO_2 composite	Electromechanical	Yes	>2.0
Kornbluh et al. (2010) [250]	VHB 4905/4910	Electromechanical	Partial* (derived energy density)	250-580
Jean et al. (2020) [234]	Silicone Elastosil 2030	Mechanical only**	No (theoretical fatigue life and energy density)	2,200

*Energy density derived estimated using the formulae in [136] and the electric field, strain and cycles to failure experimental data in [250]. This does not account for electrical losses. The range of energy density values reflects the different number of cycles to failure in different tests. For full derivation see Appendix B.7 — Through-life energy density of DEGs.
**Jean et al assumed an electrical field of 80 kV/mm to estimate energy density.

For DFGs, no data on through-life performance (including fatigue life) is reported in the literature. However, HASEL actuators have achieved over 1,000,000 fatigue cycles at electric fields of ~30 kV/mm [150]. Some potential advantages may exist in fatigue life compared to DEGs. Firstly, electricity generation is not reliant on strain in the DE layer. This means that mechanical fatigue may be less of an issue for DFGs, and also opens up the potential to use several dielectric polymers with higher resistance to electrical breakdown (BOPP has an $_{EBD}$ of ~700 kV/mm and has been demonstrated in HASEL actuators [149]). Additionally, the DF layer may be recoverable following electrical breakdown, which may reduce the frequency of replacement due to electrical fatigue. However, these advantages cannot be quantified and the through-life energy density parameter cannot be evaluated for DFGs.

Parameter 2.2) Through-life costs

The specific costs of DEG and DFG materials are shown in Table 6-20. To achieve the cut-off value for through-life cost (3.2×10^{-9} EUR/J), a corresponding level of through-life energy density must be achieved. Substituting this cut-off, along with these specific material costs and the assumptions from Table 6-4, into the through-life cost target equation (Equation 6-7), the minimum lifecycle energy density requirements shown in Table 6-20 are defined.

Table 6-20. DEG minimum lifecycle energy density based on through-life costs.

Raw material	Specific cost (EUR/kg)	Corresponding minimum through-life energy density (MJ/kg)
Natural rubber	5-10	1,600-3,100
Synthetic rubber	5-15	1,600-4,700
DFG*	7-19	2,300-6,600

*Using the same mass breakdown as [135]. See Appendix B.6 — Energy density of DFG.

For DEGs, the available experimental data has demonstrated maximum through-life energy densities in the order of 10^6-10^8 J/kg, which is significantly below the value required to meet the through-life costs cut-off. The theoretical energy density value presented by Jean et al. would be within the range required to meet the through-life costs cut-off. However, the value from Jean et al. considered only mechanical fatigue, and was not based on experimental data. For this reason, it is not considered a reliable source of data against which to evaluate this parameter. Therefore, large uncertainties exist in DEGs through-life energy density and the technology's ability to meet the cut-off value for this parameter.

For DFGs, there is no experimental or theoretical data for the lifetime performance. Therefore, the through-life costs cannot be evaluated.

Table 6-21. *Through-life costs parameter evaluation.*

	Through-life costs	Parameter evaluation
DEGs (any)	There is limited data on DEG's electro-mechanical fatigue, which is essential to estimate lifetime energy density, and therefore through-life costs. However, existing experimentally demonstrated data is in the order of 10^6-10^8 J/kg, which is significantly below the level required to meet the through-life cost parameter.	Fail
DFG	Lack of data available to assess this parameter.	N/A

Parameter 2.3) Through-life embodied carbon

The embodied carbon emissions for common raw materials used for DEGs and DFGs are shown in Table 6-22. Synthetic rubbers include acrylic and silicone. To achieve the cut-off value for through-life CO_2 (3.75×10^{-9} $kgCO_2/J$), a corresponding level of through-life energy density must be achieved. Substituting these values into Equation 6-9 with the embodied carbon data shown in Table 6-22, minimum lifecycle energy density requirements are calculated (also shown in Table 6-22). It should be noted that, for both DEGs and DFGs, the minimum lifecycle energy density that is imposed by the through-life embodied carbon emissions is lower than that imposed by the through-life costs. Therefore, if either technology achieved the minimum energy density based on the through-life costs requirement, it would also meet the cut-off for embodied carbon emissions.

Table 6-22. *Embodied carbon emissions of active materials used in dielectric elastomer generators and corresponding minimum through-life energy density data from* [254]–[257].

Raw material	Embodied carbon (kgCO2e/kg)	Corresponding minimum through-life energy density (MJ/kg)
Natural rubbers	2.5	670
Synthetic rubbers (e.g. acrylic)	3.7	990
Rubber (general)	2.85	760
Silicone oil	6.3	N/A
DFG* (acrylic + silicone oil)	5.6	1,500

*Using the same mass breakdown as [135]. See Appendix B.6 — Energy density of DFG.

For DEGs, the available experimental data has demonstrated maximum through-life energy densities in the order of 10^6-10^8 J/kg. This is the same order of magnitude that would be required to meet the through-life embodied carbon cut-off value. However, large uncertainties exist in the theoretical potential of DEGs' through-life energy density. For this reason, it is considered uncertain whether DEGs meet the through-life embodied carbon cut-off, they were therefore given a *Borderline* evaluation.

For DFGs, there is no experimental or theoretical data for the lifetime performance. Therefore, the through-life embodied carbon cannot be evaluated.

Table 6-23. *Through-life embodied carbon parameter assessment.*

	Through-life embodied carbon	Parameter evaluation
DEGs (any)	There is an overall lack of data on DEGs' electro-mechanical fatigue, which is essential to estimate lifetime energy density, and therefore through-life embodied carbon. Existing experimentally demonstrated data is in the order of 10^6-10^8 J/kg, which is similar to the level required to meet the embodied carbon cut-off value.	Borderline
DFG	Lack of data available to assess this parameter.	N/A

Parameter 2.4) Ultimate Limit State

The assessment of the conversion technology's resistance to ultimate failure is more qualitative than the previous filter parameters.

As a DEG is strained and has an electric field applied to it while it generates electricity, the following properties were deemed of importance when resisting ultimate failure:

- Rupture strain/yield strain — this could define a DEG's maximum overload capability (in terms of displacement), and whether it is likely to be able to load-shed by changing its geometry under extreme loading conditions.
- Ultimate/yield strength — this could indicate the maximum overload capability (in terms of force).
- Electrical breakdown strength — this could indicate the resistance of the material to electrical overload.

For DFGs the same properties are important in order to avoid ultimate failure, although possibly with less emphasis on extreme mechanical loads, as the DE layer in a DFG does not need to undergo large strains to generate electricity. Additionally, the fluid layer of a DFG may be recovered multiple times following electrical breakdown, which could increase its ability to survive electrical overloads.

These parameters are outlined in Table 6-24, for common DEG and DFG active materials.

Table 6-24. Ultimate failure parameters for DFG active materials.

	Ductile	Maximum rupture strain	Strength UTS (MPa)	Electrical breakdown strength
Natural rubbers	Yes	650 [146]	31 [146]	100-300 [141]
Silicone rubbers	Yes	900-1,450* [146]	7.2*-10.3 [146]	75-195 [143]
Acrylic rubber (3M VHB 4905)	Yes	820 [141]	0.69 [147]	250** [258]
Silicone oil	N/A	N/A	N/A	30-45 [135] (self-healing)

* Average from MatWeb for Silicone Rubber (accessed 06/09/2021).
**Same E_{BD} as 4910 series tapes [147].

For long lifetimes, DEGs should be cycled significantly below their rupture strain and electrical breakdown strength in normal operating conditions. Due to their high rupture, strains DEGs may also allow load shedding in extreme conditions [224]. This would suggest that, when operated in a long lifetime application, a DEG would have a significant overload potential before failure, both in terms of strain and electric field.

The DE layer in a DFG system is also likely to be operated significantly below its rupture strain, as it does not need to be strained to generate electrical energy, and may also be able to load-shed in extreme loading conditions, depending on what polymer materials are used. Regarding electrical extreme loading, DFGs have the benefit of potential recovery of the fluid layer's dielectric properties following breakdown.

Table 6-25. Resistance to ultimate failure parameter evaluation.

	Resistance to ultimate failure	Parameter evaluation
DEGs (any)	Made of elastic, flexible polymer materials. DEGs' normal operating conditions in long-life applications will be significantly below their strain and electric field operating limits. Additionally, load shedding may be possible. Therefore, DEGs are likely to have a good level of both mechanical and electrical overload potential before an ultimate failure.	Pass
DFG	Made of flexible (and potentially elastic) polymer materials. Large strains not required to generate electricity, so technology may be operated far from mechanical overload. Load shedding may also be possible. Additionally, DF layer may recover its dielectric properties following electrical breakdown.	Pass

Filter 2 — Initial assessment

The initial assessment results for Filter 2 are shown in Table 6-26. DEGs are awarded a *Fail* as they did not meet the cut-off for through-life costs based on current experimental data. It should be noted that there is limited data availability for DEGs through-life costs, or through-life embodied energy. DFGs could not be assessed against either parameter for Filter 2, as insufficient data exists on their through-life energy density. Therefore, they were awarded a borderline assessment.

Table 6-26. Initial assessment table for Filter 2.

	Through-life energy density*	Through-life costs	Through-life embodied carbon	Ultimate limit state	Initial assessment
DEGS (any)	N/A	Fail	Borderline	Pass	*Fail (FBP)*
DFG	N/A	N/A	N/A	Pass	*Borderline (NNP)*

* No cut-off value for through-life energy density

Filter 2 — Review and final decision

A review was then carried out to determine the final decision for Filter 2. The results of this review are presented in Table 6-27. The final decision for both DEGs and DFGs was that they should be allowed to pass Filter 2 as there was insufficient evidence to reject them. However, it should be noted that, for both technologies, there was limited (for DEGs) or non-existent (for DFG) fatigue life data, which is a significant source of uncertainty.

Table 6-27. Review and final decision for Filter 2.

Technology	Initial assessment	Final decision
Dielectric Elastomer Generators	Fail (FBP)	*Considered pass*
There is limited data on the through-life energy density of DEGs in the literature. This is due to a lack of data on electromechanical fatigue. Of the few studies that have reported this parameter, or provided the data necessary to derive it, the level of performance is lower than would be required to meet the through-life costs cut-off, and is close to the level required to meet the through-life embodied carbon cut-off. The properties of DEGs regarding ultimate limit state appear good, both for mechanical and electrical extreme loading. **Recommendations:** DEGs only failed one parameter cut-off in Filter 2, the through-life energy costs. However, it is considered that there is insufficient data available to be confident in this assessment. Therefore, the technology is not rejected in Filter 2. However, it should be noted that DEGs have not yet demonstrated a sufficiently high level of through-life energy density to meet the through-life cost cut-off value.		
Dielectric Fluid Generators	Borderline (NNP)	*Considered pass*
No data could be identified to assess through-life energy density of DFGs, and therefore neither through-life costs nor through-life carbon emissions can be evaluated. Some potential advantages exist regarding electromechanical fatigue life and material selection in comparison with DEGs, but the effects of these on through-life energy output cannot be quantified. Similarly to DEGs, the properties of DFGs regarding ultimate limit state appear good, both for mechanical and electrical extreme loading. **Recommendations:** DFGs have not demonstrated that they fail against any of the cut-offs in Filter 2, and therefore they are not rejected. However, it should be noted that there is no data availability on their lifetime performance. This means they have not demonstrated the performance in the through-life energy cost or lifetime embodied carbon parameters to meet the cut-off values.		

6.3 Discussion of Part B

The discussion starts with Section 6.3.1. This section discusses the key results from applying the screening process that was developed in Part B to the six direct conversion technologies. Section 6.3.2 then goes on to discuss the implications that can be drawn from the work in Part B regarding the further development of the six direct conversion technologies for wave energy applications, and the potential benefits of using the screening process to aid decision-making. Finally, Section 6.3.3 covers the limitations of the assessment of direct conversion technologies in Part B, and recommendations are made on further work that could be undertaken to build on the research.

6.3.1 Key findings from Part B

In the first filter in the screening process, cut-offs were set in two parameters related to the DCT's peak performance. The first of these parameters is the ratio of material costs to energy density of the raw material that made up the DCT (cut-off = 0.12 EUR/J). The second of these is conversion efficiency (cut-off = 35%). Of the six DCTs, piezoelectric polymer generators, piezoelectric ceramic generators, triboelectric generators and magnetostriction generators were rejected in the first filter. All these technologies have very low maximum energy densities, which would result in high material requirements — and therefore costs — to deliver a unit power output when cycled at a low (ocean wave-like) frequency. As a result, these technologies do not meet the cut-off associated with the ratio of material costs to energy density. Additionally, the demonstrated conversion efficiency of magnetostriction generators and piezoelectric polymers is very low and did not meet the cut-off value for conversion efficiency. DEGs met the cut-off values for both these parameters in Filter 1. DFGs were very close to the cut-offs for both parameters and were therefore also allowed to pass to the second filter. Additionally, the current research into dielectric fluid generators is very limited and suggests that several improvements to the technology may be enabled by using existing materials and different experimental setups.

In the second filter, DEGs and DFGs were assessed against three parameters related to through-life performance. Firstly, through-life energy costs is the ratio of DCT raw material costs to the lifetime energy density of the technology (cut-off = 3.2×10^{-9} EUR/J). The second of these was the ratio of raw material embodied CO_{2e} to the lifetime energy density (cut-off = 4.2×10^{-9} $kgCO_{2eq}/J$). The third was the ultimate limit state of the technology, which was a qualitative assessment of the technology's ability to resist ultimate failure. In Filter 2, there was limited fatigue life data available to assess DEGs and no fatigue life data available to assess DFGs. This meant there was high uncertainty in the parameters related to lifetime energy density for both technologies. Both DEGs and DFGs were assessed as having a high level of resistance to ultimate failure. For Filter 2, both technologies passed as there was insufficient evidence to reject them. However, the process did highlight that the data on fatigue life for both technologies (in realistic operational conditions) was too limited to make a confident assessment of all the parameters in Filter 2. Therefore, both technologies merit re-evaluation as more comprehensive data on their fatigue performance becomes available.

Overall, based on the parameters in which there existed comparable data between DEGs and DFGs, DEGs demonstrated higher performance.

Comparison with previous work

As reviewed in Section 5.2, only one other study was identified that sought to develop an assessment process for DCTs in wave energy applications, which was carried out by Frazer Nash consultancy [132] for Wave Energy Scotland. A significant difference between the Frazer Nash study and the work carried out in this PhD is that Frazer Nash considered the role of a DCT in their assessment to be a direct replacement for a generator in a wave energy device[29]. The work presented in this thesis aims to consider more radical applications of DCTs, which replace at a minimum the entire PTO of a wave energy converter (this is shown in Figure 6-3 on p.134). As the target application of the DCTs differed between the Frazer Nash study and the work in this PhD, a different set of parameters was developed to assess the technologies compared to those used by Frazer Nash. One of the primary differences in assessment parameters was basing the DCT material requirements on energy density in this work, compared with power density in the Frazer Nash study. This decision was taken as energy density was considered a better metric to evaluate DEG WEC performance in low-frequency applications like wave energy. Additionally, the fatigue lifetime of the DCTs was treated in a quantitative way in this work, rather than the reliance on expert judgement in the Frazer Nash study. However, it should be noted that while the target DCT application was different, the Frazer Nash study identified DEGs as the conversion technology with the highest viability of the technologies they assessed. This is consistent with the results of the work carried out in this PhD, as DEGs and DFGs were the only technologies not to be rejected from the screening process.

While the work presented in this section is a design-agnostic assessment of the direct conversion technologies, the results are also consistent with some review articles found in the literature which studied applications of the DCTs in specific wave energy devices. Review papers on piezoelectric wave energy converters [130] and triboelectric wave energy converters [128], [129] have suggested that the current power densities of wave energy devices based on these technologies are insufficient for utility-scale power generation. Similarly, in this work, both technologies were rejected in the screening process, due to low energy density. The potential to scale up DEGs for low-cost, utility-scale (100’s kW) wave energy applications, is proposed in several studies, for example [32], [189]. Given that the screening process did not reject DEGs, the results of this work are also consistent with the potential application of DEGs in low-cost, utility-scale wave energy conversion.

6.3.2 Sector implications from the results of Part B

The first implication from Part B of this research is straightforward. In the application considered for this work (where the DCT replaces at least the entire PTO of a wave energy converter), piezoelectric polymer generators, piezoelectric ceramic generators, triboelectric

[29] As discussed in Section 5.2, this essentially made it impossible for any technology to present a significant improvement over the baseline electromagnetic generator that the technologies were compared against.

generators and magnetostriction generators would not be viable in wave energy applications. It should be caveated that this viability depends on the assumptions that determine the parameter cut-off values. If these assumptions are taken to be reasonable, the recommendation is that these technologies should not be explored further for utility-scale wave energy applications, unless a significant technical breakthrough occurs that would merit their re-examination. Other applications (as discussed in the literature) that may be more appropriate for these technologies are low-power applications, such as powering sensors in off-grid, offshore locations.

A second implication from Part B is that DEGs and DFGs merit further investigation as technologies that could enable radical innovation in the wave energy sector. This is because neither technology was rejected by the screening process. However, the viability of both technologies has significant uncertainty. This is due to the lack of data around fatigue life for both technologies. As more data becomes available on the fatigue life of these technologies, it is recommended that they be re-evaluated using the screening process to establish if they meet the cut-off values for each assessment parameter.

A third implication is that the screening process developed during this research will allow evaluation of DCTs for wave energy to be made in a more consistent and transparent way in comparison with less formal assessment processes such as expert opinion. The screening process provides a consistent way to assess technologies, as the same set of parameters and cut-offs are used for each technology. The assessment process also improves transparency and reduces potential for bias, as it does not rely on expert judgement, but rather qualitative data and a set of assumptions which can be determined by the user of the assessment process. Additionally, as the process was designed to be WEC-design agnostic, it should be repeatable for other DCTs that were not considered in this study. This could potentially be used by non-specialists in DCT technology (such as those working in research funding organisations), to aid decisions about developing or supporting different technologies for wave energy applications.

6.3.3 Limitations and further work from Part B

As the screening process is WEC-design-agnostic, many assumptions were required around the non-DCT wave energy converter subsystems (such as structure, moorings and foundations). This introduces a significant amount of uncertainty into the level at which the parameter cut-offs are set (this is explored in the sensitivity analysis in Appendix B.4 — Cut-off value sensitivity analysis). The aim when setting the cut-off values used in this work was to remove any technologies that did not meet a minimum required level of performance, while not pre-emptively rejecting DCTs which may be viable in a utility-scale wave energy application. Therefore, the baseline assumptions and cut-off values that were set are generous. These cut-off values could be set at a different level, based on the preferences of the user of the screening process. Ultimately, when using the screening process to assess DCTs, understanding the assumptions that went into making the cut-offs is as important as the cut-off values themselves.

Another possible limitation is that there would be a level of substitution allowable between the different assessment parameters, which was not considered in this study. For instance, a

DCT subsystem with a high conversion efficiency should, in theory, be allowed a higher allowable cost than a conversion technology with a low conversion efficiency. It is possible these two parameters (cost per unit energy density, and efficiency) could therefore be combined into one composite parameter. However, the way in which this could be done, or how a cut-off would be set, is unclear. Additionally, given the uncertainty that already exists in the cut-off values (as explained above), the compounded uncertainty in a combined parameter would be very large. For these reasons, it was decided that trying to develop this composite parameter would add additional complexity to the process and make the results more difficult to interpret, without adding significant utility to the screening process.

A final limitation is that conversion efficiency of the DCT could only be assessed based on its potential impact on the overall WEC's CAPEX. This was because there is an established measure of the ratio of absorbed energy to structural CAPEX — the ACE metric. A similar metric does not exist for a ratio of absorbed energy to WEC embodied carbon. Therefore, the impact of DCT conversion efficiency on the overall WEC's embodied CO_{2e} was not evaluated in this work.

As covered above, the screening process was designed to be repeatable for different classes of DCT and usable by a non-expert. Future work could compare this screening process against current assessment processes (e.g. relying on expert judgement) to determine if the screening process improved the speed and/or consistency of decision-making in other organisations (see, for example, Collins and Williams trial of a screening process for smart materials on a selection of potential users to determine whether it aided decision-making [218]). Feedback from this could also be used to improve the screening process' usability for a non-expert user.

A final point is that, while not a limitation, this chapter presents a way to screen out technologies that are not viable rather than determine if a technology will necessarily be an innovation opportunity for the wave energy sector. For example, DEGs and DFGs were not rejected by the process. However, there was insufficient fatigue life data to confidently assess their performance in these parameters. As more data is produced, they should be re-assessed to determine if they meet the cut-off values set in Filter 2. In addition to this issue about data availability, there are many important areas around implementing the DCTs in large-scale wave energy devices which are not covered by the screening process. This was because, while the areas are important, they could not be readily integrated into a repeatable, device-agnostic screening process based on quantitative data. Examples of these areas include the design and modelling of a wave energy device utilising the DCT, the cost and supply chain for manufacturing of the DCT at large-scale, and the supporting control systems. Failure to perform well in such areas may limit the viability of a DCT, even when it meets the cut-offs set in the screening process. Therefore, further evaluation of a technology that passes through the screening process is recommended to assess the areas that are not covered in the screening process. This was the motivation carrying out the third part of this research, which assesses the barriers associated with DEG WEC development.

Part C: Identification and evaluation of barriers to dielectric elastomer generators in wave energy converters

Research question for Part C:

> *What development barriers currently exist for the most promising direct conversion technologies for wave energy applications? And what actions could be taken to overcome these barriers?*

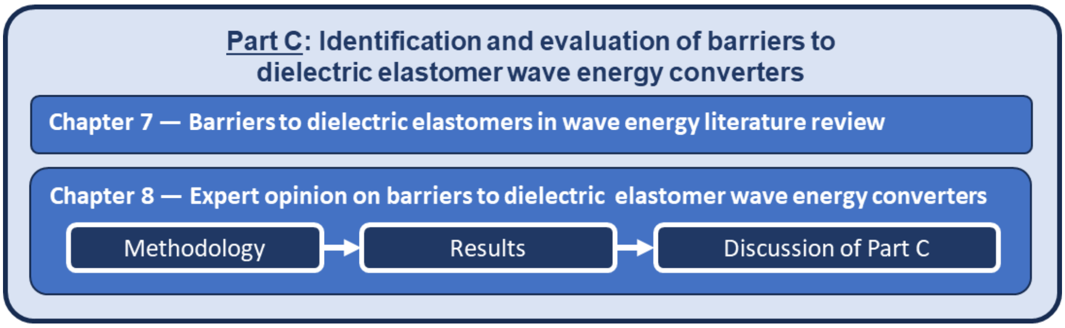
The results from Part A of this thesis highlighted the large potential benefits of radical innovation for the wave energy sector. Part B of this thesis developed an evaluation process for a class of technology (direct conversion) that could potentially be an enabler of radical innovation in wave energy applications. This process was then used to assess the potential viability of six direct conversion technologies for wave energy applications. Of the direct conversion technologies that were assessed, dielectric elastomer generators (DEGs) proved to be the most promising for wave energy converter (WEC) applications, based on the currently available data.

However, to develop an early-stage technology like DEGs to the point that it can be used in a commercially ready wave energy converter, several barriers will exist outside the parameters of the screening process. While the academic literature does deal with the barriers for DEGs in wave energy applications, a comprehensive review of these barriers does not exist. There has also been little work addressing the actions to tackle these barriers, or the prioritisation regarding how these barriers should be addressed. This kind of evaluation will be a valuable piece of analysis to enable better strategic planning of the funding and development of DEGs for wave energy applications (e.g. for a research funding organisation). Indeed, the identification of barriers and actions is one of the key functions of a strategic planning exercises such as roadmaps [259], [260] that have been applied to other renewable energy technologies such as wind and solar energy.

To address this current gap in the academic literature, Part C of this research developed a comprehensive assessment of the barriers to development of DEGs for wave energy applications. DEGs were selected having been identified as the most promising direct conversion technology that was evaluated in Part B of the research. The investigation of the barriers to DEG WEC development was undertaken in two stages:

1. Firstly, a review of the DEG WEC literature was undertaken, identifying the barriers to DEG WEC development.
2. Following the first stage, a series of semi-structured interviews were carried out with DEG WEC experts. These were used to:
   a) Identify missing barriers from the literature review.
   b) Identify the most important barriers (referred to as 'key barriers').
   c) Identify actions required to overcome these barriers.
   d) Evaluate the difficulty of carrying out these actions.
   e) Prioritise the order, where possible, in which the barriers should be addressed.

Part C of the thesis is made up of two chapters, shown below.



In Part C of this thesis, Chapter 7 presents a literature review of the barriers to DEG WEC development. Chapter 8 then presents the semi-structured interviews with DEG WEC experts, which built upon the barriers identified in the literature review. This chapter comprises a methodology section, explaining the interview process, followed by the results from the interviews. The chapter concludes with a discussion of Part C.

7 Barriers to dielectric elastomers in wave energy literature review

7.1 Review methodology

Prior to carrying out the semi-structured interviews, a review of the dielectric elastomer generator (DEG) wave energy converter (WEC) literature was carried out. This covered the barriers to DEG WEC development that were described in the literature. Additionally, a series of preliminary unstructured discussions with DEG WEC experts were carried out around the barriers to the application of DEGs in wave energy applications. The results from the preliminary discussions are not presented in this thesis. However, the barriers identified in these discussions were shared with the experts before the semi-structured interviews (see Appendix C.1 — Preliminary information for interview participants).

The literature review considered published work on DEG wave energy converters in the Web of Science database. The search terms are described in Table 4-6 in Part B of the thesis. It should be noted that for the PolyWEC project around 20 articles were published. For this reason, PolyWEC summary reports and review articles were examined during the literature review, rather than each individual article. The articles identified using the database were supplemented by additional work known to the author, both dealing with wave energy applications of DEGs, and reports from the PolyWEC project.

The unstructured preliminary discussions were carried out with four DEG WEC experts in October and November of 2021 as a precursor to work on the semi-structured interviews. Two of the experts who took part in the preliminary discussions also participated in the semi-structured interviews. These preliminary discussions were used to get an initial overview of the barriers to DEG WEC development. They did not follow the same format as the semi-structured interviews.

The outcome of the literature review is presented in this chapter.

7.2 Barriers for dielectric elastomer generator wave energy converters

7.2.1 Barrier categorisation

The word ‘barrier’ is used in this part of the thesis to signify a knowledge gap, technical limitation, or any other barrier to the development of dielectric elastomer generation-based wave energy devices. However, in the literature review, several challenges (i.e. things that need to be done to develop dielectric elastomer wave energy devices) were also recorded. Table 7-1 contains the barrier categories for DEGs in WEC applications that were identified in the literature review. It should be noted that these categories are simply a collection of barriers in similar areas, created to impose a level of order on the longlist of barriers. The columns of the table are categories/subcategories under which the barriers fall. The individual barriers are discussed in more detail in Section 7.2.2. Additionally, a level of crossover is clear in several of these categories. For example, the barrier of developing a new material to improve the performance of the DEG could have a direct effect on the manufacturing process.

Table 7-1. *Barrier categories and subcategories to the development of dielectric elastomer generators for wave energy applications identified in the literature.*

Category	**Subcategory**	**Barrier**
C1) Performance of DEG	C1.1) Lifetime of DEG in WEC operating conditions	Electrical fatigue
		Mechanical fatigue
		Environmental ageing and sea water ingress
		Combined fatigue
		Trade-off between performance and lifetime
	C1.2) DE materials and design	Development of high-performance DE materials
		Fillers for DE materials
	C1.3) Electrode materials and design	Development of high-performance electrode materials
		Electrode connection design
	C1.4) DEG performance at scale	Flaws in large-scale DEs
C2) Manufacturing DEG (at scale)	C2.1) Manufacturing DE films	Control of manufacturing process
		Manufactured scale of DE
	C2.2) Manufacturing electrodes	Electrode manufacturing
		Electrode connection manufacturing
	C2.3) DEG module fabrication and joining	Fabrication processes and bonding of DE and electrodes
		Joining DEG modules
	C2.4) Cost of manufacturing DEG	Cost of DE films
C3) System integration barriers for DEG WEC	C3.1) Design and modelling of DEG based WEC	DEG WEC design
		Modelling
		Availability of power electronics
	C3.2) Self-sensing and control	Self-sensing
C4) Environment effects of DEG	C4.1) Recyclability of dielectric elastomer generator modules	Recyclability/disposal of DEG at end of life
	C4.2) Degradation of DEG in marine environment	Chemical leaching
	C4.3) Electric shock risk	Electric shock risk if membrane damaged
C5) Other barriers		Drag forces on large devices
		Collision risk

The headings C1-C5 are used in Section 7.2.2. to describe the barriers to DEGs in WEC applications found in the literature. These categories were also used as a starting point for the structure of the semi-structured interviews (see Section 8.2).

7.2.2 Barriers to DEGs in wave energy applications

C1) Performance of DEG

C1.1) Lifetime of dielectric elastomer generators in WEC operating conditions

Electrical fatigue

Dielectric elastomers (DEs) degrade over time when subjected to electric fields. The length of this lifetime is highly sensitive to the strength of the applied electric field. The closer the strength of the electric field to the DE's electrical breakdown limit (E_{BD}), the more quickly it will fail. In a DEG, the failure of the DE due to electrical fatigue results in a short circuit between the electrodes [189], which eliminates its functionality as a generator. In addition, electrical resistance in the electrodes results in joule heating during charging and discharging, which can cause thermal fatigue. The results of experiments carried out by Chen et al. [251] showed that there was a similar inverse relationship between electric field strength and the number of charging/discharging cycles at various cycling frequencies (0.1, 0.2 and 1Hz) before failure occurred[30]. The energy density of a DEG is proportional to the square of the applied electric field (see Equation 4-4). Therefore, a trade-off clearly exists between achieving high energy densities (high electric field) and high lifetime (low electric field). Understanding the electrical lifetime of DEGs is essential to determine which DE and electrode materials can be operated at sufficiently high electric fields over a large number of cycles to be viable in wave energy applications.

Some preliminary tests have been carried out to try and determine the electrical fatigue life of dielectric elastomer transducers. For example, preliminary results showed that small samples of silicone elastomer with silicone carbon electrodes tested at 75 kV/mm (around 50% of the E_{BD}) survived an average of 2 million cycles at 1 Hz with a 50% duty cycle before breakdown [261]. It has also been suggested in the literature that electric field threshold mechanisms may exist under which DE damage is not accumulated [262], [263]. However, in general, the literature highlights that there is insufficient knowledge about the lifetime of DEGs in electric fields [2], [3].

Mechanical fatigue

As with electrical fatigue, degradation can occur in a DEG due to mechanical fatigue. Over time, the application of varying strain (above a certain level) will cause cracks to develop in the DE and stretchable electrodes, which will eventually result in failure (rupture). There is an inverse relationship between fatigue life and the maximum strain that is applied to the DE during fatigue cycles. Therefore, operating close to the tensile strength of the DE will result in a short mechanical fatigue life. As maximum energy density of a DEG is linked to the ratio between minimum and maximum strain (see Equation 4-4), there is a trade-off between high

[30] This indicates that a major factor in determining the lifetime of dielectric elastomer transducers can also be thermal cycling in the electrodes, driven by the number of charging/discharging cycles, rather than simply the accumulated time that the DE has an electric field applied to it.

energy density (high strains) and high lifetime (low strains). Understanding the mechanical lifetime of DEGs is essential to determine which DE and electrode materials can be operated at sufficiently high mechanical strains, over a large number of cycles, to be viable in wave energy applications.

It is noted in the literature that there is a good amount of data for the uniaxial mechanical fatigue life of elastomer materials [32], [262], with fatigue lives of around 10^7-10^8 cycles achieved in strain magnitudes similar to those required for DEG WEC applications [32], [245], [264]. Figure 1-9 shows several WEC architectures. Of the WEC architectures shown in Figure 1-9, architectures (b), (c) and (d) would subject a DEG to multiaxial mechanical fatigue. The literature highlights that there is relatively limited understanding of the effects of the fatigue life of elastomer materials under multiaxial fatigue, with the majority of fatigue experiments considering uniaxial fatigue [187], [265]. It is suggested by Collins et al. [187] that the use of uniaxial fatigue data may significantly over-estimate the fatigue life of DEGs which are subjected to multiaxial fatigue.

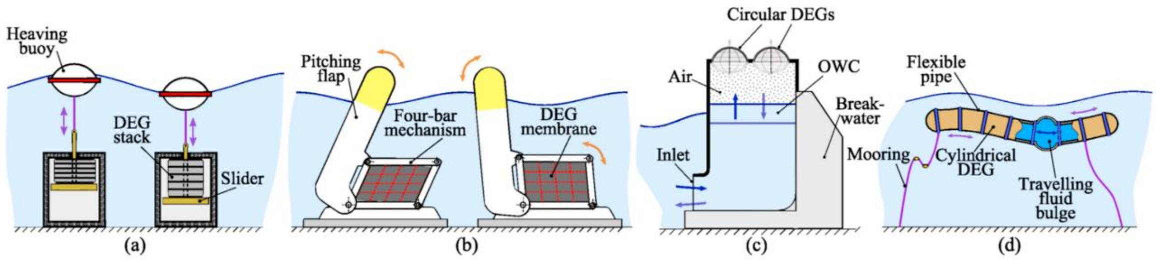


Figure 7-1. *Example wave energy converter architectures utilising dielectric elastomer power take-offs, figure reproduced from Moretti et al.* [32]. *Only architecture a is subjected to uniaxial mechanical fatigue.*

It is also noted in the literature that there is a lack of information on the mechanical fatigue life of stretchable electrodes (especially at strains >200%) [136], or the effects on electrode conductivity under mechanical fatigue cycling [262]. Both of these areas require further research.

<u>Environmental ageing and sea water ingress</u>

A DEG may be submerged in sea water in a wave energy application. Therefore, it is important to have information on the effects that the marine environment has on the lifetime of a DEG.

It is noted in the literature that there is little data on the effects of water absorption and oxidisation on the fatigue life of elastomers in a marine environment [187], [262]. Additionally, the electrodes and electrical connections of a DEG need to be sealed and water-tight [262] [266]. Some kind of encapsulation may be needed in DEG WECs to achieve this, as demonstrated by SBM [189].

<u>Combined fatigue</u>

When used to generate electricity, DEGs operate under varying levels of stretch and electric field. Therefore, they are subjected to electrical and mechanical fatigue in combination. Kornbluh et al. [134] claims that testing showed the combined electro-mechanical fatigue lifetime of DEGs to be substantially lower than the electrical or mechanical fatigue alone. The applied electric field and mechanical strain (along with the DE and electrode's mechanical and physical properties) are the determinants of a DEG's energy density (see Equation 4-4). Therefore, understanding the lifetime of a DEG under different electric field and strain cycles is required to evaluate the suitability of the technology for long-lifetime wave energy applications.

The literature highlights a lack of data on the fatigue life of DEGs under combined electromechanical fatigue [134], [136], [189]. Moretti et al. [136] indicate that better electromechanical fatigue data is essential for material (and therefore manufacturing process) selection. So far, only a small number of studies have presented a limited set of experimental data on combined electromechanical fatigue of DE materials in the literature [250], [253], [267]. It is also noted that there is limited understanding of multiaxial mechanical fatigue of elastomer materials in combination with a marine environment [187].

Trade-off between performance and lifetime

The trade-off between performance and lifetime is essentially the same barrier as the lack of information on combined electromechanical fatigue. This is reiterated here because it is mentioned several times in the literature as an area of particular importance for DEGs. As explained in Section 6.1.3, the total amount of energy a DEG can deliver before failure is a key performance parameter for long-life applications like wave energy. The lifetime energy density is a combination of both cycles to failure and energy density. However, as covered in this section, the fatigue life (cycles to failure) and energy density of a DEG are inversely related. Having good data on the relationship between energy density and lifetime for different DE and electrode materials is essential to optimise the operating electric field and strain around both lifetime and energy density.

It is noted in the literature that there is limited understanding of this trade-off between energy density and lifetime for DEGs [268]. This is true for both for the DE and electrodes [187] [263]. Moretti et al. [136] suggest that the electromechanical loading that is compatible with achieving 10^6-10^7 cycles should be investigated to define stretch and electric field levels for DEGs in wave energy applications.

C1.2) Dielectric elastomer materials and design

To maximise the performance of a DEG for wave energy applications there are several mechanical and physical properties that are desirable for the DE material (see Section 4.1). These include high E_{BD}, high permittivity, low conductivity, low hysteresis losses, high elongation at break, low stiffness and long fatigue life (electrical and mechanical) [187], [189], [262]. In addition to the properties of the DE, both mechanical and electrical fillers can be added to improve the DE's mechanical and physical properties.

Several sources in the literature suggest investigation into new materials that are optimised for DEG applications [32], [136], [189]. In addition, it is noted that more research may be needed into the use of fillers to improve mechanical properties of DEs [187], and that there is currently limited availability of fillers to improve DE electrical properties [252].

C1.3) Electrode materials and design

Electrodes for DEGs need to fulfil several requirements. They need to be highly stretchable (to accommodate the DE being stretched), and to have low resistance and high fatigue life. The electrodes also may need to isolate electrical breakdowns in the DE.

The development of suitable electrodes for DEGs is an area of ongoing research [187]. In general, there has been less research into stretchable electrodes than DE materials, with the most mature options currently being silicone-based [262]. These pair well with silicone-based DE's. However, other electrode options, such as metallic sputtering, may be necessary if other DE materials are used [262]. Additionally, the potential requirement to electrically isolate DE electrical breakdowns [189], [252] may create an additional barrier for electrode development.

Potential technical problems may also be associated with the connections between the stretchable electrodes and wire conductors and insulating materials [262].

