Examining the effectiveness of support for UK wave energy innovation since 2000

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Lost at sea or a new wave of innovation?

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Executive summary
Overview and key findings

Almost 20 years after the UK's first wave energy innovation programme came to an end in the 1980s, a new programme to accelerate the development of wave energy technology was launched. It was believed that wave energy could play a central role in helping to deliver a low-carbon, secure and affordable energy system, as well as provide an important boost to the UK economy through the growth of a new domestic industry. However, despite almost £200m of public funds being invested in UK wave energy innovation since 2000, wave energy technology remains some distance away from commercialisation. Consequently, this report examines the extent to which the failure to deliver a commercially viable wave energy device can be attributed to weaknesses in both government and industry's support for wave energy innovation in the UK.

A summary of the key findings is presented below.

- **Wave energy's failure to reach market can, in part, be attributed to weaknesses in government and industrial strategy to support wave energy innovation in the UK, most notably a premature emphasis on commercialisation and a lack of knowledge exchange.**
- **These weaknesses have resulted in a poor performance against some key innovation indicators. Examples include market leaders entering administration (e.g. Pelamis), a fall in installed and rated capacity of devices, and a lack of convergence around a dominant device design.**
- **The downturn in UK wave energy innovation performance led to multi-national incumbents (e.g. energy utilities, Original Equipment Manufacturers (OEMs)) and investors withdrawing from the sector. This led to a concerted effort from the public sector to learn from past policy mistakes via knowledge capture initiatives, led primarily by the Scottish Government.**
- **Policy learning resulted in a reconfiguration of the UK's wave energy innovation system in a bid to address these issues. Changes included a re-design of government RD&D programmes, the formation of new actor networks and the commissioning of world-class test infrastructure. These changes have already yielded some positive trends in measurable innovation performance (e.g. knowledge exchange), however, the full impact of this reconfiguration has yet to emerge.**
- **Today, the UK is home to an innovation system much better placed to deliver a commercial wave energy device. However, this newly configured system is likely to face severe disruption from wider political developments such as Brexit's impact on EU RD&D funding and the UK Government's shift away from investing in wave energy.**

This report examines the extent to which the failure to deliver a commercially viable wave energy device can be attributed to weaknesses in both government and industry's support for wave energy innovation in the UK.

(Source: Shutterstock)

Rationale

The report responds to a gap in the literature, by providing an up-to-date, mixed-method and systematic analysis of the UK's wave energy innovation system, examining its structure, performance, drivers and barriers over a 17-year period since 2000. The report's findings are aimed primarily at government and industry in a bid to help improve the effectiveness of future wave energy innovation support in the UK and accelerate the technology's journey towards commercialisation. Importantly, lessons are drawn from the case study of wave energy to help inform the design and improve the efficacy of energy innovation policy more broadly. It is hoped that these lessons will shape the UK's low-carbon energy innovation strategy and help it meet its Paris Agreement commitment to limit global temperature rise this century below 2°C above pre-industrial levels.

(Source: Wikipedia)

The report's findings are aimed primarily at government and industry in a bid to help improve the effectiveness of future wave energy innovation support in the UK and accelerate the technology's journey towards commercialisation.

Research questions and methodology

The research does not assess the technical feasibility of wave energy technology nor consider whether wave energy should be a priority for UK RD&D funding. Instead it examines the effectiveness of UK innovation support between 2000 and 2017, focusing on the following five questions:

1. How is the UK's wave energy innovation system structured and how has it evolved?
2. How well has the UK's wave energy innovation system performed and how has its performance changed over time?
3. Which factors have supported and undermined wave energy innovation in the UK?
4. What actions could be taken by the UK to accelerate wave energy innovation in the future?
5. What lessons can we learn from the case of UK wave energy innovation to help support innovation of other energy technologies?

It utilises a Technology Innovation System (TIS) framework to guide the analysis of how the UK's wave energy innovation system's structure and performance evolved during the period since 2000, and crucially the factors responsible for shaping these changes. To mobilise this framework, the analysis utilises a combination of quantitative (e.g. patents, bibliometrics, public RD&D grants) and qualitative data (e.g. expert interviews, documentary evidence). Innovation performance is measured via a set of 22 indicators, measuring both absolute and relative changes in wave energy innovation performance, the latter situating performance against other countries or energy technologies as a benchmark. Each indicator is coupled with one of the seven TIS functions outlined in Table 1.

Table 1: Description of TIS functions

TIS Function	Description
F1 – Knowledge development	The creation of technological variety achieved by a broadening and deepening of a codified knowledge[1] base via research and development (R&D).
F2 – Knowledge exchange	Exchange of information between actors facilitated by inter-actor networks.
F3 – Entrepreneurial experimentation	Entrepreneurs recognise the latent value proposition of emergent technologies and seek to realise this potential via commercial experiments. These experiments typically generate a form of tacit knowledge and in turn reduce the degree of uncertainty associated with a technology, either through success or failure.
F4 – Guidance of the search	Pressures that encourage actors to enter a technological field and subsequently guide the stage and focus of innovation activities they undertake, such as policy targets and technology roadmaps.
F5 – Resource mobilisation	Mobilisation of financial, human and physical resources critical to the technology innovation process.
F6 – Market formation	Mechanisms that create niche markets or 'protected spaces' enabling technologies to compete against initially superior incumbent technologies in order to boost levels of adoption, such as favourable tax regimes or new industry standards.
F7 – Legitimation	The act of granting legitimacy to an emerging technology by strengthening its 'fitness' with the prevailing institutional regime. TIS actors seek to achieve this by shaping existing institutions to galvanise support for this new technology amongst actors, for example via political lobbying.

Key findings

Structure and evolution of the UK wave energy innovation system

We consider the evolution of the UK wave energy innovation system in relation to four structural elements of a TIS: **actors, institutions, networks** and **technology/ infrastructure**.

Analysis of the wave energy **actor** landscape identifies a wealth of world-class universities, a burgeoning supply chain and a wide range of government, NDPB and other supporting organisations (e.g. test facilities, trade associations) offering support across the entire innovation chain. Importantly, we find that many important additions have been made to the actor landscape since 2000, such as the introduction of new funding bodies with a strong focus on mid-stage energy innovation support previously missing in the UK (e.g. Energy Technologies Institute (ETI)). The European Marine Energy Centre (EMEC) was also established in 2003, which has played a key role in assisting technology demonstration, knowledge capture and developing industry standards. However, we also find that some actors have exited the sector, most notably OEMs and energy utilities during the early 2010s, who no longer viewed wave energy as an investment priority.

Turning to **institutions**, we find an extremely complex wave energy innovation policy landscape, managed by numerous different funding agencies across three levels of government (Scotland, the UK and the EU). This landscape has also been fast changing, with a succession of new schemes emerging, each with their own eligibility criteria and objectives. An important change has been the clear shift from commercially focused, full-scale device RD&D programmes in the mid-2000s and early 2010s, some with an explicit focus on arrays (e.g. Marine Energy Array Demonstrator (MEAD)), to innovation programmes supporting early-stage development through to large-scale prototype demonstration (e.g. Wave Energy Scotland

1 Codified knowledge means 'reproducible, transparent, accessible knowledge documented or enshrined in blueprints, manuals, or sets of instructions' (Wilson & Grübler 2014 p.17).

(WES)). Many of these policy changes have unfolded against a backdrop of ambitious, high-level energy and climate change commitments from government, creating an imperative for such action.

With respect to actor **networks** the research finds a long-standing presence of scientific and industry networks since the early 2000s, whilst networks co-ordinating test facility, training and government activities were much slower to form. Following the formation of these networks, innovation system actors are much better connected than they were 15 years ago, offering linkages both nationally and internationally. Furthermore, the growth in the number and diversity of networks has meant that networks now offer excellent coverage across six key intermediary functions, ranging from: 1) relationship building, 2) capacity building, 3) knowledge transfer, 4) technology foresighting, 5) RD&D co-ordination and 6) policy advocacy. There is, however, some evidence of overlapping networks (e.g. trade associations, centres for doctoral training (CDTs), signalling some duplication of resources.

Finally, turning to **infrastructure**, the research identifies a very clear progression in the capabilities of wave energy test facilities with the introduction of large-scale multi-directional wave tanks (e.g. FloWaveTT), as well as part-, full- and array-scale open-ocean test facilities (e.g. EMEC, WaveHub). With regards to **technology**, the research finds that wave energy exists alongside a wide range of mature energy (e.g. offshore wind) and non-energy technologies (e.g. shipping, aviation, offshore construction), offering a small number of valuable opportunities for cross-fertilisation.

UK wave energy innovation performance

The study finds that UK wave energy innovation performance was measurably stronger against most indicators in the second half of the period since 2000 (c. 2008–2016) than the first (c. 2000–2007) both in absolute and relative terms but that performance has started to decline in recent years across some of these indicators, such as number of patents and level of installed capacity. Looking across the whole period since 2000, performance was strongest in terms of **knowledge development (F1)**, **knowledge exchange (F2)** and **resource mobilisation (F5)** and weakest against **entrepreneurial experimentation (F3)** and **market formation (F6)**, with a mixed performance against **guidance of the search (F4)** and **legitimation (F7)**.