C1.4) Dielectric elastomer generator performance at scale

Electrical breakdown in dielectric materials usually occurs at flaws (voids, holes or other defects) within the material [269]. The presence of these flaws within a sample of DE creates weak points [252] which will significantly reduce the DE sample's E_{BD} [269] and operational lifetime [136], [251]. Using the same manufacturing process, a small sample of DE will contain fewer of these flaws compared to a large sample. Therefore, for the same thickness of DE film, it can be assumed that the presence of flaws is proportional to the DE film's surface area [252]. This means that small-area DEGs can be operated at much higher electrical fields before breakdown in comparison with large-area DEGs [189], [252]. As the DEG will fail when the first electrical breakdown occurs (without electrical isolation of the breakdown site), this significantly limits the electrical field in which large-area DEs can be operated, which in turn limits the energy density.

It is noted by Jean et al. [189] and Andritsch et al. [252] that the reduced E_{BD} of large-scale DEGs is a significant barrier to their application in wave energy. These studies highlight that (assuming flaw-free DE manufacturing is infeasible) the presence of flaws in large samples of DE material essentially mandates the use of electrodes which can electrically isolate breakdown sites in the DE.

C2) Manufacturing DEGs at scale

C2.1) Manufacturing dielectric elastomer films

Considering the permittivity of current DE materials, a strong electric field must be applied to the DE to achieve energy densities that are useful for wave energy applications (see Section 4.1). To achieve these strong electric fields (~100 kV/mm) without the power electronics being prohibitively expensive (voltages of up to 10 kV), very thin films of DE material must be used in DEGs [32]. To be compatible with these requirements, DE films need to have thickness in the order of 100 µm [32], with a tolerance of ± 1-3% [262]. Additionally (as covered under

C1.4), the process quality needs to be extremely well controlled, even at high production rates, to minimise the number of flaws that are introduced in the DE which could lead to premature electrical breakdown [189]. For full-scale DEGs, the scale of these films will depend on the WEC design. WECs utilising a diaphragm-type PTO (in Figure 1-9) may require the manufacture of DE films with diameters of 5-10 m for full-scale devices [32].

Currently, single layer specialist DE films, meeting the specifications outlined above, can only be procured in small sizes (rolls with widths of up to 1.4m) [32]. These processes may therefore need to be redesigned if large monolithic DEGs are required (e.g. in a diaphragm-type PTO) [262]. The current cost of these small-area manufactured films is also extremely high, at around 1000 EUR/kg [32]. Whilst it has been suggested that the processes for manufacturing silicone films could be upscaled, there is uncertainty about how much the cost could be reduced utilising current production processes [262]. Additionally, it is highlighted by Moretti et al. [136] that commercially available low-cost elastomer films for non-DE applications are of insufficient quality (have too many flaws) to be used in DEG applications, and that natural rubber cannot be procured in thicknesses of under ~200 µm.

C2.2) Manufacturing electrodes and electrode connections

It is noted in Moretti et al. [262] that an in-depth manufacturing study is required for both stretchable electrodes and electrode connections. The production process may depend on whether the DEG is manufactured in a two-stage or single-stage process (see C2.3 below), and whether the electrodes have to be self-clearing/segmented.

C2.3) Dielectric elastomer generator module fabrication and joining

For large-scale WEC applications, it is highlighted in the literature that DEG modules will be likely to have a multi-layer structure where the DE layers are alternately bonded to stretchable electrodes (as shown in Figure 7-2). These layers could be produced either in a two-step process, where films and electrodes are produced individually and then bonded together, or in a single continuous process [262]. Several manufacturing processes are being considered to bond electrodes and dielectric elastomers, including pad printing, blade casting, spray coating, screen printing, inkjet printing [2] and 3D printing [5]. Work is also being carried out on the multi-layer assembly of these modules [32].

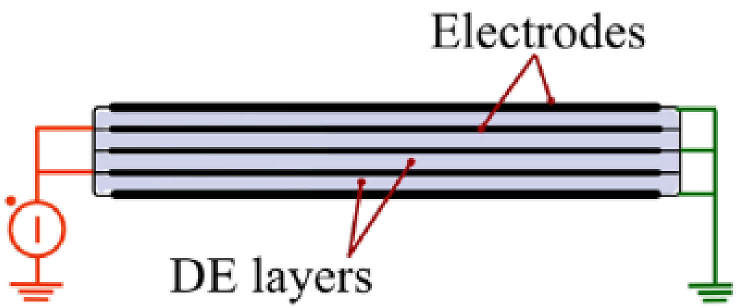


Figure 7-2. *Alternating DE layers and stretchable electrodes in a DEG module reproduced from Moretti et al.* [136].

In addition to the challenges of manufacturing individual multi-layer modules, the joining of adjacent modules may be desirable for certain DEG architectures. This would allow large-area DEGs to be produced without the same manufacturing barriers related to the current size limitations for DE films [262].

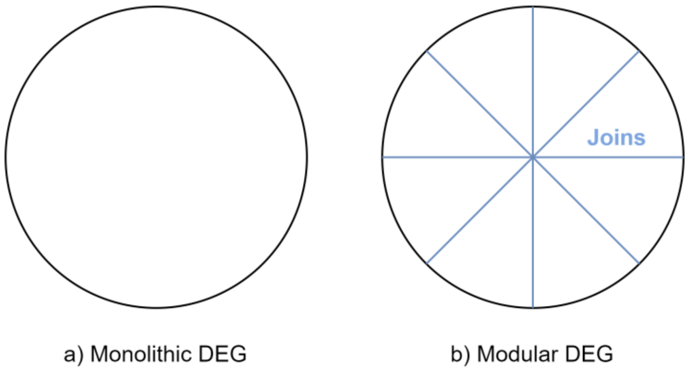


Figure 7-3. *Monolithic DEG made of large DE films vs modular DEG made of smaller joined films.*

Regarding the bonding of electrodes and the DE, it is important that scalable processes are identified [32], [262][136]. Moretti et al. [262] highlight that silicone films can already be bonded to silicone-based electrodes. However, the bonding of electrodes to other DEs (natural rubber or styrene rubber) is less strong and '*may lead to problems in the long term'* [262]. The question is also raised by Moretti et al. [262] around the use of a two-step process of manufacturing the DE and electrodes separately, or if a continuous process will be used.

Regarding the joining of DEG modules to form a large DEG, it is noted by Moretti et al. that for this solution to work the joins must maintain similar mechanical properties as the DE film [262].

C2.4) Cost of manufacturing dielectric elastomer generator

It is noted in Moretti et al. [32] that the costs of commercially available quality DE films are currently very high (see C2.1 above). It is highlighted by Moretti et al. that this is due to the manufacturing costs of these DE films and low production volumes.

These costs will need to be significantly reduced to make DEGs viable for low-cost wave energy applications.

C3) System integration barriers for DEG WECs

C3.1) Design and modelling of Dielectric elastomer generator WECs

<u>Modelling and design</u>

To take advantage of DEGs, new WEC architectures will have to be designed. In the literature, emphasis is given to the utilisation of polymeric materials for the structure of a DEG WEC, to reduce structural costs and enable load shedding [32], [187], [189], [262]. However, barriers exist in the modelling and design of these devices.

Regarding the design of these devices, large DE volumes or shear modulus can increase DEG stiffness [136]. This high DEG stiffness may need to be counterbalanced to enable WECs that are resonant at typical wave frequencies. This could include designs with large hydrodynamic inertias or negative hydrostatic stiffness [32]. Designing around overloads is another challenge for DEG WEC development [262]. Instabilities can occur in inflated elastomeric WECs where unstable deformation happens with respect to loading above a certain level [187]. These mechanical instabilities may be compounded by pull-in instabilities in DEGs [187] (see Section 4.1). Dissipations in flexible WECs may also be a challenge, as it is noted in Babarit et al. [190] that rather large energy dissipations (~50% of total absorbed energy) were present in modelling of a bulge wave type DEG WEC made of silicone.

Several studies have also highlighted the lack of modelling tools that can integrate elastomer materials [134], [187]. This includes difficulties in modelling the membrane interface [187], PTO damping [187], elastomeric material fatigue [187], and scaling laws for losses (namely DE viscosity and dielectric losses) [32].

<u>Power electronics</u>

For a DEG to deliver energy to the grid, suitable power electronics are needed. The requirements for these converters are specified by Moretti et al. [32]:

- Direct current (DC) high-voltage (HV) operation, required to implement electric fields in the order of 10^1-10^2 kV/mm on DEGs (this requires a rating of ~10 kV).
- Bidirectional intermittent electrical power fluxes: electrical energy should be supplied to the DEG for priming phase, then extracted during the following phases (see Figure 4-3).
- Handling of larger currents (and power) for brief time intervals during priming and discharging phases (T1 and T4 in Figure 4-3).

The power electronics also need to precisely control the voltage on the DEG, which is essential to achieve high energy densities (cycles for maximum energy harvesting are described in Moretti et al. [136]).

The barrier associated with power electronics is that commercially available semiconductors compatible with these specifications are not available [32]. For this reason, the use of a cascade of DC-DC converters has been proposed in the literature [32]. This reduces the output voltage requirement for each DC-DC converter, allowing suitable power electronics to be developed using existing DC-DC converters.

C3.2) Self-sensing and control

To enable high DEG energy densities, a circuit with switches is needed to control the charge and voltage on the DEG. It is noted by Moretti et al. [136] that the conditions in which these switches are operated will usually depend on the stretch state or voltage on the DEG. This means the stretch state of the DEG must be accurately estimated in order to carry out optimal control of the DEG power electronics.

Development of sensing and control strategies and efficient power electronics is highlighted as a key barrier area for DEG WEC development by Moretti et al. [136]. It is noted by Moretti et al. that using mechanical measurement of a DEG's max/min stretch can be challenging in applications like wave energy, where the amplitude varies between cycles. However, as the capacitance and level of stretch of the DEG are related (See Figure 4-1), measuring the DEG's capacitance while it deforms allows the level of stretch to be estimated [136], [189].

In addition to achieving high energy densities, multi-objective control strategies could be used to find the optimal balance of maximising energy production and limiting damage accumulation, as proposed by Hoffamn et al. [263]. However, the development of these control strategies requires data on DEG electro mechanical fatigue [263], which is currently very limited (see sections on DEG fatigue above).

C4) Environmental impacts of DEG in WEC application

C4.1) Recyclability of dielectric elastomer generator modules

Tens of tonnes of DE materials could be required in large-scale (hundreds of kW) DEG wave energy devices. Commonly used DE materials (silicone and natural rubber) are generally thermosets. This presents a barrier to sustainable end-of-life disposal, as they cannot be simply melted and reused like thermoplastics. It is noted by Moretti et al. that recycling, partial recovery (e.g. use as fillers or applications like astroturf), or energy recovery (incineration) is possible for some DE materials [262]. The recycling of DEGs may pose an additional challenge due to their multilayer nature. Studies on the recycling of entire DEG modules were not apparent in the literature.

These recyclability issues may also be relevant to the WEC structural components if polymeric materials are utilised in DEG WECs [262]. For instance, using the dimensions presented in [244], a 100m SBM device (with a capture width of ~5m [190]) would utilise approximately 260 tonnes of silicone in the tube structure.

C4.2) Degradation of dielectric elastomer generator in marine environment

Polymers can be degraded through mechanical and chemical weathering processes such as oxidation, swelling, leaching, and biodegradation [262].

It is noted by Teillant et al., that a concern related to this degradation for DE materials is the leaching of chemical additives [140] and production of microplastics. Commercially, available DEs contain a lot of additives, many of which are not chemically bonded, meaning they may leach out of the material [140]. These additives (and level of cross-linking) can also limit the biodegradability of these polymers in the marine environment [140]. Additionally, the production of microplastics can occur from weathering processes [140]. It is highlighted by Zaltariov et al. [270] that silicones do not require the use of plasticizers (an additive that can leach out of a DE), which makes them more a more environmentally friendly option for DEG WEC applications.

While these degradation risks are considered low by Teillant et al. [140], it is highlighted that knowledge gaps need to be addressed in the area of degradation of DE materials in real sea conditions.

C4.3) Electric shock risk

Teillant et al. [140] note that the high voltages required for DEG WECs (in this case polyWEC) could have a high impact on marine organisms if the membrane were damaged. Teillant et al. note that, while this is considered a low-probability event, it presents a knowledge gap, as it had not been the subject of any research at the time of writing.

C5) Other barriers

Other barriers are noted in the literature, although these may only be applicable to specific DEG WEC designs. These include:

- Knowledge gaps around collision risk for membrane-based WECs [262].
- The effects of tidal drag forces on large-area membranes. It is noted by Collins et al. [187] that tidal drag forces could place additional strain on anchoring, and could cause certain wave energy converters to yaw in accordance with tidal currents, rather than wave direction.

8 Expert opinion on barriers to dielectric elastomer wave energy converters

The academic literature (when taken together) provides an overview of the barriers to develop DEGs for wave energy. However, there has been little work to systematically identify the actions that could be taken to overcome these barriers or prioritise how they could be addressed. The systematic identification of barriers, and the actions which can be taken to address these, can play an important part in strategic planning of renewable energy development and deployment, such as roadmapping [259], [260] or technology needs assessments [271], [272].

To add value to the list of barriers that were identified from the literature review, it was decided that the opinion of experts within the field of dielectric elastomer generation and wave energy would be gathered. The process used to identify and evaluating the barriers to DEG WEC development in Part C of this thesis was as follows:

1. **Literature review**
    - Identify barriers to DEG WEC development in the literature.
    - Establish categories for these barriers.

2. **Expert interviews**
    - Identify any missing barriers from the literature review and validate the barrier categories from the literature review.
    - Identify the barriers which experts believe are most important (the 'key barriers') to DEG development in wave energy applications.
    - Identify actions that experts believe can be taken to overcome the key barriers.
    - Evaluate of the difficulty in carrying out these actions.
    - Establish if it is possible to prioritise the order in which some (or all) of these barriers should be addressed.

Carrying out these expert interviews addresses the aim of the third part of the research, which is to identify the barriers that currently exist to the most promising direct conversion technologies for wave energy applications (DEGs), and to identify the actions that could be taken to address these barriers.

In this chapter, Section 8.1 covers the methodology for gathering expert opinion, the selection of experts, the procedure to carry out the interviews, and the data analysis. This is followed by the results of the semi-structured interviews in Section 8.2, and concludes with a discussion of the results in Section 8.3.

8.1 Method for DEG WEC expert interviews

Several approaches can be used to gather expert opinion, including interviews and questionnaires, as well as nominal and interacting group approaches [273]. It was decided that a semi-structured interview format, with both closed and open questions, would be most appropriate for this study. The same initial questions would be asked, but the flexibility of a semi-structured approach would allow for additional follow-up questions to clarify the interviewee's response or gather additional information. To address complex questions related to dielectric elastomer research, allowing this additional flexibility was seen as highly beneficial compared to other data collection methods such as surveys (including Delphi approaches [274]) or fully-structured interviews. Additionally, given the typically poor response rate of surveys [273, p. 251] and high dropout rate in Delphi studies [274], these were not considered appropriate given the small pool of potential interview participants.

A workshop approach, such as a nominal group approach, would have been a good alternative to semi-structured interviews, as it facilitates both individual opinion and consensus-building. However, it is advised that these should be carried out in-person [275]. Given the wide range of geographic locations of the participants and the budget and time constraints of this work, it was considered impractical to organise workshops as part of this research.

8.1.1 Selection of experts for semi-structured interviews

Purposeful sampling was used for the selection of experts for this study. Purposeful sampling is the principle of building up a sample of participants for a study, based on their ability to satisfy the research needs of a project. Purposeful sampling is a non-probability sampling approach (it cannot be used to make inferences about a population), and is commonly used for small-scale surveys or interviews [273, p. 279], [274], [276]. This was considered to be an appropriate method to select interviewees for this work, as the aim of these interviews was to elicit the opinion of experts with significant knowledge in the areas of dielectric elastomer generation and wave energy [276], rather than make inferences about a wider population.

The experts were selected based on their knowledge in the areas of both dielectric elastomers and wave energy conversion. These experts were identified both through a review of the literature and contacts known to the PhD supervision team. In total, 9 experts were interviewed, all with backgrounds working in dielectric elastomers and wave energy. Four additional experts were invited for interviews, who either did not reply to interview requests, or declined to be interviewed. An overview of the backgrounds of the interviewees can be found in Appendix C.3 — Full interview summaries.

8.1.2 Procedure and materials to carry out semi-structured interviews

The semi-structured interviews were carried out between 03/03/2023 and 26/04/2023. Prior to this, a pilot interview was carried out on 08/02/2023 with a wave energy expert who was familiar with dielectric elastomer wave energy conversion. The results from this pilot interview are not presented in this thesis. As a result of the pilot interview, some small alterations were made to the structure of the interview schedule to reduce the ambiguity of the questions.

Prior to each interview, the interviewee was provided with preliminary information about the study. This information is presented in full in Appendix C.1 — Preliminary information for interview participants, while a summary is presented below:

- Information sheet — explaining the aims of the study and the use and protection of personal data.
- Consent form — to be returned before commencing the interview, to confirm consent to the recording of the interview and the use of personal data laid out in the information sheet.
- Barriers list — a table that summarised the barriers to dielectric elastomer-based wave energy converters that were identified through the literature review and any informal preliminary discussions held with DEG WEC experts prior to the semi-structured interviews (this is very similar to Table 7-1).
- Interview PowerPoint — a series of introductory slides that would be covered before the interview started.

After the interviewee had received the preliminary information and signed the consent form, the interview was carried out. Each interview lasted approximately one hour and was carried out virtually using Microsoft Teams, which also facilitated interview recording and transcription. Paper notes were taken alongside in case the recording failed. The interview followed a 5-stage structure, a summary of which is presented below. These stages directly address the aims of part three of this research (See Section 8.1).

1. *Introduction to the interview (5-10 mins)* — Interviewer introduces themselves, and interviewee is asked to introduce themselves. Explanation of the purpose of the study (through a short PowerPoint presentation — Appendix C.1 — Preliminary information for interview participants). Confidentiality and data protection summarised and permission sought to record.
2. *Introductory questions (5-10 mins)* — This establishes which areas the interviewee would like to discuss regarding the barriers to DEGs in wave energy (e.g. barriers in DEG manufacturing).
3. *Main interview questions (20-30 mins)* — After establishing the areas for discussion (e.g. DEG manufacturing) in the introductory questions, the main interview questions cover the following:
   i. What are the key barriers to development of DEGs in <e.g. manufacturing>?
   ii. For each of these barriers, what actions can be taken to address them?
   iii. How difficult will it be to carry out these actions?
   iv. Is the interviewee aware of work already being undertaken to address the key barrier? (Note that this question did not yield good-quality responses and therefore has not been presented in the results section)
4. *Concluding questions (5-10 mins)* — The final questions in the interview covered the following:
   i. Is there a prioritisation that the interviewee would give to addressing the barriers to DEG WEC development?
   ii. Interviewee given the opportunity to add any additional comments that covered areas that were not addressed explicitly by the questions.
5. *Closure* — Interviewee thanked for their time and next steps outlined.

The results section is structured around this interview format, where Section 8.2.1 covers the introductory questions, Section 8.2.2 covers the main questions and Section 8.2.3 covers the closing questions.

The full interview schedule containing all the interview questions is given in Appendix C.2 — Full interview schedule, and the presentation that was delivered alongside the interview is presented in Appendix C.1 — Preliminary information for interview participants. Some of the interview questions are not presented in this section, as the information yielded was not of good quality. However, a full summary is given in Appendix C.3 — Full interview summaries.

8.1.3 Data gathering and analysis

Each interview was recorded and transcribed using Microsoft Teams, with paper notes taken as a backup. A selective transcription [273, p. 305] was then carried out in NVivo, where the recording timer was taken at any important sections of the interview, and the relevant section of the interview was transcribed (correcting mistakes from the Microsoft Teams transcription). Following this, a summary of the results from the interview was tabulated (see Appendix C.3 — Full interview summaries), along with the findings from the interview under each question.

The results summary was also made available to the interviewee shortly after the interview, to give them the opportunity to modify any of their answers, or withdraw from the study, up until 01/06/2023. This information is detailed in the information sheet which was given to the interviewee prior to the interview.

The data-gathering and analysis process that was followed for each of the nine interviews is shown in Figure 8-1.

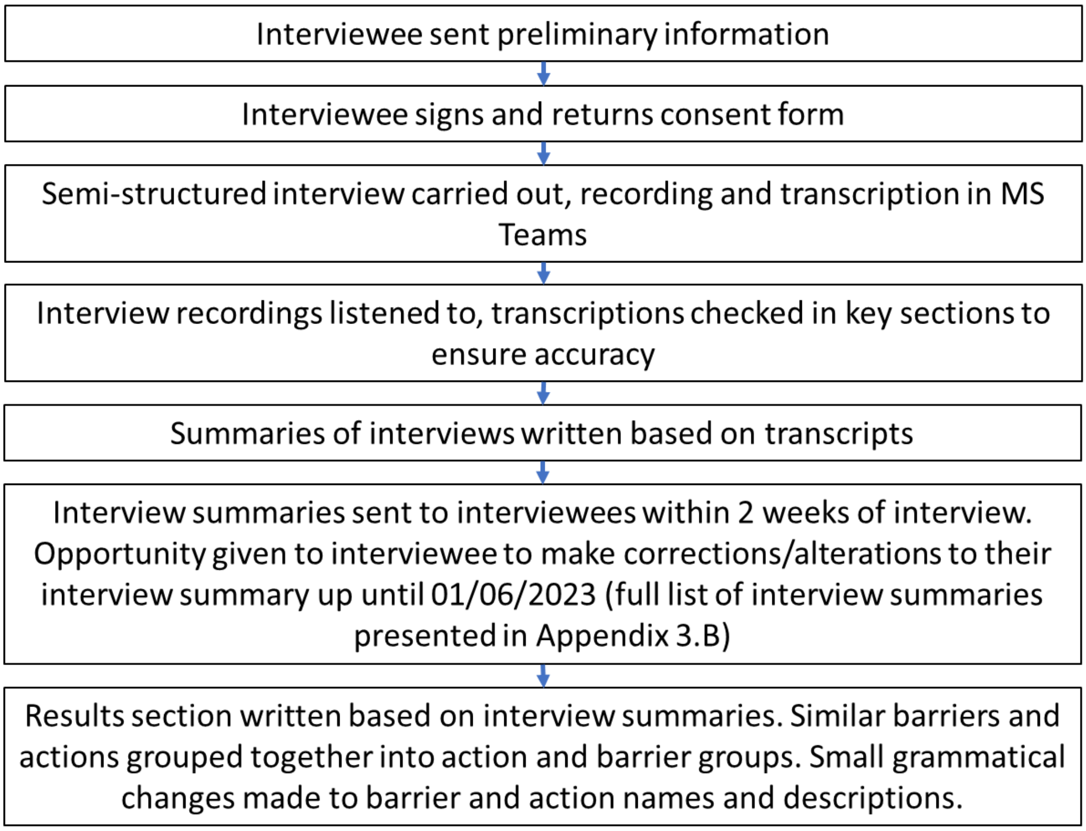


Figure 8-1. *Data gathering and analysis process followed for the semi-structured interviews.*

8.2 Results from semi-structured interviews

This section presents the results from the semi-structured interviews. Section 8.2.1 covers the categories which the interviewees chose to discuss during the interviews. Section 8.2.2 presents the key barriers and actions which were covered over the course of the interviews. Finally, the prioritisation of these barriers given by the interviewees is presented in Section 8.2.3.

In this section, the categories and subcategories that are used are the same as those identified during the literature review (see Table 7-1), with the addition of 'other barriers' subcategories (C1.5, C2.5, C3.3, C4.4). These 'other barriers' were added to capture any of the more general barriers identified by the interviewees that still fell under the high-level barrier categories. The barrier categories referred to in this section are shown in Table 8-1.

Table 8-1. Categories and subcategories of DEG WEC barriers and actions used in the semi-structured interviews.

Category	Subcategory
C1) Performance of DEG	C1.1) Lifetime of DEG in WEC operating conditions
	C1.2) DE materials and design
	C1.3) Electrode materials and design
	C1.4) DEG performance at scale
	C1.5) Other performance barriers
C2) Manufacturing DEG (at scale)	C2.1) Manufacturing DE films
	C2.2) Manufacturing electrodes
	C2.3) DEG module fabrication and joining
	C2.4) Cost of manufacturing DEG
	C2.5) Other manufacturing barriers
C3) System integration for DEG WEC	C3.1) Design and modelling of DEG based WEC
	C3.2) Control
	C3.3) Other system-integration barriers
C4) Environment effects of DEG	C4.1) Disposal of DEG
	C4.2) Degradation of DEG in marine environment
	C4.3) Electric shock risk
	C4.4) Other environmental barriers
C5) Other barriers	

8.2.1 Barrier categorisation

It is important to highlight at the start of this section that the barriers discussed with the interviewees are only a subset of barriers to DEG WEC development (a more comprehensive list of the barriers to DEG WEC development is the combination of both the literature review and the results from the interviews). This is for several reasons. Firstly, the interviews only identified what the experts considered to be key barriers to DEG WEC development. In addition, the experts were asked to discuss areas in which they had a good level of knowledge about the barriers to DEG WEC development. Finally, time constraints limited each interview to the discussion of, at most, 5-6 key barriers.

The introductory questions asked the interview participants if they agreed that the categories identified in the literature review (see Table 7-1) covered the key barriers for DEG WEC development, or if they would add any additional categories. Of the nine interviewees, eight indicated that the categories covered the key barriers, while one interviewee did not answer (however, they did not add any additional barrier categories). One of the interviewees did note that it is difficult to separate some of the barriers into individual categories due to the multidisciplinary, collaborative nature of R&D into DEG WEC development. This interviewee introduced a barrier, 'Lack of complete DEG WEC study', which highlighted the lack of coordination between these different disciplines. This was put into the 'other' category (C5) as it did not easily fit into one of the existing categories.

The categories that were discussed by the interviewees are heavily weighted to the Performance (C1) category, where eight out of nine interviewees identified key barriers to DEG WEC development. For both the Manufacturing (C2), and System integration (C3) categories, four interviewees identified key barriers to DEG WEC development. No interviewees discussed key barriers under Environmental Impact (C4). The fact that no interviews could be secured with environmental experts that had relevant experience in both DEGs and wave energy is the probable cause of this. Finally, one interviewee identified a key barrier that did not fit into the existing categories (C5).

The number of barriers listed by the interviewees, arranged by subcategory, are shown in Figure 8-2. The largest number of key barriers were mentioned under 'Lifetime of DEG in WEC operating conditions' (C1.1), where eight barriers were listed; followed by 'Design and modelling of DEG based WEC' (C3.2), where seven barriers were listed. As discussed later in this chapter (see Table 8-2), several of the barriers identified by the interviewees are very similar and can be grouped together.

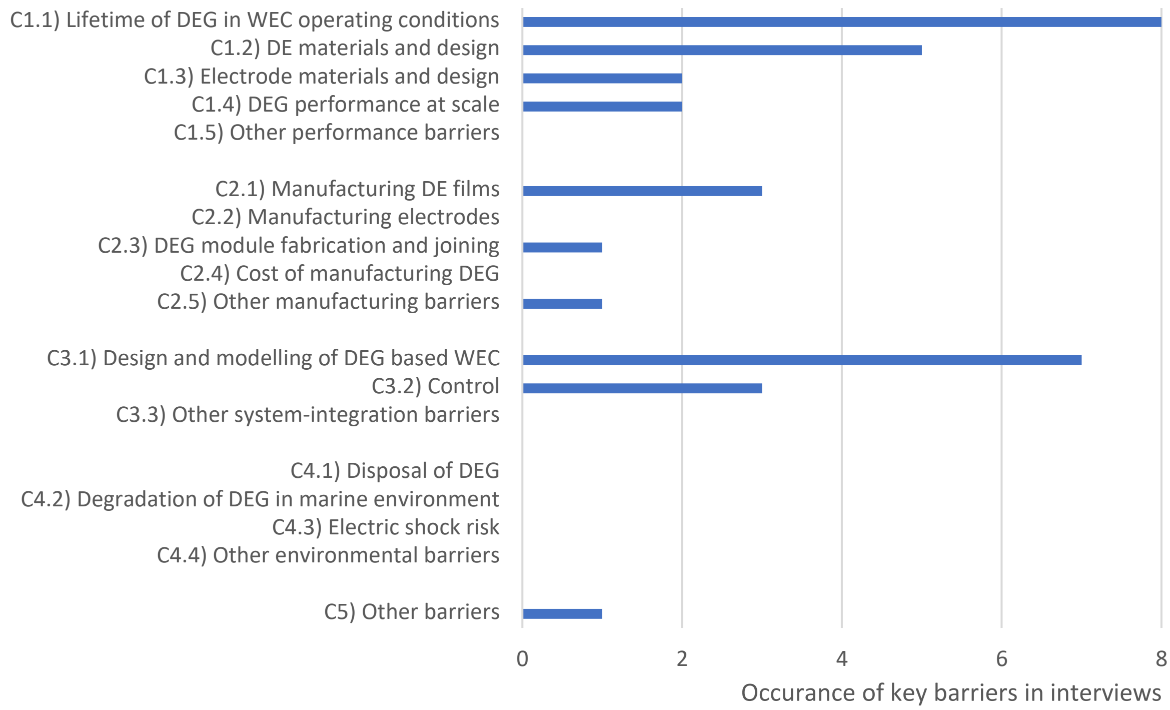


Figure 8-2. *Key barriers to DEG WEC development that were identified during the semi-structured interviews listed by barrier subcategory.*

8.2.2 Barriers and actions for DEG WEC assessment

This section covers the barriers and associated actions brought up during the semi-structured interviews. The level of difficulty associated with these actions is then covered. The barriers and actions presented in this section are the same as those shown in the interview summaries (Appendix C.3 — Full interview summaries), which were given to the interviewees to check. However, some of the barriers have been renamed to improve clarity, and grammar changes have been made to improve readability. Additionally, if separate experts mentioned the same barrier or action, these have been grouped together to highlight areas of consensus and avoid repetition. These are shown in the barrier and action groups.

In this section, each individual barrier that was brought up during the interviews has been given as a capital B with a unique number, while the curly brackets indicate the interviewee that mentioned the barrier. For example, *B12*{4} is barrier number 12, which was attributed to interviewee number 4. The actions are written as capital A's with a unique number, along with the barrier they address and the number of the interviewee. For example, *A8*(*B7*){3} is action number 8, which addresses barrier number 7, both of which were identified by interviewee number 3. It should be noted that these barrier and action numbers are ordered sequentially in the interview summaries (i.e. interviewee 1 identified *B1*-*B2*, interviewee 2 identified *B3*-*B5*, interviewee 3 identified *B6*-*B10*, and so on). However, the order in which they are presented in this section is not sequential, as they have been sorted into the categories in Table 8-1. In some cases, multiple actions were listed by an interviewee for a single barrier. In other cases, one action was proposed that addresses multiple barriers.

Following this, the action difficulty is presented. This is the interviewee's evaluation of the difficulty in carrying out the action, ranging from: very low (1), low (2), moderate (3), high (4) to very high (5) difficulty. The action difficulty was not specified for every action, which is highlighted in the results. Finally, any other comments made by the interviewee that fall under the barrier category are presented.

Some of the barriers and actions were mentioned by several interviewees. These individual barriers have been arranged into barrier groups *BG1*, *BG2*, etc. and action groups *AG1*, *AG2*, etc. For the barrier and action groups the barrier group BG or action group AG is shown. Following this, the individual barriers or actions that make up the grouping are shown in brackets. An example of a barrier group is: *BG2*(*B5*{2}, *B22*{6}) which is a group containing barriers 5 and 22 mentioned by interviewees 2 and 6 respectively. An example action group is: *AG4*(*A10*(*B8*){3}, *A11*(*B9*){3}) which is a group containing Action 10 (addressing barrier 8) and Action 11 (addressing barrier 9) which were both mentioned by interviewee 3.

Table 8-2 shows the numbered barriers and actions for the subcategories given in Table 8-1. In total, 33 key barriers were mentioned over the course of the 9 interviews. 14 of these barriers were very similar to those mentioned by other interviewees and have been put into barrier groupings. To address these barriers, 35 actions were mentioned by the interviewees, 16 of which were very similar and put into action groupings. In Table 8-2 the barriers and actions that fell into these groupings are coloured to indicate their grouping number (given at the bottom of Table 8-2).

Table 8-2. Categories and subcategories of DEG WEC barriers and actions from the semi-structured interviews.

Category	Subcategory	Barriers	Actions
C1) Performance of DEG	C1.1) Lifetime of DEG in WEC operating conditions	*B7, B11, B24, B28, B29, B12, B30, B31*	*A9, A14, A30, A31, A13, A27, A33, A8, A15, A32*
	C1.2) DE materials and design	*B4, B9, B21, B32, B33*	*A5, A34, A11, A24, A35*
	C1.3) Electrode materials and design	*B5, B22*	*A6, A25*
	C1.4) DEG performance at scale	*B3, B8*	*A10, A3, A4*
	C1.5) Other performance barriers	—	—
C2) Manufacturing DEG (at scale)	C2.1) Manufacturing DE films	*B14, B26, B27*	*A17, A28, A29*
	C2.2) Manufacturing electrodes	—	—
	C2.3) DEG module fabrication and joining	*B10*	*A12*
	C2.4) Cost of manufacturing DEG	—	—
	C2.5) Other manufacturing barriers	*B23*	*A26*
C3) System integration for DEG WEC	C3.1) Design and modelling of DEG based WEC	*B1, B2, B13, B17, B18, B19, B20*	*A16, A1, A2, A20, A21, A22, A23*
	C3.2) Control	*B6, B15, B16*	*A7, A18, A19*
	C3.3) Other system-integration barriers	—	—
C4) Environment effects of DEG	C4.1) Disposal of DEG	—	—
	C4.2) Degradation of DEG in marine environment	—	—
	C4.3) Electric shock risk	—	—
	C4.4) Other environmental barriers	—	—
C5) Other barriers		*B25*	*A27*

Barrier grouping: *BG1*, *BG2*, *BG3*, *BG4*, *BG5*
Action grouping: *AG1*, *AG2*, *AG3*, *AG4*, *AG5*

Table 8-3 and Table 8-4 present an overview of the barriers and actions respectively from Table 8-2. The difficulty ascribed to the different actions (and groups of actions) are also shown in Table 8-4. It should be noted that the action groups do not specifically correspond to the barrier groups. The exact links between barriers and actions is shown in Appendix C.4 — Links between barriers and actions. In some cases, the difficulty is not assessed, as the expert could not confidently assess it, or the difficulty was not described on a scale of 1-5. Only the categories in which key barriers were identified are shown in Table 8-3 and Table 8-4.

Table 8-3. Summary of key DEG WEC barriers identified during semi-structured interviews.

Category	Subcategory	Barrier name
C1) Performance of DEG	C1.1) Lifetime of DEG in WEC operating conditions	*BG1(B7, B11, B24, B28, B29)* **Lack of representative fatigue life data for DEGs**
		B12 **DE material property trade-offs**
		B30 **Heat dissipation around electrodes**
		B31 **Lifetime of DEG and replacement**
	1.2) DE materials and design	*B4* **Changes in DE material properties during electromechanical fatigue cycles**
		B9 **Electromechanical instabilities**
		B21 **DE materials need to operate under a specific set of conditions**
		B32 **Creep in DE materials**
		B33 **DE filler selection**
	C1.3) Electrode materials and design	*BG2(B5, B22)* **Stretchable electrodes with suitable material properties**
	C1.4) DEG performance at scale	*BG3(B3, B8)* **Defects in large-area DE membranes reducing performance**
C2) Manufacturing DEG (at scale)	C2.1) Manufacturing DE films	*BG4(B14, B26, B23)* **Lack of large-scale manufacturing infrastructure for DEs and DEGs**
		B27 **DE material selection**
	C2.3) DEG module fabrication and joining	*B10* **Joining of silicone DE**
	2.5) Other manufacturing barriers	*B23* See *BG4*
C3) System integration for DEG WEC	C3.1) Design and modelling of DEG based WEC	*B1* **Design of a WEC to utilise DEGs**
		B2 **Design of power electronics**
		B13 **Trade-offs between modular and monolithic DEGs**
		B17 **Electrical insulation of DEG**
		B18 **Scaling DEG for lab scale tests**
		B19 **Attachment of DEG to WEC structure**
		B20 **Development of numerical model**
	C3.2) Control	*BG5(B6, B15)* **Self-sensing of DEG capacitance (for deformation estimation and health monitoring)**
		B16 **DEG Control strategies**
C5) Other barriers		*B25* **Lack of complete DEG WEC study**

Table 8-4. *Actions identified during the semi-structured interviews and difficulty. The difficulty is: (1) very low (2) low (3) moderate (4) high (5) very high.*

Category	Category	Action name	Action difficulty (1-5)
C1) Performance of DEG	C1.1) Lifetime of DEG in WEC operating conditions	*AG1(A9, A14, A30, A31, A5, A34)* **DEG fatigue life testing under relevant operating conditions (cyclic mechanical & electrical fatigue and marine environment)**	2-4
		AG2(A13, A27) **Multi-disciplinary research**	2
		AG3(A33, A16) **Investigation of modular DEG WEC design**	2-3
		A8 **Repairability or redundancy in DEG system**	N/A
		A15 **Synthesis of new DE materials**	4
		A32 **Thermally conductive DE fillers**	N/A
	1.2) DE materials and design	*A5* See *AG1*	See *AG1*
		A34 See *AG1*	See *AG1*
		A11 **Actions addressing defects and volume effect** - see *AG4*	See *AG4*
		A24 **Industry focus on increasing TRL of DE materials**	3
		A35 **DE filler treatment**	3
	C1.3) Electrode materials and design	*A6* **Development of stretchable electrodes**	1-2
		A25 **Industry focus on increasing TRL of electrodes**	3
	C1.4) DEG performance at scale	*AG4(A10, A11)* **Development of suitable self-clearing electrodes**	4
		A3 **Low-defect DE materials**	2-3
		A4 **Self-healing DE materials**	N/A
C2) Manufacturing DEG (at scale)	C2.1) Manufacturing DE films	*A17* **Study existing industrial processes for polymer manufacturing**	3
		A28 **Economic and environmental study on silicone for large-scale DEG manufacturing**	3
		A29 **Assessment of SBR and silicone for DEG WEC**	N/A
	C2.3) DEG module fabrication and joining	*A12* **Improved understanding of chemical processes for silicone adhesion**	N/A
	2.5) Other manufacturing actions	*A26* **Business model for DEG manufacturing**	2
		A16 See *AG3*	2-3

Category	Category	Action name	Action difficulty (1-5)
C3) System integration for DEG WEC	C3.1) Design and modelling of DEG based WEC	*A1* **DEG WEC design from foundational principles without bias**	5
		A2 **WEC design for power electronics**	2-3
		A20 **Development of generic DEG insulation solutions**	3
		A21 **More research on DE scaling and material testing**	N/A
		A22 **More research on flexible DEG attachment**	1
		A23 **Development of numerical model and experimental data sets**	4-5
	C3.2) Control	*AG5(A7, A18)* **Development of DEG capacitance self-sensing**	1-2
		A19 **Experimental testing of advanced controls**	3
C5) Other barriers		*A27* See *AG2*	See *AG2*

The remainder of this section covers the individual barriers and actions that were discussed in the interviews, along with the difficulty of carrying out the actions. These are arranged by the barrier categories and subcategories from Table 8-2. In the case that no barriers, actions or other comments were mentioned in a particular subcategory, it is not covered in this section (this was the case for C1.5, C3.3 and C4.4). It should be noted that just because a certain category or subcategory was not mentioned during the interviews, it does not mean that no barriers exist in the category. A primary example of this would be the environmental category, in which no key barriers were identified during the interviews. However, this is probably due to the lack of expertise within the sample of experts, rather than a lack of any key environmental barriers.

Presentation of barriers and actions in this section

To present the barriers and actions, the following layout is used, shown in the box below:

> **Key barriers and actions**
>
> **Barrier** — text that is not indented signifies a barrier to DEG WEC development.
>
> - **Action** — a black bullet point signifies an action that addresses the barrier. In some cases, there are multiple actions per barrier.
>   - Difficulty of addressing action — a white bullet point signifies the difficulty in carrying out the action.
>
> **Other comments**
>
> Other points that were not specifically identified as key barriers which were made by the experts within the category are listed. These are not indented.

This hierarchy of list levels is used throughout this section (8.2.2). The one place where this varies slightly is that some of the 'difficulty of addressing action' levels contain bold text to specify a specific action if they belong to a group.

C1) Performance of DEG

C1.1) Lifetime of dielectric elastomer generators in WEC operating conditions

Key barriers and actions

Barrier Group 1: Lack of representative fatigue life data for DEGs — *BG1 (B7{3}, B11{4}, B24{7}, B28{8}, B29{9})*
Five key barriers were highlighted (by five experts), related to the lack of representative fatigue life data for DEGs. In WEC applications, a DEG needs a sufficient lifetime to recoup its capital costs. However, a barrier to DEG WECs was the lack of publicly available fatigue life data for DEGs or DE films tested under WEC relevant conditions. These relevant conditions are a combination of cyclic high amplitude electric field and mechanical strain in combination with a marine environment. It was noted by interviewees {8} and {9} that available fatigue testing data has typically investigated these sources of fatigue in isolation and that other applications do not exist where elastomer materials need to survive these combinations of fatigue. It was also highlighted by interviewee {3} that, while silicone can survive a long time under a DC electric field, there is likely to be a synergistic effect under combined cyclic electromechanical fatigue, which would probably accelerate failure. Interviewee {9} also noted that universities do not typically have the facilities to carry out these combined fatigue tests.
(It should be highlighted that Actions 34 and 5 were not brought up in relation to the

barriers that make up Barrier Group 1. These actions were brought up in relation to barrier 32 and 4 respectively. However, as both actions are part of Action Group 1, they are presented below.)

- **Action Group 1: DEG fatigue life testing under relevant operating conditions (cyclic mechanical and electrical fatigue and marine environment)** — *AG1(A9(B7){3}, A14(B11){4}, A30(B28){8}, A31(B29){9}, A5(B4){2}, A34(B32){9})*
  Six actions were suggested by interviewees that involved carrying out fatigue testing of DEGs. These tests should be carried out under conditions representative of DEG WEC operation (combination of cyclic electrical and mechanical fatigue in a marine environment), as highlighted in *BG1*. It was also suggested by interviewee {4} that these tests should address how electrical and mechanical fatigue are interrelated and the effect that DE sample dimensions have on fatigue life. Interviewee {2} highlighted that the fatigue tests should consider the relationship between defects in the DE and fatigue life. Interviewee {3} suggested that a more representative characterisation of fatigue life would be given by tests on the whole DEG, rather than just DE samples. This allows sources of failure such as inclusions between the DE and electrode to also be accounted for, which can reduce the lifetime of the DEG in comparison with a DE sample {3}. It was also noted by interviewees {2} and {9} that modelling could be used in combination with fatigue testing to predict the fatigue life of DEGs. This included potentially using AI to accelerate fatigue testing {9}. Interviewee {9} suggested that including industrial partners on DEG fatigue testing projects would help with provision of materials and testing facilities, as these facilities were considered to be expensive for universities to set up (if they did not already have them).

  The difficulty of addressing the individual actions that make up *AG1* are:

  - **Action 9: DEG fatigue life testing under relevant operating conditions** — *A9 (B7){3}*
    Interviewee noted that the difficulty of carrying out action *A9* depends on the volume effect (the volume effect is described under C1.4 in *BG3*). Interviewee highlighted that lifetime concerns would be relatively easy to address at a laboratory scale. However, when solving at a large scale it becomes a very difficult barrier. At lab scale, DE samples can be produced with few weak points (such as crack initiators). However, at large-scale (e.g. 100m rolls), the interviewee considered that making DEs defect-free was almost impossible. (This also applies to action *A8* (Repairability or redundancy in DEG system) which is presented below)
  - **Action 14: More dedicated studies on DEG lifetime —** *A14(B11){4}*
    Interviewee assessed this action as moderately difficult (3), as the action is mainly a case of understanding what needs to be measured (representative fatigue tests for DEG WEC) and cancelling out effects that make data non-representative (e.g. scale effects on acceleration).
  - **Action 30: Testing of DE membranes in realistic conditions** — *A30(B28){8}*
    Interviewee assessed this action as having a low technical difficulty (2) and did not see significant difficulty in terms of performing the experimentation.

They noted that this testing would just require time (interviewee suggested around 1 year for accelerated fatigue tests) and money to implement the testing infrastructure. However, it was highlighted that it is difficult to find financing for performing this type of activity. Interviewee noted that a single project that will fund the fatigue testing of material will typically be commissioned by companies, but that there are few companies that would be willing to invest in DEG fatigue testing at present.

  - **Action 31: Combined fatigue testing** — *A31(B29){9}*
    Interviewee assessed the actions required to address DEG fatigue (in general) as being difficult (4) but achievable. Interviewee highlighted the importance of collaboration with the industry to achieve these actions (an example was given of the cable industry). In addition, the need for collaboration between people with different backgrounds was noted, which can make communication challenging when working on combined fatigue research. A lack of expertise within high-voltage electronics was also noted by the interviewee, which is required for electrical fatigue characterisation of DEGs.
  - **Action 34: Fatigue testing** - *A34(B32){9}*
    Same difficulty and justifications given as *A31* (combined fatigue testing). (Action 34 addresses B32 (Creep in DE materials), which is covered in C1.2)
  - **Action 5: Modelling and fatigue testing of DE materials** — *A5(B4){2}*
    Assessed as moderate difficulty (3), as interviewee highlighted these would be standard tests and modelling, and the equipment to carry out these tests will already exist. However, interviewee highlighted testing would be time-consuming and would require a dedicated project. (Action 5 addresses *B4* (Changes in DE material properties during electrotechnical fatigue cycles), which is covered in C1.2)

- **Action Group 2: Multi-disciplinary research** — *AG2(A13(B11 & B12){4}, A27(B24 & B25){7})*
  Two actions related to the importance of multidisciplinary research to address DEG barriers were suggested by two interviewees {4}{7}. Interviewee {4} highlighted that more input is needed from materials science to address issues around fatigue life and the trade-off between different DE properties. It was highlighted by interviewee {7} that research into DEGs for wave energy applications is a very interdisciplinary area, including chemistry and materials, experimentalists, device designers, modellers and electronics. Therefore, it was suggested that research actions should be headed by interdisciplinary people. Interviewee {7} highlighted that this would allow new proposed DEG solutions to be evaluated from the perspective of different disciplines. For example, iteration between material science and testing would ensure any new DE and electrode materials are tested under realistic conditions. Also, iteration between the testing and device design, for example material selection based on performance in fatigue tests that characterise the mechanical loading and electrical field that the material will experience during operation.

The difficulty of addressing the individual actions that make up *AG2* are:

- **Action 13: Involvement of materials science** — *A13(B11 & B12){4}*
  Difficulty not specified for this action. (Action 13 also addresses *B12* (DE material property trade-offs), which is covered below)
- **Action 27: Multi-disciplinary research** — *A27(B24 & B25){7}*
  Interviewee assessed this action as low difficulty (2). The interviewee considered that if sufficient funding was allocated to a multidisciplinary team, the complete materials development/testing/device testing process could be carried out in 5 years. Additionally, the interviewee highlighted that the DEG WEC community already has a good level of knowledge of the researchers working in certain areas. It was suggested that a driving organisation like WES or SuperGen could connect researchers. (Action 27 also addresses *B25* (Lack of complete DEG WEC study), which is covered in C5)

- **Action 8: Repairability or redundancy in DEG system** — *A8(B7){3}* Interviewee highlighted that if watertightness of DEG modules is lost due to mechanical failure (e.g. through fatigue), the entire DEG system can become inactive. Therefore, an action should be taken to find a way to either make replacement of a DEG module, or a way to allow the system to continue to operate, after a failure of one of its components.

  - Interviewee noted that this action has the same difficulty and justifications as action *A9* (DEG fatigue life testing under relevant operating conditions) which is described above, although not rated on a scale of 1-5.

Barrier 12: DE material property trade-offs — *B12{4}*
Energy density of DEGs is related to the DE material's permittivity and maximum applied electric field. However, if new materials are synthesised with high E_{BD} and permittivity, they also must have a long lifetime. Interviewee highlighted that work in this area is preliminary and there is little knowledge of the potential trade-offs between these different DE material requirements.

- **Action 13: Involvement of materials science** — *A13(B11 & B12){4}*
  This action is part of *AG2* (Multi-disciplinary research), which is described above.

  - Difficulty not specified for this action.

Barrier 30: Heat dissipation around electrodes — *B30{9}*
Joule heating will occur in electrodes as DEG is charged and discharged. Interviewee highlighted that this may cause heat accumulation in DE material next to the electrodes and thermal ageing. This could affect the DE and potentially also the electrodes (for example, in cables, heat generation in the conductor causes thermal ageing in the surrounding

insulation). It was highlighted by the interviewee that, in general, plastics (such as DEs) have low heat conduction, which will increase heat accumulation.

- **Action 32: Thermally conductive DE fillers** — *A32(B30){9}*
  Interviewee highlighted that thermally conductive fillers could be added to the DE layer to reduce heat build-up. This filler would have to be an electrical insulator, for example ceramic fillers. It was noted that this is an area that has had limited research.

  - Difficulty not specified for this action.

Barrier 31: Lifetime of DEG and replacement — *B31{9}*
Interviewee highlighted that the lifetime of the DEG may be shorter than the WEC lifetime (based on the lifetime of common rubber components, e.g. gaskets). If large DEG sheets need to be replaced at sea this could present operational difficulties.
(It should be noted that Action 16 was not brought up in relation to Barrier 31 in the interviews, instead being highlighted as an action to address Barrier 13. However, as Action 16 is part of Action Group 3, it is presented below.)

- **Action Group 3: Investigation of modular DEG WEC design** — *AG3(A33(B31){9}, A16(B13){4}*)
  Two interviewees highlighted investigation into increased modularity of DEG WEC design as an action. It was highlighted by interviewee {4} that such an investigation could consider if it is feasible to break the DEG down into multiple DEG patches, or isolate the sections of a membrane (within a DEG stack) that have experienced E_{BD}. It was also highlighted by interviewee {9} that modular DEGs would be easier to replace at sea and would also help with manufacturing constraints around large-area DEs.

  The difficulty of addressing the individual actions that make up *AG3* are:

  - **Action 33: Increased modularity of DEGs** — *A33(B31){9}*
    Interviewee assessed this action as having a low difficulty (2). They highlighted that there is currently limited research into modular DEGs and that control systems would become more complex for modular DEGs. However, this was not considered a highly difficult action to carry out.
  - **Action 16: Promote the investigation of modular concepts** — *A16(B13){4}*
    Interviewee assessed this as moderate difficulty action (3). This interviewee believes there is a margin to think about different concepts for modularity. The interviewee highlighted that there may be some complications in implementing these, such as separate power electronics for separate DEG modules. (This action addresses *B13* (Trade-offs between modular and monolithic DEGs), which is covered in C3.1)

Other comments

Lifetime *{8}*
For fatigue testing, the interviewee noted that preliminary results have been obtained for electromechanical fatigue, but that significant work is still to be carried out. This especially depends on how the membrane will be deformed during the system's lifetime, as different types of deformation (e.g. multiaxial vs uniaxial) will affect the DEG's fatigue lifetime.

C1.2) Dielectric elastomer materials and design

Key barriers and actions

Barrier 4: Changes in DE material properties during electrotechnical fatigue cycles — *B4{2}*
Interviewee noted that there is a lack of knowledge of the effects of mechanical fatigue on DE material's permittivity and E_{BD} strength. Interviewee was aware of work that had been carried out under constant electric field, but not aware of many experiments including mechanical and electrical cycling.

- **Action 5: Modelling and fatigue testing of DE materials** — *A5(B4){2}*
  Action 5 is part of *AG1* (DEG fatigue life testing under relevant operating conditions), which is described in C1.1.

  - The difficulty of achieving Action 5 is covered in AG1.

Barrier 9: Electromechanical instabilities — *B9{3}*
Interviewee noted that increasing permittivity of DE material increases the Maxwell pressure between the electrodes [277]. If Maxwell pressure exceeds the compressive strength of the DE, an instability occurs. Interviewee highlighted that permittivity therefore increases the ease of electromechanical instabilities. This means there is a limit on the permittivity increase of DE materials. However, interviewee noted this is only valid for a DEG system where failure is driven by electrotechnical instabilities, rather than material defects.

- **Action 11: Actions addressing defects and volume effect** — *A11(B9){3}*
  Action 11 is covered under *AG4* (Development of suitable self-clearing electrodes) (Other comments on Action 11: Interviewee highlighted that the theoretical energy density of existing DE materials is already sufficiently high for wave energy applications (~1000 J/kg). However, in large DEG systems, energy density will be driven by defects unless work is done to address the volume effect. Interviewee sees this this to be more of a limiting factor than formulating new materials, especially considering the trade-off between electromechanical instabilities and permittivity.)

  - Same difficulty and justifications as *A10* (Development of suitable self-clearing electrodes), which is described in C1.4.

Barrier 21: DE materials must operate under specific set of conditions — *B21{6}*
Interviewee highlighted that DE materials need to have multiple characteristics such as survivability in a harsh ocean environment, good electrical and mechanical properties, long

fatigue life, as well as being scalable and being bondable with flexible electrodes. Interviewee highlighted that these required material parameters are very challenging to achieve all together, and that current DE materials have limitations. Interviewee sees silicones as best choice, but noted that the correct formulation and manufacturing process have not been found. It was highlighted that, at present, silicones are expensive, have limited dielectric strength, have limited elasticity, and that they harden under strain.

- **Action 24: Industry focus on increasing TRL of DE materials** — *A24(B21){6}*
  Interviewee recommended that companies working in silicone and printed electronics should be involved in demonstrating dielectric elastomers in relevant environments with industry-validated materials and manufacturing. This interviewee highlighted that industrial application of the materials is needed to ensure sufficient reliability.
    - Assessed as moderate difficulty (3), as interviewee highlights that all that is required is a return on investment for an industrial application. Interviewee believes that technology already exists that can increase the readiness of DEs.

Barrier 32: Creep in DE materials — *B32{9}*
Interviewee highlighted that it is difficult to find DE materials that have low creep properties (silicone, for example, experiences creep). It was highlighted that creep will change geometry of DEG WEC over time, which could cause issues working on the WEC hydrodynamics. For instance, an Anaconda (i.e. bulge-wave) type WEC will increase in tube diameter through creep.

- **Action 34: Fatigue testing** — *A34(B32){9}*
  This action is part of *AG1* (DEG fatigue life testing under relevant operating conditions), which is described in C1.1.
  (Interviewee noted that long-term fatigue testing is needed to determine how DE materials grow over a series of stretching cycles (see *AG1*). This interviewee highlighted that there is research using AI technology to predict the behaviour of elastomers under fatigue load, using a smaller number of data points.)
    - Same difficulty and justifications as *A31* (Combined fatigue testing), which is part of *AG1* (DEG fatigue life testing under relevant operating conditions). *AG1* is described in C1.1.

Barrier 33: DE filler selection — *B33{9}*
Interviewee noted that fillers can be very beneficial in DEs, but they need to be chosen carefully. It was noted that testing of nano-fillers is quite novel research, which has normally focused on basic tests in a dry environment. Hydrophilic fillers (such as silica) easily absorb water, which can create a conductive pathway within the DE, causing electrical breakdown at a lower electric field. Interviewee highlighted a knowledge gap about how well these fillers perform in a marine environment (DEG WEC conditions).

- **Action 35: DE filler treatment** — *A35(B33){9}*
  Interviewee noted that hydrophobic treating can be applied to the fillers, but this

would increase costs. Interviewee also noted that water absorption tests should be done to saturate DE materials with fillers before the E_{BD} is measured.

  - Assessed as moderate difficulty (3). Interviewee highlighted that, even using the same fillers, the results from different suppliers vary significantly. For this reason, selecting the filler and supplier is time-consuming.

Fatigue life of DEs — *{3}*
Noted as a barrier, which is covered under C1.1.

Inclusion of flaws in DEs — *{3}*
Noted as a barrier, which is covered under C1.4.

<u>Other comments</u>

Use of high permittivity fillers in DE — *{2}*
Interviewee notes that using high permittivity fillers in elastomers creates localised electric field concentrations. These reduce the overall E_{BD} of the composite, reducing the achievable energy density (this is discussed in Roscow et al. [278]).

DE materials and design — *{8}*
Interviewee believes a significant amount of work has been done by the research community on DEs. However, simple materials seem to be better for DEG applications than filled materials. Good materials known about at the moment are silicone elastomer and SBR rubber. Interviewee highlighted that SBR is generally handled by companies, not researchers, and therefore is less studied.

C1.3) Electrode materials and design

<u>Key barriers and actions</u>

Barrier Group 2: Stretchable electrodes with suitable material properties — *BG2 (B5{2}, B22{6})*
Interviewees {2} and {6} highlighted that development of stretchable electrodes with suitable material properties is a barrier to DEGs in wave energy applications. Interviewee {6} highlighted that these electrodes would need to be compliant, have similar mechanical properties to DE, be able to adhere to DE, have a low thickness, and have low resistance. It was noted by interviewee {2} that the solutions used in present DEG experiments have issues. For example, carbon grease is liable to flow or change properties. Interviewee {6} noted that silicone mixed with carbon black works as a flexible stretchable electrode, but has quite a high resistance, resulting in energy losses.

- **Action 6: Development of stretchable electrodes** *A6(B5){2}*
  Interviewee highlighted that electrodes need to be developed that are similar in terms of mechanical properties to the DE. Possible solutions noted were using a filler in an elastomer to make it conductive, or carbon nanotubes. This interviewee also

suggested that it could be investigated whether carbon grease may work at scale. However, interviewee stated that this was unlikely.

- Interviewee assessed this action as very low to low difficulty (1-2), as the electrode does not need to survive high electric fields (as in the DE), and other applications (such as wearable electronics) are also developing stretchable electrodes. Interviewee believes suitable stretchable electrodes can be achieved with a good composite material. It was noted, however, that complexities could exist in bonding of the electrodes to the DE.

- **Action 25: Industry focus on increasing TRL of electrodes** — *A25(B22){6}*
  Interviewee highlighted that this is similar to *A24* (Industry focus on increasing TRL of DE materials) under C1.2. Interviewee noted that a material is needed for the electrodes that is reliable and has been validated in relevant industrial application (like printed electronics).

  - Interviewee assessed this action as moderate difficulty (3) and very similar to the difficulty of *A24* (Industry focus on increasing TRL of DE materials). Interviewee indicated the only difference from *A24* is that the electrodes need to be conductive, be manufactured over the DE film, and be adhered to the DE film.

<u>Other comments</u>

Electrode materials — *{8}*
Interviewee's research group typically use carbon black in DEG experiments (as it is easy to use). As the system is operating at high voltage, the electrode resistance is normally not considered. However, interviewee noted that some failure in DEGs may be caused by the heating of carbon black. The higher resistance electrodes may heat the membrane and cause damage over time, which has not been investigated so far. The interviewee suggests that separate (or modular) electrodes would be a good way to proceed with electrode design. This interviewee's research group has tested separate electrodes in the laboratory, which the interviewee described as 'OK'. Interviewee considered that self-clearing electrodes would present an issue in DEGs, as they create a point of mechanical failure following clearing.

C1.4) Dielectric elastomer generator performance at scale

<u>Key barriers and actions</u>

Barrier Group 3: Defects in large-area DE membranes reducing performance — *BG3(B3{2}, B8{3})*
Two interviewees highlighted that, as a DE membrane is scaled up, there will be a higher probability of a defect creating a weak point in a DE material (also referred to as the 'volume effect') {2}{3}. These create points of electrical failure in large-scale DE's. This was noted by interviewee {2} as being especially important when the DEG is stretched to a high strain and has a large electric field applied to it. Interviewee {3} noted that, when testing DE

material samples that are a few mm in size, a high E_{BD} is observed which is sufficient for energy production (for silicone over 200 kV/mm). However, as the material is scaled up to hundreds of square metres, it is very hard to avoid contamination or air bubbles in the DE sample, significantly limiting the DEG's performance {3}. The interviewee believed that defect-free DEs cannot be achieved for systems composed of hundreds of square metres of DE, even if precautions are taken to reduce these defects {3}.

- **Action 3: Low defect DE materials** — *A3(B3){2}*
  Interviewee suggests that DEs should be produced with reduction of defect quantity and size. This interviewee highlighted that this route was taken in the capacitor market with conventional high-quality polymers.

  - Interviewee assessed this action as low to moderate difficulty (2-3). This interviewee considered low-defect DE materials a more sensible route than having an extremely modular DEG. The interviewee also noted that production of low-defect DE materials is an action for industry, but that industry needs to see that there is a market for these materials.

- **Action 4: Self-healing DE materials** — *A4(B3){2}*
  Interviewee highlighted that self-healing DEs could potentially be developed for DEGs. These could reduce the defects in a DE material.

  - Difficulty of action not specified.

- **Action Group 4: Development of suitable self-clearing electrodes** — *AG4(A10(B8){3}, A11(B9){3})*
  Interviewee {4} highlighted two actions around the development of self-clearing electrodes. The interviewee noted that a self-clearing electrode, which isolates an E_{BD} site, would allow the DEG system to survive even if there are several breakdowns during its lifetime. This also addressed another barrier (*B9* Electromechanical instabilities) discussed by the interviewee. (It should be noted that these self-clearing electrodes would need to have the same requirements as the stretchable electrodes mentioned in *BG2*, in addition to the self-clearing properties)

  The difficulty of addressing the individual actions that make up *AG4* are:

  - **Action 10: Development of suitable self-clearing electrodes** — *A10(B8){3}*
    Assessed as high difficulty (4). Interviewee noted that self-clearing electrodes exist in HV capacitor industry, however these are not stretchable electrodes. The same self-clearing electrodes will need to be developed, but with stretchable materials. Interviewee noted that silicone-based electrodes that are currently used in DEGs will not work for self-clearing electrodes, and therefore some other option will be required. Interviewee highlighted that metals work well for self-clearing as there is a sharp transition above the metal's melting point. However, these are not stretchable. Carbon nanotubes show self-clearing properties at lab scale, but in order to burn (clear) the carbon nanotube, oxygen is required. Interviewee stated that it is unclear

how or whether oxygen would be available in a multilayer DEG assembly. It was also highlighted that adhesion will be important if using different self-clearing electrodes (e.g. carbon nanotubes or graphene). If the DE and electrode layers are not properly bonded together, friction between the layers could spread the electrode and diminish the self-clearing properties.

- **Action 11: Actions addressing defects and volume effect —** *A11((B9){3})*
  Same difficulty and justifications as A10.

Other comments

High-performance DEs — *{2}*
Interviewee stated that using high permittivity fillers in elastomers creates localised electric field concentrations. This interviewee highlighted that this reduces the overall E_{BD} of the composite, therefore reducing the achievable energy density (this is covered in Roscow et al. [278]). Interviewee considered the use of composite DEs as very difficult (5). This interviewee described the use of composite DEs as 'sort of impossible'.

Performance at scale — *{8}*
Interviewee noted that, in theory, there is no decrease in performance as DEGs are upscaled to intermediate scale (up to 1m), which has been confirmed. However, upscaling DEGs to a large-scale system entails a problem with manufacturing. Therefore, performance at scale is strictly related to the manufacturing category.

C2) Manufacturing DEGs at scale

C2.1) Manufacturing dielectric elastomer films

Key barriers and actions

Barrier Group 4: Lack of large-scale manufacturing infrastructure for DEs and DEGs — *BG4(B14{4}, B26{8}, B23{6})*
Three interviewees {4}, {6} and {8} highlighted the lack of large-scale manufacturing infrastructure for DE films and full DEG assemblies. This limits the scale at which DEG WEC prototypes can be produced. It was highlighted by interviewees {4} and {8} that multiple-metre width DE films with a suitably low thickness (100-200 μm) are not commercially manufactured at present. Additionally, it was highlighted that moving to these large scales introduces a higher possibility of flaws or inclusions in DE membranes {4}{8}, meaning additional quality control processes will need to be put in place {8}. Interviewees {8} and {6} noted that they believe existing industrial manufacturing processes can be upscaled for this application (such as printed electrodes {6}). However, it was highlighted that this upscaling would require very specific manufacturing investment, as there is currently no other market for these large-scale DE or DEG membranes {8}{6}. For this reason, interviewee {6} highlighted that a business case for large-scale DE membranes will be needed to enable these investments.

- **Action 17: Study existing industrial processes for polymer manufacturing** — *A17(B14){4}*
  Interviewee noted that the available manufacturing processes, such as those used in the rubber and plastic manufacturing sectors, should be investigated (for example, a 'landscaping' study). This would identify the limitations of existing manufacturing processes for DEG WEC applications.

  - Interviewee assessed this as a moderate difficulty action (3), as they considered it a matter of identifying and speaking to the right companies.

- **Action 28: Economic and environmental study on silicone for large-scale DEG manufacturing** — *A28(B26){8}*
  Interviewee noted that a study should be carried out to understand if silicone elastomer-based DEGs may enable cost effective and sustainable wave energy converters. In such a study, the price of the manufacturing infrastructure could be included as a variable to estimate the maximum manufacturing infrastructure costs that are allowable for a cost effective DEG WEC. Interviewee suggested that this study could be based on the size of the potential future DEG WEC market.

  - Interviewee assessed this as a moderate difficulty action (3). They highlighted that this action can be achieved by gathering the right partners, especially companies that are experts in the area of silicone manufacturing. The interviewee considered this as the most important action, as it allows other large-scale testing, that require large-scale DE membranes, to go ahead (e.g. lifetime tests and large-scale prototyping).

- **Action 26: Business model for DEG manufacturing** — *A26(B23){6}*
  Interviewee highlighted the need to develop a business model for large-scale DEG applications to incentivise industry to work on the development of the manufacturing process. It was highlighted that, for industry to invest in scaling up production processes for such a specific application, sufficient demand needs to be expected.

  - Assessed as low difficulty (2). Interviewee noted that more complex technologies are being produced than multilayer DE and electrodes. However, multilayer DE and electrode manufacturing has to be done at large-scale. Once demand can be demonstrated, existing processes such as deposition (e.g. printing) can be scaled up.

Barrier 27: DE material selection — *B27{8}*
Interviewee highlighted that silicone is a candidate material for DEG wave energy converters but that it is expensive, especially commercially available thin membranes. It was noted that another elastomer, SBR, has good mechanical and electrical properties, but that it is not normally used in academic research and would require a different manufacturing process to silicone.

- **Action 29: Assessment of SBR and silicone for DEG WEC** — *A29(B27){8}*
  The interviewee recommended that an investigation into cheaper formulation of silicon elastomer, specifically designed for DEG WEC applications, should be carried out. It was also noted that the manufacturing cost of silicone membranes is currently very high. Involvement of industrial partners (such as WACKER) would improve the understating of economies of scale that could be expected through mass production. The other option noted by the interviewee is switching to a different type of DE material such as SBR, which has good mechanical and electrical properties. However, SBR is not commonly used in academic research and will require a different manufacturing process from silicone membranes. Collaboration with SBR experts is required to assess its viability.

  - Difficulty not assessed for this action.

<u>Other comments</u>

Manufacturing process for silicone DE — *{3}*
Interviewee highlighted that a suitable manufacturing process for silicone DE sheets has been developed (for rolls of DE). However, the costs of manufactured silicone are still an issue.

The following difficulty evaluation was not allocated to a specific barrier or action:

  - **Manufacturing of large DE membranes, in general** — *{4}*
    Interviewee noted that, if the target is metre-scale DE membranes, the actions required to address this would be difficult to very difficult (4-5). This interviewee highlighted that there could be limitations in how the manufacturing processes work, for instance if you want to calendar or roll membranes, it will be difficult to ensure sufficiently precise alignment over the length of multiple metres.

C2.2) Manufacturing electrodes and electrode connections

<u>Other comments</u>

Electrode manufacturing — *{8}*
Interviewee highlighted that work has shown electrodes can be spray-coated successfully. This interviewee noted that spray-coating is a simple process, and it is also scalable for very large membranes.

C2.3) Dielectric elastomer generator module fabrication and joining

<u>Key barriers and actions</u>

Barrier 10: Joining of silicone DE — *B10{3}*
Interviewee highlighted that adhesion to silicone DE is difficult under the type of fatigue cycles found in WEC applications. This could result in failure between modules (module-to-

module joining), within modules (electrode-to-DE joining), or between the DEG and waterproof encapsulation. It was noted that a good static adhesion can be achieved. However, it is difficult to avoid de-lamination over thousands or millions of fatigue cycles. This means that, while a DE material may survive high cycles of mechanical fatigue during lab tests, in a DEG WEC application, the joins are the weak points. Therefore, the system has to be designed around these rather than the base silicone material.

- **Action 12: Improved understanding of chemical processes for silicone adhesion** — *A12(B10){3}*
  Interviewee highlighted that chemical experts are required to work on the chemical processes for silicone adhesion. If better adhesion processes cannot be found or developed, the DEG system may need to be designed around the mechanical fatigue life of the current joins.
    - Interviewee could not evaluate the difficulty, as this is not their area of expertise.

Other comments

Module fabrication and joining — *{8}*
Interviewee noted that module fabrication and joining can be done. Their research group has performed small-scale experiments, which require verification of fatigue life. This interviewee noted that further work is required in this area.

C2.4) Cost of dielectric elastomer generator manufacturing

Other comments

Cost of manufacturing — *{8}*
Interviewee sees this as a significant problem and one of the major aspects that should be considered to understand whether the technology is viable.

C2.5) Other manufacturing barriers

Key barriers and actions

B23{6} **Scaling DEG manufacturing process**
This is part of *BG4* (Lack of large-scale manufacturing infrastructure for DEs and DEGs), which is presented in C2.1.

- *A26(B23){6}* **Business model for DEG manufacturing**
  This is covered under *BG4.*

Other comments

Sustainable business model for DEG WEC — *{6}*
Interviewee highlighted that the business model for DEG WECs needs to consider the region's laws and regulation in developing the technology. Also, as it is unlikely that a DEG will last for an entire WEC lifetime without service, so the DEG WEC's lifecycle (such as servicing or replacement of DEG modules) also needs to be considered. Interviewee highlighted that if the right parameters are not being considered in the business model, technologies that are more economically sustainable will win out over more environmentally sustainable ones. Technologies that already exist with established supply chains will be more competitive (economically) compared to an emerging technology. For this reason, the right business model for DEG WECs will measure the advantages of the technology both in terms of economics and environmental impact.

Manufacturing (in general) — *{8}*
Interviewee sees this as a significant problem, mostly due to the investment required, rather than from a technical point of view.

C3) System integration barriers for DEG WECs

C3.1) Design and modelling of dielectric elastomer generator WECs

Key barriers and actions

Barrier 1: Design of a WEC to utilise DEGs — *B1{1}* Interviewee highlighted that, at present, it is not necessarily known what the best geometry or configuration is to utilise DEGs in a wave energy converter. Interviewee does not believe that the best use of DEGs for wave energy converters has been considered, as much of the R&D has focused on replacing conventional PTO systems with DEGs. This interviewee highlighted that conventional PTO replacement may be attempting to evaluate DEGs under a paradigm that may not be appropriate. Interviewee believes this gives a false representation of the potential of DEGs in wave energy applications.

- **Action 1: DEG WEC design from foundational principles without bias** — *A1(B1){1}* Interviewee noted that an evaluation of the potential of DEG-based wave energy converters should be carried out, without being influenced by the wave energy conversion community or current wave energy conversion thought processes. This will lead to a more honest evaluation of DEGs on their own, rather than as a replacement for conventional WECs.
    - Interviewee assessed this as a very high difficulty barrier (5). This interviewee highlighted that, based on how other domains of technologies have evolved, it requires significant amounts of time until mainstream acceptance of a technology is achieved. Interviewee anticipates it will take a significant amount of time just to get buy-in to consider the use of DEGs in wave energy conversion. This interviewee attributed this lack of acceptance to (1) DEG

WECs falling under the umbrella of utility-scale wave energy conversion; and (2) more specifically, WEC designers or developers have their own ideas about the best WEC design, which typically are not based on DEGs. Interviewee highlighted that this means there are a low number of developers already interested in DEGs, making DEGs an 'underdog out of the gate' compared to other kinds of energy conversion.

Barrier 2: Design of power electronics — *B2{1}*
DEGs require a pre-charge to generate electricity. Interviewee highlighted that this adds a layer of complexity compared to a conventional generator where the power is flowing from the generator to the grid. They considered that the question of whether this is a large barrier or not, is largely dependent on WEC design. This interviewee highlighted that if there is redundancy through distributed modular DEGs throughout WEC, the reliability of the power electronics may be less important.

- **Action 2: WEC design for power electronics** — *A2(B2){1}*
  Interviewee highlighted that design for DEG WECs power electronics needs to consider the connection to utility grid, as this will be the probable source of pre-charge. Another area for consideration raised by this interviewee was having a level of redundancy or contingency built into power electronics.

    - Interviewee assessed this as a low to moderate difficulty action (2-3). This interviewee states this is as an obstacle, but not based on a paradigm change in the same way that is needed to design the WEC (in general) for DEGs. This interviewee considers it very likely the know-how to design power electronics already exists in other electrical engineering sectors.

Barrier 13: Trade-offs between modular and monolithic DEGs — *B13{4}*
Interviewee highlighted that it is not clear if it is better to have a DEG PTO consisting of large units or many smaller ones. Interviewee noted that the selection of smaller versus large-scale DEG modules has effects on the capital cost, deployment method, and the response of the DEG WEC.

- **Action 16: Promote the investigation of modular concepts —** A16 *(B13){4}*
  Action 16 is part of *AG3* (*Investigation of modular DEG WEC design)* which is described in C1.1.

    - This is covered under *AG3.*

Barrier 17: Electrical insulation of DEG — *B17{5}*
Interviewee highlighted that electrical insulation of the DEG is an issue for the testing of WECs with a submerged DEG. In an ocean environment, there are safety concerns. For test basin trials, the issue is possible damage to instrumentation and also the safety of people working on basin tests.

- **Action 20: Development of generic DEG insulation solutions** — *A20(B17){5}*
  Interviewee highlighted that development of a generic insulation design would give

additional confidence when testing DEGs (e.g. in wave basins). This interviewee also highlighted that the solution of encapsulating DEG developed by SBM should be investigated to see if it is design-specific or could be applied to DEGs more generally.

- Interviewee assessed this as a moderate difficulty action (3). It was noted that SBM have already come up with a solution for their device and that it should not be very difficult to develop solutions specific to different WEC designs.

Barrier 18: Scaling DEG for lab scale tests — *B18{5}*
Interviewee highlighted that for lab-scale DEGs, very thin sheets of DE are required, and sourcing these DE sheets can be a problem.

- **Action 21: More research on DE scaling and material testing** — *A21(B18){5}*
  Interviewee suggested that more work needs to be done on the scaling and material testing of DEs. This includes establishing what manufacturing processes work for full-scale and model-scale DEG WECs.

  - Interviewee could not confidently evaluate the difficulty of this action.

Barrier 19: Attachment of DEG to WEC structure — *B19{5}*
DEG may need to be connected to a rigid or semi-rigid WEC structure, while maintaining pre-stretch. Interviewee highlighted that for the DEG WEC that they are studying, there are multiple rigid-to-flexible joints, where a flexible material (e.g. the DEG) is connected to a rigid structural component. This joint needs to transfer stretch to the DEG, while being waterproof. Additionally, the joint will determine the WEC's dynamics. At present, it is unclear what the best joining option is (for instance, clamping or gluing).