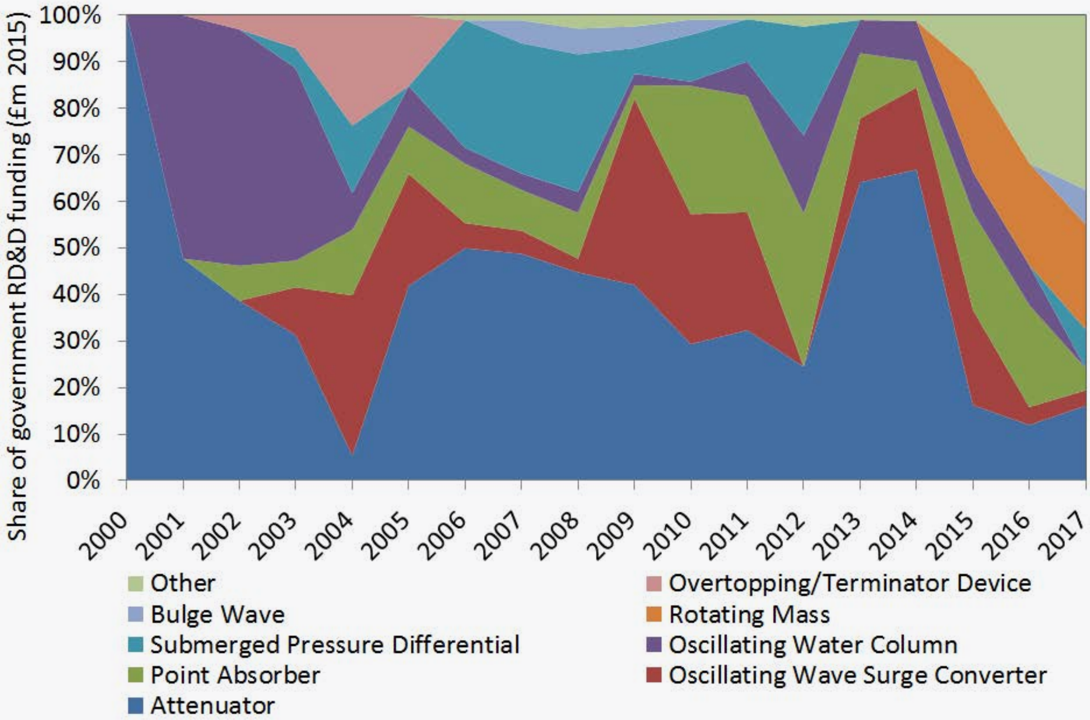
The UK performed strongly in terms of **knowledge development (F1)**, as an international leader in scientific publications and wave energy patents. Despite being a global leader in wave energy patents the UK did witness a significant decline in total patents from 2010 and a reduction in its share of global wave energy patents since 2005. The UK also performed strongly in terms of **knowledge exchange (F2)**, with an increase in the average number of wave energy project partners, as well as an increase in the number of projects with partners from both industry and science, and from outside the wave energy sector, evidencing cross-fertilisation.

The UK also performed strongly in terms of **resource mobilisation (F5)**, with funding in the second half of the period almost four times higher than the first in real terms. Furthermore, the UK Government's budget for ocean energy RD&D as a share for all renewables also grew to 31% in 2014, up from a 19% average share during the period. Human resources also measured strongly, with a large number of higher education engineering degrees, although half of the companies engaged in publicly funded wave energy projects since 2000 had fewer than 50 employees, suggesting a large number of small companies working in the sector with relatively few staff and resources.

The UK performed poorly in terms of **market formation (F6)** with the number of wave energy developers steadily falling from 30 in 2011 to 24 in 2016, with 14 developers filing for administration during this time, including market leaders Pelamis and Aquamarine Power. The other indicator is cumulative installed capacity, which, despite growing from 0.5MW in 2008 to 3.5MW in 2012, dropped to 1.2MW in 2016. Both indicators suggest a shrinking market.

The UK also performed poorly in terms of **entrepreneurial experimentation (F3)**, with a clear divergence of technology design rather than a convergence identified through RD&D grants (Figure 1) and installed capacity. There was also little evidence of technology maturation with the average rated capacity of devices falling by 56% in the second half of the period versus the first and wave energy's levelised cost of electricity (LCOE) growing from 2009 and remaining very high compared to other renewables.

Figure 1: Share of RD&D funding committed to different wave energy device designs 2000–2017 (source: author)



NOTE: Funding for 2017 only for grants up to 1st June 2017. Covers both experimental development and demonstration.

The research found a mixed performance in terms of the **guidance of the search (F4)**. The analysis identified an increase in the number of foresight reports in recent years, albeit with a shift in focus from later stage demonstration and commercialisation to more fundamental experimentation. However, in parallel, explicit government targets for wave energy deployment have steadily reduced in ambition before being removed altogether by the UK Government.

Legitimation (F7) of wave energy technology also exhibited a mixed performance. Whilst there was a large number of UK government publications (e.g. white papers, parliamentary reports) calling for the need to support wave energy, there was a clear change in direction from the early 2010s, with a removal of formal wave energy deployment targets and a decline in vocal support from government ministers. This was at odds with the UK general public's support for wave and tidal energy, which averaged 74% since 2012, greater than the figure for onshore wind (67%) and equal to that for offshore wind (74%).

Structural drivers of and barriers to wave energy innovation

The study considered the structural mechanisms that have served to block or induce wave energy innovation in the UK. We categorise these drivers and barriers according to four structural dimensions: actors, institutions, networks and technology/infrastructure.

Actors

Knowledge exchange (F2) was hindered by a lack of knowledge codification, meaning that knowledge generated from RD&D projects remained tacit and was limited to the experiences of their staff rather than the wider sector. However, investments in knowledge capture schemes and a requirement to licence intellectual property (IP), for example via Scotland's WES, have helped to address this problem. These efforts to learn from past experience, coupled with a government capacity to translate learning into policy actions, have led to wide-ranging structural changes to the UK's wave energy innovation system, albeit mostly constrained to efforts led by the Scottish Government.

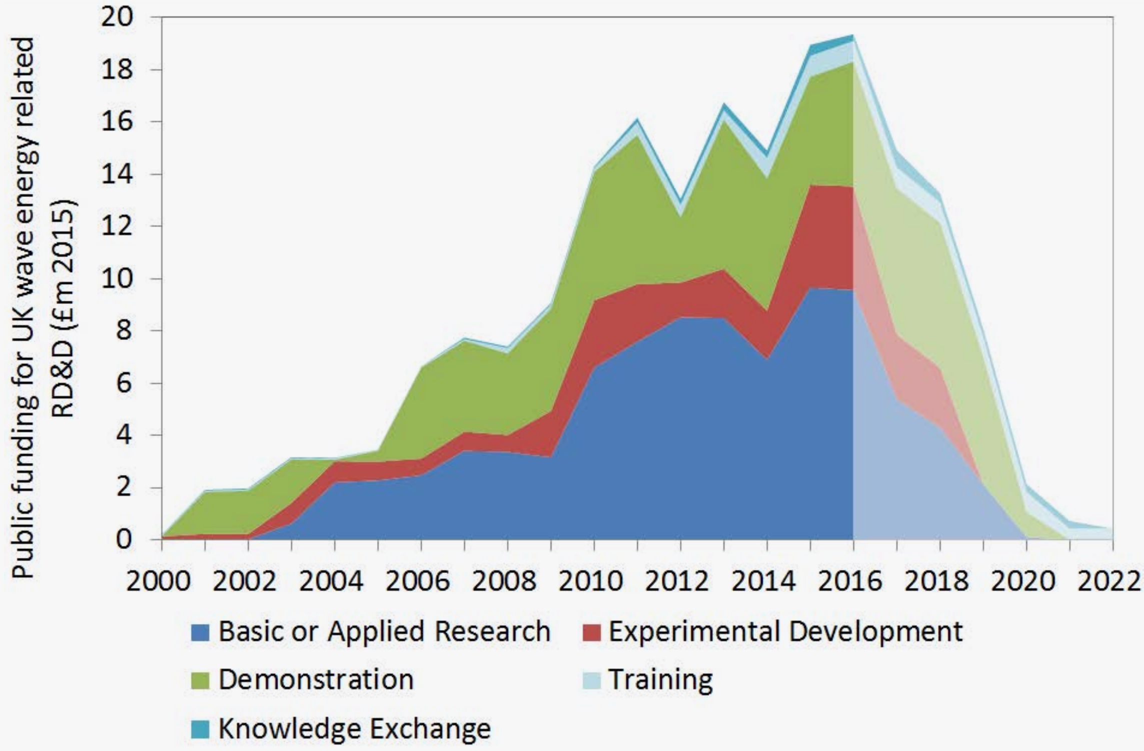
The limited breadth of technical and business expertise, linked to the very small size of UK wave energy developers, has negatively impacted on their capacity for *knowledge development (F2)* and *entrepreneurial experimentation (F3)*. This was exacerbated by a culture of undertaking most activities in-house because of a desire to build up internal capabilities and the view that some highly specialised activities could be outsourced to the wider supply chain.

Even so, the UK wave energy supply chain was overall considered to be strong, underpinned by a steady supply of skilled personnel and centred around the formation of niche markets (e.g. off-grid islands, aquaculture) and test facilities (e.g. the EMEC). Nonetheless, intermittent funding and the lack of a long-term strategy were considered to have led to a leakage of skilled personnel outside the sector. Human and financial resources were also dramatically improved and then subsequently reduced by the entry and exit of market incumbents (e.g. energy utilities, OEMs). They had been enticed in part by the introduction of market–pull mechanisms but lost confidence in wave energy following a lack of technological progress against initial expectations.

Institutions

A major institutional barrier was the overwhelming emphasis on full-scale device demonstration, with a view to 'fast tracking' progress to commercial array-scale projects before the underpinning early- to mid-stage R&D had been performed (Figure 2). Reasons for the UK going 'too big, too soon' included public and private sector funds being made available to progress the technology as quickly as possible following developers' highly optimistic claims about the promise of wave energy. The outcome was that developers had over-promised in order to receive funds but then subsequently under-delivered, in turn eroding investors' confidence in wave energy and reducing their willingness to invest in the technology *(resource mobilisation (F5))*, triggering the collapse of leading firms (e.g. Pelamis) and further undermining the sector's *legitimacy (F7)*. Underpinning these developments was a poor understanding of the scale of the innovation challenge and the associated time and funds required to overcome it, as well as a lack of rigorous, objective procedures to review the credibility of funding proposals.

Figure 2: UK public RD&D funding for wave energy-related projects by innovation stage since 2000 (source: author)



NOTE: Includes RD&D activity explicitly related to wave energy or cross-cutting marine energy. Excludes test infrastructure. RD&D grants covered up to 1st June 2017.

Another issue was that a large proportion of the UK's budget for wave energy RD&D went unspent because developers could not meet over-ambitious funding criteria and/or struggled after the financial crisis to secure the necessary private sector match funding required to access these public funds. Finally, financial *resources (F5)* were channelled away from wave and towards more mature technologies because of wave energy RD&D grant funding being bundled with tidal energy and long-term revenue payments with other renewables such as offshore wind for Contracts for Difference (CfDs). To address this, an explicitly wave energy-focused, 100% funded, earlier stage innovation programme called WES was established, with an objective and transparent stage-gated funding allocation procedure. Finally, the lack of a long-term strategy for wave energy innovation *(guidance of the search (F4))* was blamed on a combination of short-term public spending review periods and a lack of political commitment to foresight reports (e.g. roadmaps), due to a lack of consensus building and detail relating to next steps.