- **Action 22: More research on flexible DEG attachment** — *A22(B19){5}*
  Interviewee highlighted that further research should be carried out into flexible polymer attachment between DEG and rigid parts of WEC.

  - Interviewee assessed this as a very low difficulty action (1). Interviewee thought it probable that a solution already exists.

Barrier 20: Development of numerical model — *B20{5}*
Interviewee highlighted that it is difficult to model the hydrodynamic response of flexible WEC structures, especially for submerged membranes. The interviewee expects additional difficulty coupling this with electro-elastic response of the DEG. Also, the interviewee noted that there is a lack of experimental data which can be used to validate DEG WEC hydrodynamic models.

- **Action 23: Development of numerical model and experimental data sets** — *A23(B20){5}*
  Interviewee highlighted that an option is to carry out more experiments which can be used to validate DEG WEC numerical models. This data should be made available to researchers, to help further the development of numerical models.

- Interviewee assessed this as a high to very high difficulty action (4-5), as the modelling requires multiple coupling solutions. However, this interviewee noted that Flex WEC software from Wave Venture Ltd. is in development to model the hydrodynamic response.

Other comments

Design and modelling of DEG-based WEC — *{8}*
Interviewee believes that the tools to do this are already available.

Power electronics — *{8}*
Interviewee believes this can be done. However, it needs to be determined whether this is economically viable. This interviewee noted that the components to develop power converters are not a concern. The interviewee also highlighted that there is the possibility of using two power converters — one for the charging of the DEG, which requires a high current for a very short time; and then another for harvesting, which manages lower values of current. Interviewee highlighted that separating the two may be beneficial as a solution.

Multiple topologies — *{5}*
The interviewee noted that this is not a key barrier; therefore, it has been excluded from remainder of this document.

C3.2) Self-sensing and control

Key barriers and actions

Barrier group 5: Self-sensing of DEG capacitance (for deformation estimation and health monitoring) — *BG5(B6{2}, B15{4})*
Two interviewees {2} and {4} noted that the lack of DEG capacitance self-sensing is a barrier to DEG WECs, with only a small amount of preliminary work carried out to date {4}. Both interviewees highlighted that being able to self-sense DEG capacitance would allow the implementation of more advanced controls to maximise conversion efficiency {4}{2}. Additionally, interviewee {2} noted that capacitance self-sensing may allow degradation of the DE to be monitored.

- **Action Group 5: Development of DEG capacitance self-sensing** — *AG5(A7(B6){2}, A18(B15){4})*
  Two interviewees highlighted that DEG capacitance self-sensing should be developed to enable better estimation of DEG deformation and health monitoring. It was noted that capacitance self-sensing is already applied in DE actuators {2}. It was also highlighted that self-sensing could be investigated systematically in an application more relevant to wave energy {4} (For instance, real-time self-sensing using DEG topologies and deformation profiles that are more relevant to wave energy {4}).

  The difficulty of addressing the individual actions that make up *AG5* are:

- **Action 7: Capacitance measurement** — *A7(B6){2}*
  Interviewee assessed this action as very low to low difficulty (1-2), as this interviewee considered measuring capacitance not to be fundamentally difficult. Capacitance can then be used to estimate deformation if calibrated against a model. This interviewee also highlighted that capacitance changes are already monitored for breakdown monitoring in piezoelectrics and deformation estimation for DEAs.

- **Action 18: Investigation of self-sensing for WECs** — *A18(B15){4}*
  Interviewee assessed action as low difficulty (2), as they did not envisage any principal obstacles to achieve DEG self-sensing.

Barrier 16: DEG control strategies — *B16{4}*
Interviewee highlighted that most control strategies used in prototype DEGs are based on simple heuristics (for example, constant voltage), which are not optimal. The use of more optimal control strategies could increase the DEG performance, or increase lifetime by limiting the maximal or average electric field for the same energy output. Additionally, the condition of the DE may be monitored through sensing and control. This interviewee noted that better estimation of the DEG dynamics is required to implement more optimised control strategies, which necessitate self-sensing (see *AG5* Development of DEG capacitance self-sensing, which is presented above).

- **Action 19: Experimental testing of advanced controls** — *A19(B16){4}*
  Interviewee highlighted that many people are working on control strategies (a few on DEG-specific control), but there has been little work on experimental setups. Interviewee highlighted that these control strategies should first be tested in dry-run and hardware-in-the loop setups before transitioning to small-scale wave tank tests.

    - Interviewee assessed action as moderate difficulty (3). This interviewee highlighted that it may be difficult to bring control strategies into real systems while preserving all the conditions that make them optimal on paper.

<u>**Other comments**</u>

Self-sensing — *{8}*
Interviewee noted that this can be done and is feasible to use with control systems. This interviewee highlighted that the complicated aspects of control apply to wave energy converters in general, such as predicting the incoming waves.

C4) Environmental impacts of DEG in WEC application

C4.1) Recyclability of dielectric elastomer generator modules

Other comments

Recyclability of silicone — *{3}*
Interviewee highlighted that recyclability of silicone, including the whole DEG module, should be feasible, mentioning a company that carries out silicone recycling (Eco USA recycling).

Recyclability — *{8}*
Interviewee highlighted the need to understand recyclability of membranes as this will feed into an evaluation of the cost of the system.

C4.2) Degradation of dielectric elastomer generator in marine environment

Other comments

Degradation in the marine environment — *{8}*
Interviewee noted that degradation of DEGs in the marine environment has to be studied. This interviewee highlighted that, to date, the results that have been considered are for the degradation of standard rubber components in water, and are not strictly related to DEs. A major problem seen by the interviewee is the intake of water by the DE membrane. For short-term behaviour (weeks), this interviewee did not consider immersion in water as a problem, but long-term water immersion has to be investigated and studied.

C4.3) Electric shock risk

Other comments

Electric shock risk — *{8}*
Interviewee noted that, for the scale of DEGs the interviewee has worked on so far, with the power of a few watts, little energy is stored. Considering a full system, with a considerable amount of energy harvested, electric shock risk is a consideration that should be investigated.

C5) Other barriers

Key barriers and actions

Barrier 25: Lack of complete DEG WEC study — *B25{7}*
Interviewee highlighted that, to date, no studies have taken a DEG from material synthesis to power generation. This means that, currently, developments at one stage are not feeding though to subsequent stages. Interviewee highlighted that it cannot be determined if new DE materials or electrodes are suitable for a WEC device without testing in the right

conditions. To determine these test conditions and develop suitable test rigs for the DE materials and electrodes, the parameters of a device's operation (such as expected magnitude and direction of stretch, electric field) are required.

- **Action 27: Multi-disciplinary research** — *A27(B24 & B25){7}*
  This action is part of AG2 (Multi-disciplinary research) which is described in C1.1.

    - This is covered under *AG2.*

Other comments

Cost of DEG WECs: Non-DEG structural costs — *{8}*
Interviewee highlighted that a significant contribution in the cost of the DEG WEC system which they previously worked on was the non-DEG structure. This interviewee suggested that, when performing a study on DEG WEC cost effectiveness, low-cost structural materials should be considered, such as those in the WES competition for materials [279]. This interviewee noted that interesting options may be plastic-based structures. If alternative low-cost structural materials are not used, the price of steel and the price of concrete will play a significant role in the cost effectiveness of the entire system.

Cost of DEG WECs: Lifetime of DEG and replacements — *{8}*
Interviewee highlighted that work should be done to determine if the possible limits in lifetime of the DEG may be addressed by considering maintenance every five years to replace just the membrane. This scenario could be considered instead of having the DEG survive for the entire 20 years.

Cost of DEG WECs: WEC scale for DEGs — *{8}*
Interviewee noted that wave energy companies generally consider very large systems leading to very large DEG membranes. This is problematic for dielectric elastomer scaling-up (as in C1.4). Interviewee suggested a possible route for consideration is multiple smaller-sized WEC systems, which may be easier to realise from the point of view of the DEG. However, it was noted that, as the membrane size decreases, the rigidity increases, making it more difficult to put the system in resonance. For this reason, other types of converters like dielectric fluids systems are being investigated. This interviewee highlighted that, even if very small-scale DEG WECs do not work, an intermediate scale may be a good approach.

8.2.3 Prioritisation of barriers

The final question given to the interviewees was the priority that they would propose for addressing the various barriers to DEG WEC development. Some interviewees gave a single priority barrier, while others provided a highest priority and then secondary priority barrier or barriers. For this reason, this section is split into a list of highest priority barriers to be addressed, followed by secondary priority barriers. It should be noted that interviewee {6} was accidentally asked to list priority actions, rather than prioritise the order in which barriers should be addressed.

Highest priority barriers

Innovative strategies for DEG WECs — *{1}*
Interviewee considered the lack of innovative strategies to use DEGs for wave energy conversion as the highest priority barrier. This interviewee highlighted the need to develop conceptualization and innovation techniques, and the necessary mindset and culture to develop wave energy converters that are specifically based on DEGs.

DEG reliability at scale — *{2}*
Interviewee considered DEG reliability at scale as the highest priority barrier. This interviewee highlighted that being able to model the statistical distribution of DE failure with relation to the scale of DE materials would be very beneficial.

Volume effect — *{3}*
Interviewee considered the volume effect (reduction in DEG performance at scale) to be the highest priority barrier. This is because the volume effect presents a trade-off between having a large system (for large-scale electricity generation) and achieving a high energy density due to the volume effect (due to reductions in E_{BD} and mechanical fatigue life at scale). Interviewee stated that, if the volume effect is not solved, the technology (DEGs) cannot be competitive with other forms of electricity generation.

DE materials and design — *{4}*
Interviewee considered DE materials and design to be the highest priority barrier. Addressing this would consist of seeing how much the DE material properties can be improved, while also considering appropriate electrodes. Interviewee considered that, currently, lifetime is the biggest question for DEGs. However, this interviewee highlighted that, to study lifetime, the materials need to be identified that will actually be used in a DEG WEC. They noted that the same applies to the manufacturing processes of the DEG. For this reason, they proposed DE materials development as the highest priority barrier to be addressed.

DEG Manufacturing — *{5}*
Interviewee considered manufacturing to be the highest priority barrier. This interviewee highlighted that, even if the WEC is theoretically plausible, there is a need to know if it is practically possible, otherwise there is no point in developing the technology. For this reason, the interviewee considered manufacturing as the first barrier that should be addressed.

DEG competitive advantage[31] — *{6}*
Interviewee considered measurement of DEG’s competitive advantage in comparison with other technologies to be the highest priority action.

[31] Interviewee {6} was mistakenly asked to list priority actions. This is different to the question put to the other interviewees, who were asked which barriers they would prioritise addressing.

Lack of fatigue life data — *{7}*
Interview considered the highest priority barrier to be the lack of experimental data for the fatigue life of the best available DE materials and electrodes, as identified by DEG community. This interviewee highlighted that data is needed for combined multiaxial mechanical fatigue, electrical fatigue and environmental degradation. The interviewee also highlighted that it is a priority to make this data available to the community, so it can be used to predict performance of new devices.

Upscaling DEG manufacturing[32] — *{8}*
Interviewee considered the upscaling of DEG manufacturing as a high priority barrier, as this has been a limitation in all of their work on DEG WEC developments. They highlighted that, if this barrier were addressed, it would allow them to respond to many more project funding calls with DEG WEC projects. The interviewee also highlighted that a manufacturing process that is open to multiple developers would be beneficial, as this would allow different developers to progress their DEG WEC technologies, rather than just one company to develop one technology.

DEG verification in realistic conditions[32] — *{8}*
Interviewee considered verification of performance, degradation and lifetime of the DEG in realistic conditions as a high priority barrier. This interviewee highlighted that addressing this would consist of a preliminary study at small scale, followed by testing at large-scale.

Investigation of alternative DEG materials[32] — *{8}*
Interviewee considered the investigation of alternative materials for the DEG as another priority barrier to be addressed. This would include carrying out further study in collaboration with industry, including the use of SBR for DEGs.

DEG performance and manufacturing — *{9}*
Interviewee considered DEG performance and manufacturing as the priority barriers to be addressed. This interviewee highlighted that the power electronics, WEC design, and modelling must be based on the DEG performance and manufacturing. Within performance, the interviewee considered the highest priority barrier to be combined fatigue testing, especially emphasising electrical fatigue under changing thickness membranes.

Secondary priority barriers

Outreach activities — *{1}*
Interviewee considered the second highest priority barrier to be outreach to promote the technology (DEGs) and its potential application in wave energy conversion. The interviewee highlighted that this could help accelerate the use of DEGs in wave energy applications by leveraging existing experience in other technology areas, such as soft robotics and material science.

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[32] Interviewee {8} did not give an explicit prioritisation between these different barriers, and therefore all these barriers have been listed as highest priority.

DEG electromechanical fatigue life — *{3}*
Interviewee considered the second highest priority barrier to be understanding the combined electromechanical lifetime of DEGs, as there has been limited investigation in this area.

Fatigue life of DEG — *{4}*
Interviewee stated that, following selection of DE material and electrode, the second priority barrier is addressing the lifetime of the whole DEG assembly. Following this, the interviewee highlighted that the next priority barrier would be the manufacturing process for the whole DEG, both DE and electrodes together.

{5} Interviewee emphasised that, after manufacturing is addressed, the other barrier categories — performance, system integration, and environment — can be addressed in parallel.

Manufacturing process31 — *{6}*
Interviewee considered the second highest priority action was working on the manufacturing process, as this will help select the right materials for both the electrodes and the DE.

Large-scale fatigue testing — *{7}*
Interviewee considered that the second highest priority barrier to be addressed was fatigue tests at device scale on the best available DE materials and electrodes, to validate their lab-scale performance. This interviewee highlighted that this data should be made available to the community so it can be used to predict performance of new devices.

8.3 Discussion of Part C

The discussion starts with Section 8.3.1, which discusses the key results from Part C and compares these to the existing literature. Section 8.3.2 then discusses the implications that can be drawn from Part C regarding the future development strategy for DEG WEC technology. Finally, Section 8.3.3 outlines the limitations of the work in Part C, and recommendations are made for future work that could build on this research.

8.3.1 Key findings from Part C

Over the course of nine expert interviews, 33 barriers were identified to the development of DEGs for wave energy applications.

Of these 33 barriers, the most commonly cited were barriers related to the lifetime of a DEG in WEC operating conditions (8 barriers), the design and modelling of a DEG-based WEC (7 barriers), and the dielectric elastomer materials and design (5 barriers). Some barriers were also identified by multiple experts. These were collected in Barrier Groups, which are listed below:

i. Lack of representative fatigue life data for DEGs (5 barriers)

ii. Stretchable electrodes with suitable material properties (2 barriers)
iii. Defects in large-area DE membranes reducing performance (2 barriers)
iv. Lack of large-scale manufacturing infrastructure for DEs and DEGs (3 barriers)
v. Self-sensing of DEG capacitance (2 barriers)

These barrier groups highlighted that there are some areas of consensus between experts about the key barriers to DEG WEC development. The prime example of this was the lack of representative fatigue data for DEGs, which was identified as a key barrier by over half of the experts that were interviewed. It should also be noted that all the barrier groups were also identified in the literature review.

The key barriers that were only identified by one expert may need to be treated with a little more caution. Most of these barriers were also (at least partially) highlighted in the literature review, which does support their importance. This does indicate that there is at least a level of consensus around these barriers being key to DEG WEC development.

Finally, there is a subset of the barriers that were identified by only one expert that were not highlighted in the literature review. These were: *B9* Electromechanical instabilities; *B32* Creep in DE materials; *B18* Scaling DEG for lab-scale tests; *B19* Attachment of DEG to WEC structure; and *B25* Lack of complete DEG WEC study[33]. These barriers should possibly be treated as more preliminary in nature, given that they were only mentioned by one expert and were not explicitly covered in the literature review.

To address these barriers, 35 actions were identified by the experts over the course of the interviews. As with the barriers, some actions were identified by multiple experts. These actions were collected into Action Groups, which are listed below:

i. DEG fatigue life testing under relevant operating conditions (6 actions)
ii. Multi-disciplinary research (2 actions)
iii. Investigation of modular DEG WEC design (2 actions)
iv. Development of suitable self-clearing electrodes (2 actions[34])
v. Development of DEG capacitance self-sensing (2 actions)

These action groupings identified some areas where a level of consensus exists for the development of DEG WECs (with the possible exception of self-clearing electrodes, where the experts had diverging opinions). In particular, carrying out DEG fatigue testing under relevant operating conditions was identified by five experts as an action to be undertaken, which could address six of the barriers to DEG WEC development.

[33] It should be noted that the lack of a complete DEG study, while only mentioned explicitly by one expert, had very similar themes around the importance of coordination between different disciplines that was mentioned by several experts.
[34] It should be noted that both of these actions were identified by the same expert.

The actions only identified by one interviewee may highlight areas with less consensus around what is required to overcome a specific barrier. Some form of additional verification of these actions may be beneficial, as described above for the individual barriers.

There is also the case of contradictory actions suggested by different experts to address the same barrier. For example, to address the third barrier group (defects in large area DE membranes reducing performance), three actions were recommended: reduction of defect quantity and size in DE material; the development of suitable self-clearing electrodes; and (potentially) developing self-healing DE materials. There was a level of disagreement between the experts on the practicability of each other's suggested actions, with one expert {3} suggesting that sufficiently low-defect polymers were not achievable for DEG WEC applications, and another expert {8} suggesting that self-clearing electrodes would be problematic in DEG WEC applications. This again highlights that these actions may be seen as more preliminary, and a consensus view may not exist in the sector on which action(s) are most appropriate to take.

Regarding the difficulty of carrying out the actions, these were evaluated by the experts on a scale of 1-5, where the corresponding difficulty is: (1) very low, (2) low, (3) moderate, (4) high, (5) very high. In general, the experts assessed actions where minimal adaption of existing solutions was required as low difficulty (1-2). These included: the development of flexible joins for the DEG to WEC structure; development of flexible electrodes (although it should be noted that the development of self-clearing flexible electrodes was considered high difficulty); carrying out multidisciplinary DEG research; developing a business model for DEG manufacturing; and DEG capacitance self-sensing. The highest difficulty actions (4-5) were those that were highly specific to DEG WEC applications, with little perceived research that is transferable. These included: the synthesis of new DE materials for DEG WECs; the development of self-clearing flexible electrodes; the design of wave energy converters specifically for DEG applications; and the development of modelling tools and experimental data sets for DEG WECs. Finally, there were other actions that fell between the lower and higher difficulty ratings (2-4). These were either actions that were rated as moderate difficulty by an individual expert, or, in the case of action groups, where a large range of difficulties were given by the different experts. For example, the first action group (DEG fatigue life testing under relevant operating conditions) was considered low to moderate difficulty (2-3) by one expert, moderate difficulty (3) by two experts, and high difficulty (4) by two experts. This highlights that there may not be consensus between experts on the difficulty of achieving certain actions. Additionally, this may highlight the ambiguity inherent in using a qualitative scale to assess the difficulty of an action.

The final interview question given to the experts, was if a prioritisation could be suggested in which the barriers to DEG WEC development should be addressed. Some experts presented both highest and secondary priority barriers, while others only presented highest priority barriers. The most commonly cited highest priority barrier related to lack of data around DEG fatigue life, which was identified by three experts. Two experts highlighted that the reduction of DEG performance at large-scale was a highest priority barrier. Two experts highlighted manufacturability of DEGs at large-scale as a highest priority barrier. Two experts also highlighted the identification of suitable DEG materials as a highest priority barrier. This prioritisation again highlighted that there are some areas of consensus, and other areas where less consensus exists. For example, four of the experts highlighted fatigue testing as either a highest priority or secondary priority barrier. However, one of the experts suggested that materials development and selection was higher priority than fatigue testing, to ensure that the most appropriate DEG materials were subsequently fatigue tested. This highlights that, while there is a subset of barriers that seems to be considered higher priority, there is some uncertainty about the exact order in which they should be addressed.

An overall theme of the barrier and action assessment for DEGs was the diverse range of barriers to DEG WEC development and the actions required to overcome them. It was highlighted in several interviews that this makes DEG WEC development highly multidisciplinary in nature. Trade-offs exist in multiple areas of DEG WEC development. For instance, trade-offs exist between different DEG material properties, the design of the DEG as monolithic or modular, and DEG WEC scale and performance. To address these trade-offs, DEG WEC development will require expertise encompassing materials science, electronics, experimental design, wave energy converter design and modelling, polymer manufacturing, and environmental impact. Additionally, close collaboration will be needed between research organisations and industry to scale DEG WECs and evaluate their economic viability. This is because, as highlighted in the interviews, the manufacturing infrastructure does not currently exist for the large-scale DEGs that are needed to progress DEG WEC technology to larger-scale prototype testing and eventually full-scale devices (unless extremely modular DEGs are used). Additionally, the current cost is extremely high for DE sheets that are suitable for DEG applications. These DE sheets are currently produced in low volumes and at a small scale. It was highlighted in the interviews that industry collaboration will be required to evaluate how these costs may fall when the volume and scale of DEG manufacturing is increased, which is essential to understand the potential cost competitiveness of the technology.

A final theme from the interviews was that significant uncertainty still exists in several areas of DEG WEC development. These include the lifetime of DEGs in wave energy applications, the performance of DEGs at large-scale, and the cost of large-scale DEGs in high volume manufacturing. Additionally, environmental impacts of DEGs for wave energy applications have seen relatively limited investigation in the literature. Uncertainty in these key areas highlights that, at present, it may be difficult to confidently evaluate whether DEGs are a viable technology for application in economically, and environmentally, viable wave energy devices.

Comparison with previous work

The barriers identified during the semi-structured interviews can be compared with the literature that was reviewed in Chapter 7. As already highlighted, the experts agreed that the barrier categories taken from the literature review (see Table 7-1, p.171) captured the key barriers to DEG-based wave energy converters, with only one expert suggesting that an additional barrier category should be added. In general, there was strong agreement with the literature review, with the majority of barriers identified by the experts also (at least partially) covered by the literature review. This is shown in Table 8-5.

Table 8-5. The key DEG WEC barriers identified by the experts compared to the literature review.

Barrier name	Covered in literature review
BG1 (B7, B11, B24, B28, B29) **Lack of representative fatigue life data for DEGs**	Yes
B12 **DE material property trade-offs**	Yes (partially)
B30 **Heat dissipation around electrodes**	Yes
B31 **Lifetime of DEG and replacement**	Yes (partially)
B4 **Changes in DE material properties during electromechanical fatigue cycles**	Yes (partially)
B9 **Electromechanical instabilities**	No (regarding the impact of DE permittivity on instabilities)
B21 **DE materials need to operate under a specific set of conditions**	Yes
B32 **Creep in DE materials**	No
B33 **DE filler selection**	Yes (partially)
BG2 (B5, B22) **Stretchable electrodes with suitable material properties**	Yes
BG3 (B3, B8) **Defects in large-area DE membranes reducing performance**	Yes
BG4 (B14, B26, B23) **Lack of large-scale manufacturing infrastructure for DEs and DEGs**	Yes
B27 **DE material selection**	Yes (partially)
B10 **Joining of silicone DE**	Yes (partially)
B1 **Design of a WEC to utilise DEGs**	Yes (partially)
B2 **Design of power electronics**	Yes
B13 **Trade-offs between modular and monolithic DEGs**	Yes (partially)
B17 **Electrical insulation of DEG**	Yes (partially)
B18 **Scaling DEG for lab-scale tests**	No
B19 **Attachment of DEG to WEC structure**	No
B20 **Development of numerical model**	Yes
BG5 (B6, B15) **Self-sensing of DEG capacitance (for deformation estimation and health monitoring)**	Yes
B16 **DEG control strategies**	Yes
B25 **Lack of complete DEG WEC study**	No

The semi-structured interviews also added additional detail around some of the barriers that was not present in the literature review. For instance, while the importance of DE joining was highlighted in the literature by Moretti et al. [262], more detail was presented in the interviews about how this joining may cause failure within a DEG WEC —between DE and electrode, between DEG modules, and between DEG and encapsulation. Some barriers were also added that were not present in the literature review, for instance B9 highlighted that increasing the permittivity of the DE will also increase the ease of DEG failure through pull-in instabilities. Through the barrier grouping and prioritisation, this work has also highlighted the key barriers around which there was greatest consensus, and identified barriers which experts considered the most urgent to address. The literature did not present any systematic prioritisation or consensus around the barriers to DEG WECs.

The work undertaken for this thesis also builds on the literature by laying out the actions that DEG WEC experts believe can be taken to address the key barriers to DEG WEC development. Only one previous study, the PolyWEC roadmap [262], gives a set of detailed recommended actions to develop DEG WECs. The present research supports the findings of the PolyWEC roadmap, and also identifies actions that were not noted in the PolyWEC study, such as the barriers and actions around the volume effect and the lack of a complete DEG WEC study. By interviewing experts with experience on a broad range of DEG WEC projects, this work also identified areas of consensus and uncertainty around DEG WEC barriers and actions. This had not been done in any previous studies found in the literature. These areas of consensus were highlighted by the grouping of barriers and actions carried out in this research. This grouping showed where clear actions exist that should be carried out to develop the DEG WEC sector, such as fatigue testing. Additionally, areas of more uncertainty were identified, such as performance at scale, where different actions were suggested by different experts.

8.3.2 Sector implications from the results of Part C

During this work, key barriers and actions were identified to the development of DEG WECs. As noted at the beginning of this section, there was a level of agreement between experts, and between the experts and the literature review, around some of these barriers. Specifically, the consensus around the barrier groups implies that, for DEG WECs to be developed, it is likely that these barriers must be addressed. For the other barriers, which were only identified by individual experts, it is recommended that additional verification to determine if they are key to the DEG WEC sector's development is carried out[35]. This verification could be through some form of consensus-forming activity, such as workshops, that brought together a wide range of DEG WEC experts.

To address these barriers, actions were identified by the experts. Again, for some of these actions, there was a high level of consensus between the experts. This would imply that these actions have a high likelihood of addressing key barriers to DEG WEC development. It is recommended that the high consensus actions are part of the future research strategy for the DEG WEC sector, including: fatigue testing for DEGs under relevant conditions; the need for strong collaboration between disciplines in DEG WEC research, including materials science, experimental development, device design and manufacturing; development of self-sensing for DEG applications; and investigation of modular DEG WEC designs. Other actions were only identified by a single expert, or there were conflicting actions identified by different experts to address the same barrier. For these actions, as with the barriers, it is recommended that further verification is carried out through consensus forming exercises.

Another important theme to highlight from the expert interviews was that DEG WEC research is muti-disciplinary in nature. To develop the technology at scale, there will be important roles for both research organisations and industry, which will require significant coordination to be carried out efficiently. This is an area which one of the experts highlighted as currently lacking in DEG WEC development (see *B25*). Work that aims to increase collaboration between the

[35] Although it should be noted that some of these barriers have agreement with the literature review, which would suggest that they are important to address.

stakeholders in DEG WEC development is likely to be beneficial to the development of the technology.

8.3.3 Limitations and further work from Part C

Some limitations are present in this work. The first is due to the use of semi-structured interviews to gather expert opinion. While this was deemed the best approach, given the constraints to carrying out this work (see Section 8.1), it does also introduce some restrictions. A key restriction of using semi-structured interviews is that there is no room for communication between the experts. In some areas, there was a variety of opinions between experts — for example where multiple actions were suggested to address the same barrier, or where a wide range of difficulty ratings were given to an action. A dialogue between the experts would have provided each expert with additional information, and might have led to greater consensus in some cases. Further work in the form of consensus forming activities, such as workshops, would be beneficial to further validate barriers and actions in the areas where less consensus was identified in the semi-structured interviews.

A second limitation is due to the composition of the DEG WEC experts that were interviewed. The participation of experts in the interviews relied on their response to email requests for interviews. Due to the relatively limited research in environmental barriers to DEG WEC development, only a small number of potential interviewees were identified. None of the environmental experts invited to participate in the interviews responded. This is important to bear in mind when considering the results presented in Part C of the present thesis. While the experts interviewed in this section did not highlight any key barriers[36] related to DEG WEC environmental impact, this could be due to their lack of expertise in these specific areas, rather than a lack of environmental barriers associated with DEG WECs. If the present research on barriers and actions for DEG WEC development were to be extended, the inclusion of environmental experts in further work is highly recommended.

Finally, further work in this area should establish a plan to carry out the actions to address the barriers to DEG WEC development. This is not a limitation of the present research, as this kind of work is well outside of the scope of a PhD project and is more in the domain of a research network, industry body, or funding organisation. However, without a plan, these key barriers and actions may not be acted upon in a systematic way by the DEG WEC community. A strategic forward plan (such as a roadmap) would fulfil the role of assigning actions to specific stakeholders, which would increase the likelihood that the key barriers and associated actions to develop DEG WECs are acted on. Additionally, a strategic forward plan should include workshops between a broad range of stakeholders. If carried out correctly, this could address the other limitations to this study, around communication between the different experts and the lack of environmental experts' input. Additionally, given the multi-disciplinary nature of the barriers and required actions to develop DEG WECs, bringing together a broad range of stakeholders into consensus-forming activities such as workshops would be highly beneficial in aiding coordination of research activities. For these reasons, a recommendation

[36] While no key barriers were identified in the environmental category, some other comments were made. These can be found under C4.1, C4.2 and C4.3 in Section 8.2.2.

of further work is that a strategic forward plan, such as a technology roadmap be developed for the DEG WEC sector. Several forms of strategic forward planning processes for technology development exist, including technology roadmapping (TRM), technology needs assessments (TNA) and technology action plans (TAP) [272], [280]. The most popular of these approaches, especially for the development of single renewable energy technologies, is probably the technology roadmap approach. For this reason, the potential benefits specific to a roadmap for DEG WEC development are described below. However, the processes for TRMs, TNAs and TAPs are similar in many respects and share many of the same benefits.

The technology roadmapping process has some overlap with the identification of technology barriers and actions that was carried out during this research. This research has established a strong baseline regarding the current barriers to DEG-based wave energy, and identified some of the actions that are likely to be needed to address these barriers. These would form a useful starting-point for any TRM workshops on DEG WECs. However, carrying out a formal roadmapping exercise would have several differences. These are largely around: 1) consensus-forming activities, which was not enabled by the semi-structured interview format in the present research; and 2) allocation of actions to specific stakeholders, which is not within the scope of this research. Some of the key potential benefits of carrying out a formalised roadmapping process for the DEG WEC sector are outlined below:

- Building consensus — Carrying out workshops as part of a roadmapping exercise would enable knowledge sharing and a consensus view to be developed around the targets, barriers and actions for DEG development, considering the requirements from different perspectives (such as manufacturing, materials science and environment). This would help address the differences in knowledge between the experts that were interviewed during this research, and possibly address some of the areas where consensus between the experts in the key barriers and actions was not clear.
- Coordination — Workshops, and dialogue in general, would allow better coordination of DEG research between different stakeholders, reducing duplication of research. Workshops could identify knowledge/research gaps that none of the stakeholders were currently working on or had previously considered.
- Buy-in and accountability — Involving the right stakeholders (such as the polymer manufacturing industry, research groups, and renewable energy funding organisations), and allocating specific actions to the stakeholders, would increase the likelihood of the identified actions being carried out. Without this engagement, a good plan for the DEG WEC sector can be created that does not have the required buy-in to be implemented.
- Follow-up — Good roadmaps are updated periodically. This would facilitate, for example, updated milestones, barriers and actions, as more information becomes available. This is important for a developing technology such as DEGs, where some areas contain large uncertainty. These re-evaluations would take into account new data as it becomes available, such as fatigue test data, to establish if the technology is still considered to have potential in wave energy applications.

The points above highlight that a strategic forward plan, involving a broad selection of relevant stakeholders, could be particularly beneficial for the development of the DEG WEC sector. While a roadmapping exercise was not appropriate to carry out during this research, it would build upon the work presented in this thesis and help translate a development plan for the DEG WEC sector into actions that are allocated to, and implemented by, specific stakeholders. It should also be noted that a poorly planned or executed roadmap will not bring these benefits to the sector. These often lack the necessary buy-in from key stakeholders to carry out the recommended actions. Ensuring that key TRM success factors are adhered to (see, for instance, UNFCCC [280]), and utilising guidance documents (such as the IEA roadmapping guidance [259]) would help improve the chances of successful implementation for a DEG WEC roadmap.

9 Conclusions, contribution to knowledge and impact

The overall research question posed at the beginning of this thesis is as follows:

> *Could direct conversion be an enabling technology in achieving cost-competitive wave energy?*

The research presented in this thesis aimed to answer this question in three parts, as illustrated in Figure 9-1.

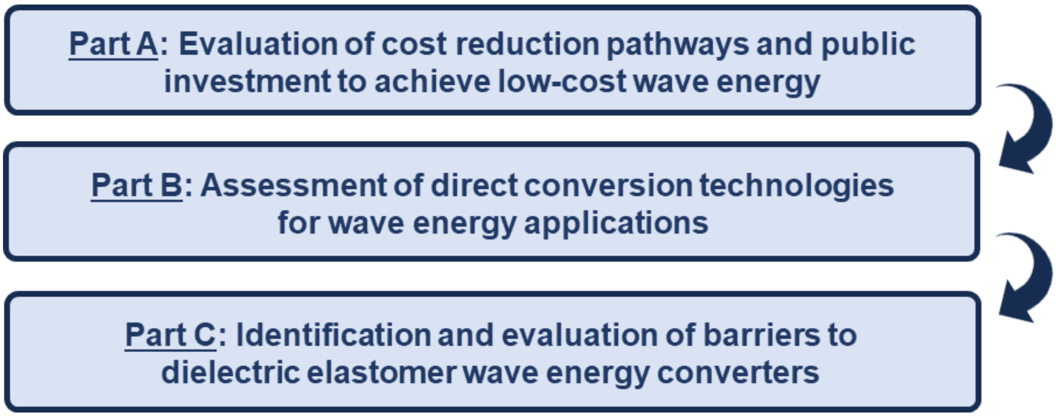

Figure 9-1. *Parts of thesis.*

Part A of the thesis investigated the impact that successful radical innovation could have on the learning investment required to achieve cost-competitive wave energy. This evaluated the learning investment under scenarios for the wave energy sector where cost reduction was achieved through incremental, deployment-related cost reductions and scenarios where innovation cost reductions were also achieved. Part B then investigated whether direct conversion technologies may be an enabler of this kind of radical innovation in the wave energy sector. In Part B, a screening process was developed to evaluate the potential viability of a direct conversion technology for wave energy applications. Six direct conversion technologies were then evaluated using the process. Part C then identified barriers that exist to the most promising direct conversion technology (dielectric elastomers) from Part B. The actions that are required to overcome these barriers were also identified. This was done through an initial literature review, which was built upon with a series of semi-structured interviews with experts.

Regarding the answer to the overall research question, the results from Part A of this thesis demonstrated that successful radical innovation significantly reduces the learning investment required to achieve cost-competitive wave energy. Radical innovation could therefore play an important role in enabling cost-competitive wave energy. Turning to an exploration of whether direct conversion may deliver this radical innovation, Part B demonstrated the application of a novel two-stage screening process for direct conversion technologies. This established that two direct conversion technologies may have potential in wave energy applications — dielectric elastomers and dielectric fluid generators. However, there is a lack of fatigue life data for both of these technologies which makes their suitability for wave energy applications uncertain at present. Part C of this thesis identified barriers that exist to the application of the most promising of these technologies (dielectric elastomer generators) in wave energy. Therefore, the answer to the overall research question is that it is possible that direct conversion technologies could be an enabling factor in achieving low-cost wave energy. This is because some of these technologies (dielectric elastomer and dielectric fluid generators) could potentially enable radical innovation. However, even for the most promising of these technologies, significant work remains to reduce uncertainty in their performance and break down barriers to their development. A number of key barriers were identified in Part C, along with actions that should be taken to address these.

The remainder of the conclusions starts by revisiting the three research questions that support the overall research question in Section 9.1. This section summaries how the work presented in this thesis answered each of these questions and any recommendations that can be made based on the research. The main contributions to knowledge from the research are then summarised in Section 9.2 along with the wider impact of this research.

9.1 Thesis conclusions

9.1.1 Conclusions from Part A

> ***Q1*** *What level of learning investment may be required to achieve cost-competitive wave energy through incremental, deployment-related cost reductions? And what effect could developments of radical innovation have on this learning investment?*

To determine the level of learning investment required to achieve cost-competitive wave energy through incremental deployment cost reductions, a single-factor experience curve model was developed that could estimate the learning investment associated with a wave energy deployment scenario. Radical (or step-change) innovation was then modelled as discontinuities in the experience curves. Scenarios with radical innovation were then evaluated using the model to determine the effect this had on the total learning investment.

In the modelling, an estimated 59 billion euros in learning investment would be required for the wave energy sector to achieve a cost-competitive LCoE (100 EUR/MWh) through deployment-related cost reductions under the baseline assumptions. This figure is of a similar magnitude to the subsidy that has been required for the large-scale deployment of other forms of renewable energy technology such as solar PV and onshore wind. Given the lack of commercial deployment of wave energy technology, the assumed learning rate and starting LCoE in the modelling is subject to high levels of uncertainty. For this reason, a sensitivity analysis was carried out on these two parameters. The sensitivity analysis found that, within a range of assumptions from the literature, the learning investment to achieve cost-competitive wave energy through deployment-related cost reductions could range between feasible (tens of billions of euros) and unfeasible levels (hundreds to thousands of billions of euros). The sensitivity analysis also showed that both a relatively high learning rate and low starting LCoE are needed for wave energy to achieve cost-competitiveness at a reasonable level of learning investment.

The inclusion of step-change innovation in this modelling resulted in a significant reduction in the learning investment required to achieve the 100 EUR/MWh target in all the scenarios that were evaluated. For example, a 25% reduction in LCoE through innovation, resulted in an approximately two thirds reduction in learning investment under the baseline scenario. This was the case both in scenarios where deployment and innovation happened in parallel, and where deployment was delayed until an innovation had been developed. Given the assumptions made in the work about the costs of carrying out innovation programmes, this research found that the subsequent savings in learning investment were large in comparison to the costs of the innovation programmes. This means that, even if the success rate of these programmes is low (i.e. multiple programmes have to be run to yield a successful innovation), they can still offer good value for money.

The findings from this work therefore support the following recommendations. Firstly, support for wave energy should focus on driving down the initial costs of commercial wave energy. This is because cost reductions made through innovation (reducing the initial cost of wave energy) have the potential to dramatically reduce subsequent learning investment. This could be through supporting the development of innovations in wave energy converter design and subsystems (such as direct conversion technology based WECs). Secondly, as wave energy is deployed commercially, government support that incentivises high learning rates is also important in lowering learning investment. This could include supporting policies such as digressing or competitive revenue support. The final recommendation is that, as data from commercial deployments of wave energy becomes available, learning investment estimates should be re-evaluated to determine whether the sector is on a viable pathway to achieve cost competitiveness. Given that learning investment is highly backloaded in the deployment scenarios, abandoning support for a technology on a slow cost reduction trajectory may be advisable, even if significant learning investments have already been made.

9.1.2 Conclusions from Part B

> ***Q2*** *Does direct conversion offer an innovation opportunity for the wave energy sector? And how can the potential of different direct conversion technologies for wave energy applications be consistently assessed in a repeatable manner?*

In Part B of this research, a screening process was developed that can be used to evaluate the potential viability of direct conversion technologies for wave energy applications in a consistent manner. This screening process was developed around a set of parameters that were seen as essential to the use of a direct conversion technology in wave energy, regardless of the configuration of the wave energy converter. These parameters were based on the cost, energy output, lifetime, durability, and embodied carbon of the direct conversion technologies. Minimum performance requirements were determined in these parameters. Failure to meet these minimum requirements results in a technology being rejected from the process. Given that this process was developed around quantifiable parameters that should be essential for any DCT in a wave energy application, it should be both consistent and repeatable. This screening process was then used to evaluate six direct conversion technologies to determine whether they offered opportunities for innovation in the wave energy sector.

Six direct conversion technologies were evaluated: dielectric elastomer generators (DEG), dielectric fluid generators (DFG), piezoelectric polymer generators, piezoelectric ceramic generators, triboelectric generators, and magnetostriction generators. Of these six technologies, the latter four were rejected. This was because they clearly did not meet the minimum required performance in one or more of the assessment parameters. Additionally, there was no compelling reason to believe the required performance improvement would be forthcoming in these parameters. The other two technologies (DEGs and DFGs) passed the screening process. Neither DEGs or DFGs demonstrated that they would not meet the minimum required level of performance in any of the assessment parameters. Of the two technologies, where comparable data existed, DEGs performed better in the screening process parameters. However, for both DEGs and DFGs there was insufficient fatigue life data to make a confident assessment of any of the parameters associated with fatigue life. Re-evaluation of these technologies would be merited as additional fatigue life data becomes available.

Overall, the screening process highlighted that only DEGs and DFGs may offer an innovation opportunity for the wave energy sector out of the six technologies that were assessed (when considering the use case and assumptions made to carry out the screening process). However, even for these technologies, significant knowledge gaps exist around fatigue life. In addition to these results, a key output is the development of a repeatable screening process. This process can be used to assess other direct conversion technologies in the future that may be considered for potential wave energy applications.

Based on these results, the following recommendations can be made. Firstly, in the application considered for this work, the development of piezoelectric polymer generators, piezoelectric ceramic generators, triboelectric generators, and magnetostriction generators would not be viable in wave energy applications. Therefore, limited effort should be put into developing these technologies for wave energy applications unless a significant technology breakthrough occurs. The second recommendation is that DEGs and DFGs are considered potential innovation opportunities for the wave energy sector, as they were not rejected by the screening process. However, gathering more complete data on both these technologies' fatigue life is highly recommended to make a more confident evaluation of their potential.

9.1.3 Conclusions from Part C

> ***Q3*** *What development barriers currently exist for the most promising direct conversion technologies for wave energy applications? And what actions could be taken to overcome these barriers?*

In Part B of the thesis, DEGs were identified as the most promising direct conversion technology that was assessed using the screening process. For this reason, they were the focus of Part C of the thesis.

To identify the barriers to the development of dielectric elastomer-based wave energy converters, a systematic literature review was carried out to develop an initial list of barriers. This list of barriers was then built upon by carrying out a series of semi-structured interviews with DEG WEC experts. These interviews established what the experts saw as key barriers to

DEG WEC development and the actions that they judged should be taken to address these barriers.

The semi-structured interviews identified 33 key barriers to DEG WEC development and 35 actions that the experts identified to address these barriers. Additionally, areas of consensus were identified between the experts for several of the barriers and actions. These areas of consensus provide additional verification that these are barriers and actions that should be focused on to develop dielectric elastomer wave energy conversion. For the other barriers and actions where consensus was not identified between the experts, some additional verification may be needed to determine whether they are key to the development of dielectric elastomer-based wave energy conversion. This could be carried out through activities such as workshops between DEG and wave energy experts.

Based on these results, the following recommendations can be made. Firstly, barriers and actions where consensus between experts was identified are likely to be important avenues of further work for the development of dielectric elastomer-based wave energy conversion. It is recommended that future development strategies for the dielectric elastomer wave energy sector consider these consensus barriers and actions. Secondly, the development of a strategic forward plan for the dielectric elastomer wave energy sector is recommended, which could build on the findings of this research. A strategic forward plan would assign actions to specific stakeholders, which would increase the likelihood of their being carried out. Additionally, carrying out a strategic forward plan would include consensus-forming activities such as workshops. These would enable dialogue between different stakeholders, which was not a feature of the semi-structured interviews carried out during this research. This could help form consensus in some of the areas where different opinions existed between the experts interviewed in Part C.

9.2 Contribution to knowledge and research impact

The main contributions to knowledge and impacts on the wave energy sector from the research presented in this thesis are summarised below.

Contributions to knowledge from Part A

- Part A of this thesis presented the first evaluation in the academic literature of the impact that innovation could have on the learning investment required to achieve cost-competitive wave energy. Previous studies on this topic are found in non-academic literature (see Section 2.2.2), but these provided a very limited set of scenarios and no information on their modelling methodologies. Both of these limitations of previous work were addressed in this research.
- The work presented in Part A of the thesis furthers the understanding of the investment required to achieve low-cost wave energy through either incremental cost reductions associated with large-scale deployment, or cost reductions associated with targeted innovation support.

Impact from Part A

A journal article [74] was published based on the modelling developed in Part A of this research. At the time of writing this thesis, the journal article has gained a high number of citations[37], demonstrating an impact on the academic research in this field. Additionally, the modelling methodology from Part A was used in a deliverable for a Horizon 2020 funded project — DTOceanPlus [73]. The use of this research in a collaborative international project again demonstrates its wider impact within the ocean energy research community.

Contributions to knowledge from Part B

- The research presented in Part B is the first time in the academic literature that an assessment process has been developed to assess the viability of direct conversion technologies for wave energy applications. Although an assessment process had previously been developed in the non-academic literature, it considered a different use case of the direct conversion technologies and contained some potential limitations (outlined in Section 5.2) which this work addresses. The process developed during this research was used to evaluate the potential viability of six direct conversion technologies for wave energy applications. These technologies had not previously been compared and evaluated for wave energy applications in a single study using a consistent set of evaluation criteria.
- Along with the results from evaluating the specific direct conversion technologies, a key contribution from Part B is the assessment process that was developed. As the process uses a defined set of parameters and cut-off values, it should provide a framework to make evaluations of direct conversion technologies for wave energy applications in a more transparent and consistent way.

Impact from Part B

Informed by the findings of Part B of this research, Wave Energy Scotland are funding research into dielectric elastomer generators and dielectric fluid generator-based wave energy conversion. These activities include a Wave Energy Scotland concept creation call for DEG or DFG based wave energy converters and providing partial funding for a Supergen call to develop modular DEG or DFG generators that can be used in wave energy applications. Additionally, Wave Energy Scotland plans to use an adapted version of the screening process to evaluate the potential viability of other direct conversion technologies which may have applications in wave energy.

[37] The journal article had gained 11 citations on Google Scholar as of 01/11/2023.

Contributions to knowledge from Part C

- Building upon existing literature, the research in Part C presents a more detailed overview of the barriers that exist to the development of DEGs for wave energy applications. This was extended by soliciting expert opinion on the actions that should be taken to address these barriers. Only one other study in the literature attempted to develop a comprehensive list of actions for DEG wave energy converter development [262]. This thesis builds upon that earlier study with additional recommended actions.
- As this work gathered opinions independently from a variety of experts, areas of consensus were able to be identified around key barriers to DEG wave energy converter development and the actions that should be taken to address these barriers. This has not been done in previous studies. These areas of consensus form a strong basis for the future activities that are required to develop the DEG wave energy converter sector.

Impact from Part C

To help coordinate research and development efforts for direct conversion-based wave energy, Wave Energy Scotland plans to develop a research agenda for DEG and DFG based wave energy conversion. For DEGs, this research agenda will build on the key barriers and actions to DEG WEC development that were identified in Part C of this research.

10 Bibliography

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11 Appendix

Appendix A.1 — Wind and solar PV deployment rates

Global cumulative deployed capacity per year for onshore wind and solar PV, based on REN21 data [117]. The choice of 30% increase per year for the wave energy modelling falls between the two technologies deployment rates.

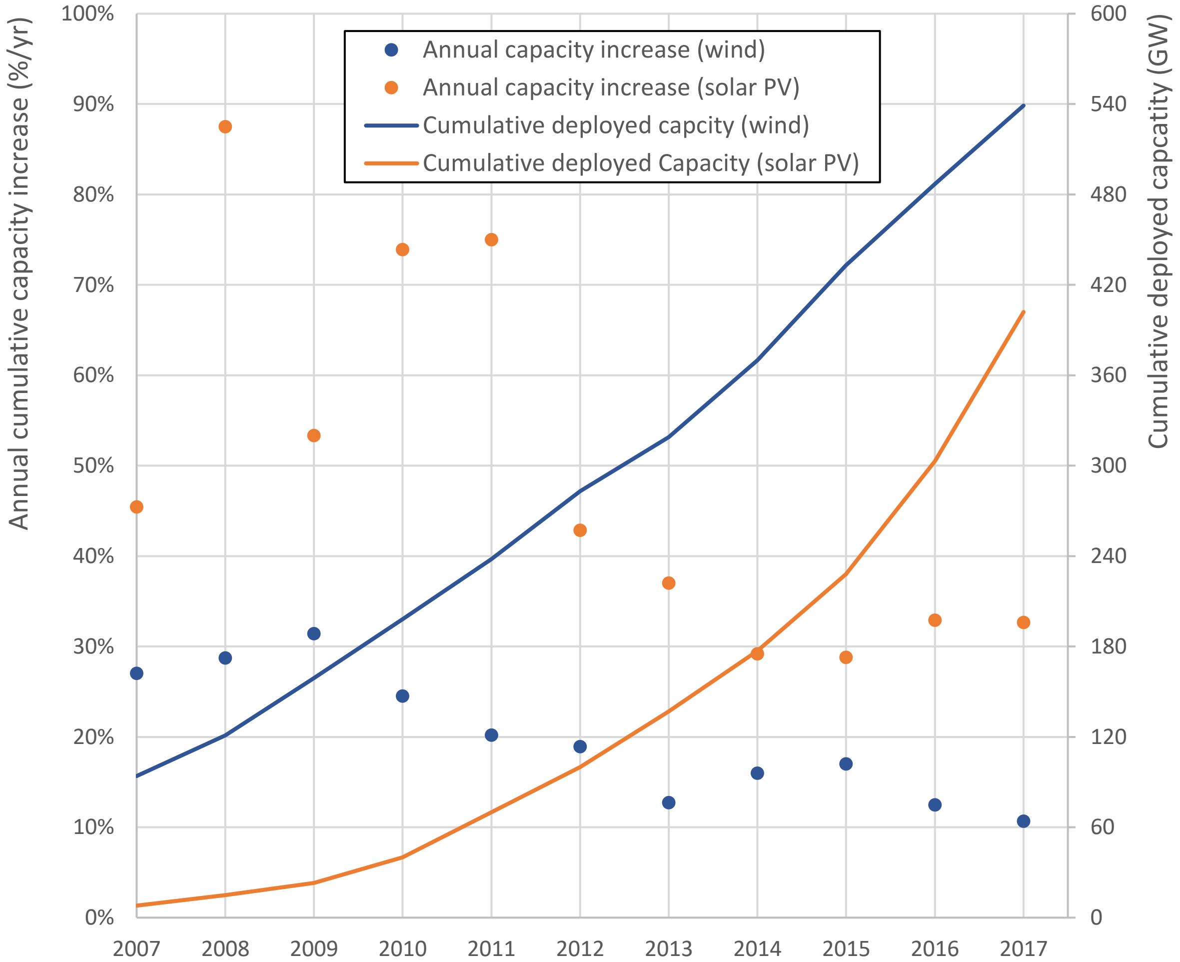

Figure 11-1. *Global cumulative deployed capacity for onshore wind and solar PV from 2007-2017 based on REN21 data* [117]*. Lines indicate global cumulative deployed capacity, dots represent the percentage cumulative deployed capacity increase per year.*

Appendix A.2 — Currency conversion

Monetary conversion between different years and currencies delt with in a two-stage process during this thesis. This is based on the process used by the IPCC to compare prices and costs from different years between regions [281]. For sources of price data in this thesis, unless otherwise stated it is assumed prices are quoted in the same year as the year of publication. The base year used in this thesis for costs and prices is 2020 and the currency is Euros (EUR). The two stages used to convert costs and prices to this EUR_{2020} are:

- Monetary data is inflated/deflated in its original currency to its value in 2020 (e.g. USD_{2010} -> USD_{2020}).
- Monetary data is converted to 2020 EUR using the 2020 average exchange rate (e.g. USD_{2020} -> EUR_{2020}).

The inflation factor used was consumer price index (CPI) for all calculations. Euro zone data was used to represent EUR inflation and exchange rates. The data used for currency inflation and conversion is presented in Table 11-1.

Table 11-1. *Inflation and exchange rate values used to convert monetary values, data from* [282]–[286].

	Inflation CPI (2000 = 1)			**Exchange rates (currency to EUR)**	
Year	**EUR** [284]	**USD** [283]	**GBP** [282]	**USD** [286]	**GBP** [285]
2000	1	1	1	1.08	1.64
2001	1.03	1.03	1.01	1.12	1.61
2002	1.05	1.04	1.03	1.06	1.59
2003	1.08	1.07	1.04	0.88	1.45
2004	1.10	1.10	1.05	0.80	1.47
2005	1.13	1.13	1.07	0.80	1.46
2006	1.16	1.17	1.10	0.80	1.47
2007	1.18	1.20	1.13	0.73	1.46
2008	1.23	1.25	1.17	0.68	1.26
2009	1.24	1.25	1.19	0.72	1.12
2010	1.26	1.27	1.23	0.75	1.17
2011	1.30	1.31	1.29	0.72	1.15
2012	1.33	1.33	1.32	0.78	1.23
2013	1.35	1.35	1.36	0.75	1.18
2014	1.35	1.37	1.38	0.75	1.24
2015	1.35	1.38	1.38	0.90	1.38
2016	1.35	1.39	1.38	0.90	1.22
2017	1.37	1.42	1.42	0.89	1.14
2018	1.39	1.46	1.46	0.85	1.13
2019	1.41	1.48	1.48	0.89	1.14
2020	1.42	1.50	1.50	0.88	1.13
2021	1.45	1.57	1.53	0.85	1.16
2022	N/A	1.70	1.67	0.95	1.17

Appendix A.3 — CORDIS and WES funding data

Table 11-2 shows he targeted cost reduction, level of funding and time for from relevant wave and tidal innovation projects from the Community Research and Development Information Service (CORDIS) database[38] of EU-funded projects. This table was reproduced from DTOceanPlus deliverable 8.3 [73].

Table 11-2. *Wave and Tidal innovation project targeted cost reductions, funding and time from the CORDIS data base.*

Project name/ Acronym	Type	Subsystem(s)	AEP	OPEX	CAPEX	LCoE	Funder(s)	Funding* (EURm)	Time (months)
AQUAGEN	Wave	PTO	20%	-25%			FP7	1.7	*39*
CableFish	Tidal	Installation			-75%		MRCF		*12*
CF2T	Tidal	Foundation			-30%		Ocean ERA-NET	1.5	35
CORES	Wave	PTO, control, moorings, risers, data acquisition and instrumentation					FP7	3.45	*42*
D2T2	Tidal	PTO				-30%	H2020	2.2	42
DemoTide	Tidal	Array + foundation				-73%**	H2020	20.3	36
ELEMENT	Tidal	Control				-17%	H2020	5	36
EnFAIT	Tidal	Array + O&M		-20%	-20%		H2020	14.9	*60*
FloTEC	Tidal	Device + mooring + blades	50%			-20%	H2020 + Saltire Prize	9.7 + £3.4 m	50
GEOWAVE	Wave	Mooring					FP7	1.1	*35*
IMAGINE	Wave	PTO			-50%	-48.50%	H2020	3.8	42
InToTidal	Tidal	Device					H2020	2	24
LAMWEC	Wave	Device + Mooring & Foundation testing					Ocean ERA-NET	0.9	36
MacArtney wet-mate connector	Both	Installation					ETI	£1.1 m	
MAT4OEC	Both	Materials/ coatings				-reduce	Ocean ERA-NET	0.64	*30*
MegaRoller	Wave	PTO	26%	-75%		-26.60%	H2020	4.9	36

[38] https://cordis.europa.eu/projects/

NEMMO	Tidal	Blades/ Materials				-70%	H2020	4.98	*42*
OCEAN_2G	Tidal	Device					H2020	1.9	22
Pelamis ETI	Wave	Structure							
POLYWEC	Wave	Novel PTO material					FP7	2.06	*51*
PowerKite	Tidal	PTO	17%				H2020	5.1	24
REMO	Tidal	Maintenance		-50% (mainten ance)			FP7	1.1	*24*
SEABLADE	Tidal	Blades		-reduce			Ocean ERA-NET	0.39	24
Sea-Titan	Wave	PTO					H2020	3.9	36
TAOIDE	Both?	PTO (wet-gap generator for tidal)							*48*
TIDAL-EC	Tidal	PTO	+increa se			-reduce	FP7	1.04	18
TIM	Both	Mooring					Ocean ERA-NET	0.29	24
TIPA	Tidal	PTO				-29%	H2020	4.4	36
TOPFLOTE	Tidal	PTO (pitch regulation)	+increa se		- reduce		Ocean ERA-NET	1.2	29
UMACK	Both	Mooring + installation			-50% (moori ng) -50% (install ation)	-9.5%	Ocean ERA-NET	2	35
UPWAVE	Wave/ wider	Device					H2020	20.7	*60*
WaveBoost	Wave	PTO	25%			-18% (low) -27.5% (high)	H2020	4	36
WavePiston	Wave	Device					H2020	2.5	32
WEP+	Wave	PTO + Storage							18
*Funding in €m unless otherwise noted. Values as quoted and have not been adjusted for inflation. ** Quote in JRC (2018) "The project aims to reduce cost of electricity from 450 EUR/MWh to 120 EUR/MWh." (note this was adjusted due to a typo in the D8.3 report)									

The attrition rate of projects with the wave energy Scotland programme is shown in Table 11-3.

Table 11-3 *Attrition rate within the Wave Energy Scotland programmes.*

Programme	**Number of Participants (of which direct entrants)**		
	Stage 1 (TRL 1-3)	**Stage 2 (TRL 3-5)**	**Stage 3 (TRL 5-6)**
NWEC	8	4	2
Power Take-Off	10	10 (6)	5 (1)
Structural Materials and Manufacturing Processes	10	3	2

Control Systems	13	3	2
Quick Connection Systems	7	4	-
Total	**48**	**24 (6)**	**11 (1)**
Average	**10**	**5**	**3**

The estimates of total investment and duration of a wave energy innovation programme are shown in Table 11-4. These are based on Wave Energy Scotland data for stages 1-3 and CORDIS data for stage 4.

Table 11-4. *Estimates of Investment and Duration for innovation programme. This is based on Wave Energy Scotland data for stages 1-3 and CORDIS data for stage 4.*

Stage	**Investment per concept (€k)**	**Number of concepts**	**Total investment (€m)**	**Duration (months)**
1) Concept development	62 - 333	10	0.62 - 3.33	3 - 12
2) Design optimisation	250 - 810	5	1.25 - 4.05	9 - 16
3) Scaled demonstration	633 - 4429	3	1.90 - 13.3	12 - 24
4) Commercial-scale single device demonstration	300 - 15000	2	0.60 - 29.8	12 - 60
Total for single subsystem	**-**	**-**	**4.4 - 50.5**	**36 - 122**

Appendix A.4 — Global wave energy resource

The average global wave energy resource data from Gunn and Stock Williams is shown in Table 11-5. This is an estimate of average wave power that flows across buffer 30 nautical miles from the coastline. Gunn and Stock Williams also estimated the average extractable wave energy resource from an array of Pelamis P2 WECs which is also shown in Table 11-5. This assumed an array spacing of 5 units per km, and also was not optimised for different wave climates, so may be a conservative estimate. It is assumed that the power matrix used by Gunn and Stock Williams referred to power output rather than absorbed power, as this was not specified in their work.

Table 11-5. *Average power incident at 30nm from ocean facing coastlines and average extractable power from an array of Pelamis P2 WECs. High and low values show 95% confidence intervals. Data from Gunn and Stock Williams* [5].

		Average power (GW)		
		Low	**Med**	**High**
Average power of wave energy incident on ocean-facing coastlines	**Europe**	250	270	290
	World	2060	2110	2160
Average extractable power by an array of Pelamis P2 WECs	**Europe**	14.1	14.6	14.1
	World	95.3	96.6	97.9

If the average power shown in Table 11-5 is divided by a capacity factor of 30% an estimate of the corresponding rated power of wave energy devices can be made. This is shown in Table 11-6. It should be noted that the rated power corresponding to the total incident wave energy is an upper limit as it implicitly assumes a 100% wave energy absorption and conversion efficiency.

Table 11-6. *Rated power corresponding to the average power values in Table 11-5.*

		Rated power (GW)		
		Low	**Med**	**High**
Rated power of wave energy incident on ocean-facing coastlines at 30% capacity factor	**Europe**	833.3	900.0	966.7
	World	6866.7	7033.3	7200.0
Rated power of array of Pelamis P2 WECs at a 30% capacity factor	**Europe**	47.0	48.7	47.0
	World	317.7	322.0	326.3

Additionally, if the average power estimates are multiplied by the number of hours per year (including leap years = 8776 h/year) the energy per year can be estimated shown in Table 11-7.

__Table 11-7.__ Energy generation per year corresponding to the average power values in Table 11-5.

		Energy per year (GWh/y)		
		Low	**Med**	**High**
Total wave energy incident on ocean-facing coastlines	**Europe**	2191500	2366820	2542140
	World	18057960	18496260	18934560
Extractable energy by array of Pelamis P2 WECs	**Europe**	123601	127984	123601
	World	835400	846796	858191

Appendix B.1 — Energy density of triboelectric generators

Experimentally demonstrated energy density of triboelectric generators

The highest power rating for a triboelectric generator which was cycled at 1 Hz in the literature is 0.11 W/m^2. This is equivalent to an energy density of 0.11 J/m^2 [172].

If the 0.1 mm thick PTFE (with a density of 2150 kg/m^3) used as the triboelectric material in the same study is considered (negating the mass of the second triboelectric layer which is one of the electrodes) the energy density is equal to 0.51 J/kg.

Theoretical energy density of triboelectric generators

The theoretical maximum energy density of triboelectric generators is limited by electrical breakdown. In most triboelectric generators this would largely be due to the breakdown of the air gap [170]. However, in Lateral Sliding (LS) mode or contact Free Standing mode the breakdown of the triboelectric layers is the limiting factor. In this case energy densities of up to 10 J/kg for a PDMS based LS mode triboelectric generator have been simulated by Fu et al. [170]. However, this assumes a surface charge density of 500 µC/m^2 can be achieved, which is far higher than the values achieved by current solid-solid triboelectric generators (typically ~100 µC/m^2 [240]). Only liquid-solid triboelectric generators have achieved surface charge densities in this range (up to 430 µC/m^2 was achieved using liquid Galinstan as one of the triboelectric materials by Tang et al. [240]).

Appendix B.2 — Direct conversion technology publication data

Apart from one publication on piezoelectric wave energy conversion, all of the studies identified in the database dated from 2000 onwards. A time series from 2000 to the end of 2020 of the cumulative publications (from the filtered articles in Table 4-6) are presented in Figure 11-2, alongside their cumulative citations (including self-citation).

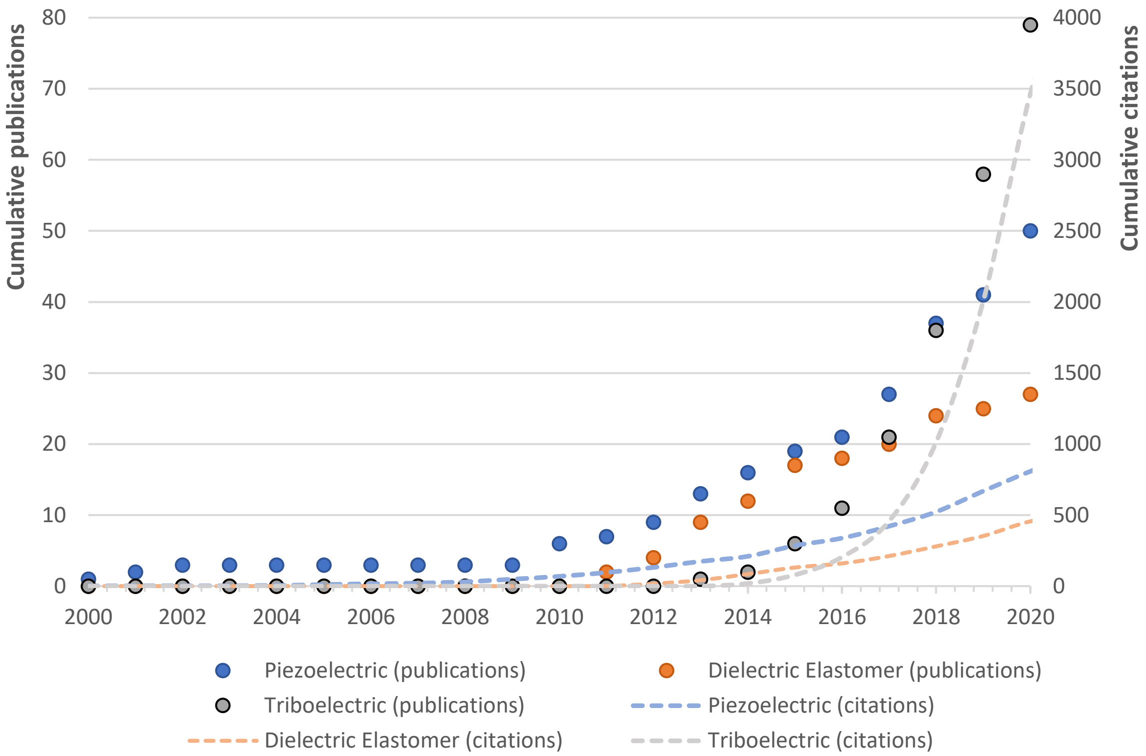

Figure 11-2. *Cumulative publications and citations from year 2000 to the end of 2020 for wave energy research based on each of the studied technologies. Retrieved from the Web of Science database, magnetostriction and dielectric fluid wave energy converters not shown as no publications were found in the database search.*

Appendix B.3 — Evaluation of IEA-OES T12 and TPL

Table 11-8 and Table 11-9 show the metrics used by the IEA-OES [29] and TPL [204] assessment processes to evaluate wave energy converters. These metrics were evaluated to see if they (or a proxy) would be used in the direct conversion technology (DCT) screening process. This was done by asking, for each area, if a clear cut-off could be defined and if a proxy parameter was available to assess a DCT. Notes are given to describe if the assessment parameter is applicable to DCT screening and finally what assessment parameters could be used for the DCT as a proxy for the metrics.

Table 11-8. *IEA OES wave energy converter assessment areas* [29].

IEA-OES T12 assessment area	Metric	Clear cut-off value?	Proxy available for DCT?	Notes	Assessment parameter for DCT
Power capture	Power capture - power matrix (kW)	No	No	Design specific, cannot be defined for DCT, also no clear cut-off	
	Capture length (m)	No	No	Design specific, cannot be defined for DCT, also no clear cut-off	
Power conversion	Conversion efficiency	Yes	Yes	Conversion efficiency of DCT can be measured	Conversion efficiency
Controllability	Controllability scale rating	No	Maybe	Design specific, cannot be defined for DCT, also no clear cut-off	
Reliability	Mean time to failure	Yes	Yes	Fatigue life is a good predictor of MTTF along with ULS	Fatigue life + ULS
	Failure rate	Yes	Yes	Fatigue life is a good predictor of FR along with ULS	Fatigue life + ULS
Survivability	Design conditions boundary	No	Yes	No clear cut-off, may define limits for DCT in terms of electrical and mechanical limits	ULS
	Likelihood of exceeding an acceptable level of damage or loss of functionality, with	Yes	No	Design specific, cannot be defined for DCT	

	or without taking suitable protective action				
Maintainability	Range of acceptable environmental conditions	Yes	No	Design specific, cannot be defined for DCT	
	Mean time to repair (or maintain)	Yes	No	Design specific, cannot be defined for DCT	
	Cost to repair	Yes	Yes	Through-life costs include number of replacements and cost of replacements (similar to cost of repair)	Through-life costs + ULS
Install-ability	Range of acceptable environmental conditions for installation (or recovery)	Yes	No	Design specific, cannot be defined for DCT	
	Mean time to install	Yes	No	Design specific, cannot be defined for DCT	
	Transit speed	Maybe	No	Design specific, cannot be defined for DCT, also no clear cut-off	
	Cost to install (or recover)	Yes	No	Design specific, cannot be defined for DCT	
Manufacturability	Manufacturing readiness level	Maybe	Yes	Can be defined for DCT, but no clear cut-off, none of the DCTs are at a high MRL	MRL (not used as assessment parameter)
	Time to manufacture	Yes	No (for early stages)	DCTs all at early stages, large-scale manufacturing hard to assess	
	Cost to manufacture	Yes	No (for early stages)	DCTs all at early stages, large-scale manufacturing hard to assess	
Affordability	CAPEX	Yes	Yes	Can be estimated on a raw material costs basis	Cost per unit energy output
	OPEX	Yes	Yes	Can be estimated based on fatigue life and raw material costs basis	Through-life costs + ULS
	LCoE	Yes	Yes	Can sort of be quantified for the PTO only	Through-life costs

Table 11-9. *Wave energy stakeholder requirements* [206].

Stakeholder requirement	Sub-requirements	Clear cut-off value?	Proxy available for DCT?	Notes	Assessment parameter
Market competitive LCoE	Low CAPEX: • Low-cost design • Low-cost manufacturing • Low transportation costs • Low installation costs	• Yes • Yes • Yes • Yes	• Yes • No (for early stages) • No • No	Capex can be based on material costs at an early stage Others: Design specific, cannot be defined for DCT, also no clear cut-off	Cost per unit energy
	Low OPEX: • High reliability • High durability	• Yes • Yes	• Yes • Maybe		Through-life costs ULS
	Generate large amounts of electricity: • Absorb large amounts of wave energy • Have a high conversion efficiency	• No • Yes	• No • Yes	Absorbed energy - Design specific, cannot be defined for DCT, also no clear cut-off Conversion efficiency can be measured	Conversion efficiency
	Have a high availability: • High reliability • High durability	• Yes • Yes	• Yes • Yes		Through-life energy density
	Low financing rate	Yes	No	Design specific, cannot be defined for DCT	
	Low insurance rate	Yes	No	Design specific, cannot be defined for DCT	
Secure investment opportunity	Low uncertainty in costs and revenues: • Low uncertainty in OPEX	• Yes • Yes • Yes • Yes	• No • No • No • No	Design specific, cannot be defined for DCT	

	• Low uncertainty in availability • Low uncertainty in energy production • Low uncertainty in CAPEX				
	Be survivable: • Able to survive extreme loads/responses • Able to survive grid failures or grid loss • Able to avoid/survive two collisions • Be survivable in temporary conditions	• Yes • Yes • Yes • Yes	• Yes • No • No • No	Loads - need a DCT that can survive overloads Others - Design specific, cannot be defined for DCT	ULS
Reliable for grid operations	Be forecastable	Maybe	No	Design specific, cannot be defined for DCT, possibility of cut-off	
	Stable AEP	No	No	Design specific, cannot be defined for DCT, also no clear cut-off	
	Useful to the grid	No	No	Design specific, cannot be defined for DCT, also no clear cut-off	
Benefit society	Beneficial to local communities	No	No	Design specific, cannot be defined for DCT, also no clear cut-off	
	Low GHG energy source	Yes	Yes	Embodied emissions of DCT raw materials can be measured	Through-life embodied carbon
	Low pollution energy source	Yes	Maybe	Possible to measure this, although can be mitigated in	

				PTO through encapsulation etc.
	Minimal impact on taxpayers and electricity consumers	No	No	Essentially this is LCoE + deployed volume, cannot be quantified
	Contribution to energy security	No	No	Portfolio level requirement, WE will be intermittent and will not provide much additional energy security compared to other RETs
Be acceptable to permitting and certification	Environmentally acceptable	Yes	Maybe	Can evaluate aspects like CO2, issues around toxicity can be mitigated in PTO through encapsulation etc. Other issues are device/array related
	Acceptable to other users in the area	Yes	No	Design specific, cannot be defined for DCT
	Grid compliant	Yes	No	Design specific, cannot be defined for DCT
Acceptable regarding safety		Yes	No	Design specific, cannot be defined for DCT
Deployable globally		Yes	No	Design specific, cannot be defined for DCT

Appendix B.4 — Cut-off value sensitivity analysis

The baseline scenario used in Table 6-4 are shown in Table 11-10, along with a more optimistic and pessimistic scenario. It should be noted that AEP_{perMW} is simply the annual energy production per MW rated power of the wave energy converter.

Table 11-10. *Baseline, optimistic and pessimistic assumptions for the wave energy converter.*

Metric	Unit	Baseline	Optimistic	Pessimistic
Build time	years	2	2	2
OPEX	% CAPEX/yr	3	2	8
Capacity Factor	%	30	40	25
AEP_{perMW}	MWh/MW/y	2630	3506	2192
Real discount rate	%	8.6	8.6	15
Operational WEC lifetime	years	20	25	15
DECEX	% CAPEX	0	0	0

The second set of assumptions are around the total contribution to WEC CAPEX and lifecycle carbon that are permissible for the DCT subsystem. In the baseline scenarios 32.5% of WEC's total CAPEX is assumed to be attributable to the DCT subsystem and 27% of WEC embodied carbon is assumed to be attributable to the DCT subsystem. These represent 50% of the structure, prime mover and PTO budget, in terms of CAPEX or embodied emissions. The high and low scenarios are shown representing ± 50% change in the CAPEX and embodied emissions budget for the DCT subsystem.

Effect on Parameter 1.1) Conversion efficiency cut-off

As discussed in Sections 5.1 and 6.1.3 the ACE metric developed by NREL [29] is a measure of the average capture width (the ratio of average absorbed wave power (kW) to the energy in the wave resource (kW/m) measured in a set of climates) divided by the structural costs of a WEC's load bearing components and its foundations. For the purposes of this analysis, it is assumed that ACE covers the cost of the Structure, Prime mover, Foundations and moorings and DCT subsystem, in total 75% of the WEC's capital costs. Additionally, a 25 kW/m wave resource was assumed. Therefore, the annual energy production of our hypothetical WEC per million euros of WEC CAPEX ($AEP_{per\ mEUR}$) can be estimated using the following formula, where η is the conversion efficiency of the DCT.

$$AEP_{per\ mEUR} = ACE * 25{,}000 * \ 0.75 * \ \eta$$

Equation 11-1. *AEP per mEUR derived from ACE and conversion efficiency.*

The $AEP_{per\ mEUR}$ value can be used as an input for a standard LCoE calculation using the assumptions in Table 11-10. This allows a minimum conversion efficiency to be defined for a specific ACE value which would allow the LCoE target of 100 EUR/MWh to be achieved as shown in Table 11-11. The resource level of 25 kW/m is constant in all scenarios as the WEC must be cost effective in a wide range of sites.

Table 11-11. Conversion efficiency required to meet LCoE of 100 EUR/MWh.

	Required conversion efficiency (%)		
	Baseline	Optimistic	Pessimistic
ACE = 12 m/mEUR	71.5	61.9	N/A
ACE = 25 m/mEUR	34.3	29.7	64.3

As it is assumed that ACE covers the cost of the Structure, Prime mover, Foundations and moorings and DCT subsystem, the assumptions around the CAPEX budget for the DCT do not effect the required conversion efficiency.

Effect on Parameter 1.3) Raw material cost per unit energy cut-off

The effects of these different scenarios on the overall CAPEX budget (consistent with meeting the LCoE target of 100 EUR/MWh) for the hypothetical WEC and DCT subsystem are shown in Table 11-12. These were calculated in the same way as the baseline CAPEX budget, using an Excel spreadsheet and goal seek, using the input data from Table 11-10. The optimistic scenario results in a higher CAPEX budget for the WEC and DCT subsystem being permissible, while the pessimistic scenario results in a lower CAPEX WEC and DCT subsystem being permissible.

Table 11-12. Effect on CAPEX budget from different scenarios.