Networks

Actor *knowledge exchange (F2)* was considered to be constrained by a combination of: (1) a culture of developers operating secretively in order to protect IP; (2) the UK's decentralised model of innovation that prioritises competition over collaboration; and (3) a strong focus on device-level innovation funding, which removed the incentive for actors to develop common solutions to shared problems. Again, steps were taken to address these issues – for example, WES imposed a requirement on awardees to licence their IP, share lessons and formulate consortia in order to be awarded funds.

Industry–science collaboration was constrained by fundamental differences in the working cultures and timeframes adopted by the two communities, as well as a lack of joint industry–science funding that offered a jointly acceptable working arrangement. The introduction of funding for joint science projects (e.g. WES, Energy Catalyst (EC)) and the establishment of CDTs offering industrial placements to students have helped to address these issues.

International collaboration was considered to be undermined by a belief that the UK could tackle the wave energy challenge alone as a leader of wave energy, as well as a perceived bias towards domestic wave technology. However, funding schemes either demanded or encouraged the formation of international consortia (e.g. EU Horizon2020) have helped to promote international collaboration.

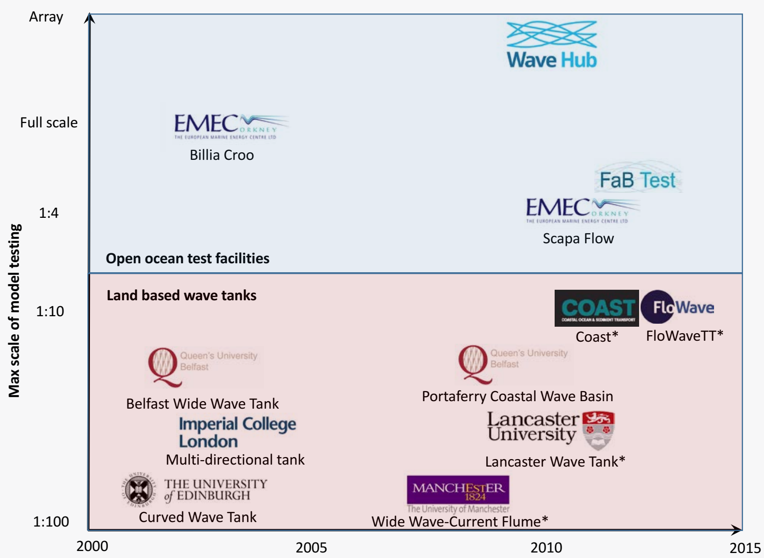
Cross-government co-ordination was generally considered to be weak, resulting in a poorly co-ordinated policy landscape encouraging resource duplication and lack of a clear pathway to market. Instead, numerous different RD&D schemes were being delivered simultaneously by different funding agencies at three different levels of government (devolved administrations, UK and EU), often with overlapping remits. This was in part linked to the lack of an effective central cross-government body responsible for co-ordinating wave energy or energy innovation more broadly, although new bodies have since been formed to improve levels of co-ordination (e.g. the Energy Innovation Board (EIB)).

Technology and infrastructure

The unique characteristics of wave energy technology were considered to have slowed down its innovation journey, most notably developers' conservative approach to testing in a very hostile ocean environment and a limited number of weather windows for testing. Furthermore, whilst levels of cross-fertilisation increased following a concerted effort to harness lessons from other sectors (e.g. automotive, materials science, commercial shipping and defence) via programmes such as WES, overall, wave energy was considered to represent a fundamentally new technological challenge that shared relatively few overlaps with established technologies.

Turning to infrastructure, the UK's wave energy test facilities were considered to be the best in the world. However, concerns were raised about the cost of accessing these facilities and the in-built bias of some facilities towards particular device designs. The biggest barrier raised was the lack of test facilities filling the gap between testing of very small-scale and full-scale devices. However, the introduction of state-of-the-art new generation wave tanks (e.g. FloWaveTT) and open-ocean part-scale 'nursery' test sites (e.g. the EMEC's Scapa Flow) were considered to have filled this gap, with UK facilities now offering excellent coverage across the entire innovation chain (Figure 3).

Figure 3: Evolution of land-based wave tanks and open-ocean test facilities since 2000 (source: author)



NOTE: Selection of facilities is for illustrative purposes and does not include all test tanks constructed during this period.

* Facilities that also have tidal current generation capability

(Source: Dave Morris)

Policy recommendations

In light of the research's key findings, we present ten policy recommendations to help improve the effectiveness of the UK's future support for wave energy innovation and help accelerate the technology's journey towards commercialisation.

1. **Retain access to EU innovation funding post-Brexit** – Brexit poses a major risk to EU wave energy funding, accounting for 27% (£53m) of all wave energy-related RD&D committed since 2000, and in 2016 EU funding (£6.3m) was greater than that from the UK Government (£6m). It is essential that the UK retains access to EU innovation funds following Brexit negotiations, especially EU Framework Programmes (FPs) (i.e. Horizon2020). Exiting from the EU will also remove the UK's primary platform for international RD&D collaboration, making it necessary to identify alternative ways to collaborate internationally to achieve the critical mass of resources and expertise necessary to commercialise wave energy, possibly via new international platforms such as Mission Innovation.[2]

2. **Allow time for new UK wave energy innovation policy landscape to take effect** – The UK wave energy innovation system has undergone a major reconfiguration over the past few years and the effects of this have not yet been fully felt. This new configuration must be given time to take effect before its efficacy is critiqued and decisions made to engage in any additional wide-scale restructuring.

3. **Develop a long-term Scottish wave energy strategy in a new political order** – With the UK Government significantly reducing its support for wave energy and the threat of EU funds being withdrawn after Brexit, the Scottish Government could find itself acting alone in developing wave energy technology. Consequently, a strategy must be put in place that presents a credible path towards delivering a commercial wave energy device in Scotland that is resilient to the potential withdrawal of UK Government and/or EU funds. This should situate the development of wave energy in the context of a wider portfolio of energy technologies that the Scottish Government has identified as playing a key role in the future as part of its recent energy strategy (Scottish Government 2017c) and outline the steps required to integrate the various sub-components developed by the WES programme into a single, commercial device.

4. **Improve co-ordination of UK energy innovation policy landscape** – There are still significant opportunities to improve the degree of co-ordination of wave energy RD&D support both within and across different levels of government. It remains to be seen how effective the UK's newly formed EIB and UKRI will be in co-ordinating energy RD&D investment at UK level. It is recommended that, to ensure co-ordination with bodies operating at different levels of government, these new networks engage closely with both the devolved administrations (e.g. the Scottish Government) and the EU. Furthermore, a top-down body responsible for wave energy at UK level, similar to Scotland's WES model, could also improve co-ordination of wave energy RD&D.

5. **Share and synthesise lessons from past and present wave energy innovation programmes** – Outputs from publicly funded later stage wave energy RD&D projects have not traditionally been made available for public consumption because of issues around IP protection and private sector match funding. In contrast, the Scottish Government's WES programme and the EU's FPs require awardees to share their key findings via project reports, enabling the wider sector to learn lessons from past projects and avoid making the same mistakes. It is critical that this approach is applied across all future publicly funded wave energy RD&D programmes in the UK and efforts should also be made to capture knowledge generated from past public RD&D projects, expanding upon WES's current knowledge capture exercise.

2 Through Mission Innovation, 22 countries and the EU are taking action to double their public clean energy R&D investment over five years. In addition, Mission Innovation members encourage collaboration among partner countries, share information and co-ordinate with businesses and investors.

6. **Acknowledge that support for wave energy has been historically low and intermittent** – Since 1974, ocean energy has been allocated approximately $1.8bn[3] of IEA members' public energy RD&D budget versus $25bn for solar PV and $7.5bn for wind energy. Furthermore, funding for wave energy has been much more intermittent than most other energy technologies, split across two phases during the 1970s and 1980s and the 2000s and 2010s, increasing the likelihood of significant knowledge depreciation between these periods of concentrated investment. In this context, key policy decisions should be made against the backdrop that wave energy has not enjoyed the same level or consistency of RD&D support in comparison to more mature renewables such as wind and solar energy.

7. **Avoid competition for subsidies with established low-carbon energy technologies** – Emerging technologies, such as wave energy, can be out-competed for subsidies on a cost basis when in direct competition with significantly more mature technologies. Specific examples include separating wave energy from the same EMR CfD allocation as significantly cheaper technologies such as offshore wind energy and avoiding wave energy becoming bundled into wider marine energy RD&D programmes where it must compete with more mature technologies such as tidal range and tidal stream.

8. **Avoid need for private sector match funding to support wave energy RD&D** – The need to secure private sector investment to be awarded public grants has placed intense pressure on wave energy developers to 'fast track' their innovation timeline and avoid knowledge exchange in a bid to protect their IP. Furthermore, the financial crisis and wave energy's slow progress saw private sector funds become more difficult to secure, in turn making access to public funds difficult. State aid compliant procurement frameworks such as WES can avoid the need for private sector match funding, offering a 100% intervention rate. Opportunities should be explored to apply this procurement model more widely, not just for wave but for other energy technologies.

9. **Support wave energy niche market formation** – A shift towards demonstrating wave energy devices in niche markets (e.g. off-grid islands, aquaculture) enables developers to learn valuable lessons through 'learning by doing' in both real-world ocean and market environments, as well as providing both government and investors with greater confidence in the technology's prospects. When wave energy is ready for full-scale demonstration, funds for wave energy RD&D should facilitate deployment in 'real-world' niche markets. However, funds should be awarded to developers that present an evidence-based roadmap that outlines how their technology can progress beyond small-scale niche application and towards wide-scale deployment.

10. **Enable easy access to wave energy test facilities** – Access to the UK's world-class test facilities has required developers to secure public sector funds via open competitions, and the corresponding levels of private sector match funding. This process involves significant time and effort, channelling developers' resources away from RD&D. To ensure developers can quickly and easily access these facilities, a state aid compliant UK-wide 'innovation voucher' scheme should be established to enable 'free at the point of use' access to those that have passed through preliminary stage-gated phases of development with independently verified positive results, building upon lessons learnt from the Europe-wide est infrastructure access schemes such as FORESEA and MARINET.

3 Includes all forms of ocean energy, not just wave energy.

Wider lessons to support energy technology innovation

We draw a number of broader lessons from the case of UK wave energy innovation in order to improve our understanding of how energy technology innovation unfolds and how it can best be supported. This will help to inform both the design of energy innovation policy and development of innovation theory.

1. **Innovation systems can become destabilised and reconfigured** – Traditionally, TIS evolution has been considered to follow a broadly linear and positive development trajectory, incorporating two main phases: *formation and growth* (Bergek, Jacobsson, et al. 2008a). The case of wave energy highlights how a TIS may indeed follow a non-linear and more challenging development path involving distinct phases such as: (1) *disintegration*, in the face of destabilising forces such as the failure of market leaders and the withdrawal of government funds; (2) *reconfiguration* of structural elements potentially in a concerted effort to improve the efficacy of the TIS in reaction to system failures; and/or (3) *stagnation*, where a prolonged period of little investment results in low levels of activity, possibly inducing knowledge depreciation, but where investment is sufficiently high to preserve some key aspects of the TIS (e.g. research institutes, test facilities).

2. **Test infrastructure innovation co-evolves with energy technology innovation** – To date, the role of infrastructure in the technology innovation process has normally been characterised as one enabling technology deployment – for example, via integration with existing electricity networks (Gallagher et al. 2006). However, this research identifies the key role test facilities play in enabling technology innovation. Furthermore, the research finds that test infrastructure is subject to a process of innovation similar to that of the technologies of which it enables testing (e.g. wave energy). Crucially, test infrastructure also co-evolves with the technologies it is designed to test. Devices are designed with test facility capabilities in mind, whilst test facilities are designed around the key characteristics of emergent device designs.

3. **Technology innovation relies on policy innovation** – The research finds that government reflected upon and learned lessons from the successes and failures of past wave energy policy, using these to inform the design of its current policy framework. Paramount to successful energy innovation policy making is the iterative process of policy design, experimentation, 'learning by doing' and subsequent refinement based on lessons learnt, which represents its own discrete form of innovation (Petmesidou & Gonz 2015; Mintrom 1997). This process of policy innovation is reliant upon the presence of personnel with the capacity and appetite to develop innovative policies (i.e. policy entrepreneurs) (Petmesidou & Gonz 2015), as well as intra- and inter-organisational networks that enable knowledge exchange and a culture that rewards policy innovation rather than discouraging it.

4. **Devolution creates a complex but diverse innovation system** – Whilst research has considered how innovation policy unfolds in regions subject to multiple layers of governance (Sotarauta & Kautonen 2007; Kuhlmann 2001) little work has examined how devolution impacts upon the evolution and performance of an energy innovation system. The case of wave energy is inextricably linked with devolution in the UK both upwards to the EU and downwards to devolved administrations such as the Scottish Government. On the one hand, devolution has led to a complex, multi-level energy innovation governance framework that has created difficulties in terms of co-ordination and policy landscape navigation. On the other, it has created diversity, meaning that the UK Government's move away from wave energy has not entirely dictated the fortunes of wave energy, with support continuing to flow from the EU and Scottish Government. Furthermore, Scottish Government, the smallest and most agile of the three governments, demonstrated the strongest ability to learn from past policy performance and translate this into action.

5. **Innovation relies on the capture and codification of tacit knowledge** – The case of wave energy identifies that, too often, tacit knowledge (i.e. 'know-how') was lost when companies ceased trading, personnel moved on or knowledge was stockpiled due to confidentiality issues. Successful technology innovation relies on tacit knowledge being codified and, wherever possible, shared. However, it should be acknowledged that some tacit knowledge cannot easily be codified, making it difficult to transfer or 'sticky' (Hippel 1994; Brodbeck & Polanyi 1960). Finally, codification can help protect against knowledge depreciation during periods of relatively low RD&D funding (Wilson & Grübler 2014), as was the case for UK wave energy during the 1980s and 1990s.

6. **Competition and collaboration must be balanced according to stage of innovation** – The case of wave energy supports the need for a balance between competition and collaboration or closed and open innovation (Chesbrough 2003). It points to the need for a stronger emphasis on collaboration during the earlier TRLs to ensure technology developers do not operate in isolation but instead benefit from knowledge sharing and the pooling of human and financial resources. As the technology moves closer to market, the emphasis may gradually shift towards competition in a bid to encourage convergence around a single optimal device design. Even so, it is important that areas for collaboration are clearly demarcated and built on sectoral consensus, with suitable platforms put in place to facilitate collaboration (e.g. JIPs).

7. **Regional innovation clusters offer a locus for market formation** – A growing body of literature points to the importance of 'regional innovation clusters', which constitute a geographical concentration of key structural elements underpinning innovation (e.g. actors, institutions, networks, infrastructure), facilitating key innovation functions such as knowledge exchange and market formation (Muro & Katz 2010). The wave energy case study supports this view in the examples of the EMEC and the University of Edinburgh, which have formed centres of excellence with their own entrepreneurial ecosystems. Consideration must therefore be given to where and how regional energy innovation clusters will be established and opportunities to build these around test facilities, which already see a high concentration of actors, resources and infrastructure (e.g. grid connection).

8. **Protected spaces help to shield emerging technologies from competition against mature technologies** – To avoid emerging technologies becoming 'crowded out', it is essential that they are not in direct competition with more established technologies for the same RD&D funding. This finding supports the view outlined in the socio-technical transitions and strategic niche management literature that emerging technologies should be protected by the formation of 'sheltered spaces' such as niche markets (Schot & Geels 2008), enabling gradual technological maturation through 'learning by doing' and 'learning by using', as well as improving stakeholders' confidence in the technology via successful real-world deployment.

9. **Characteristics of technology influence its innovation journey** – The case of wave energy points to the unique technical challenges it has faced, such as the need to test in a very hostile ocean environment and the lack of synergies with established technologies. It is critical that, when comparing the progress of different energy technologies, their respective characteristics are acknowledged because these will shape the pace and nature of their development trajectory. This echoes research by Nemet (2014) who identified how smaller, modular energy technologies (e.g. solar PV) tended to benefit from a faster rate of learning versus large, site-assembled technologies (e.g. nuclear) because they underwent a much larger number of iterations due to their lower costs and build times.

Recommendations for future research

Looking forward and focusing specifically on research relating to strategies for wave and marine energy innovation, the report identifies the need for:

1. a continued mixed-method assessment to monitor how structural changes are impacting upon the UK's wave energy innovation performance over a long-term period;
2. firm-level case studies of wave energy developers' experiences to offer a detailed understanding of their innovation journey and interaction with the wider innovation system;
3. a similar study that focuses on tidal stream innovation to offer insights into the challenges facing a technology closer to commercialisation; and
4. an international cross-country comparison of wave or marine energy innovation system performance, with follow-on case study research to examine the underlying factors responsible for some countries performing better or worse than others.

Turning to energy technology innovation studies more broadly, the report identifies the need for a systematic mixed-method comparison of different energy technology case studies across different countries to identify best-practice innovation strategies. This assessment could include a cost–benefit analysis of innovation policy frameworks, comparing innovation inputs (e.g. RD&D investment) and outputs (e.g. levelised cost of electricity, unit cost and installed capacity) and/or outcomes (e.g. CO_2 emission reduction, job creation). This could help to identify the countries with best-practice innovation strategies and present a focus for more detailed case study research. Any such analysis should account for both public and private RD&D investment.

Pelamis machine installed at the Agucadoura Wave Park (Source: Wikipedia)

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List of acronyms and abbreviations

BEIS	Department of Business, Energy and Industrial Strategy
BWEA	British Wind Energy Association
CAPEX	Capital expenditure
CDT	Centres for doctoral training
CfD	Contracts for Difference
CEO	Chief Executive Officer
CFO	Chief Financial Officer
CHP	Combined Heat and Power
CPC	Cooperative patent classification
DCLG	Department for Communities and Local Government
DEFRA	Department for Environment, Farming and Rural Affairs
DECC	Department of Energy and Climate Change
DETR	Department of the Environment, Transport and the Regions
DfID	Department for International Development
DfT	Department for Transport
DG	Directorates General
DTI	Department of Trade and Industry
EC	European Commission
EERA	European Energy Research Alliance
EIB	Energy Innovation Board
EMEC	European Marine Energy Centre
EMF	Electricity Market Reform
EngD	Engineering doctorate
EPO	European Patent Office
EPSRC	Engineering and Physical Sciences Research Council
ERDF	European Regional Development Fund
ETI	Energy Technologies Institute
ETSU	Energy Technology Support Unit
EU	European Union
EU ETS	EU Emissions Trading System
FORESEA	Funding Ocean Renewable Energy through Strategic European Action
FP	Framework programme
FREDS	Forum for Renewable Energy Development in Scotland
GDP	Gross Domestic Product
GW	Gigawatt
HESA	Higher Education Statistics Authority
HIE	Highlands and Islands Enterprise
HoCECCC	House of Commons Energy and Climate Change Committee
ICOE	International Conference on Ocean Energy
ICT	Information and communications technology
IDCORE	Industrial Doctorate Centre in Offshore Renewable Energy
IEA	International Energy Agency
INORE	International Network on Offshore Renewable Energy
IP	Intellectual property
IPCC	Intergovernmental Panel on Climate Change
IPPI	International Public Policy Institute
ITI	Intermediate Technology Institute
kW	Kilowatt
JIP	Joint industry programme
LCICG	Low Carbon Innovation and Coordination Group
LCIG	Low Carbon Innovation Group
LCOE	Levelised cost of electricity
LIMPET	Land Installed Marine Power Energy Transmitter
M&A	Mergers and acquisitions
MARINET	Marine Renewables Infrastructure Network
MEA	Marine Energy Accelerator