	CAPEX Budget (mEUR/MW)		
	Baseline	Optimistic	Pessimistic
WEC	2.3	3.3	1.1
DCT subsystem (32.5% of WEC CAPEX)	0.61	0.93	0.27
DCT subsystem -50% (16.25% of WEC CAPEX)	0.31	0.47	0.14
DCT subsystem +50% (48.75% of WEC CAPEX)	0.92	1.4	0.41

Effect on Parameter 2.2) Through-life energy costs cut-off

If the same assumptions from Table 11-10 and the CAPEX budgets from Table 11-12 are input the effect of the different scenarios on the through-life costs cut-off can be shown. Understandably there is less difference between scenarios here, as the changes in allowable CAPEX are offset by changes in the lifetime energy production (this is because $LEC_{cut-off} = CAPEX_{target}/LT_{WEC} \times AEP_{perMW}$ see Equation 6-8).

Table 11-13. Effect on through-life energy cut-off from different scenarios.

	Through-life cost cut-off (EUR/GJ)		
	Baseline	Optimistic	Pessimistic
DCT subsystem (32.5% of WEC CAPEX)	3.2	2.9	2.3
DCT subsystem -50% (16.25% of WEC CAPEX)	1.6	1.5	1.2
DCT subsystem +50% (48.75% of WEC CAPEX)	4.8	4.4	3.5

Effect on Parameter 2.3) Through-life embodied carbon cut-off

Through-life embodied carbon is not affected by the assumptions in Table 11-10 as these are made on a per unit cost basis.

Table 11-14. Effect on embodied carbon cut-off from different scenarios.

System/subsystem	Emissions per MWh ($KgCO_{2eq}$/MWh)
DCT subsystem (27% of WEC embodied CO_{2e})	13.5
DCT subsystem -50% (40% of WEC CAPEX)	20.25
DCT subsystem +50% (15% of WEC CAPEX)	6.75

Appendix B.5 — ACE value of other WECs

This shows the data used to calculate the ACE values shown in Table 6-8. ACE values were estimated for the Core Power Ocean [27], [231], Aquabuoy [227] and WEPTOS [228] devices using data from the literature on device mass, materials and power absorption. The ACE value for Aqua harmonics testing was taken from the wave energy prize test results presented in Dallman et al. [215] which were converted into 2020 Euros.

Table 11-15. *Data and assumptions required to estimate ACE for a selection of Wave energy converters.*

	CPO [27], [231]	**Aquabuoy** [227]	**WEPTOS** [228]
Structural mass (kg)	78000	71000	1380000
Notes (mass)	No details	Floater only	WEC, no ballast
Mass steel (%)	83.76	100	100
Mass GFRP (%)	16.24%	0	0
Notes (Cost)	Non-GFRP mass assumed as steel	Assumed mass is steel	Assumed mass is steel
Wave Flux (kw/m)	26	28	26
AAE (MWh)	727	314	10,842*
CW (m)	3.19	1.28	47.57

* Assuming PTO efficiency of 90%

The capture widths in Table 11-15 were calculated by dividing the annual absorbed energy (AAE) by the number of hours per year multiplied by the wave energy flux.

The mass of steel and GFRP from Table 11-15 were multiplied by the fabricated material costs in Table 11-16 to calculate the total structural costs.

Table 11-16. *Density and fabricated material cost data from* [213].

Material	**Density (kg/m^3)**	**Cost per kg (EUR$_{2020}$/kg)**
Steel - A36	7850	2.71
Filament wound fibre glass	2000	4.97

The capture widths in Table 11-15 were then divided by these structural costs to give an estimation of ACE for each WEC. The capture width for most WECs tested during the wave energy prize did not vary significantly in different sea states, for this reason, it seems valid to use estimated ACE for single sea states as a benchmark for the current state of the art.

Appendix B.6 — Energy density of DFG

Derivation of DFG energy density from experiments

To derive an energy density, cost per kg and embodied carbon per kg for DFGs the proportions of both elastomer (DE) and fluid (DF) in a DFG must be known. In [135] the energy density with respect to the DE layer (ED_{DE}) and the DF layer (ED_{DF}) are provided. Therefore, the overall energy density of the DFG (ED_{DFG}) can be calculated using the formulation in Equation 11-2.

$$ED_{DFG} = \frac{1}{\frac{1}{ED_{DE}} + \frac{1}{ED_{DF}}}$$

Equation 11-2. *Energy density of DFG.*

As the inverse of this energy density is the mass of DFG per unit energy, the contribution of the DE and DF to the total DFG mass can also be calculated. This is shown for the experimental set from [135] in Table 11-17.

Table 11-17. *Contribution to DFG mass from DE and DF.*

	Energy density (J/kg)		Mass per unit energy (kg/J)		Contribution to total mass (%)
	Demonstrated	Theory	Demonstrated	Theory	
DE (synthetic)	179.0	699.7	0.0056	0.0014	27
DF (silicone oil)	63.8	249.4	0.016	0.0040	73
DFG	47.0	183.8	0.021	0.0054	100

Combining these mass breakdowns with the material unit costs the cost per kg of the DFG from [135] can be estimated. This is shown in Table 11-18.

Table 11-18. *Cost of DFG based on mass contribution of DE and DF.*

	Cost (EUR/kg)		Cost contributions (EUR/kg DFG)	
	Min	Max	Min	Max
DE (synthetic)	5	15	1.34	4.31
DF (silicone oil)	8	20	5.84	14.6
DFG	N/A	N/A	7.18	18.91

The same process can be followed using raw material embodied carbon to estimate the embodied CO_{2e} per kg of the DFG from [135]. This is shown in Table 11-19.

Table 11-19. *Embodied CO_{2e} of DFG based on mass contribution of DE and DF.*

	Embodied carbon ($kgCO_{2e}$/kg)
DE (synthetic)	3.7
DF (silicone oil)	6.3
DFG	5.6

True energy density of DFG systems

It is important to note that these performance values (both experimental and theoretical) refer to a single experimental set up described in Duranti et al. [135]. This experiment was not optimised in terms of design or materials, therefore significant improvements are likely possible which could improve energy density and conversion efficiency.

There is now some experimental evidence that there is a shielding effect when a dielectric polymer is placed between the electrodes and the dielectric liquid, this can allow the liquid to survive electric fields significantly above their quoted E_{BD} [149]. As the energy density is proportional to the stack's E_{BD}^2 this means that the theoretical energy density of DFGs could be significantly higher if it is not limited by the liquid's E_{BD} (this limit is assumed in the energy density equations used in [135]). Personal communication with an expert in dielectric generators/actuators suggested that, due to this shielding effect, DFGs true theoretical energy density could be as high or higher than DEGs depending on the employed materials.

Additionally, as the materials used in DFGs are required to be flexible, but not stretchable, the use of other materials (such as BOPP) which are used in commercial capacitors and HASEL actuators have far better electrical properties (both E_{BD} and permittivity) and would also potentially be suitable for some configurations in DFG applications. Personal communication with a dielectric generators/actuators expert highlighted that the utilisation of these materials in DFGs could significantly improve achievable energy densities of DFG systems.

Appendix B.7 — Through-life energy density of DEGs

The parameters used to estimate the through-life energy density of the DEG experiment presented in [250] are shown in Table 11-20. The material was specified as VHB 4905/4910 which are both polymer tapes made of the same material.

Table 11-20. *parameters used to estimate DEG through-life energy density.*

Parameter	Value	Source
Relative permittivity $\varepsilon/\varepsilon_0$	4.14	[136]
Material density (kg/m^3)	960	[287]
Electric field strength in test (kV/mm)	64	[250]
Area strain in test (%)	200	
Cycles to failure in test	2.3-5.3 $\times10^6$	

The equations presented in [136] can be used to estimate the maximum energy density of this set up. This is shown in Equation 11-3.

$$W_e = \varepsilon \Omega E^2 f_g$$

Equation 11-3. *Energy density of DEG.*

Where ε is the dielectric permittivity of the DE layer, Ω is the volume of the DE layer, E is the electric field applied to the DE layer during the experiment, and f_g is a parameter dependent on the ratio of stretch on the DEG between in its maximum and minimum stretch configurations, shown in Equation 11-4.

$$f_g = \ln \frac{(\lambda_1 \lambda_2)_{Max}}{(\lambda_1 \lambda_2)_{Min}}$$

Equation 11-4. *Geometric parameter describing DEG strain.*

For the experiment presented in [250] the area strain was 200%, therefore $\frac{(\lambda_1 \lambda_2)_{Max}}{(\lambda_1 \lambda_2)_{Min}} = 2$. If this area strain is substituted into Equation 11-3 and Equation 11-4 we get a maximum theoretical energy density of 104.1 J/kg. This can then be multiplied by the number of cycles to failure (2.3-5.3 million) as shown in Equation 11-5.

$$LED = ED \times N$$

Equation 11-5. *Through-life energy density of a conversion technology.*

Where ED is the cycle energy density, N is the cycles to failure and LED is the through-life energy density. The result of this calculation is a maximum through-life energy density of 2.39-5.51 $\times10^8$ J/kg. This through-life energy density is an overestimate as it assumes an idealised charging/discharging cycle and losses are discounted.

Appendix C.1 — Preliminary information for interview participants

This appendix contains the following preliminary information that was provided to the interviewees before the interview:

- Information sheet — explaining the aims of the study and the use and protection of personal data.
- Consent form — to be returned before commencing the interview, to confirm they consented to the recording of the interview and the use of personal data laid out in the information sheet.
- Barriers list — a table that summarises the barriers to dielectric elastomer based wave energy converters that were identified through the literature review and informal discussions (this is very similar to Table 7-1).
- Interview power point — a series of introductory slides that would be covered before the interview started.

Information sheet for participants

Project title: Identifying and evaluating the key barriers to the development of dielectric elastomer generators for wave energy applications.

Researcher: Paul Kerr, PhD candidate, University of Edinburgh

Contact details:

Aim: Gathering expert opinion on the key barriers[39] associated with developing dielectric elastomer generators for large-scale wave energy applications.

Objectives:

1. Identify the key barriers to development dielectric elastomers for wave energy applications.
2. Gather expert opinion on the difficulty of overcoming these barriers.
3. Gather expert opinion on what actions could be taken to overcome these barriers.
4. Gather expert opinion on the order in which these barriers should be addressed.

Methods: Literature review has been used to identify barriers to development of dielectric elastomers for wave energy applications. This will be supplemented by expert opinion by carrying out semi-structured interviews.

Dissemination: A summary of the anonymised interview findings will be included in my PhD thesis. This will be distributed to the participants before the 1st of June 2023 to ensure they do not have issues with their contributions. Full interview transcripts and identifying information will not be disseminated outside of the PhD supervision team.

Confidentiality: The confidentiality of all data will be preserved to protect the privacy of the participants and their companies/institutions. Data will be anonymised as far as possible.

Consent: All participants must provide written consent (see attached consent form). All participants may withdraw their contributions up until the 1st of June 2023. This can be done by using the contact email above.

Data protection: The personal data collected during this work will be interview recordings and notes taken summarising the interviewees responses. Data collected during this project will only be used for the explicit permission that has been obtained from the participants. Any personal data will be made available on request, and will be deleted following the completion of the study (before 1st June 2024).

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[39] A barrier can be a knowledge gap, technical limitation or any other barrier to the development of dielectric elastomer generation based wave energy devices

Updating contributions: The participants may update their contributions following their interview up until the 1st of June 2023.

Consent form

I agree to participate in the research project entitled *'Identifying and evaluating the key barriers to the development of dielectric elastomer generators for wave energy applications.'*

I have received a copy of the information sheet for participants. I am aware that the content of the interviews will be fully anonymized, and I can withdraw or amend my contribution up until the 1st of June 2023.

Name:

Signature:

Date:

Review of existing barriers to the application of dielectric elastomers in wave energy

Table 11-21 contains the barriers[40] to develop DEGs for WEC applications that were identified in a literature review and some preliminary discussions with DEG WEC experts (any potential solutions to these barriers are also shown highlighted in green). The first three columns of the table are categories/subcategories which the barriers fall under. These categories have simply been created to impose a level of order on the list of challenges and are somewhat arbitrary in nature. Additionally, a level of crossover is clear in several of these categories (for example the challenge of developing a new material to improve the performance of the DEG could have a direct effect on the ability to manufacture DEG modules).

Table 11-21. *Barriers to the development of dielectric elastomer generators for wave energy applications identified in the literature and preliminary discussions with wave energy experts. Barriers written in plain text, potential solutions written in highlighted text.*

Category	**Subcategory**		**Description of gaps and barriers and potential solutions**	
			Evidence from literature	**Evidence from preliminary discussions**
Performance of DEG	Lifetime of DEG in WEC operating conditions	Electrical fatigue	The lifetime of the DE (and therefore the DEG) is strongly dependent on the strength of the electric field that is applied to it [189]. However, there is a lack of information about the lifetime of DEs in electric fields [32], [262].	Lack of information on DEG lifetime in electric fields Possibility of electric field threshold mechanisms exist for damage accumulation of DE

[40] The definition of barrier used in this chapter is a 'knowledge gap, technical limitation or any other barrier to the development of dielectric elastomer generation based wave energy devices' however in the literature review several challenges (i.e. things that need to be done to develop dielectric elastomer wave energy devices) were also recorded.

			Possibility of electric field threshold mechanisms exist for damage accumulation of DE [3[263]]	
		Mechanical fatigue	Mechanical fatigue effects DEG lifetime. A DEG may be strained uniaxial or equiaxial depending on WEC geometry. Most fatigue studies for DE materials based on uniaxial loading which could overestimate the lifetime of equiaxial loaded DEG membranes [187]. There is a lack of information about bi-axial fatigue of DE materials. There is also a lack of information about the conductivity degradation and lifetime of electrodes under mechanical fatigue [262] especially for high strains (>200%) [136].	Lifetime of DE unpredictable in different loading conditions, large differences between single vs multi axial loading. DE fatigue considered complicated compared to other materials. Potential for crack growth in the DE through fatigue at E_{BD} sites. Bonding of encapsulation to silicone is difficult under multiple mechanical fatigue cycles.
		Environmental aging and sea water ingress	Little research on effect seawater and ageing has on fatigue life of DEs with only a few studies [187], [262]. DEG materials may need to be marinized [266]. Electrical connections (and electrodes [262]) need to be sealed and watertight [266]. Encapsulation can reduce water ingress, as demonstrated by SBM [189].	Water ingress has a 'non-negligible' effect on E_{BD} and permittivity of DE. Water ingress can be designed around, e.g. through encapsulation.

		Combined fatigue	Lack of studies on the combined effects of electrical and mechanical fatigue on lifetime of DEG [134] which will be key in determining materials and manufacturing process [136]. Especially the combination of high strains and high electric fields [189]. The effects of multiaxial fatigue coupled with the marine environment has little research, with limited facilities available to perform these tests [187].	More testing needs to be done on DEG fatigue. Autonomous testing on DEG materials outside the scope of most universities. Combined electromechanical fatigue very important, must be considered separately from electrical or mechanical.
		Trade-off between performance and lifetime	Work needed to study the trade-off between lifetime and energy density for DEGs [268] both for DE and electrodes [187][263]. Need to determine the DEG electro mechanical loading that is compatible with 10^6 - 10^7 fatigue cycles [136]. Multi-objective optimisation control mechanisms may be able to limit damage to DEG with limited impact on energy production [263].	Trade-off between mean time to failure and energy density, we need to establish a minimum required energy density for WEC applications.
	DE materials and design	Development of high-performance DE materials	Optimum DE material still subject of research, must be optimised for fatigue and large-scale manufacturing [187], [262] along with properties that maximise energy density and minimise losses [189], [262]. Materials currently in	Development of DE materials with high E_{BD} to improve energy density and potentially lifetime and reduction of dissipations.

			use are not designed/optimised for DEG applications. Need to develop new DE materials with optimized dielectric properties [136]. Material properties may be improved through dielectric fillers (nanodielectrics) however these are not widely commercially available [252] NR suggested as best for structural material in flexible WECs (low cost) [187] Silicone best for DEG (better electrical properties) [187]	Current off the shelf materials not optimised around all the different parameters required for DEGs.
		Fillers for DE materials	Optimum amounts of particle filler and reinforcement requires further research to ensure designs can operate in a wide pressurisation operational window, whilst avoiding material instabilities [187]. Dielectric fillers also suggested to improve electrical characteristics, however these are not widely commercially available [252].	Silica fillers generally work well (if properly dispersed) for DE mechanical properties, less certainty around use of fillers for electrical properties.
	Electrode materials and design	Development of high-performance electrode materials	Electrodes for DEGs need to fulfil several requirements (e.g. stretchable, flexible and have low resistance [9]). The best material/process still unclear for these electrodes [262].	

			Several potential options exist. Silicone based is most mature [262]. Corrugated metallic electrodes could offer extensibility in one direction [187], [252] carbon based (e.g. nanotubes also option)	
		Electrode connection design	Connection required between power electronics and electrodes in DEG. Stress relieving connections required for transition between stretchable electrodes and rigid wires [189]	
	DEG performance at scale	Flaws in large-scale DEs	Increased likelihood of electrical failure in large area DE films due to higher probability of flaws within sample [134], [189] (proportional to area of dielectric [252]) this can severely limit the operating field for large DE films. Three main options to resolve this: segmentation of electrodes [189], self-clearing electrodes (both used in capacitor industry - must be developed for deformable materials [252]) or segmentation of DE [134] (additionally a flaw-free DE would solve issue, but manufacturing considered unfeasible)	Increased likelihood of electrical failure in large area films due to higher probability of flaws permittivity also lower. Self-clearing or segmented electrodes required. This needs to be stable through high number of fatigue cycles and have good adhesion to DE. Modular DEG could help, however power electronics more complex. Self-healing materials Carbon nano-tube or graphene self-clearing electrodes in development.

Manufacturing DEG (at scale)	Manufacturing DE films	Control of manufacturing process	DE membranes need to be produced in thin uniform films with few flaws. High level of control of process quality therefore required at high production rates [189]. Films not designed for DEG applications generally of insufficient quality (e.g. materials such as styrene rubber and natural rubber) [136]. Natural rubber also cannot be procured in films of <200 µm [136].	
		Manufactured scale of DE	DE films can only be procured in small sizes, industrial production of single layer DE of rolls with width of only up to 1.4 m [32]. These process will need to be redesigned for greater widths if required for DEG WEC [262]. Current manufacturing process only at small-scale for silicone, this can be upscaled however currently very expensive [262]. Manufacturing processes not mentioned for other DE materials. DE manufacturing can be investigated using processes already adopted in plastics industry: Calendaring production lines, dealing with the automatic mixing	Large scale uniform and thin membrane is difficult to manufacture, there are not many other applications that also require these characteristics. Currently, precise DE film cannot be manufactured at a large-scale. For example, large discs of DE very hard to manufacture. Small-scale DE becomes too stiff without stiffness compensation or multiple small modules joined together. Strips could be joined together to make shapes that would be difficult to manufacture otherwise.

			of compounded materials and shape setting through a cascade of rolls [32].	
	Manufacturing electrodes	Electrode manufacturing	Manufacturing study needed for electrodes [262].	
		Electrode connection manufacturing	Manufacturing study needed for electrode connections [262].	
	DEG module fabrication and joining	Fabrication processes and bonding of DE and electrodes	Lack of scalable processes for fabrication and bonding of DE and Electrodes [32], [262][136]. Bonding between silicone DE and silicone electrodes easy however, for Styrene rubber and NR manufacturing process undefined for whole modules [262]. Potential processes for fabricating DEG modules include pad printing, blade casting, spray coating, screen printing and inkjet printing [32] roll to roll electrode decomposition [262] and 3D printing [187].	Silicone DE and silicone electrodes can be joined easily.
		Joining DEG modules	If modular DEGs are joined together then a joining process needs to be developed that maintains similar mechanical properties at joins [262]. This is needed to avoid stress concentrations.	

	Cost of manufacturing DEG	Cost of DE films	Costs of manufacturing DE films currently very high and production volumes are low [32].	DE films for small-scale applications currently very expensive and produced in small batches.
		Cost of manufactured DEG		Uncertainty about the costs of scale manufacturing DEGs.
System integration challenges for DEG WEC	Design and modelling of DEG based WEC	DEG WEC design	To take advantage of DEGs, new WEC architectures need to be designed. These could be soft and compliant [32]. Proposed that these could use elastomeric composite laminates for the prime mover and tensile membrane structures for the WEC structure [262]. Large DE volumes or shear modulus can increase DEG stiffness [136] this may need to be counterbalanced to enable resonant WECs (e.g. large hydrodynamic inertia or negative hydrostatic stiffness) [32]. Instabilities can occur in inflatable DEG membranes [187]. Mechanical losses in tube walls of bulge wave WECs significant [190]. Overload protection required for DEG [262].	WECs need to be designed that take into account of the limitations of current DEG manufacturing processes and also limit structural costs. Moderate strains needed in DEG WEC to allow a reasonable energy density and limit material requirements.

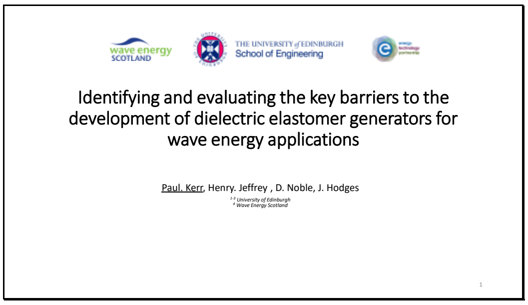
			Pressure differential diaphragm WECs have natural stiffness compensation [266].	
		Modelling	Lack of hydrodynamics modelling tools that can integrate elastomer materials [134], [187]. This includes difficulties in modelling the membrane interface [187], PTO damping [187], elastomeric material fatigue [187] and scaling laws for efficiency [32].	
		Availability of power electronics	Basic components already exist for power electronics at full-scale, however they are not available for small-scale < 1:5 prototypes [262]. DC-DC converters with the correct specifications 'virtually unavailable' [32]. High voltage DC-DC power electronic systems have been recently introduced by ABB [262] for marine renewable energy. Further investigation required to see if they are suitable for DEGs. Input-parallel output-series (IPOS) cascading of DC-DC converters enables the high driving voltages required by DEGs while using standard electronic components [136].	DC-DC converters with specifications for large DEG WECs do not exist. No other markets exist for these high voltage DC-DC converters. Struggle to find single components for this application at a small scale. Architecture relatively simple and efficiencies of >90% demonstrated already. Easy enough to adapt existing components.

	Control	Self-sensing	Development of robust sensing and control strategies (based on self-sensing or external DEG stretch sensing) and efficient power electronics that can operate in random wave conditions [136]	Self-sensing highlighted as being important and processes already have been developed.
Environment effects of DEG	Disposal of DEG	Recyclability/disposal of DEG at end of life	Recycling, partial recovery or energy recovery (incineration) possible for some DE materials [262] however recycling processes are not commonly used for these materials at present. No studies on recycling of DEG modules, may be complicated due to multiple thin layers of alternating materials. Natural rubber is biodegradable [136]	
	Degradation of DEG in marine environment	Chemical leaching	Commercially available DE membranes have a lot of additives that have different roles. Many additives are not chemically bonded so can leach out [140]. Weathering of DE can also result in the creation of microplastics [262]. Silicones more environmentally friendly as they do not use plasticisers which can leech [288]. Additionally they have the most stable polymer chain [140]	
	Electric shock risk	Electric shock risk if membrane damaged	Potential electric shock hazard if membranes are damaged [140].	

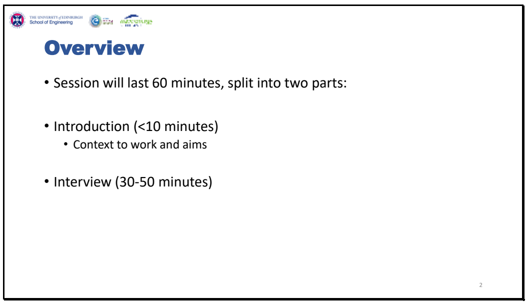
Other challenges		Drag forces on large devices	large membrane devices can be adversely effected by tidal drag (location specific) [187].	
		Collision risk	Lack of knowledge around the collision risk associated with membrane based WECs [262].	

Interview power point slides

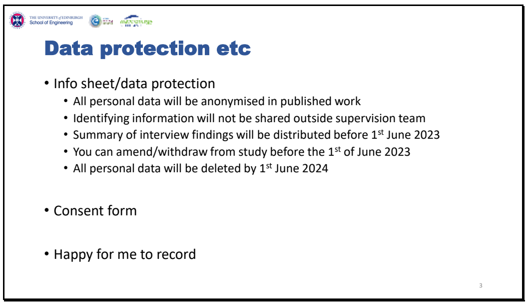
Slide 1



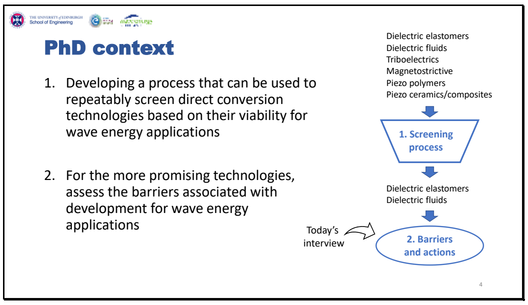
Slide 2



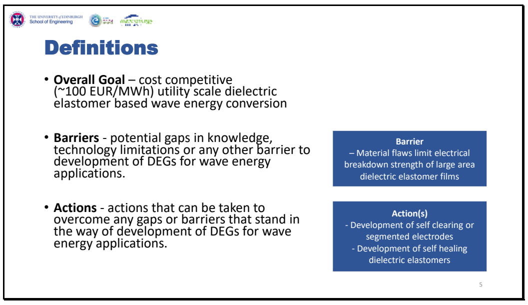
Slide 3



Slide 4



Slide 5



Slide 6

Aims of discussing barrier and actions

- Develop comprehensive list of the barriers to DEG development for wave energy applications
- Expert opinion on:
  - Importance
  - Actions
  - Difficulty
  - Prioritisation
- Outcome – an evaluation of the research required to adapt DEGs for wave energy applications
- Focus on areas that you have experience
- Not focussing on generic wave energy barriers

Importance
What are the key barriers?

Actions
What actions can be taken to overcome barriers?

Difficulty
How difficult will the actions be to achieve?

Prioritisation
What order should we address barriers?

6

Slide 7

Research challenges – method

Literature review

- Review existing literature on DEG WECs
- Create list of existing barriers and potential solutions
- Arrange into categories

Semi-structured interviews with DEG WEC experts

- Update list of barriers
- Assess the importance and difficulty of these barriers
- What actions are needed to overcome barriers
- Is there an order in which barriers should be addressed

7

Slide 8

Category	Sub-Category
Performance of DEG	Lifetime of DEG in WEC operating conditions
	DE materials and design
	Electrode materials and design
	DEG performance at scale
Manufacturing DEG (at scale)	Manufacturing DE sheets
	Manufacturing electrodes
	DEG module fabrication and joining
	Cost of manufacturing DEG
System integration challenges for DEG WEC	Design and modelling of DEG based WEC
	Power electronics for DEG
	Self sensing and control
Environment effects of DEG	Recyclability of DEG at end of life
	Degradation of DEG in marine environment
	Electric shock risk if damaged

8

Slide 9

Interview questions – overview

- **Introductory questions** (5-10 mins)
  - Establishing the areas for discussion
- **Main questions** (20-30 mins)
  - Importance of addressing barrier(s)
  - Actions to address barrier(s)
  - Difficulty of carrying out action(s)

  } Repeated for each barrier we discuss
- **Closing questions** (5 mins)
  - An order in which barriers should be addressed?

9

Slide 10

Introductory questions

- Is there anything you don't understand or need clarified?
- Does this show the key categories where barriers exist to the development of DEGs for wave energy?
- Which categories would you like to discuss during this interview? (focus on areas in which you have knowledge)

10

Slide 11

Main questions

- In the area of… what do you think the key barriers for DEGs in wave energy applications?

Slide 12

Main questions - for each barrier

1. What makes this an important barrier to dielectric elastomers in wave energy applications?
2. What action (or actions) do you think are needed to overcome this barrier?
3. How difficult do you think it will be to achieve these actions?
   scale of 1-5 where: 1) Very Low 2) Low 3) Moderate 4) High 5) Very High
4. Are you aware of work being done that could address these actions?
   or transferable solutions from other sectors etc.

Slide 13

Closing questions

- Looking at all the barriers, do you think some are higher priority than others?
- Any other comments

Appendix C.2 — Full interview schedule

This appendix presents the interview schedule that was used to conduct the interviews. The main questions are shown in black text, while potential prompts to be used during the interview are shown in blue italic text.

Introduction questions

1. Is there anything you don't understand or need clarified?

This can be from what I've presented or the information I sent out in advance.

2. Does this show the key areas where barriers exist to the development of DEGs for wave energy?

<show table>

Or if there is something you would add to the list of categories

If something comes to mind, we can come back to this

3. Which areas would you like to discuss during this interview?

Areas in which you have a good amount of knowledge regarding the barriers to DEG WEC development

<note down barriers>

Main questions

The following questions will be asked for each category:

4. In the area of… what do you think the key barriers are to DEGs in wave energy applications?

knowledge gaps, technical limitations or other barriers

Define key - knowledge gaps and technical barriers that if not addressed have a high (>50%) chance of stopping DEG WECs from being viable

OK so we will start with…

5. What do you think makes this an important barrier to dielectric elastomers in wave energy applications?

6. What action (or actions) do you think are needed to overcome this barrier?

Technology development, research and testing etc.

7. How difficult do you think it will be to achieve these actions?

This can be in terms of the time, resources, equipment, investment etc.

So if you could put it on a scale of 1-5 where Very Low/Low/Moderate/High/Very High

Why is it difficult to address this barrier?

8. Are you aware of work that could address these actions?

Are solutions under development? (if so what)

Could solutions be transferred from other sectors? (if so what)

Will a bespoke solution need to be developed?

Closing questions

9. Looking at all the barriers, is there any way you would prioritise addressing these?

Could you give the order of any barriers you believe need to be addressed before moving on to others?

Why would you need to address this barrier before moving onto the next one?

10. Any other comments

Thank you again for taking part, I will get the summary of our discussion to you within two weeks.

Appendix C.3 — Full interview summaries

This Appendix presents the interview summaries for each of the interviews with the DEG WEC experts. These summaries were sent out to allow any changes to be made by interviewees following their interviews. Identifying personal information has been removed from these summaries (interviewees name or organisation). The barrier and action indexes have also been added to the appendix.

Interviewee 1

Individual summary tables

- Background in mechanical engineering, design, modelling, instrumentation and controls for wave energy converters
- Spent the last 13 years in the wave energy sector

Prioritisation:

1. Need to address the lack of innovative strategies for the use of DEGs in wave energy.
2. Outreach activities, need to get the word out about DEGs and their potential applications in wave energy. This could help leverage existing experience in other technology areas.

Table 11-22. *Interview 1 summary table. The selected for interview column indicates the categories that were discussed during the interview based on the participant's expressed expertise, highlighted italic text indicates a critical challenge that was not identified in the literature, green highlighted cells indicate the areas discussed in interview*

Category	Subcategory	Key barriers	Actions	Difficulty (1-5)
Performance of DEG	Lifetime of DEG in WEC operating conditions			
	DE materials and design			

	Electrodes materials and design			
	DEG performance at scale			
Manufacturing of DEG (at scale)	Manufacturing DE sheets			
	Manufacturing electrodes			
	DEG module assembly and joining			
	Cost of manufacturing			
System integration	Design and modelling of DEG based WEC	Design of a WEC to utilise DEGs - we don't necessarily know what the best geometry or configuration is to utilise DEGs in a wave energy converter. Considering DEGs as conventional PTO replacements may not be appropriate.	DEG WEC design from foundational principles without bias - need to evaluate the potential of DEG based wave energy converters without the influence of wave energy conversion community or conventional wave energy conversion thought processes.	*5*
	Power electronics for DEG	Design of power electronics - DEGs require a pre-charge to generate electricity. This adds a layer of complexity compared to a conventional generator.	WEC design for power electronics - need to consider the fundamentals such as connection to utility grid for pre-charge and building in redundancy/contingency for power electronics.	*2-3*
Environmental impact	Recyclability of DEG at end of life			
	Degradation of DEG materials in marine environment			
	Electrical shock risk			

Key barriers and actions from interview

1. **Is there anything you don't understand or need clarified?**

All clear.

2. **Does this show the key categories where barriers exist to the development of DEGs for wave energy?**

Agreed that the categories and subcategories sounded appropriate.

3. **Which categories would you like to discuss during this interview?**

Happy to discuss any category.

Main questions

Barrier category: All categories.
Subcategory:

4. **In the area of… what do you think the key barriers are to DEGs in wave energy applications?**

B1 Design of a WEC to utilise DEGs

B2 Design of power electronics

5. **What do you think makes this an important barrier to dielectric elastomers in wave energy applications?**

B1 Design of a WEC to utilise DEGs - we don't necessarily know what the best geometry or configuration is to utilise DEGs in a wave energy converter. Doesn't believe that we have seen the best use or consideration of DEGs for wave energy converters, as a lot of R&D has focused on replacing conventional PTO systems with DEGs. We need to ask why DEGs are considered as a potential replacement for conventional PTOs and if this makes sense. Considering DEGs as conventional PTO replacements is trying to classify, characterize and evaluate DEGs under a paradigm that may not be appropriate for DEG's. Believes this gives a false representation of the potential of DEGs in wave energy applications.

B2 Design of power electronics - DEGs require a pre-charge to generate electricity. This adds a layer of complexity compared to a conventional generator where the power is flowing from the generator to the grid. Likely to be very dependent on WEC design if this is a large barrier or not. If there is redundancy through distributed DEGs throughout WEC the reliability of the power electronics may be less important.

6. **What action (or actions) do you think are needed to overcome this barrier?**

A1 (B1) DEG WEC design from foundational principles without bias (addressing design of a WEC to utilise DEGs) - an evaluation of the potential of DEG based wave energy converters without being influenced by the wave energy conversion community or current wave energy conversion thought processes. This would lead to a more honest evaluation of DEGs on their own, rather than as a replacement for conventional WECs.

A2 (B2) WEC design for power electronics (design of power electronics) - consider fundamentals such as the connection to utility grid, as this will likely be source of pre-charge and having a level of redundancy/contingency built in to power electronics.

7. **How difficult do you think it will be to achieve these actions?**

A1 (B1) DEG WEC design from foundational principles without bias (5) - based on how other domains of technologies have evolved, it requires significant amounts of time until mainstream acceptance is achieved. Anticipates it will take a significant amount of time just to get buy-in to consider the use of DEGs in wave energy conversion. This lack of acceptance comes as the technology is under the umbrella of utility-scale wave energy conversion. Then specifically WEC designers/developers have their own ideas about the best WEC design, which typically is unlikely to be based on DEGs. This means there are a low number of developers already interested in DEGs, which makes DEGs an underdog out of the gate compared to other kinds of energy conversion.

A2 (B2) WEC design for power electronics (2-3) - an obstacle, but not based on a paradigm change in the same way that is needed to design the WEC (in general) for DEGs. Very likely the know-how to design power electronics already exists in other electrical engineering sectors.

8. **Are you aware of work that could address these actions?**

A1 (B1) DEG WEC design from foundational principles without bias - NREL project investigating DEG wave energy conversion as part of the technology domain of distributed energy transducers for wave energy applications. Prize called InDEEP[41] has been launched which gives the broader public the opportunity to win money based on developing distributed energy transducers, DEGs is a viable option for this. WEC developers/concepts including Bombora emWEC, SBM S3, PolyWEC.

A2 (B2) WEC design for power electronics - any major industries working in power electronics are likely to have relevant transferable knowledge e.g. EVs, electrical utilities.

[41] https://americanmadechallenges.org/challenges/indeep/

Closing questions

9. Looking at all the barriers, is there any way you would prioritise addressing these?

Highest priority is the lack of innovative strategies for the use of DEGs for wave energy conversion. Need to develop conceptualization and innovation techniques and mindset and culture that can develop wave energy converters that are specifically based on DEGs.

Second highest priority is outreach activities. Getting the word out about the technology (DEGs) and that it can be used for wave energy conversion. This could help accelerate the use of DEGs in wave energy applications by leveraging existing experience in other technology areas, such as soft robotics and material science.

10. Any other comments

Interviewee 2

Individual summary tables

- Materials background, not wave energy specifically
- Works in functional composite materials, including dielectric elastomers

Prioritisation:

1. Reliability at scale and being able to model the effect scale has on the statistical distribution of failure of a DE sample
2. All other barriers

Table 11-23. Interview 2 summary table. *The selected for interview column indicates the categories that were discussed during the interview based on the participant's expressed expertise, highlighted italic text indicates a critical challenge that was not identified in the literature, green highlighted cells indicate the areas discussed in interview*

Category	Subcategory	Key barriers	Actions and potential knowledge transfer	Difficulty (1-5)
Performance of DEG	Lifetime of DEG in WEC operating conditions	Defects and reliability at scale - at large scales there will be a higher probability of a defect which will create a weak point in a DE material. This is an issue when DE is subjected to large amplitude cyclic mechanical fatigue and electric fields.	Low defect DE materials - reduction of defect quantity and size in DE materials. This is the route the capacitor market has taken with conventional high-quality polymers.	2-3
	DE materials and design	Changes in DE material properties during fatigue cycles - lack of knowledge of the effects of mechanical fatigue on DE material's permittivity and E_{BD} strength.	Modelling and fatigue testing of DE materials - standard tests and modelling, and the equipment already exists. However, time consuming and requires dedicated project.	3
	Electrodes materials and design	Stretchable electrodes - electrodes for DEGs required to be stretched to same level as DE. However traditional electrodes such as metallic paint are not stretchable.	Development of stretchable electrodes - don't have to deal with the electric fields you do in the DE. Believes this can be achieved with a good	1-2

			composite material. Other applications such as wearable electronics also working on this.	
	DEG performance at scale	(see lifetime)		
Manufacturing of DEG (at scale)	Manufacturing DE sheets			
	Manufacturing electrodes			
	DEG module assembly and joining			
	Cost of manufacturing			
System integration	Design and modelling of DEG based WEC			
	Power electronics for DEG			
	Control and self-sensing	Sensing of DE deformation and health - will enable more optimised charging and discharging cycles and monitoring of any defects.	Measuring capacitance - fundamentally not difficult and can be used to estimate deformation if calibrated against a model. Also, capacitance changes already monitored for breakdown monitoring in Piezoelectrics and deformation estimation in DEAs.	1-2
Environmental impact	Recyclability of DEG at end of life			
	Degradation of DEG materials in marine environment			
	Electrical shock risk			

Key barriers and actions from interview

1. **Is there anything you don’t understand or need clarified?**

All made sense.