MEAD	Marine Energy Array Demonstrator
MEPB	Marine Energy Programme Board
MESAT	Marine Energy – Supporting Array Technologies
MFA	Marine Farm Accelerator
MRCF	Marine Renewables Commercialisation Fund
MRDF	Marine Renewable Deployment Fund
MRes	Master of Research
MRPF	Marine Renewables Proving Fund
MSO	Marine Supply Obligation
MW	Megawatt
NDPB	Non-departmental public body
NER300	New Entrants Reserve 300
NERC	Natural Environment Research Council
NFFO	Non-Fossil Fuel Obligation
O&M	Operations and maintenance
OEE	Ocean Energy Europe
OEM	Original Equipment Manufacturer
OES	Ocean Energy Systems
Ofgem	Office for Gas and Electricity Markets
OPEX	Operational expenditure
OREC	Offshore Renewable Energy Catapult
ORECCA	Offshore Renewable Energy Conversion platforms – Coordination Action
ORJIP	Offshore Renewables Joint Industry Programme
OWA	Offshore Wind Accelerator
OWC	Oscillating water column
PATSTAT	Worldwide Patent Statistical Database
PhD	Doctorate of Philosophy
PRIMARE	Partnership for Research in Marine Renewable Energy
PTO	Power take off
PV	Photovoltaic
PWh	Perwatt hour
R&D	Research and development
R&I	Research and Innovation
RCUK	Research Councils UK
RD&D	Research, development and demonstration
REA	Renewable Energy Association
REMS	Centre for Doctoral Training in Renewable Energy Marine Structures
REIF	Renewable Energy Investment Fund
RO	Renewables Obligation
ROC	Renewable Obligations Certificate
ROS	Renewable Obligation Scotland
ROV	Remotely operated vehicle
SEAB	Scottish Energy Advisory Board
SET	Strategic Energy Technologies
SME	Small- to medium-sized enterprise
SRO	Scottish Renewables Obligation
TCP	Technology Collaboration Programme
TGL	Tidal Generation Ltd
TINA	Technology Innovation Needs Assessment
TIS	Technology innovation system
TNEI	The Northern Energy Initiative
TRL	Technology readiness level
TWh	Terawatt hour
UK	United Kingdom
UKAS	United Kingdom Accreditation Service
UKCMER	UK Centre for Marine Energy Research
UKERC	UK Energy Research Centre
UKRI	UK Research and Innovation
VC	Venture capitalist
W&T KTN	Wave & Tidal Knowledge Network
WATERS	Wave and Tidal Energy: RD&D Support
WATES	Wave and Tidal Energy Scheme
WEC	Wave energy converter
WEFO	Welsh European Funding Office
WES	Wave Energy Scotland
WMES	Centre for Doctoral Training in Wind & Marine Energy Systems
WTSET	Wave and Tidal Stream Energy Technologies

1

Introduction

Wave energy has long been identified as a potentially significant contributor to the UK's electricity supply mix. It has been estimated that wave energy in UK waters could provide up to 70 TWh/annum of electricity generation[4] (AMEC & Carbon Trust 2012), equivalent to approximately 21% of the UK's electricity supply in 2015 (BEIS 2016b).

As a low-carbon energy source, wave energy has the potential to help the UK meet its 2050 target of reducing its greenhouse gas emissions by 80% against its 1990 baseline. Furthermore, as a domestic natural resource, wave energy can help deliver on other government objectives such as improving energy security by replacing imported fossil fuels (e.g. gas, coal) and promoting economic growth through the birth of a new home-grown industry.

To capture this prize, the UK has invested heavily in wave energy RD&D, but despite this significant investment, wave energy technology has yet to become commercially viable. Whilst this may in part be attributed to the scale of the associated engineering challenge and the viability of the technology, questions remain about whether this slow progress could also be attributed to government and industry's strategy to accelerate wave energy technology innovation in the UK. This report therefore examines how well the UK has performed in accelerating wave energy technology since 2000 and the socio-technical factors responsible for supporting or undermining wave energy innovation, not least government policy.

1.1 Rationale

The report's findings are aimed primarily at government and industry in a bid to help improve the effectiveness of UK public wave energy innovation support and accelerate the technology's journey towards commercialisation. Importantly, lessons are drawn from the case study to help inform the design and improve the efficacy of energy innovation policy more broadly. It is hoped these lessons will help shape the UK's low-carbon energy innovation strategy and help it meet its Paris Agreement commitment to limit global temperature rise this century well below 2°C above pre-industrial levels.

The report also makes an important contribution to the extant literature on the structure, performance, drivers and barriers of wave energy innovation. Whilst a wealth of research has already examined the structure, performance, drivers and barriers of wave energy innovation, both in the UK (Winskel et al. 2006; Jeffrey et al. 2013; A. Vantoch-Wood 2012) and other countries (Corsatea & Magagna 2014; Magagna et al. 2016; Andersson et al. 2017), the extant research poses a number of limitations that this report seeks to address.

First, only a handful of studies have employed a systematic analysis of wave energy technology innovation performance that considers a broad spectrum of causal factors and how these inter-relate (Corsatea & Magagna 2014; A. Vantoch-Wood 2012; Andersson et al. 2017). Furthermore, very few of these systematic studies have focused specifically on the UK and those that have were conducted some years ago, thus failing to take into account the major changes the sector has recently undergone (see A. Vantoch-Wood 2012).

Second, studies of wave energy technology innovation tend to be bundled together as part of a broader focus on marine energy innovation. However, wave energy presents a characteristically distinct technology when compared to other marine technologies (e.g. tidal stream, tidal range), most of which are also at very different stages of development (Mofor et al. 2014), thus demanding that research focuses exclusively on wave energy technology.

4 Takes into account practical constraints such as the: capability of existing wave energy technologies, needs of other sea users (e.g. shipping, fishing) and need to mitigate environmental impact (AMEC & Carbon Trust 2012).

Third, with the exception of Vantoch-Wood (2012) and Andersson et al. (2017), most marine energy innovation studies have employed either a predominantly qualitative or quantitative approach to analysis, rather than a mixed-methods approach and the balanced assessment this provides.

Finally, whilst various excellent historical accounts of wave energy innovation exist (Ross 2002; Ross 1996; Wilson 2012), analyses of UK wave energy innovation performance and policy support tend to provide snapshots of particular moments in time rather than a longer term view of how innovation systems have evolved over time and how this evolution has shaped innovation performance.

1.2 Research questions

In this context, this report provides an up-to-date systematic mixed-method analysis of how the UK wave energy innovation system's structure and performance have evolved and the underlying factors responsible. This report examines the period since 2000 as this corresponds with a renaissance in UK support for wave energy technology innovation, following a cessation of intense government support dating back to the late 1970s and early 1980s. The study employs a Technology Innovation System (TIS) approach, analysing both qualitative and quantitative data to address the following questions:

1. **How is the UK's wave energy innovation system structured and how has it evolved?**
2. **How well has the UK's wave energy innovation system performed and how has its performance changed over time?**
3. **Which factors have supported and undermined wave energy innovation in the UK?**
4. **What actions could be taken by the UK to accelerate wave energy innovation in the future?**
5. **What lessons can we learn from the case of UK wave energy innovation to help support innovation of other energy technologies?**

It is important to note that the research focuses explicitly on the effectiveness of the UK's wave energy innovation strategy, examining in particular how government policy successes and failures have influenced wave energy's path towards commercialisation. Consideration of the technical feasibility of wave energy technology and whether it should represent a priority for future innovation funding sit outside the remit of this report.

1.3 Structure of this report

This report is structured as follows: Section 2 presents a literature review of the fundamentals and drivers of wave energy technology innovation. Section 3 presents the research's analytical framework and research strategy, introducing some core concepts of the TIS literature. Section 4 outlines the research's data collection. Section 5 maps the structure of the UK's wave energy innovation system and how this has evolved since 2000. Section 6 presents an analysis of the performance of the UK's wave energy innovation system. Section 7 examines the factors responsible for supporting or undermining wave energy technology innovation in the UK. Finally, Section 8 discusses the report's key findings and identifies policy recommendations to accelerate wave energy innovation in the future, as well as lessons for supporting energy technology innovation more broadly.

2

Literature review: fundamentals and drivers of wave energy technology innovation

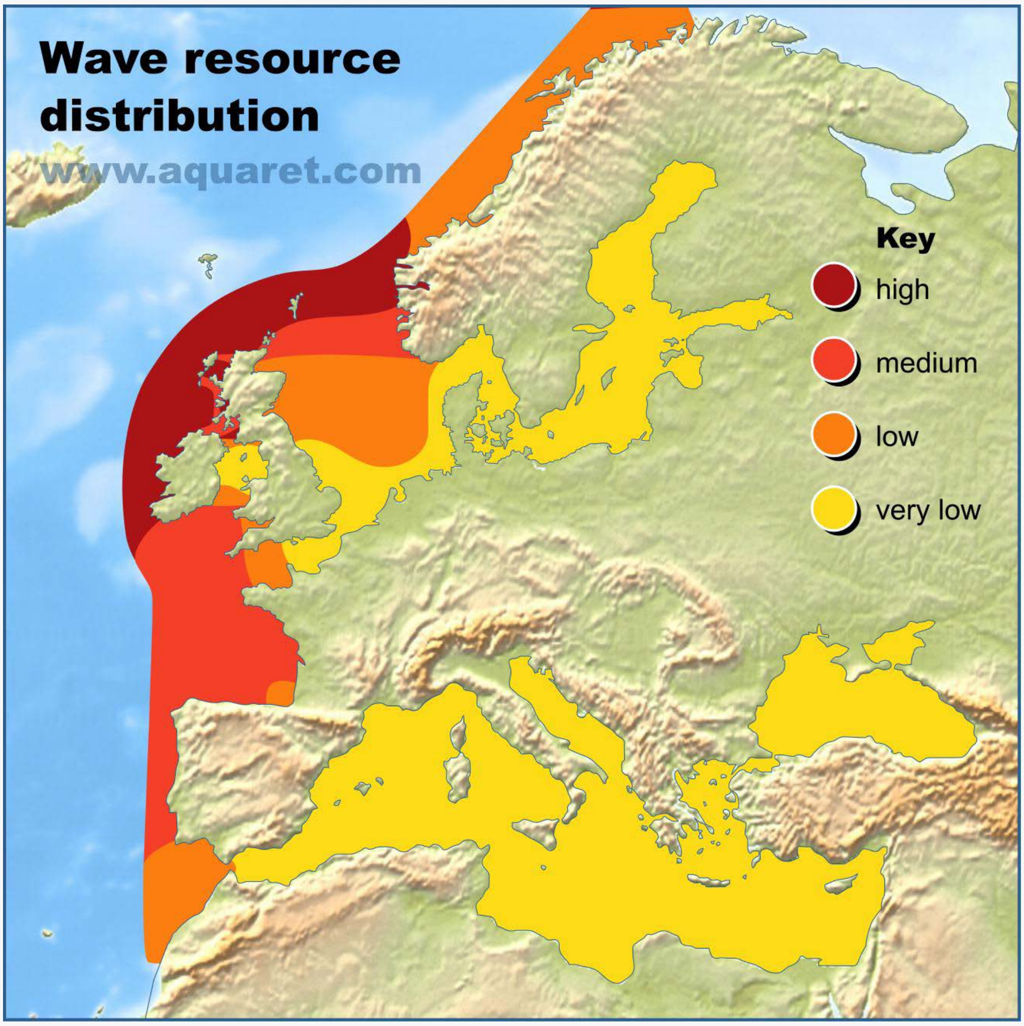
2.1 Fundamentals of wave energy technology

Waves are generated when the wind blows over the ocean's surface, itself a function of temperature and pressure differentials caused by the distribution of solar energy (Barstow et al. 2008). Wave energy carries both kinetic and gravitational potential energy, the level of which is a function of both the height and period of the wave (Barstow et al. 2008). Importantly, sea waves offer the highest energy density of all renewable energy sources (Clément et al. 2002). For example, the intensity of solar energy intensity is typically between 0.1–0.3kW/m^2 when incident on a horizontal surface. In comparison wave power offers an 'average power flow intensity of 2–3kW/m^2 of a vertical plane perpendicular to the direction of wave propagation just below the water surface (Falnes 2007)' (Drew et al. 2009 p.887).

The Intergovernmental Panel on Climate Change (IPCC) estimates that the global theoretical wave energy potential is 32PWh per annum, roughly twice the global electricity supply of 2008 (17PWh per annum) (Lewis et al. 2011; Mørk et al. 2010). This estimate of total theoretical wave energy potential is, however, unconstrained by economic and geographical factors or the availability of wave energy technology.

The UK's mid-latitude location within the Atlantic Ocean means that the country is excellently placed to capture this resource, with a total theoretical wave energy potential of 230 TWh per annum for electricity generation (AMEC & Carbon Trust 2012). However, when accounting for the capability of existing wave energy technologies, the needs of other sea users (e.g. shipping, fishing) and the need to mitigate environmental impact, this estimate falls to 70TWh per annum. Figure 1 illustrates the distribution of the UK's wave energy resources, emphasising the high levels of wave energy incident on the North West coast of Scotland and to a lesser extent, the South West cost of England (Aquaret 2012).

Figure 1: Offshore and nearshore practical resource distribution (Source: www.aquaret.com)



Harnessing the power of the waves requires the deployment of a wave energy convertor (WEC) capable of converting kinetic and gravitational potential energy into electricity. A host of challenges are associated with achieving this aim, as highlighted by Drew et al. (2009):

- Conversion of a slow (~0.1Hz), random and high-force oscillatory motion into a useful motion capable of driving a generator can be a problem. For example, heaving and nodding type devices are not directly compatible with conventional rotary electrical machines and so a transmission system is required.
- As waves vary in height and period, their respective power levels vary accordingly. This variable input must be converted into a smooth electrical output for grid-connected power generation, meaning that an array of devices or some form of energy storage system are often necessary.
- Ocean environments are characterised by multi-directional waves, meaning that devices must be able to generate electricity from waves coming from a variety of directions.
- Whilst power production generally takes place in relatively benign conditions, devices must be able to cope with rare but highly damaging waves generated during extreme ocean conditions, incurring additional costs in terms of engineering design and manufacture (Leijon et al. 2006).
- Devices must be capable of withstanding a highly corrosive ocean environment which marine vessels and structures have to contend.

Wave energy convertors typically incorporate six sub-components integrated within a single device to convert ocean waves into electricity. These sub-components are as follows (LCICG 2012):

- **Power Take Off (PTO):** Technology that converts kinetic energy into electricity. It can be converted directly to electricity via a rotary or linear electric generator or a hydraulic system.
- **Structure and prime mover:** The fluid mechanical process by which the device captures energy from the ocean, through oscillation or rotation.
- **Control:** Systems and software to safeguard the device and optimise its performance under a range of operating conditions.
- **Foundations and moorings:** The manner in which the device is held in place, typically a moored, floating structure (moorings can be flexible or rigid) or a seabed structure (e.g. gravity-based or foundations).
- **Installation:** The process by which the device is installed, influenced by the device location and station keeping method.
- **Connection:** The method by which energy is transferred to shore. This can be an electrical connection – high voltage alternating or direct current – or, in some cases, a hydraulic connection.

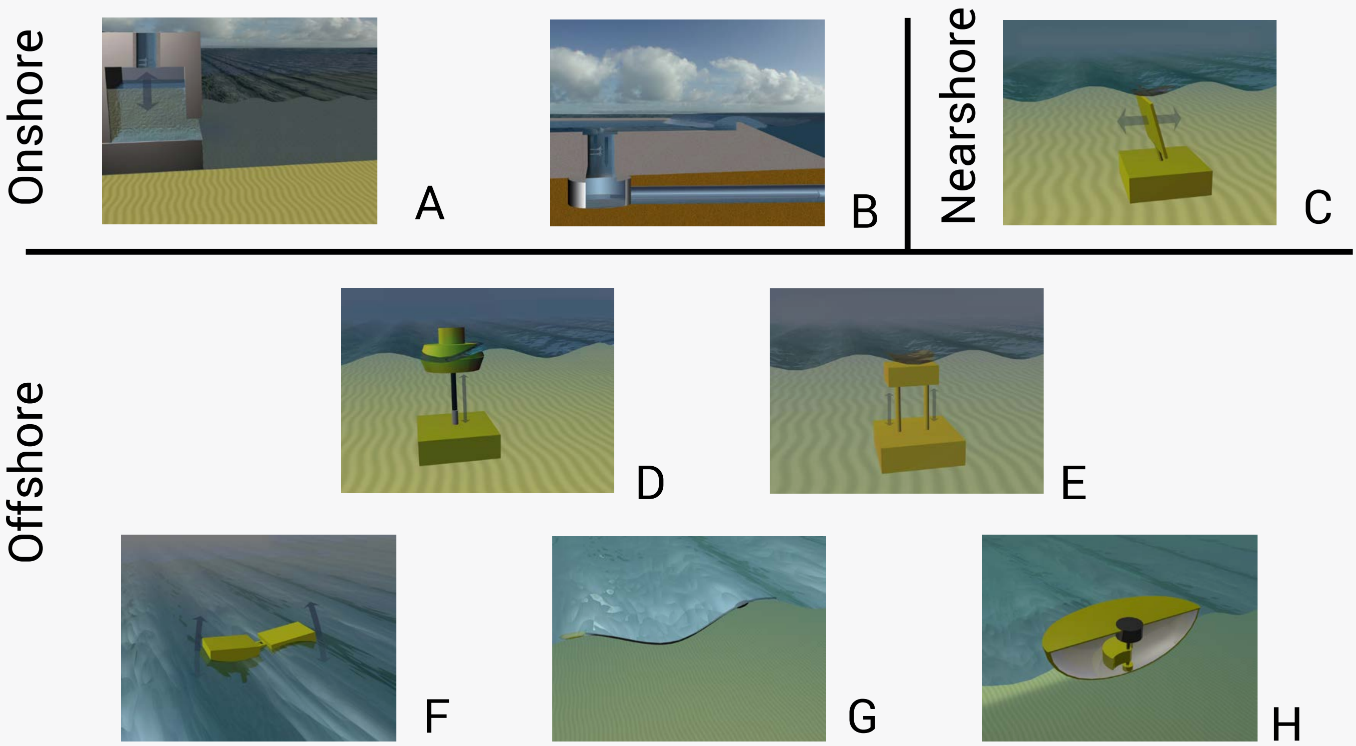
Wave energy is available at varying ocean depths, meaning that WECs are deployed in three characteristically distinct ocean environments: onshore, nearshore and offshore. Onshore devices tend to be integrated into a natural rock face or man-made breakwater (SI Ocean 2012). These have the advantage of being close to the utility network and relatively easy to maintain. They are less likely to be damaged because wave energy is lost because of friction with the seabed, although this also reduces the potential resource for capture (SI Ocean 2012; Drew et al. 2009).

Nearshore devices are located in water shallow enough to allow them to be fixed to the seabed either via pinned pile foundations or gravity mass (SI Ocean 2012) and typically where waves start breaking. This in turn provides 'a suitable stationary base against which an oscillating body can work' (Drew et al. 2009 p.888). Disadvantages of these devices are similar to those of shoreline devices.

Offshore devices are located in water tens of metres deep and tethered to the seabed using tight or slack moorings mass (Drew et al. 2009; SI Ocean 2012). They are a much greater potential energy resource than onshore or nearshore devices but are more difficult to construct, operate and maintain and must be designed to survive more extreme conditions (Drew et al. 2009).

Figure 2 and Table 1 present the eight most common wave energy device designs and the ocean environments they are typically deployed in.

Figure 2: Schematic of typical wave energy devices (adapted from www.aquaret.com)



Note: A – Oscillating water column (OWC); B – Over-topping device or terminator WEC;

C – Oscillating wave surge convertor; D – Point absorber; E – Submerged pressure differential device;

F – Attenuator; G – Bulge wave device; H – Rotating mass convertor

Table 1: Typical wave energy convertors (Magagna & Uihlein 2015; EMEC 2016f)

Location	Device type	Description
Onshore	Oscillating water columns (OWC)	These use the oscillatory motion of a mass of water induced by a wave in a chamber to compress air to drive an air turbine. The water column acts as a piston on the air volume, pushing it through the turbine as the waves increase the water level in the chamber, drawing it as the water level decreases. OWCs are commonly installed onshore in self-contained structures and less commonly as floating OWCs.
	Over-topping devices or terminators	Waves breaking on a ramp are collected in a reservoir above the free water surface. This then flows through a low-head hydraulic turbine. Commonly applied to onshore environments but also deployed offshore.
Nearshore	Oscillating wave surge converters	These devices exploit the surging motion of nearshore waves to induce the oscillatory motion of a flap in a horizontal direction. They are often bottom-mounted devices with floating devices also under development.
Offshore	Point absorber	Point absorbers are normally heaving/pitching devices that exploit the relative motion between an oscillating body and a fixed structure or component. They can be moored to the seabed or installed on the seabed through a large foundation mass.
	Submerged pressure differential	These devices are fully submerged devices, exploiting the hydro-dynamic pressure induced by waves to force an upward motion of the device, which then returns to its starting position once the pressure differential is reduced.
	Attenuator	These generate an oscillatory motion between adjacent structural components, which activates the PTO, either by pumping high-pressure fluids through a hydraulic motor or by operating a direct-drive generator. Attenuators are designed to operate offshore, and are commonly surface floating.
	Bulge wave	These use wave-induced pressure to generate a bulge wave within a flexible tube. As the bulge wave travels within the device it increases in size and speed. The kinetic energy of the bulge is used to drive a turbine at the end of the tube.
	Rotating mass converters	These exploit the relative motion of waves to induce pitching and rolling in a floating body, thus forcing the rotation of an eccentric mass contained within the device. As the mass rotates it drives an electrical generator.
	Other	These include novel wave energy devices currently under development and not fitting any of the above categories.