2. **Does this show the key categories where barriers exist to the development of DEGs for wave energy?**

Yes, thinks it shows all categories. Would consider using the word reliability instead of lifetime.

3. **Which categories would you like to discuss during this interview?**

DEG lifetime, DE materials and design, Electrode materials and design, DEG performance at scale, Self-sensing

Main questions

Challenge category: Performance
Subcategory: DEG lifetime, performance at scale

4. **In the area of… what do you think the key barriers are to DEGs in wave energy applications?**

B3 Defects and reliability at scale - at larger scale there is higher probability of a defect in the sample.

Use of composite DEs - using high permittivity fillers in elastomers creates localised electric field concentrations.

5. **What do you think makes this an important barrier to dielectric elastomers in wave energy applications?**

B3 Defects and reliability at scale - at large scales there will be a higher probability of a defect which will create a weak point in a DE material. When you're stretching the DEG to high strain and applying large electric fields there will be an even greater probability of failure. Weibul statistics can be used to predict the number of defects or weak points in a sample as it is scaled up.

High performance DEs - using high permittivity fillers in elastomers creates localised electric field concentrations. These reduce the overall E_{BD} of the composite, reducing the achievable energy density (See [278]).

6. **What action (or actions) do you think are needed to overcome this barrier?**

A3 (B3) Low defect DE materials (addressing defects and reliability at scale) - reduction of defect quantity and size. This is the route the capacitor market has taken with conventional high-quality polymers.

A4 (B3) Self-healing DE materials (addressing defects and reliability at scale) - potentially interesting to develop self-healing DEs. This could reduce the defects in a DE material.

Composite materials (addressing defects and reliability at scale) - does not think this is a good option.

7. **How difficult do you think it will be to achieve these actions?**

A3 (B3) Low defect DE materials (2-3) - seems like a more sensible route than having an extremely modular DEG. This is for industry to do, however they need to see that there is a market for it.

Composite materials (5) - sort of impossible.

8. Are you aware of work that could address these actions?

A4 (B3) University of Warwick working on self-healing DE materials. However, with these materials you need to clean out the breakdown site and wait 24h, which may be difficult to implement in a WEC.

Not aware of DEG specific high quality elastomer manufacturing.

Challenge category: Performance
Subcategory: DE materials

4. **In the area of… what do you think the key barriers are to DEGs in wave energy applications?**

B4 Changes in DE material properties during electrotechnical fatigue cycles - lack of knowledge of the effects of mechanical fatigue on DE material's on permittivity and E_{BD} strength.

5. **What do you think makes this an important barrier to dielectric elastomers in wave energy applications?**

B4 Changes in DE material properties during electrotechnical fatigue cycles - not noted, however these will effect the DEGs energy density and its ultimate reliability. Work has been done on static experiments, but not aware of a lot of work done on experiments including mechanical and electrical cycles.

6. **What action (or actions) do you think are needed to overcome this barrier?**

A5 (B4) Modelling and fatigue testing of DE materials (to address changes in DE material properties during electrotechnical fatigue cycles) - develop a better understanding of what is happening in DE's that induces failure. This would include both simulation and experiments testing DE materials under combined electrical and mechanical fatigue cycles. This could help better quantify the effect of defects on DE material's reliability.

7. **How difficult do you think it will be to achieve these actions?**

A5 (B4) Modelling and fatigue testing of DE materials (3) moderate difficulty as these would be standard tests and modelling, and the equipment will already exist. However, it would be time consuming and require a dedicated project.

8. **Are you aware of work that could address these actions?**

Not aware of any.

Challenge category: Performance
Subcategory: Electrode materials and performance

4. **In the area of… what do you think the key barriers are to DEGs in wave energy applications?**

B5 Stretchable electrodes - electrodes for DEGs required to be stretched to same level as DE.

5. **What do you think makes this an important barrier to dielectric elastomers in wave energy applications?**

B5 Stretchable electrodes - silver or platinum paint traditionally used for their experiments on ceramics, however these would crack and lose their electrical connection if applied to a DE. Carbon grease used in prototypes, but liable to flow or change its properties. Using carbon nanotubes or composite elastomers could work if interface is good between DE and electrode.

6. **What action (or actions) do you think are needed to overcome this barrier?**

A6 (B5) Development of stretchable electrodes (addressing Stretchable electrodes) - develop electrodes that are similar in terms of mechanical properties to the DE, this could be using a filler in an elastomer to make it conductive.

Use of carbon grease (addressing Stretchable electrodes) - investigate if carbon grease can work at scale, however stated that unconvinced by this.

7. **How difficult do you think it will be to achieve these actions?**

A6 (B5) Development of stretchable electrodes (1-2) low difficulty as don't have to deal with the electric fields you do in the DE and other applications (such as wearable electronics) are also developing stretchable electrodes. Believes this can be achieved with a good composite material. Complexities could come with the adhesion and bonding of the electrodes to the DE.

8. **Are you aware of work that could address these actions?**

A6 (B5) Stretchable and wearable electronics, including nanowires embedded in elastomers. Pooi Lee at Nanyang Technological university is working on that - https://doi.org/10.1016/j.mattod.2017.12.006

Challenge category: Systems integration
Subcategory: Self-sensing and control

4. **In the area of… what do you think the key barriers are to DEGs in wave energy applications?**

B6 Sensing of DE deformation and health - being able to sense the level of deformation on the DE and if there are any issues with it's structural health.

5. **What do you think makes this an important barrier to dielectric elastomers in wave energy applications?**

B6 Sensing of DE deformation and health - need to charge and discharge DEG at right times to maximise efficiency. For this the level of deformation and/or capacitance of the DE need to be known. Additionally, being able to monitor if there is any degradation in the DE would allow the onset of failure to be sensed.

6. **What action (or actions) do you think are needed to overcome this barrier?**

A7 (B6) Capacitance measurement (addressing sensing of DE deformation and health) - this can be used to estimate the DEGs deformation and state of health of the DE. This is already employed in DE actuators.

7. **How difficult do you think it will be to achieve these actions?**

A7 (B6) Capacitance measurement (1-2) low difficulty as measuring capacitance is fundamentally not difficult and can be used to estimate deformation if calibrated against a model. Also, capacitance changes already monitored for breakdown monitoring in Piezoelectrics and deformation estimation for DEAs.

8. **Are you aware of work that could address these actions?**

A7 (B6) Patrick Keogh and others in bath using capacitance self-sensing on actuators to estimate DEA deformation.

Closing questions

9. Looking at all the barriers, is there any way you would prioritise addressing these?

Reliability at scale is the highest priority. Being able to model the statistical distribution of failures relation to the scale of DE materials would be very beneficial.

10. Any other comments

Interviewee 3

Individual summary tables

- Works on DEG systems design for wave energy
- Includes work on material selection, electrical and mechanical characterisation and manufacturing processes

Prioritisation:

1. Addressing volume effect, if this is not solved large-scale applications will not be a competitive form of electricity generation.
2. understanding the combined electro mechanical lifetime of DEGs as there is currently limited knowledge of this.

Table 11-24. *Interview 3 summary table. The selected for interview column indicates the categories that were discussed during the interview based on the participant's expressed expertise, highlighted italic text indicates a critical challenge that was not identified in the literature, green highlighted cells indicate the areas discussed in interview*

Category	Subcategory	Key barriers	Actions and potential knowledge transfer	Difficulty (1-5)
Performance of DEG	Lifetime of DEG in WEC operating conditions	Lack of understanding of electromechanical coupling effects on lifetime - likely a synergistic effect of mechanical and electrical fatigue on DEG, there is limited knowledge about this.	Repairability or redundancy in system - this would allow continued operation after either an electrical or mechanical failure. Fatigue testing - full DEG fatigue testing in relevant environment will give most representative characterisation.	Depends on volume effect
	DE materials and design	Fatigue life of DEs - covered elsewhere. Inclusion of flaws in DEs - covered elsewhere. Electromechanical instabilities - increasing permittivity of DE material increases the Maxwell pressure between the electrodes.	Actions addressing defects and volume effect - theoretical energy density of DE materials is already sufficiently high for WEC applications. Therefore, the highest priority for materials is addressing defects and volume effect which limits electrical and mechanical performance of DE.	

	Electrodes materials and design	Adhesion between self-clearing electrodes and DE - adhesion will be important using self-clearing electrodes (e.g. carbon nanotubes or graphene) to silicone DE. This is because silicone-based electrodes are not suitable for self-clearing.	(see joining)	N/A
	DEG performance at scale	DE material properties for very large quantities of film - when DE is scaled up to 100's of m^2 it is almost impossible to avoid localised weak points caused by voids or inclusions. These sites initiate E_{BD} or mechanical fatigue, limiting the DEG's performance.	Development of suitable self-clearing electrodes - these need to isolate an E_{BD} site. This would allow the DEG the system to survive even if there are several electrical breakdowns. This is already done in the HV capacitor industry for non-stretchable electrodes.	4-5
Manufacturing of DEG (at scale)	Manufacturing DE sheets	Not considered a barrier for silicone sheets.		
	Manufacturing electrodes			
	DEG module assembly and joining	Joining of silicone DE - Adhesion to silicone is difficult under fatigue, this could be joining of: DE to electrodes, DEG module to encapsulation or DEG module to DEG module.	Improved understanding of chemical processes for silicone adhesion - chemical experts required to develop better understanding of chemical processes for silicone adhesion.	N/A
	Cost of manufacturing	Considered to still be a potential issue for DE sheet manufacturing.		
System integration	Design and modelling of DEG based WEC			
	Power electronics for DEG			
Environmental impact	Recyclability of DEG at end of life	Silicone DEGs can be recycled.		
	Degradation of DEG materials in marine environment			
	Electrical shock risk			

Key barriers and actions from interview

1. **Is there anything you don’t understand or need clarified?**

All clear.

2. **Does this show the key categories where barriers exist to the development of DEGs for wave energy?**

Need to consider electrical and mechanical lifetime separately as they are distinct. The effect of operating conditions, humidity or water absorption in polymer and the effect of this on electrical properties is very important.

3. **Which categories would you like to discuss during this interview?**

Lifetime of DEG, DE materials and design, Electrode materials and design, Performance at scale, Fabrication and joining.

Main questions

Challenge category: Performance
Subcategory: Lifetime of DEG

4. **In the area of… what do you think the key barriers are to DEGs in wave energy applications?**

B7 Lack of understanding of electromechanical coupling effects on lifetime - the effects of electric field on silicone has been investigated, and has shown a good lifetime under a constant electric field. However, if you combine both cyclic electrical and mechanical fatigue there is probably a synergistic effect. This probably results in faster failure than if you simply apply a DC voltage to the material and wait for its failure. There is a lack of other applications where elastomers (such as silicone) are subjected to high cycle large amplitude mechanical and electrical fatigue.

5. **What do you think makes this an important barrier to dielectric elastomers in wave energy applications?**

B7 Lack of understanding of electromechanical coupling effects on lifetime - DEG needs sufficient lifetime to recoup capital costs, however there is limited understanding of the achievable lifetime of DEGs in wave energy applications.

6. **What action (or actions) do you think are needed to overcome this barrier?**

A8 (B7) Repairability or redundancy in system (to address lack of understanding of electromechanical coupling effects on lifetime) - With electrical failure if you have multiple DEGs in your system if one fails then the system continues to operate with only a small impact on performance. If watertightness of DEG modules is lost due to mechanical failure the entire system can become inactive. Either a replacement of a DEG module or a way to allow the system to continue to operate after a failure of one of its components is required.

A9 (B7) Fatigue testing (to address lack of understanding of electromechanical coupling effects on lifetime) - fatigue testing of materials could be part of solution, but you will get a characterisation fatigue behaviour that may not be sufficient for DEGs in a real environment. You probably need to enhance the fatigue performance of the materials for a real system so you are operating far from the mechanical limits. Testing of whole DEG modules will give a better characterisation.

7. **How difficult do you think it will be to achieve these actions?**

A8 & A9 (B7) Both actions - depends on volume effect. Addressing lifetime concerns would be relatively easy at a laboratory scale, however, when solving at a large-scale with a system composed of multiple modules with tonnes of DEs then it becomes a very difficult barrier. At lab scale you can produce a very nice sample with few weak points (crack initiators etc.). But if you want to make your DEG 100m long, then making it defect free is almost impossible.

8. **Are you aware of work that could address these actions?**

A8 & A9 (B7) Testing carried out by interviewee combining both mechanical fatigue of elastomers and the effect this has on E_{BD} strength. Electrical characterisation is being carried out both with DE and electrodes. This is important as defects (e.g. inclusions) in electrode, can cause thinning of DE when stacked together, which results in local areas of enhanced electrical field. Additionally local electric fields are higher at edges of capacitor (fringe effects). Therefore, electrical characterisation is better on a representative DEG system rather than just the DE. This is also true for mechanical fatigue as a crack could initiate in the electrode and spread through entire system.

Challenge category: Performance
Subcategory: DEG performance at scale

4. **In the area of… what do you think the key barriers are to DEGs in wave energy applications?**

B8 DE material properties for very large quantities of film

5. **What do you think makes this an important barrier to dielectric elastomers in wave energy applications?**

B8 DE material properties for very large quantities of film - testing material samples that are a few mm in size (cylinders with a few mm diameter) high E_{BD} is observed (for silicone over 200 kV/mm) which is sufficient for good energy production. However, as you scale up to 100's of m^2 it is very hard to avoid contamination or air bubbles in the DE sample. This results in localised weak points were E_{BD} occurs, significantly limiting the DEGs performance. In interviewees opinion you can take all the precautions to reduce these defects, however defect free DEs cannot be achieved for systems composed of 100's of m^2 of DE.

6. **What action (or actions) do you think are needed to overcome this barrier?**

A10 (B8) Development of suitable self-clearing electrodes (addressing DE material properties for very large quantities of film) - developing self-clearing electrodes which isolate an E_{BD} site would allow the DEG the system to survive even if there are several breakdowns during its lifetime.

7. **How difficult do you think it will be to achieve these actions?**

A10 (B8) Development of suitable self-clearing electrodes (4) - probably high level of difficulty. These electrodes exists in HV capacitor industry, however these are not stretchable electrodes, so you need to do the same but with stretchable materials. Metals work well as you get a sharp transition when you go above melting temperature that allows self-clearing. However, these are not stretchable. Silicone based electrodes will not work, therefore some other option will be required. Carbon nanotubes show self-clearing properties at lab scale, however, to burn the carbon nanotube you need oxygen. Not clear if/how you would have oxygen in a multilayer DEG assembly.

Adhesion between self-clearing electrodes and DE (N/A) -silicone-based electrodes can easily adhere to silicone DE. However, adhesion will be important using different self-clearing electrodes (e.g. carbon nanotubes or graphene). If the DE and electrode layers are not properly bonded together then you will get friction which could spread the electrode, which could diminish the self-clearing properties.

8. **Are you aware of work that could address these actions?**

A10 (B8) Carbon nano tubes potential option, research is being done into this. Graphene electrode have been tested by interviewee's organisation showing self-clearing properties. A process like spraying will be needed to coat the electrodes onto the DE.

Challenge category: Performance
Subcategory: DE material and design

4. **In the area of… what do you think the key barriers are to DEGs in wave energy applications?**

Fatigue life of DEs - covered in first section.

Inclusion of flaws in DEs - covered in first section.

B9 Electromechanical instabilities - increasing permittivity of DE material increases the Maxwell pressure between the electrodes.

5. **What do you think makes this an important barrier to dielectric elastomers in wave energy applications?**

B9 Electromechanical instabilities - Maxwell pressure increased by increasing DE permittivity [277]. Stress in the DE prevents system collapse. If the Maxwell pressure exceeds the compressive strength of the DE then you get an instability. Therefore, permittivity increases the ease of electromechanical instabilities. In a DEG system which is driven by electrotechnical instabilities therefore this creates a limit on the permittivity increase. This is only valid for a system that is driven by electromechanical instabilities due to the materials properties, not defects.

6. **What action (or actions) do you think are needed to overcome this barrier?**

A11 (B9) Actions addressing defects and volume effect (addressing electromechanical instabilities) - the theoretical energy density of existing DE materials are already sufficiently high for wave energy applications (~1000 J/kg). However large systems energy density will be driven by defects unless work is done to address the volume effect. This is more of a limiting factor than formulating new materials, especially considering the trade-off between electromechanical instabilities and permittivity.

7. **How difficult do you think it will be to achieve these actions?**

See DE properties for very large quantities of film.

8. **Are you aware of work that could address these actions?**

See DE properties for very large quantities of film.

Challenge category: Manufacturing
Subcategory: Joining

4. **In the area of… what do you think the key barriers are to DEGs in wave energy applications?**

B10 Joining of silicone DE - adhesion to silicone is difficult under fatigue, this could be joining of DE to electrodes, DEG module encapsulation or other DEG modules.

5. **What do you think makes this an important barrier to dielectric elastomers in wave energy applications?**

B10 Joining of silicone DE - adhesion to silicone difficult under fatigue cycles as will be found in DEG WEC. A good static adhesion can be achieved, but difficult to avoid de-lamination over thousands or millions of fatigue cycles. This could result in failure between modules (module to module joining), within modules (electrode to DE joining) or between the DEG and waterproof encapsulation. This means you can have a material that survives high cycles of mechanical fatigue during lab tests, however when using it in reality the joins are the weak points and the system has to be designed around these rather than the base silicone material.

6. **What action (or actions) do you think are needed to overcome this barrier?**

A12 (B10) Improved understanding of chemical processes for silicone adhesion (addressing Joining of silicone DE) - chemical experts required to address this barrier who understand the chemical processes for silicone adhesion. If better adhesion processes cannot be found/developed the DEG system may need to be designed around the mechanical fatigue life of the current joints.

7. **How difficult do you think it will be to achieve these actions?**

A12 (B10) Couldn’t answer as not area of expertise.

8. **Are you aware of work that could address these actions?**

A12 (B10) Improved understanding of chemical processes for silicone adhesion - often modification of surface chemistry and surface properties of silicone are used to aid adhesion. Plasma treatment can modify surface properties ineffective over long durations. Increasing surface roughness may be an option, however potentially difficult with silicone DE.

Closing questions

9. **Looking at all the barriers, is there any way you would prioritise addressing these?**

Volume effect is highest priority as there is a trade-off between having a large system (for large-scale electricity generation) and achieving a high energy density (due to reductions in E_{BD} and mechanical fatigue life) due to volume effect. If this is not solved the technology cannot be competitive with other forms of electricity generation.

Second priority is understanding the combined electromechanical lifetime of DEGs as there has been limited investigation on this.

10. **Any other comments**

Manufacturing process (for rolls of DE) has been solved for silicone DE sheets. Costs however still an issue.

Recyclability of silicone, including the whole DEG module, should be feasible. Company that carries out silicone recycling (Eco USA recycling https://www.ecousarecycling.com/)

Interviewee 4

Individual summary tables

Background:

- Worked for 10 years in DEs.
- Started of specifically on wave energy but more recently has worked in actuators, loudspeakers and sensors.
- Work on wave energy included multi-physics modelling and wave tank testing.

Prioritisation:

1. Synthesis of new DE materials and compatible electrodes.
2. Lifetime testing of whole DEG (electromechanical fatigue tests).
3. Manufacturing, investigate appropriate process for DE and electrode combination.
4. Other categories.

Table 11-25. *Interview 4 summary table. The selected for interview column indicates the categories that were discussed during the interview based on the participant's expressed expertise, highlighted italic text indicates a critical barrier that was not identified in the literature, green highlighted cells indicate the areas discussed in interview*

Category	Subcategory	Key barriers	Actions	Difficulty (1-5)
Performance of DEG	Lifetime of DEG in WEC operating conditions	Lifetime of DEGs - lack of knowledge about DEG lifetime under representative wave energy operating conditions.	Dedicated studies on DEG lifetime - study interrelation of mechanical and electrical fatigue, lifetime under different cyclic electric field strengths and effects of size of DE sample on lifetime.	3
	DE materials and design	DE material properties - need to synthesise optimised DE materials, however limited understanding of physical limitations around interdependence of these properties (e.g. EBS and permittivity)	Synthesis of new DE materials and better understanding of physical principles - synthesis of DE materials focusing on increased E_{BD} and permittivity. Determine if there is a physical reason	4

			for trade-offs between E_{BD}, permittivity and electrotechnical fatigue life.	
	Electrodes materials and design			
	DEG performance at scale	Trade-offs between modular and monolithic DEGs - not clear which is best option or feasible for WECs.	Promote the investigation of modular concepts - e.g. breaking DEG into multiple patches, or isolating E_{BD} in DE sheets within DEG modules.	3
Manufacturing of DEG (at scale)	Manufacturing DE sheets	Manufacturing large DE membranes - not clear how feasible it is to manufacture large DE membranes as no-one has done this to date.	Study existing industrial processes - processes should be investigated that are being used in other sectors e.g. rubber and plastic manufacturing to identify limitations.	3
			Manufacturing of large DE membranes (in general)	4-5
	Manufacturing electrodes			
	DEG module assembly and joining			
	Cost of manufacturing			
System integration	Design and modelling of DEG based WEC	Self-sensing - lack of research into self-sensing for DEG applications.	Investigation of self-sensing for WECs - using more realistic DEG WEC conditions (e.g. DEG topologies and deformation profiles that are representative of wave energy applications)	2
		Control strategies - commonly used control strategies for DEGs are sub-optimal.	Experimental testing of advanced controls - develop experimental setups for DEG WEC control to test modelled control strategies.	3
	Power electronics for DEG			
Environmental impact	Recyclability of DEG at end of life			
	Degradation of DEG materials in marine environment			
	Electrical shock risk			

Summary of interview questions

1. **Is there anything you don't understand or need clarified?**

Everything understood.

2. **Does this show the key categories where barriers exist to the development of DEGs for wave energy?**

Covers the main open questions.

3. **Which categories would you like to discuss during this interview?**

Lifetime, Manufacturing, system level design and modelling, performance at scale, self-sensing and control.

Main questions

Challenge category: Performance
Subcategory: Lifetime and DE materials

4. **In the area of… what do you think the key barriers are to DEGs in wave energy applications?**

B11 Lifetime of DEGs - there is no knowledge around what the lifetime of DEGs would be under typical operating conditions that would be experienced in wave energy applications. Electrical fatigue appears to be the bottleneck.

B12 DE material properties - if new materials are synthesised for DEGs, we know that to maximise energy density (and therefore power density) they must be able to survive high electric fields and have high permittivity. However, if we synthesise new materials with high E_{BD} and permittivity they also need to have a long lifetime. Work in this area to explore the possibility of trade-offs between these different requirements when synthesising materials is preliminary and there is little knowledge about what the physical limitation could be (for instance the possibility of a trade-off between permittivity and E_{BD}).

5. **What do you think makes this an important barrier to dielectric elastomers in wave energy applications?**

B11 Lifetime of DEGs - lifetime is one of the metrics that determines if a DEG will be feasible in WEC applications, however even the order of magnitude of the expected lifetime of DEGs in wave energy applications is unknown (weeks, months, years etc.).

B12 DE material properties - energy (and therefore power) density highly related to the permittivity and especially the maximum applied electric field. It is essential to understand what electric field can be applied to the DE, to determine the performance will be and if the material is feasible for wave energy applications.

6. **What action (or actions) do you think are needed to overcome this barrier?**

A13 (B11 & B12) *Involvement of materials science* (to address both lifetime of DEGs & DE material properties) - a lot of work has been done at WEC system design level, however less work has been done on the materials science.

A14 (B11) More dedicated studies on DEG lifetime (to address lifetime of DEGs) - this should answer; how are mechanical and electrical fatigue interrelated to one another, how does cyclic lifetime change as a function of the electric field level and how does this lifetime change with the dimensions of the samples.

A15 (B12) Synthesis of new materials and understanding physical principles (to address DE material properties) - synthesis of new DE materials, focusing on increased E_{BD} and permittivity. Determine if there are physical reasons that these properties cannot be increased at the same time, and what the effect of synthesising materials with better E_{BD} and permittivity has on the DE's mechanical properties and electro-mechanical fatigue life. Understanding the effects that processing custom materials has on electro-mechanical fatigue life also needs to be considered.

7. **How difficult do you think it will be to achieve these actions?**

A14 & A15 (B11 & B12) More dedicated studies on DEG lifetime & synthesis of new materials and understanding physical principles - not unfeasible, the outcome is however highly uncertain as it is basic research. Selecting right sequence for the actions is main difficulty, as we need to be testing the correct materials with the correct fatigue tests.

A14 (B11) More dedicated studies on DEG lifetime (3) - mainly a case of understanding what needs to be measured (representative fatigue tests for DEG WEC) and cancelling out effects that make data non-representative (e.g. scale effects on acceleration).

A15 (B12) Synthesis of new materials and understanding physical principles (4) - difficulty is that you cannot give up much performance in one DE property without compromising the DEG's overall performance.

8. **Are you aware of work that could address these actions?**

A14 (B11) Lifetime of DEGs - several groups trying to address cyclic lifetime of DEs (EPFL in Switzerland, Bologna university and Wacker chemical corporation) although believes that most tests so far have focused on electrical aging. Believes that the Wacker silicone DE's have been designed for long lifetime applications.

A15 (B12) DE material properties - research groups, mainly in universities working on material properties, specifically E_{BD} and permittivity (for example DTU in Denmark and EMPA in Switzerland).

Challenge category: Manufacturing
Subcategory: Modularity of DEGs, scale of membrane manufacturing

4. **In the area of… what do you think the key barriers are to DEGs in wave energy applications?**

B13 Trade-offs between modular and monolithic DEGs - not clear if it is best, or feasible, to have a DEG PTO consisting of large units or many smaller ones.

B14 Manufacturing large DE membranes - not clear how feasible it is to manufacture large DE membranes as no-one has done this to date. Lots of manufacturers producing large rubber membranes, however too thick for DEG applications. Flaws and inclusions are more likely in large DE membranes, limiting their lifetime.

5. **What do you think makes this an important barrier to dielectric elastomers in wave energy applications?**

B13 Trade-offs between modular and monolithic DEGs - choice of smaller vs large-scale DEG modules has effects on cost, deployment and will alter the mechanics and dynamics of the DEG WEC.

B14 Manufacturing large DE membranes - very thin membranes are needed for DEGs to limit the required voltage. DE membranes of sufficient thinness are not manufactured in multi-meter widths currently.

6. **What action (or actions) do you think are needed to overcome this barrier?**

A16 (B13) Promote the investigation of modular concepts (to address trade-offs between modular and monolithic DEGs) - promote the design of modular DEG WEC concepts e.g. is it feasible to break the DEG down into multiple DEG patches or isolate the sections of a membrane (within a DEG stack) that have experienced E_{BD}.

A17 (B14) Study existing industrial processes (to address manufacturing large DE membranes) - the available processes should be investigated that are being used in other sectors e.g. rubber and plastic manufacturing. This would identify the limitations of existing processes. This could be in the form of a landscaping study.

7. **How difficult do you think it will be to achieve these actions?**

A16 (B13) Promote the investigation of modular concepts (3) - believes there is a margin to think about different concepts for modularity. May be some complications in implementing these however, such as separate power electronics for separate modules.

A17 (B14) Study existing industrial processes (3) - just a matter of identifying and speaking to the right companies.

Manufacturing of large membranes, in general (4-5) - if target is metre scale the actions to address would be difficult to very difficult. There could be limitations in how the manufacturing processes work, for instance if you want to calendar or roll membranes it will be difficult to ensure sufficiently precise alignment over the length of metres.

8. **Are you aware of work that could address these actions?**

A16 (B13) Trade-offs between modular and monolithic DEGs - work has been done by the university of Saarland on self-healing DEs for actuation applications.

A17 (B14) Manufacturing large DE membranes - Parker corporation have developed the largest silicone DE membranes (1-1.5m diameter, and 50-100 μm thick). NR and styrene rubbers are being produced in large membranes, but for completely different applications which do not consider E_{BD} and uniformity of thickness.

Challenge category: System-integration
Subcategory: Control and self-sensing

4. **In the area of… what do you think the key barriers are to DEGs in wave energy applications?**

B15 Self-sensing - lack of research into self-sensing for DEGs, only a small amount of preliminary work.

B16 Control strategies - most control strategies used in prototype DEGs are based on simple heuristics, e.g. constant voltage, which are not optimal. Self-sensing may be necessary to better estimate the dynamics of the DEG which is required to implement more optimised control strategies.

5. **What do you think makes this an important barrier to dielectric elastomers in wave energy applications?**

B15 Self-sensing - possibility of performing more advanced controls, while at the same time saving in external sensors and components.

B16 Control strategies - firstly the possibility of increasing the performance, or increase lifetime by limiting the maximal or average electric field (or if you recover some energy density through control it may be possible to stress the material less). Secondly, potentially monitoring the condition of the DE, through sensing and control.

6. **What action (or actions) do you think are needed to overcome this barrier?**

A18 (B15) Investigation of self-sensing for WECs (to address self-sensing) - self-sensing could be investigated systematically in an application more relevant to wave energy. For instance, real time self-sensing using DEG topologies and deformation profiles that are more relevant to wave energy.

A19 (B16) Experimental testing of advanced controls (to address control strategies) - many people are working on control strategies (a few on DEG specific control) however little work on experimental setups. These control strategies should be tested in dry run and hardware in the loop setups. Then transitioning to small-scale wave tank tests.

7. **How difficult do you think it will be to achieve these actions?**

A18 (B15) Investigation of self-sensing for WECs (2) - no principle obstacles are foreseen to the achieve self-sensing.

A19 (B16) Experimental testing of advanced controls (3) - may be difficult to bring control strategies into real systems while preserving all the conditions that make it optimal on paper.

8. **Are you aware of work that could address these actions?**

A18 (B15) Self-sensing - only aware of work by Gianluca Rizzello from Saarland university. Preliminary work, that would be worth extending perhaps.

A19 (B16) Control strategies - preliminary work on advanced controls by Giacomo and colleagues. Mostly this has been done in simulation, the next stage is to apply this work to experimental setups.

Closing questions

9. Looking at all the barriers, is there any way you would prioritise addressing these?

First DE materials and design, seeing how much the material properties can be improved, also considering the appropriate electrodes. Then address lifetime of the whole DEG assembly. Then look at manufacturing of the whole DEG, both DE and electrodes together. Then the other areas.

Lifetime is biggest question at the moment, however we need to study lifetime for the materials that will actually be used in a DEG WEC. Same goes for manufacturing processes of the DEG. For this reason, materials should be developed first.

10. Any other comments

Interviewee 5

Individual summary tables

- Background in ocean engineering and civil engineering.
- Now works on modelling the response of flexible wave energy converters.

Prioritisation:

1. Manufacturing
2. Performance (specifically lifetime)
3. Systems integration
4. Environment

Table 11-26. *Interview 5 summary table. The selected for interview column indicates the categories that were discussed during the interview based on the participant's expressed expertise, highlighted italic text indicates a critical challenge that was not identified in the literature, green highlighted cells indicate the areas discussed in interview*

Category	Subcategory	Key barriers	Actions and potential knowledge transfer	Difficulty (1-5)
Performance of DEG	Lifetime of DEG in WEC operating conditions			
	DE materials and design	DEG electrical insulation - issue of safety and potential equipment damage with submerged DEG.	Development of generic insulation options for DEGs - this would increase confidence when testing in wave basins etc.	3
	Electrodes materials and design			
	DEG performance at scale			
Manufacturing of DEG (at scale)	Manufacturing DE sheets			

	Manufacturing electrodes			
	DEG module assembly and joining			
	Cost of manufacturing			
System integration	Design and modelling of DEG based WEC	Development of numerical model for DEG WECs - for flexible WEC designs where the DEG is submerged it is difficult to model the WEC's hydrodynamic response. Also expected difficulty coupling hydrodynamic response with the DEGs electro-elastic response. Also, a lack of experimental data to validate models.	Development of numerical model and experimental data sets - additional experiments can be carried out to generate available data for comparison with numerical models.	4-5
		Attachment of DEG to WEC structure - requirement in some DEG WEC designs for connection between rigid structural components and DEG. This needs to transfer stretch, while maintaining waterproof properties. Additionally, these joins will determine WEC's dynamics.	More research on flexible attachment - research into flexible or polymeric hinges between DEG and rigid parts of WEC.	1
		Scaling and materials testing - very thin sheets of DE required in lab tests, sourcing these DE sheets can be a problem.	More research on scaling and material testing - notes that manufacturing process will determine if DEG WECs can be developed at small or large-scale.	N/A
	Power electronics for DEG			
Environmental impact	Recyclability of DEG at end of life			
	Degradation of DEG materials in marine environment			
	Electrical shock risk			

Key barriers and actions from interview

1. **Is there anything you don’t understand or need clarified?**

All clear

2. **Does this show the key categories where barriers exist to the development of DEGs for wave energy?**

Table covers the broad categories and subcategories.

3. **Which categories would you like to discuss during this interview?**

System integration and manufacturing.

Main questions

Challenge category: System integration
Subcategory:

4. **In the area of… what do you think the key barriers are to DEGs in wave energy applications?**

B17 Electrical insulation of DEG - this is an issue for the testing of WECs with a submerged DEG.

B18 Scaling DEG - scaling down the DEG materials.

B19 Attachment of DEG to WEC structure - attachment of DEG to rigid or semi-rigid WEC structure, while maintaining pre-stretch.

B20 Development of numerical model - for DEG WEC we need to have a numerical model that can take both the electro elastic and hydrodynamic responses simultaneously.

Multiple topologies - this was noted not to be a key challenge, therefore it has been excluded from remainder of this document.

5. **What do you think makes this an important barrier to dielectric elastomers in wave energy applications?**

B17 Electrical insulation of DEG - in an ocean environment there are safety concerns, for test basin the issue is the instrumentation and also safety of people working on basin tests.

B18 Scaling DEG - scaling the DEG down to lab scale results in very thin sheets of DE required. Sourcing these DE sheets can be a problem.

B19 Attachment between DEG and WEC structure - for the WEC that they are studying there are multiple rigid to flexible joints, where a flexible material (e.g. the DEG) is connected to a rigid structural component. This joint needs to transfer stretch to the DEG while being waterproof. Additionally the joint will determine the WECs dynamics. At present it is unclear what the best joining option is (e.g. clamping, screwing or pasting).

B20 Development of numerical model - difficult to model the hydrodynamic response of submerged flexible WEC structure. Then, expected difficulty coupling this with electro-elastic response of the DEG. Also, a lack of experimental data to validate DEG WEC hydrodynamic models.

6. **What action (or actions) do you think are needed to overcome this barrier?**

A20 (B17) Development of generic DEG insulation solutions (addressing electrical insulation of DEG) - development of a generic insulation design would give additional confidence when testing (e.g. in wave basins). SBM developed solution of encapsulating DEG, need to see if this is design specific or could be used generally.

A21 (B18) More research on scaling and material testing (addressing scaling DEG) - also mentioned that manufacturing comes into this. Manufacturing processes that work for full-scale and model scale are still under investigation.

A22 (B19) More research on flexible attachment (addressing attachment between DEG and WEC structure) - research into flexible or polymeric hinges to attach DEG to rigid parts of WEC.

A23 (B20) Development of numerical model and experimental data sets (addressing development of numerical model) - an option is to carry out more experiments which can be used to compare to numerical models. This data should be made available to help further model development.

7. **How difficult do you think it will be to achieve these actions?**

A20 (B17) Development of generic DEG insulation solutions (3) - SBM have already come up with a solution for their device. It should not be very difficult to develop solutions specific for different WEC designs.

A21 (B18) More studies on scaling and material testing (N/A) - could not confidently evaluate this.

A22 (B19) More research on flexible attachment (1) - likely that a solution already exists, when manufacturing and scaling is sorted this should not be a pressing issue.

A23 (B20) Development of numerical model and experimental data sets (4-5) - difficult to very difficult as it requires a lot of coupling solutions. However, Flex WEC software from Wave Venture Ltd. in development to model hydrodynamic response.

8. **Are you aware of work that could address these actions?**

A20 (B17) Development of generic DEG insulation solutions - mentioned SBM encapsulation of DEG.

A22 (B19) More research on flexible attachment - clamping has been used by, for instance, PolyWEC. Something similar used for the FlexWave preliminary investigation.

A23 (B20) Development of numerical model and experimental data sets - team at Wave Venture Ltd. are working on this[42].

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[42] See https://gtr.ukri.org/projects?ref=31905#/tabOverview

Closing questions

9. Looking at all the barriers, is there any way you would prioritise addressing these?

Manufacturing is first priority, then lifecycle and performance. In parallel system integration can be taken forward. Environment also needs to be considered in parallel. From a WEC design perspective the prioritisation is, manufacturing, performance, systems integration and then environment.

Importance of doing manufacturing first is that, even if the WEC is theoretically plausible we need to know if it is practically possible, otherwise there is no point.

10. Any other comments

Interviewee 6

Individual summary tables

- PhD on failure mode analysis for DEG electromechanical fatigue.
- Developed stochastic model to measure and analyse static failure mode of DEG transducers, mainly focusing on E_{BD} of DE. Also developed dynamic model of electromechanical damage accumulation.

Prioritisation:

1. Developing a sustainable business model for DEG WECs.
2. Identification of suitable industrial manufacturing processes for DEG and compatible materials.

Table 11-27. *Interview 6 summary table. The selected for interview column indicates the categories that were discussed during the interview based on the participant's expressed expertise, highlighted italic text indicates a critical challenge that was not identified in the literature, green highlighted cells indicate the areas discussed in interview*

Category	Subcategory	Key barriers	Actions and potential knowledge transfer	Difficulty (1-5)
Performance of DEG	Lifetime of DEG in WEC operating conditions			
	DE materials and design	DE materials need to operate under a specific set of conditions - combination of material properties required that are very challenging to achieve all together.	Industry focus on increasing TRL of DE materials - companies working in silicone and printed electronics need to be involved in demonstrating the DE in relavent environments using industry validated materials and manufacturing processes.	3
	Electrodes materials and design	Electrodes need to operate under a specific set of conditions - difficult to find something with all the required material properties that is also conducive.	Need a material that is reliable, but also has been validated in relevant industrial application like printed electronics.	3
	DEG performance at scale			

Manufacturing of DEG (at scale)	Manufacturing DE sheets	Scaling manufacturing process - this will require a specific manufacturing process. Processes that are used in other fields like printed electronics can be used, however needs to be scaled up.	Need to develop business model of the DEG's application in order to convince the industry to work on the development of the large-scale manufacturing process.	2
	Manufacturing electrodes			
	DEG module assembly and joining			
	Cost of manufacturing			
System integration	Design and modelling of DEG based WEC			
	Power electronics for DEG			
Environmental impact	Recyclability of DEG at end of life			
	Degradation of DEG materials in marine environment			
	Electrical shock risk			
Other	Sustainable model for using DEGs in wave energy applications	Business model for DEGs that has all of the failure modes in mind, including lifecycle environment and economics.	Rather than just the product development, there needs to be a focus on the context of the energy system more widely (including the regional factors, such as regulation, policies etc.) to develop a sustainable business model for DEG WECs.	N/A

Key barriers and actions from interview

1. **Is there anything you don't understand or need clarified?**

No

2. **Does this show the key categories where barriers exist to the development of DEGs for wave energy?**

Covers main areas.

3. **Which categories would you like to discuss during this interview?**

Performance of DEGs

Manufacturing

Main questions

Challenge category: Performance
Subcategory: DE materials and electrodes

4. **In the area of… what do you think the key barriers are to DEGs in wave energy applications?**

B21 DE materials - needs to operate under a specific set of conditions.

B22 Electrodes - needs to operate under a specific set of conditions.

5. **What do you think makes this an important barrier to dielectric elastomers in wave energy applications?**

B21 DE materials - the DE materials need to survive a very particular set of conditions, harsh ocean environment, high voltages and need to be scalable. Combination of material parameters required that are very challenging to achieve all together. High level of elasticity, dielectric strength and high level of dielectric permittivity required and you need to have a material which you can apply compliant electrodes to. Also the material needs to sustain long lifetime with a low level of dielectric loss with resistance to mechanical fatigue and resistance to a harsh environment like sea water. Current materials have limitations. Acrylic very viscoelastic, resulting in high energy loss. Silicone is good, but expensive and has limited dielectric strength, limited elasticity and hardens under strain. Silicones are best choice, but correct formulation and manufacturing process have not been found.

B22 Electrodes - these need to be compliant, have similar mechanical properties to the DE, very low thickness and be able to adhere to DE. Difficult to find something with all these properties that is also conducive. Silicone mixed with carbon black (or other particles) works, but has quite high resistance. Main issue related to this is energy loss, not believed that heat build-up is of big issue.

6. **What action (or actions) do you think are needed to overcome this barrier?**

A24 (B21) Industry focus on increasing TRL of DE materials (addressing DE materials) - companies working in silicone and printed electronics need to be involved in demonstrating the DE in relevant environments and with industry validated materials and manufacturing. Industrial application of the materials needed to ensure sufficient reliability.

A25 (B22) Industry focus on increasing TRL of electrodes (addressing electrodes) - similar to DE requirements. Need a material that is reliable, but also has been validated in relevant industrial application like printed electronics.

7. **How difficult do you think it will be to achieve these actions?**

A24 (B21) Industry focus on increasing TRL of DE materials (3) - not high difficulty, all is required is return on investment for an industrial application. Believes there is already technology that can increase the readiness of DEs.

A25 (B22) Industry focus on increasing TRL of electrode (3) - very similar to DE. Only difference is that electrodes need to be conductive and need to be manufactured over the DE film (compliant to film as well).

8. Are you aware of work that could address these actions?

A24 & A25 (B21 & B22) Both actions - Not aware of work directly working on this for DEGs. However transferable manufacturing processes from printable electronics. Printed electronics work on substrate which could be DE and the methods of manufacturing of nanoparticle materials which can be conductive would be applicable to electrodes.

Challenge category: Manufacturing
Subcategory: Scaling manufacturing process

4. **In the area of… what do you think the key barriers are to DEGs in wave energy applications?**

B23 Scaling manufacturing process -DEG WEC will require membranes of large size.

5. **What do you think makes this an important barrier to dielectric elastomers in wave energy applications?**

B23 Scaling manufacturing process - This will require a specific manufacturing process. Can use processes that are used in other fields like printed electronics, however needs to be scaled up. This results in a very specific application, which will require a business model.

6. **What action (or actions) do you think are needed to overcome this barrier?**

A26 (B23) Business model for DEG manufacturing (addressing scaling manufacturing process) - need to develop business model of the DEG's application to convince the industry to work on the development of the manufacturing process. In order for industry to invest in scaling up a production processes for such a specific application, demand needs to be expected.

7. **How difficult do you think it will be to achieve these actions?**

A26 (B23) Business model for DEG manufacturing (2) - more complex things are being produced that muli-layer DE and electrodes, however it has to be done at large-scale. Once demand can be demonstrated, existing processes such as deposition (e.g. printing) can be scaled up.

8. **Are you aware of work that could address these actions?**

A26 (B23) Business model for DEG - there is a lot of choice of manufacturing processes with printed electronics where you need to print both the dielectric and the conductive ink.

Challenge category: Other
Subcategory: Sustainable model for using DEGs in wave energy applications

4. **In the area of… what do you think the key barriers are to DEGs in wave energy applications?**

Sustainable model - a business model for DEGs that has all of the failure modes in mind.

5. **What do you think makes this an important barrier to dielectric elastomers in wave energy applications?**

Sustainable model - needs to consider the business model requirements dependant on the location where the technology is deployed. Need to consider the regions laws and regulation in developing the technology. Also as it is unlikely to last for an entire WEC lifetime without service, therefore the DEG WECs lifecycle (servicing, replacement of DEG modules etc) also need to be considered.

6. **What action (or actions) do you think are needed to overcome this barrier?**

Rather than just the product development, there needs to be a focus on the context of the energy system more widely to develop a sustainable business model for DEG WECs. This includes regional factors such as regulation, policy etc.

7. **How difficult do you think it will be to achieve these actions?**

Main difficulty is that if the right parameters are not being considered technologies that are more economically sustainable will win out over more environmentally sustainable ones. Technologies that already exist with established supply chains will be more competitive (economically) compared to an emerging technology. The right business model for DEG WECs will measure the advantages of the technology both in terms of economics and environmental impact.

8. **Are you aware of work that could address these actions?**

Nothing specifically for wave energy.

Closing questions

9. Looking at all the barriers, is there any way you would prioritise addressing these?

First priority is measurement of the technology's competitive advantage compared to other technologies. Then move on to the manufacturing process which will help select the right materials for both the electrodes and the DE.

10. Any other comments

Interviewee 7

Individual summary tables

Background:

- Experimental work on DEGs, material characterisation of fatigue and viscoelastic behaviour

Prioritisation:

1. Carry out combined (mechanical, electrical and environmental) fatigue testing on best available DE materials and electrodes - make this data publicly available.
2. Carry out combined fatigue testing at device scale to validate lab scale performance - make this data publicly available.
3. Address other barriers.

Table 11-28. *Interview 7 summary table. The selected for interview column indicates the categories that were discussed during the interview based on the participant's expressed expertise, highlighted italic text indicates a critical challenge that was not identified in the literature, green highlighted cells indicate the areas discussed in interview*

Category	Subcategory	Key barriers	Actions and potential knowledge transfer	Difficulty (1-5)
Other	Lack of complete study on DEG WEC	Lack of complete study - that takes DEG from material synthesis to power generation. Developments in one area e.g. materials are not being fed through to realistic testing at the moment.	Multi-disciplinary research - research actions need to be headed by multidisciplinary people. This will enable iteration between materials science, experimentalists, device design and electronics. This will allow solutions to be identified that work across all these areas.	2
Performance of DEG	Lifetime of DEG in WEC operating conditions	No experimental data - for DEG under electromechanical fatigue (data that is publicly available)	Same as integration, proper combined fatigue testing highlighted as part of the iteration process between material science, experiments and device design.	N/A

	DE materials and design	(Highlighted that we have high performance materials already available)		
	Electrodes materials and design	(Highlighted that we have high performance electrodes already available)		
	DEG performance at scale			
Manufacturing of DEG (at scale)	Manufacturing DE sheets	(highlighted that DE already manufacturable for some available materials)		
	Manufacturing electrodes			
	DEG module assembly and joining			
	Cost of manufacturing			
System integration	Design and modelling of DEG based WEC	(highlighted the good availability of promising DEG WEC designs)		
	Power electronics for DEG			
Environmental impact	Recyclability of DEG at end of life			
	Degradation of DEG materials in marine environment			
	Electrical shock risk			

Key barriers and actions from interview

1. **Is there anything you don’t understand or need clarified?**

Understands

2. **Does this show the key categories where barriers exist to the development of DEGs for wave energy?**

Agrees that this covers most barriers, however adds that DEG WECs is a multidisciplinary research area, therefore these many barriers cannot be treated separately.

3. **Which categories would you like to discuss during this interview?**

Barrier category from Mokarram’s perspective:

Lack of testing data

Lack of coordination between different research disciplines (materials, experimentalists, device designers, electrical engineers)

Main questions

Challenge category: Performance/approach to DEG WEC research
Subcategory: Lack of complete study

4. **In the area of… what do you think the key barriers are to DEGs in wave energy applications?**

B24 Lack of fatigue life data - no experimental data under electromechanical fatigue. Highlighted that data may exist in private sector, but there is no access to this.

B25 Lack of complete study - to date no studies have taken DEG from material synthesis to power generation. This means that when a new DE material, electrode etc is developed it is not then tested in realistic operating conditions. Also, the parameters of a device's operation (expected magnitude and direction of stretch, electric field etc.) are required to develop the test rigs for these DE materials and electrodes. Developments at one stage are not feeding though to subsequent stages at the moment.

5. **What do you think makes this an important barrier to dielectric elastomers in wave energy applications?**

B24 Lack of fatigue life data - same as below, fatigue life testing feeds into a complete study.

B25 Lack of complete study - we cannot determine if new DE materials or electrodes are suitable for a device without testing in the right conditions. In addition to know what the right test conditions are, we need the input of device developers (e.g. if the material will experience pure biaxial stretching, then the fatigue life should not be based on equi-biaxial fatigue data).

6. **What action (or actions) do you think are needed to overcome this barrier?**

A27 (B24 & B25) Multi-disciplinary research (to address lack of complete study and lack of fatigue data) - research into DEGs for wave energy is a very interdisciplinary area, chemistry & materials, experimentalists, device designers/modellers and electronics. The research actions need to be headed by interdisciplinary people. This means that when a new solution is proposed there can be an assessment of whether it overcomes the problems from the point of view of all the different disciplines. This will also facilitate iteration between the materials and testing e.g. testing any new DE and electrode materials in realistic test environments. And also, iteration between the testing and device design, e.g. selecting a material based on its performance in tests that mimic the mechanical loading, electrical field etc. that it will experience in operation.

7. **How difficult do you think it will be to achieve these actions?**

A27 (B24 & B25) Multi-disciplinary research (2) - difficulty of carrying this out is low (not severe). If a large pot of money was allocated to a multidisciplinary team the complete, materials, testing, device testing loop could be solved in 5 years. Additionally, the DEG WEC community already knows each other and who is working in specific areas. A driving organisation like WES or SuperGen can connect researchers.

8. Are you aware of work that could address these actions?

A27 (B24 & B25) Multi-disciplinary research - at a macro scale Supergen ORE hub is the kind of organisation that joins all the dots. The same structure can be set up at a medium scale for research into DEG WECs.

Closing questions

9. **Looking at all the barriers, is there any way you would prioritise addressing these?**

First priority is the lack of experimental data for fatigue, for best available DE materials and electrodes as identified by DEG community. Data is needed for combined multiaxial mechanical fatigue, electrical fatigue and environmental degradation.

Following this, carrying out some tests at device scale on these DE materials and electrodes to validate their lab scale performance.

Making this data available to the community so it can be used to predict performance of new devices.

Then the other barriers can be addressed.

10. **Any other comments**

Interviewee 8

Individual summary tables

Background:

- Has worked on DEG based wave energy conversion for over 10 years on several projects
- This work has included membrane modelling, coupling of hydrodynamics and membrane response, prototyping both in lab and wave tanks and reliability testing

Prioritisation:

1. Upscaling of manufacturing process that is available to multiple developers of DEG WECs
2. Verification of performance, degradation and lifetime of the DEG in realistic conditions
3. Investigation of alternative materials, including SBR

Table 11-29. *Interview 8 summary table. The selected for interview column indicates the categories that were discussed during the interview based on the participant's expressed expertise, highlighted italic text indicates a critical challenge that was not identified in the literature, green highlighted cells indicate the areas discussed in interview*

Category	Subcategory	Key barriers	Actions and potential knowledge transfer	Difficulty (1-5)
Performance of DEG	Lifetime of DEG in WEC operating conditions	Limited fatigue life data - work on fatigue life of DE membranes is limited as published results have considered membranes tested in air.	Testing of DE membranes in realistic conditions - carry out fatigue tests on DE membranes using a realistic mechanical strain and electric field in relevant environmental conditions (seawater).	2+
	DE materials and design	See manufacturing DE sheets.		
	Electrodes materials and design			
	DEG performance at scale			

Manufacturing of DEG (at scale)	Manufacturing DE sheets	Lack of manufacturing infrastructure - certain types of DEG currently cannot be scaled up past a certain level due to the lack of large-scale (≥5x5m) DE membrane manufacturing infrastructure.	Economic and environmental study on silicone for large-scale DEG manufacturing - carry out a study to understand if silicone elastomer based DEGs may enable cost effective and sustainable wave energy converters and the maximum allowable cost of DE membrane manufacturing infrastructure.	3
		Material selection - current material (silicone) is very expensive in thin membranes. The type of material (SBR vs silicone etc.) will also define manufacturing process for DE membranes.	Assessment of SBR and silicone - assess the costs of scale manufacturing of silicone with industrial partners, also evaluate viability of SBR as alternative with industrial partners.	
	Manufacturing electrodes			
	DEG module assembly and joining			
	Cost of manufacturing	See manufacturing DE sheets.		
System integration	Design and modelling of DEG based WEC			
	Power electronics for DEG			
Environmental impact	Recyclability of DEG at end of life			
	Degradation of DEG materials in marine environment			
	Electrical shock risk			

Key barriers and actions from interview

1. **Is there anything you don't understand or need clarified?**

Everything understood.

2. **Does this show the key categories where barriers exist to the development of DEGs for wave energy?**

Not specified, did not add any categories.

3. **Which categories would you like to discuss during this interview?**

Manufacturing DEG at scale

Lifetime

Cost effectiveness

Main questions

Challenge category: Manufacturing
Subcategory: Manufacturing DEG at scale

4. **In the area of… what do you think the key barriers are to DEGs in wave energy applications?**

B26 Lack of manufacturing infrastructure - There is a lack of infrastructure to make large-scale DE membranes (≥5x5m) with a thickness of 100-200 µm and be able to layer these membranes in a multilayer stack. No new technology is required, just upscaling current processes, with suitable quality control (QC) implemented in DEG manufacturing processes to ensure uniform membrane thickness and no damage to membrane (can use QC techniques such as cameras or electrical measurements).

B27 Material selection - silicone is a candidate material for DEG wave energy converters however it is expensive, especially current prices of thin silicone membranes. SBR has good mechanical and electrical properties, however it is not normally used in academic research and will require a different manufacturing process to silicone.

5. **What do you think makes this an important barrier to dielectric elastomers in wave energy applications?**

B26 Lack of manufacturing infrastructure - certain types of DEG WECs (using large membranes - e.g. PolyWEC) currently cannot be scaled up past a certain level due to the lack of large-scale DE membranes. This means funding calls for DEG WECs cannot be accessed for large-scale prototypes. There is limited demand for industry to invest in the manufacturing infrastructure as WECs are the only (current) market for large-scale DE membranes.

B27 Material selection - silicone material is expensive, especially in thin membranes at present. The type of material (SBR vs silicone) will also define manufacturing process for DE membranes.

6. **What action (or actions) do you think are needed to overcome this barrier?**

A28 (B26) Economic and environmental study on silicone for large-scale DEG manufacturing (addressing Lack of manufacturing infrastructure) - carry out a study to understand if silicone elastomer based DEGs may enable cost effective and sustainable wave energy converters. Price of the manufacturing infrastructure can be included as a variable to try and determine the maximum manufacturing infrastructure costs that are allowable for a cost effective DEG WEC. This study can be based on the size of the potential future DEG WEC market.

A29 (B27) Assessment of SBR and silicone (addressing Material selection) - silicone is a candidate material for DEG wave energy converters, however it is expensive. We should try to understand if there could be the possibility of using cheaper formulation of silicon elastomer specifically designed for DEG WEC applications that does not have all the other requirements of silicon, like biocompatibility etc. The manufactured cost of silicone membranes is also very high at the moment. The economics of mass production need to be understood, this requires involvement of industrial partners such as WACKER. The other possibility is switching to another type of material such as SBR, which has good mechanical and electrical properties. However, SBR is not usually used in academic research and will require a different manufacturing process to silicone membranes. This needs to be discussed with an expert in SBR.

7. How difficult do you think it will be to achieve these actions?

A28 (B26) Economic and environmental study on silicone for large-scale DEG manufacturing (3) - this can be achieved by gathering the right partners, especially companies that are experts in the area. This is the most important action as it allows other large-scale testing to go ahead that require large-scale DE membranes (e.g. lifetime tests and operation at large-scale).

8. Are you aware of work that could address these actions?

Aware that SBM may have a large-scale DE membrane manufacturing process.

Does not know of groups working on this. Upscaling the manufacturing process is very specific to wave energy sector as all other DEG applications are small-scale. For this reason, you don't typically find producers of DE membranes that address these larger scales.

Challenge category: Performance
Subcategory: Lifetime

4. **In the area of… what do you think the key barriers are to DEGs in wave energy applications?**

B28 Limited fatigue life data - work on fatigue life of DE membranes is limited as published results have considered membranes tested in air.

5. **What do you think makes this an important barrier to dielectric elastomers in wave energy applications?**

B28 Limited fatigue life data - we need to understand the fatigue life of DEGs to determine if they meet the requirements of lifetime for a wave energy converter. Lifetimes of over 5 years may be complicated as it may require significant reduction in operating strain and/or electric field, reducing the energy density of the DEG. However, this is hard to evaluate due to the limited data on DE membrane fatigue life in representative conditions.

6. **What action (or actions) do you think are needed to overcome this barrier?**

A30 (B28) Testing of DE membranes in realistic conditions (addressing Limited fatigue life data) - first action is to carry out fatigue tests on DE membranes, even at small scale, using a realistic mechanical strain and electric field in relevant environmental conditions (seawater).

7. **How difficult do you think it will be to achieve these actions?**

A30 (B28) Testing of DE membranes in realistic conditions (2+) - Technically the difficulty is low (2) doesn't see a significant difficulty in terms of the performing the experimentation. This just requires time (around 1 year for accelerated fatigue tests) and money to implement the testing infrastructure. However, it is difficult to find financing for performing this type of activity. Very hard to find a single project that will fund the fatigue testing of materials. Typically, these are commissioned by companies, however there are few that would be willing to invest in this at present.

8. **Are you aware of work that could address these actions?**

Not aware of any relevant testing.

Closing questions

9. Looking at all the barriers, is there any way you would prioritise addressing these?

First priority is upscaling manufacturing as this has been a limitation in all of their DEG WEC developments. If this is taken care of it would allow them to respond to a lot more project calls with DEG WEC projects. A manufacturing process that is open to multiple developers would be good as this would allow different developers to progress their DEG WEC technologies, rather than just one company develop one technology.

Another priority is verification of performance, degradation and lifetime of the DEG in realistic conditions. First preliminary study at small scale, then testing at large-scale.

Investigation of alternative materials is another priority area. Carrying out a further study in collaboration with industry, including the use of SBR for DEGs.

10. Any other comments

Summary of barrier categories

Covered the main barriers in each of the subcategories, these are summarised below:

Lifetime - Preliminary results have been obtained for electromechanical fatigue, but significant work still to be carried out. Especially depending on how the membrane will be deformed during the system's lifetime.

DE materials and design - believes a lot of work has been done by research community on DEs. However, simple materials seem to be better for DEG applications than filled materials. Good materials known about at the moment are silicone elastomer and SBR rubber. SBR is generally handled by companies, not researchers, and therefore is less studied.

Design tools - Tools are more or less available and they have always been able to design a system that can harvest energy. These design tools appear to be ok at the moment.

Electrode materials - Problem with conductivity, they typically use carbon black as it is easy to use. As system is operating at high voltage electrode resistance is normally not considered. However, some failure in DEGs may be caused by the heating of carbon black. Higher resistance electrodes may heat the membrane and cause damage over time, this has not been investigated so far. Making separate electrodes is a good way to proceed and they have tested this in the laboratory and they are OK. Considered that self-clearing electrodes would present an issue in DEGs as they create a point of mechanical failure.

Performance at scale - In theory there is no decrease in performance as they move up to an intermediate scale, up to 1m. This has been confirmed. However, when you move up to large scale system there is a problem with manufacturing, so the performance at scale is strictly related to the manufacturing category.

Manufacturing - Significant problem, mostly due to the investment required, rather than a technical point of view.

Electrode manufacturing - Electrodes can be spray coated, they have been able to manufacture electrode with the spray coating. That is very simple process and it also operates for very large membranes.

Module fabrication and joining - Module fabrication and joining can be done. They have performed small-scale experiments requires verification from the fatigue. This needs to be studied further.

Cost of manufacturing - Significant problem, one of the major aspects that should be considered to understand whether the technology is viable.

Design and modelling of DEG based WEC - Believes that we have the tools to do this.

Power electronics - Believes this can be done, just a matter of understanding whether it is affordable or not. The components to develop power converters are not a concern. In particular, there could be two power converters. One for the charging of the DEG, which requires a high current for a very short time. Then another for harvesting which manages lower values of current. Maybe separating the two would be beneficial as a solution.

Self-sensing - This can be done and also for the control it is something that is feasible. The complicated aspects of control apply to wave energy converters in general, predicting the incoming waves etc.

Recyclability - We need to understand recyclability of membranes and this is a part of the evaluation of the cost of the system.

Degradation in the marine environment - This is something that has to be studied. Up to now we have just considered the results that are available for the degradation of standard rubber components in water, but not strictly related to the DEs. A major problem here is the intake of water by the membrane. For short term behaviour (weeks), immersion in water is no problem. For long term it has to be investigated and studied.

Electric shock risk - At the scale we have worked so far, with the power of a few watts little energy is stored. Considering a full system with a lot of energy harvested in the system this is something that should be investigated.

Summary - The next step is the need to scale up. At small scale, more or less everything works. But to go to large-scale significant investments are required. Therefore, before making such investments, it would be required to try to make an assessment of whether the technology can be environmentally sound and cost effective. So maybe starting from the results at the small-scale in term of energy performance, look at the perfectly scaled performance at a larger scale. Then try to analyse the sustainability and the cost effectiveness of such a system and then try to understand whether a significant investment in manufacturing is actually worth it or not. So this I believe is the path to try to have dielectric elastomer generators as a potential system for wave energy systems.

Cost effectiveness of DEG based wave energy converters

Other additional points on the cost effectiveness of DEG based WECs from experience:

Non DEG structural costs - Significant contribution in the cost of the DEG WEC system was the structure which was not actually the generator. When performing a study on DEG WEC cost effectiveness, maybe consider a DEG mounted on a structure that is low cost like those in the WES competition for structures. It would be interesting to consider using plastic and/or inflatable structures. Otherwise, the price of steel and the price of concrete is going to play a significant role in the cost effectiveness of the entire system.

Lifetime of DEG and replacements - Determine if the possible limits in lifetime of the DEG may be compensated by considering maintenance every five years to replace just the membrane. This scenario could be considered instead having the DEG survive for the entire 20 years.

WEC scale for DEGs - Wave energy companies generally consider very large systems leading to very large DEG membranes. This is problematic for dielectric elastomer scaling up (as covered above). A possible route could be considered is smaller size system rather than just one single 500 kW system. Maybe try to consider the effectiveness of multiple, for example 10 or 20 kW system. It may be easier to realise from the point of view of the DEG. However as you shrink the membrane size the rigidity of the membrane plays significant role, so it is more difficult to put the system in resonance. For this reason, we are trying to use other type of converters like dielectric fluids systems. Those could be an alternative to this approach. Even if very small-scale does not work an intermediate scale may be a good approach.

Interviewee 9

Individual summary tables

Background:

- Carried out a PhD working on insulation materials for electrical cables
- Now works on elastomeric materials for WECs in general, with a partial focus on DEG WEC applications

Prioritisation:

1. Barriers around fatigue
2. Performance (all)
3. Manufacturing (all)
4. Other barriers

Table 11-30. *Interview 9 summary table. The selected for interview column indicates the categories that were discussed during the interview based on the participant's expressed expertise, highlighted italic text indicates a critical challenge that was not identified in the literature, green highlighted cells indicate the areas discussed in interview*

Category	Subcategory	Key barriers	Actions and potential knowledge transfer	Difficulty (1-5)
Performance of DEG	Lifetime of DEG in WEC operating conditions	Combined fatigue - knowledge gap around combined effect of electric field, mechanical strain and marine environment.	More combined fatigue testing - setup may be expensive for university, projects with industrial partners could help. Potentially transferrable knowledge from FOW cable insulation.	4 (for the issue of fatigue in general)
		Heat dissipation around electrodes - heat dissipation from electrode current flow may cause heat build up in DE, resulting in thermal aging.	Thermally conductive fillers - may be added to DE to dissipate heat. However, these would need to not compromise E_{BD} strength. Potentially ceramic fillers, however little research in this area.	
	DE materials and design	Creep - hard to find DE materials that are not affected by creep. Creep changes geometry	More combined fatigue testing - needed to determine how material changes shape under	

		of WEC over time, changing its hydrodynamics.	fatigue cycles. Work under way on machine learning fatigue tests which could accelerate this process by reducing data requirements.	
		Fillers - hydrophilic fillers (e.g. silica) easily absorb water, this can create conductive pathway in DE reducing E_{BD} strength. Knowledge gap of fillers performance in marine environment.	Hydrophilic treating - can be applied to fillers, however this would increase costs. Water absorption tests - can be carried out to saturate DE before E_{BD} is measured.	3
	Electrodes materials and design			
	DEG performance at scale	Replacement of DEGs - lifetime of rubber parts typically lower than that of WEC, difficulty in replacing large rubber parts at sea.	Increasing modularity of DEGs - use of more modular DEGs would make replacements easier and also help with manufacturing constraints. However, will increase complexity of control systems. Potential transfer of knowledge from wind and solar industry on control systems.	2
Manufacturing of DEG (at scale)	Manufacturing DE sheets			
	Manufacturing electrodes			
	DEG module assembly and joining			
	Cost of manufacturing			
System integration	Design and modelling of DEG based WEC			
	Power electronics for DEG			
Environmental impact	Recyclability of DEG at end of life			
	Degradation of DEG materials in marine environment			

	Electrical shock risk			

Key barriers and actions from interview

1. **Is there anything you don't understand or need clarified?**

All understood.

2. **Does this show the key categories where barriers exist to the development of DEGs for wave energy?**

Interviewee thought it covered most categories and did not add any

3. **Which categories would you like to discuss during this interview?**

Performance (lifetime, DEG performance at scale, DE materials and design)

Main questions

Challenge category: Performance
Subcategory: Lifetime

4. **In the area of… what do you think the key barriers are to DEGs in wave energy applications?**

A9 Combined fatigue - specifically the combination of electrical field, mechanical strain and marine environment. Very little research that has looked at all three effects on DEs.

B30 Heat dissipation around electrodes - this may cause heat accumulation in DE material and thermal aging.

5. **What do you think makes this an important barrier to dielectric elastomers in wave energy applications?**

B29 Combined fatigue - can't find a material at a scale level that has been tested in this situation. Many people testing electrical or mechanical fatigue in isolation, however very hard to find any research into mechanical and electrical fatigue and environmental aging at once. Also, universities do not typically have the facilities to carry out these tests.

B30 Heat dissipation - effects the DE and potentially the electrodes as well, for example in a cable you have heat generation in the conductor and then build-up of heat in the surrounding insulation which results in thermal aging. In general plastics are not good in heat conduction, resulting in heat accumulation.

6. **What action (or actions) do you think are needed to overcome this barrier?**

A31 (B29) Combined fatigue testing (addressing combined fatigue) - More testing is needed. However, these facilities are quite expensive for a university to set up if they do not already have them. Including industrial partners on projects that can provide material and testing facilities could help with this.

A32 (B30) Conductive fillers (addressing heat dissipation) - Potential to add thermally conductive fillers to the DE layer. It would have to be something that was not electrically conductive such as a certain ceramics. However, this is an area that has not had a lot of research.

7. **How difficult do you think it will be to achieve these actions?**

A31 (B29) Actions to address fatigue, generally (4) - It is difficult but with some effort we believe we can achieve that. If we learn from the cable industry and also collaborate with the industry. In addition, collaboration needed between people with different backgrounds. There is a lack of people that work in high voltage electronics. This means there is a lack of people that can work on the electrical problems of DEGs. It is also time consuming and challenging communicating between the different parts of the team when working on combined fatigue.

8. Are you aware of work that could address these actions?

A31 (B29) Combined fatigue - FOW cables need insulation which is flexible and can maintain high electric field without an E_{BD}. This is similar to DEGs. However, DEG will need to achieve strains of 200-300% as well.

Challenge category: Performance
Subcategory: DEG performance at scale

4. **In the area of… what do you think the key barriers are to DEGs in wave energy applications?**

B31 Lifetime of rubber parts - this will typically be shorter than the WEC lifetime (e.g. rubber parts such as gaskets), making replacements of these large parts while at sea could be challenging.

5. **What do you think makes this an important barrier to dielectric elastomers in wave energy applications?**

B31 Difficulty in making replacements of large-scale rubber parts at sea. This could present operational difficulties.

6. **What action (or actions) do you think are needed to overcome this barrier?**

A33 (B31) Increased modularity of DEGs (to address lifetime of rubber parts) - These would be easier to replace and would also help with manufacturing constraints around large area DEs.

7. **How difficult do you think it will be to achieve these actions?**

A33 (B31) Increased modularity of DEGs (2) - there is currently limited research into this and control systems would become more complex for modular DEGs. However not considered highly difficult.

8. **Are you aware of work that could address these actions?**

A33 (B31) Increased modularity of DEGs - we can learn from control technologies used in wind and solar to address the control difficulties associated with modular DEGs.

Challenge category: Performance
Subcategory: DE materials

4. **In the area of… what do you think the key barriers are to DEGs in wave energy applications?**

B32 Creep - time dependent deformation under load, silicone is affected by creep, difficult to find DE materials that have low creep properties.

B33 Fillers - fillers are can be very beneficial in DEs, however they have to be carefully chosen. Common fillers such as Silica are hydrophilic. Testing of nano-fillers is quite novel research, they normally focus on basic tests in dry environment. They may perform well in these environments, this would not necessarily indicate good performance in DEG WEC conditions. There is a knowledge gap about how well they perform in a marine environment.

5. **What do you think makes this an important barrier to dielectric elastomers in wave energy applications?**

B32 Creep - Creep will change geometry of DEG WEC over time. For instance, in the anaconda type WEC it becomes fatter and fatter. This could cause issues for the people working on the hydrodynamics. You are adding an unpredictable non-linear parameter.

B33 Fillers - Hydrophilic fillers easily absorb water. This can create a conductive pathway within the DE which causes E_{BD} at a lower electric field.

6. **What action (or actions) do you think are needed to overcome this barrier?**

A34 (B32) Fatigue testing (to address creep) - for now long-term testing needed to determine how the material grows over a series of stretching cycles. Same as fatigue tests mentioned earlier. Also there is research into AI technology to predict the behaviour of elastomers under fatigue load using a smaller number of data points.

A35 (B33) Filler treatment (to address fillers) - hydrophobic treating can be applied to the fillers, but this would increase costs. Also water absorption tests should be done to saturate materials with fillers before the E_{BD} is measured.

7. **How difficult do you think it will be to achieve these actions?**

A34 (B32) Fatigue testing (4) - same tests and reasoning as above

A35 (B33) Filler treatment (3) - Even using the same fillers, the results from different suppliers varies dramatically. It is a time consuming process to find out which supplier is best.

8. **Are you aware of work that could address these actions?**

A35 (B33) Filler treatment - work already done on making them hydrophilic.

Closing questions

9. Looking at all the barriers, is there any way you would prioritise addressing these?

Performance and manufacturing are the priority. You have to base the power electronics, WEC design and modelling on the DEG performance and manufacturing. Also if the performance cannot be solved there is no DEG WEC industry so no need to worry about recycling at end of life.

Within performance combined fatigue testing is most important. Especially emphasising electrical fatigue on changing thickness membranes.

10. Any other comments

Electrical breakdown is biggest concern. There is in general a lack of similar technologies where knowledge can be transferred.

Appendix C.4 — Links between barriers and actions

The links between the barriers and actions are shown in Table 11-31.

Table 11-31. *Barriers and associated actions to dielectric elastomer wave energy converters from the semi-structured interviews. Also shows the groupings that the barriers and actions fall under.*

Interview	Category	Barrier	Barrier group	Barrier name	Action	Action Group	Action name
3	1.1	7	1	Lack of understanding of electromechanical coupling effects on lifetime (note that could also come under C1.2)	8		Repairability or redundancy in DEG system
3	1.1	7	1	Lack of understanding of electromechanical coupling effects on lifetime (note that could also come under C1.2)	9	1	Fatigue testing
4	1.1	11	1	Lifetime of DEGs	13	2	Involvement of materials science
4	1.1	11	1	Lifetime of DEGs	14	1	More dedicated studies on DEG lifetime
7	1.1	24	1	Lack of fatigue life data	27	2	Multi-disciplinary research
8	1.1	28	1	Limited fatigue life data	30	1	Testing of DE membranes in realistic conditions
9	1.1	29	1	Combined fatigue data	31	1	Combined fatigue testing
2	1.3	5	2	Suitable stretchable electrodes	6		Development of stretchable electrodes
6	1.3	22	2	Electrodes needs to operate under a specific set of conditions	25		Industry focus on increasing TRL of electrodes
2	1.4	3	3	Defects and reliability at scale	3		Low defect DE materials
2	1.4	3	3	Defects and reliability at scale	4		Self-healing DE materials
3	1.4	8	3	DE material properties for very large quantities of film	10	4	Development of suitable self-clearing electrodes
4	2.1	14	4	Manufacturing large DE membranes	17		Study existing industrial processes for polymer manufacturing

8	2.1	26	4	Lack of manufacturing infrastructure	28		Economic and environmental study on silicone for large-scale DEG manufacturing
6	2.5	23	4	Scaling DEG manufacturing process	26		Business model for DEG manufacturing
2	3.2	6	5	Sensing of DE deformation and health	7	5	Capacitance measurement
4	3.2	15	5	Self-sensing	18	5	Investigation of self-sensing for WECs
4	1.1	12		DE material property trade-offs	13	2	Involvement of materials science
4	1.1	12		DE material property trade-offs	15		Synthesis of new DE materials
9	1.1	30		Heat dissipation around electrodes	32		Thermally conductive DE fillers
9	1.1	31		Lifetime of DEG and replacement	33	3	Increased modularity of DEGs
2	1.2	4		Changes in DE material properties during electrotechnical fatigue cycles	5	1	Modelling and fatigue testing of DE materials
3	1.2	9		Electromechanical instabilities	11	4	Actions addressing defects and volume effect (see A10)
6	1.2	21		DE materials needs to operate under a specific set of conditions	24		Industry focus on increasing TRL of DE materials
9	1.2	32		Creep in DE materials	34	1	Fatigue testing, same as A31
9	1.2	33		DE filler selection	35		DE filler treatment
8	2.1	27		DE material selection	29		Assessment of SBR and silicone for DEG WEC
3	2.3	10		Joining of silicone DE	12		Improved understanding of chemical processes for silicone adhesion
1	3.1	1		Design of a WEC to utilise DEGs	1		DEG WEC design from foundational principles without bias
1	3.1	2		Design of power electronics	2		WEC design for power electronics
4	3.1	13		Trade-offs between modular and monolithic DEGs	16	3	Promote the investigation of modular concepts
5	3.1	17		Electrical insulation of DEG	20		Development of generic DEG insulation solutions
5	3.1	18		Scaling DEG for lab scale tests	21		More research on DE scaling and material testing

5	3.1	19		Attachment of DEG to WEC structure	22		More research on flexible DEG attachment
5	3.1	20		Development of numerical model	23		Development of numerical model and experimental data sets
4	3.2	16		Control strategies	19		Experimental testing of advanced controls
7	5.1	25		Lack of complete DEG WEC study	27	2	Multi-disciplinary research