2.2 Drivers of wave energy technology innovation

With the basic principles of wave energy technology and some of the associated innovation challenges identified in Section 2.1, this sub-section explores some of the factors considered to be most critical to supporting successful innovation of wave energy technology. We outline these factors in relation to four categories that form the basis of this research's TIS analytical framework (see Section 3): *actors, institutions, networks and infrastructure/technology*.

Actor-related factors include the importance of incumbent market actors positively engaging in the wave energy process, providing valuable knowledge, capabilities and financial resources to support wave energy RD&D (Andersson et al. 2017). Another issue is ensuring that small start-up companies, which typically drive the initial growth of nascent industries, possess the technical and managerial resources necessary to deliver successful large-scale and complex technology RD&D projects such as wave energy (RAB 2008).

Institutional factors typically focus around government policy. The first to be discussed is the importance of a long-term consistent funding regime that avoids 'boom and bust' cycles and can induce company failures during periods of limited funds but, during periods of abundant funding, can pressurise developers to spend funds quickly whilst still available (Vantoch-Wood 2012). Clear government visions, strategies or roadmaps for wave energy are considered critical to underpinning such long-term strategy (Andersson et al. 2017). Second is the importance of demand–pull mechanisms such as long-term subsidy revenue payments enticing actors to engage with wave energy technology demonstration and stimulated market formation (Corsatea 2014; Allan et al. 2011; Jeffrey et al. 2014; Andersson et al. 2017). Third is the need to avoid the premature commitment of funds to later stage innovation, such as array-scale demonstration, before sufficient earlier stage investment has been made (RAB 2008; Jeffrey et al. 2014; Jeffrey et al. 2013; Mclachlan 2010; HoCECCC 2012).

Finally, it is necessary to strike a balance between technology device design convergence and divergence. On the one hand this means avoiding narrowing down the number of device designs or 'picking winners' prematurely because this can 'lock in' sub-optimal designs before rival designs have been given the opportunity to demonstrate their potential (Vantoch-Wood 2012). On the other it involves ensuring that the number of funded device designs is steadily reduced to ensure that RD&D investment is not split across numerous designs indefinitely as this can dilute the impact of this RD&D funding and the pace with which the technology matures (RAB 2008; SI Ocean 2012; Magagna & Uihlein 2015).

Network-related factors include the importance of inter-actor collaboration and knowledge exchange to share lessons learnt and best practice (Winskel 2007; LCICG 2012; Foxon et al. 2005; Mclachlan 2010; Andersson et al. 2017; RAB 2008). Emphasis is placed on international (Corsatea 2014; Vantoch-Wood & Connor 2013) and industry–science collaboration (Winskel 2007). Another key factor is the importance of a well-co-ordinated policy framework that avoids numerous, over-lapping autonomous institutions simultaneously delivering similar funding programmes potentially inducing a duplication of effort (Jeffrey et al. 2014; HoCECCC 2012; Vantoch-Wood 2012; Mclachlan 2010; Andersson et al. 2017).

Infrastructure- and *technology*-related factors include the importance of world-class test infrastructure, enabling frequent experimentation and demonstration of marine energy technology in different environments (Jeffrey et al. 2014; Mclachlan 2010; Corsatea 2014; Andersson et al. 2017)

In the summary sections for each of the results chapters we compare and contrast this report's findings with the extant literature to consider how they support or contradict previous research, and also highlighting the novelty of the research.

3

Analytical framework

Having reviewed the fundamentals and key drivers of wave energy technology, we now turn to the analytical framework of this report to assess the effectiveness of the UK's wave energy innovation support strategy.

This study mobilises Technology Innovation System (TIS) theory to map the evolution of the UK's wave energy innovation system, measure its performance and identify the factors responsible for shaping its performance. A TIS can be defined as 'a network or networks of agents interacting in a specific technology area under a particular institutional infrastructure to generate, diffuse, and utilise technology' (Carlsson & Stankiewicz 1991 p.94). It is composed of a variety of core elements, namely actors, institutions, networks and technology/infrastructure, to perform a host of different functions such as the development of knowledge or the mobilisation of resources that help to support the development and deployment of new technology (Jacobsson & Bergek 2011; Bergek, Jacobsson, et al. 2008b; Jacobsson & Karltorp 2013; Hekkert et al. 2011; Wieczorek & Hekkert 2012; Suurs 2009). In line with previous TIS studies (Bergek, Jacobsson, et al. 2008b; Oltander, G., Perez Vico 2005; Wieczorek & Hekkert 2012; Hekkert et al. 2011), this study follows five sequential analytical steps (Figure 3), each corresponding to one of the five research questions outlined in Section 1.1.

Figure 3: Analytical framework to assess effectiveness of UK's wave energy innovation system (source: author)

Step 1 → Map the structure and evolution of the UK wave energy innovation system.

Step 2 → Quantitatively measure UK wave energy innovation performance.

Step 3 → Structure–function analysis of innovation inducement and blocking mechanisms

Step 4 → Recommend actions to improve UK wave energy innovation performance.

Step 5 Identify wider lessons for energy innovation strategies and TIS theory.

We expand upon the specific actions taken to deliver on Steps 1-3 that form the basis of the research's data collection and analysis.

3.1 Step 1 – mapping the structure and evolution of the TIS

The first step involves mapping the structure of the UK's wave energy innovation system to understand how it works and how its structure has evolved over time. To do this, we assess its structure according to the four key structural dimensions of a TIS system (i.e. actors, networks, institutions and technology/infrastructure), defined as follows:

- **Actors** – the organisations responsible for developing, diffusing and implementing new technologies, most commonly knowledge and education institutes (e.g. universities), industry and market actors (e.g. technology developers, suppliers, customers), government and non-departmental public bodies[5] (NDPBs) (e.g. policy makers, funders) and supporting organisations (e.g. venture capitalists, trade associations).
- **Institutions** – the 'rules of the game' that characterise actors' behaviour, expectations and values (North 1990). These include formal institutions (e.g. regulations, laws) and informal institutions (e.g. routines, expectations).
- **Networks** – these connect actors and shape their activities through, for example, co-ordination and knowledge exchange. They typically centre upon scientific, industrial or governmental actors, or a combination of these.
- **Technology and infrastructure** – the technological systems and infrastructural networks that facilitate technology innovation. These commonly include test facilities, complementary technologies and distribution/transmission networks.

In line with Wieczorek and Hekkert (2012), mapping the structure of the TIS helps to identify the presence and characteristics of key structural components before determining their capacity to stimulate innovation (see Step 3 in Section 3.3). This study grants particular attention to how the TIS structure has evolved over time, highlighting how important structural components have emerged or disappeared, as well as how their capacity to facilitate innovation has changed. To map the sector, data is drawn from expert interviews (Section 4.1.1) and a desk-based survey, utilising publicly available documentation.

3.2 Step 2 – measuring performance of TIS functions

This step measures how well the UK wave energy TIS is performing in terms of developing and deploying wave energy technology. Performance is compared against seven TIS functions over the period 2000 to 2017, with each TIS function defined as a specific interaction between the different structural components of the TIS system that, in turn, deliver outcomes with a positive bearing on the development, deployment and adoption of emerging technology (Edquist 2001; A. Johnson & Jacobsson 2000; Hekkert & Negro 2009). Assessment of TIS function performance therefore helps to identify weaknesses or 'bottlenecks' potentially undermining wave energy innovation (Smits & Kuhlmann 2004; Markard & Truffer 2008). In essence, if a TIS's functions are all performing strongly then, assuming basic viability of the technology, it should steadily progress towards commercialisation. However, should one or more functions perform poorly, the technology could fail to reach maturity (Edquist 2001; A. Johnson & Jacobsson 2000; Hekkert & Negro 2009). The seven TIS functions this study employs are outlined in Table 2.

5 A body with a role in the processes of national government, but not a government department or part of one, accordingly operating to a greater or lesser extent at arm's length from ministers (UK Government 2016)

Table 2: Description of TIS functions (source: see below)

TIS Function	Description
F1 – Knowledge development	The creation of technological variety achieved by a broadening and deepening of a codified knowledge[6] base via research and development (R&D).
F2 – Knowledge exchange	Exchange of information between actors facilitated by inter-actor networks.
F3 – Entrepreneurial experimentation	Entrepreneurs recognise the latent value proposition of emergent technologies and seek to realise this potential via commercial experiments. These experiments generate tacit knowledge that in turn helps to reduce the degree of uncertainty associated with a technology, either through success or failure.
F4 – Guidance of the search	Pressures that encourage actors to enter a technological field and subsequently guide the stage and focus of innovation activities they undertake, such as policy targets and technology roadmaps.
F5 – Resource mobilisation	Mobilisation of financial, human and physical resources critical to the technology innovation process.
F6 – Market formation	Mechanisms that create niche markets or 'protected spaces' enabling technologies to compete against initially superior incumbent technologies in order to boost levels of adoption, such as favourable tax regimes or new industry standards.
F7 – Legitimation	The act of granting legitimacy to an emerging technology by strengthening its 'fitness' with the prevailing institutional regime. TIS actors seek to achieve this by shaping existing institutions to galvanise support for this new technology amongst actors, for example via political lobbying.

Adapted from (Hekkert et al. 2007; Hekkert & Negro 2009; Bergek, Jacobsson, et al. 2008b; Suurs & Hekkert 2009; Kemp et al. 1998; Jacobsson & Bergek 2011; Jacobsson & Karltorp 2013; Bento & Wilson 2016)

To assess the performance of these functions, we examine 22 indicators, each of which are coupled with a specific TIS function (Table 3). The selection of indicators is informed by a literature review of TIS function indicator frameworks (Bento & Wilson 2016; Hillman et al. 2011; Hu et al. 2017), as well as the constraints imposed by the availability of data and the appropriateness of these measures for our case study of wave energy. All 22 indicators assess absolute changes in performance, i.e. the actual difference in the indicator over a period of time. However, where possible, the research also considers how the UK's wave energy innovation performance has changed in relative terms. Consequently, measures of relative performance are taken for 11 indicators, typically as a share of overall output at national or international level, such as the UK's share of global wave energy patents or scientific publications. Where such comparisons are not possible, wave energy is benchmarked against the progress of other renewable electricity generation technologies – for example, changes in the level of installed capacity versus tidal stream.

6 'Codified knowledge means reproducible, transparent, accessible knowledge documented or enshrined in blueprints, manuals, or sets of instructions' (Wilson & Grübler 2014 p.17)

Table 3 outlines the selected indicators for this study, alongside the TIS functions they aim to measure, the time period covered and qualitative and/or quantitative sources of data, which are described in more detail in Section 4.

Table 3: Quantitative indicator framework for measuring wave energy innovation performance against TIS functions

TIS function	Sub-theme	Time period	Absolute indicator	Relative indicator	Data source
F1 - Knowledge development	Early TRL[1]	2000–2016	Number of UK scientific wave energy publications	Share of global UK wave energy scientific publications	Scopus (Section 4.2.2)
		2000–2016	Number of UK scientific wave energy publication citations	Share of global UK wave energy scientific citations	
	Mid-TRL	2000–2013	Number of UK wave energy patents	Share of global UK wave energy patents	PATSTAT (Section 4.2.3)
F2 – Knowledge exchange	Generic	2000–2017	Average number of UK wave energy RD&D project partners		Multiple (Section 4.2.1)
	International	2000–2016	Number of UK international co-authored wave energy scientific publications	Share of UK international co-authored wave energy scientific publications	Scopus (Section 4.2.2)
		2000–2013	Number of UK international co-authored wave energy patents	Share of UK international co-authored wave energy patents	PATSTAT (Section 4.2.3)
		2000–2016	Number of non-UK wave energy RD&D project partners	Share of non-UK wave energy RD&D project partners	Multiple (Section 4.2.1)
	Cross-fertilisation	2000–2016	Number of wave energy RD&D project partners from other sectors	Share of wave energy RD&D project partners from other sectors	
	Industry–science	2000–2016	Number of joint industry–university wave energy-related projects	Share of joint industry–university wave energy-related projects	
		1970–2017	Number of wave energy university start-ups		Spinouts UK database (Spinouts UK 2017) and company/ university websites

TIS function	Sub-theme	Time period	Absolute indicator	Relative indicator	Data source
F3 – Entrepreneurial experimentation	Technological maturity	2000–2017	Largest share of funding awarded to single wave energy device design		Multiple (Section 4.2.1)
		2000–2017	Unit capacity of wave energy devices (MW)		Multiple (see Section 4.2.4)
		2009–2017	Wave energy levelised cost of electricity ($/MWh)		Bloomberg Intelligence (Bloomberg 2017)
F4 – Guidance of the search	-	2000–2017	Number of wave energy technology foresight exercises		Multiple (see Section 4.2.4)
		2000–2017	Number and ambition of wave energy deployment targets		
F5 – Resource mobilisation	Financial	2000–2016	Level of public wave energy RD&D investment (£m 2015)	Share of UK renewables budget	Actual spend – Multiple (Section 4.2.1) Budget – IEA RD&D database
	Human	2010–2016	Number of engineering doctorate and higher degrees		Higher Education Statistics Authority (HESA 2017)
		2000–2016	Number of medium and large companies engaged in UK wave energy RD&D projects	Share of medium and large companies engaged in UK wave energy RD&D projects	Multiple (Section 4.2.1)
F6 – Market formation	-	2000–2016	Number of UK wave energy developers		Desk-based survey
		2007–2016	Level of wave energy installed capacity in UK (MW)	Share of UK marine industry	Multiple (see Section 4.2.4)
F7 – Legitimation	Government	1999–2017	Support outlined in public reports for wave energy		Desk-based survey
	Public	2012–2017	Public support for wave and tidal energy		BEIS Energy & Climate Change Public Attitudes Tracker (BEIS 2017c)

NOTE: Adapted from (Bento & Wilson 2016; Hillman et al. 2011; Hu et al. 2017). [1] Technology Readiness Level (TRL)

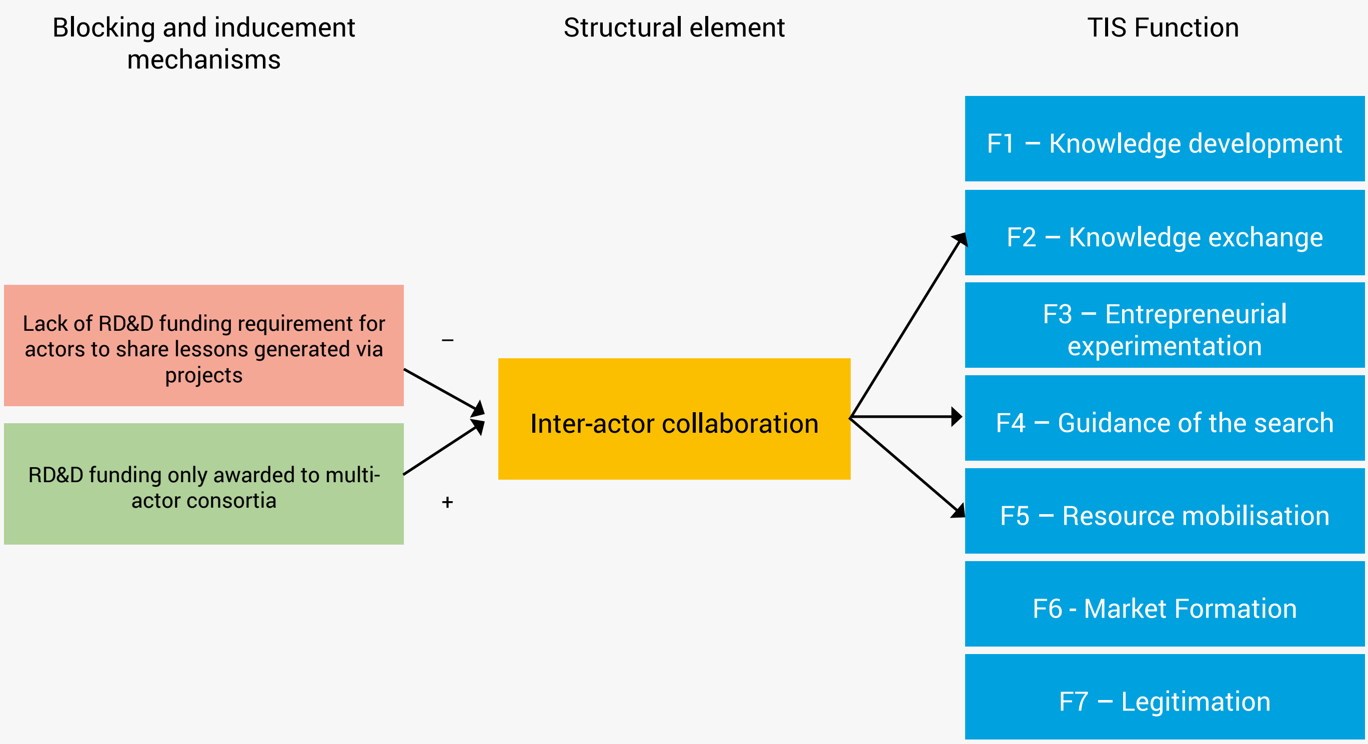
3.3 Step 3 – structure–function analysis of innovation inducement and blocking mechanisms

Step 3 seeks to link the structure of the UK wave energy innovation system (Step 1 – Section 3.1) with its performance across different functions (Step 2 – Section 3.2) to help us understand how the system's structure has supported or undermined innovation performance. This follows the logic that unfulfilled system functions are a manifestation of structural problems within the TIS (Hekkert et al. 2011), associated with the presence and/or quality of structural elements (Wieczorek & Hekkert 2012) known as inducement or blocking mechanisms (Jacobsson & Karltorp 2013; Bergek, Hekkert, et al. 2008; Patana et al. 2013).

This report synthesises these approaches to employ a three-tiered approach to diagnose of the factors responsible for shaping the performance of the UK's wave energy innovation system and the process is replicated for each of the four structural dimensions (actors, institutions, networks and technology). First, inducement and blocking mechanisms are identified that have served to support or undermine wave energy technology innovation. Second, these mechanisms are associated with a specific structural element identified through the data as having an important bearing on the innovation process. The traffic light colour coding indicates the overall impact of the structural element on the TIS functions. Third, these structural elements are linked to specific TIS functions that they have either supported or undermined, as indicated by arrows.

A worked example is provided for the structural dimension of *networks* and is presented in Figure 4, which forms the basis of the summary diagrams presented in Section 7. Firstly, a requirement from government for all publicly funded RD&D projects to include multiple partners is identified as an inducement mechanism. Secondly, this mechanism helps to build networks, a key structural element necessary for inter-actor collaboration. Thirdly, this in turn facilitates *knowledge exchange (F2)* between actors, helping them to pool their human and financial *resources (F5)*. In contrast, a related blocking mechanism might be the lack of a requirement for actors to share lessons generated from publicly funded RD&D projects, potentially undermining the degree of interaction and exchange between actors and, consequently, reducing the degree of *knowledge exchange (F2)* and failing to inform the *guidance of the search (F4)* for future projects . On balance, these two mechanisms result in inter-actor collaboration having a mixed impact on TIS functions, meaning that it is shaded yellow rather than green (positive) or red (negative).

Figure 4: Worked example of TIS structure–function analysis (source: author)



3.4 Contribution to wider TIS literature

We briefly acknowledge some of the common criticisms levelled at the TIS functions approach as a tool for analysis of TIS performance and the ways in which this research aims to address these.

First, most TIS case studies tend to rely on ex-post qualitative analysis of innovation system performance, omitting the use of quantitative metrics to corroborate qualitative data (Gazis 2015; Jacobsson & Bergek 2011; Winskel et al. 2014; Grübler & Wilson 2014; Grübler et al. 2012). This research thus employs a mixed-methods approach, using a combination of qualitative and quantitative data to enable data triangulation and in turn more robust results (Section 3.4).

Second, TIS studies have been criticised for failing to fully capture the evolution of a TIS throughout its lifetime, instead providing a snapshot of its structure and performance for a given moment in time (Gazis 2015; Bergek, Jacobsson, et al. 2008b; Winskel et al. 2014). Consequently, a need for research that explores the temporal dimension and history of energy technology innovations (Wilson & Grübler 2014), especially the importance of the timing and sequence of events. Such analysis can offer a more comprehensive understanding of the evolution of TISs that goes beyond the commonly identified phases of formation, growth and stability (Gazis 2015; Bergek, Jacobsson, et al. 2008b; Winskel et al. 2014), exploring variations of this pattern that might involve alternative stages such as disruption, decline and reconfiguration. This study consequently grants particular attention to the chronology of events and how this has influenced changes to TIS structure and performance.

Third, the TIS framework has been criticised for failing to acknowledge the influence of exogenous factors on the success or failure of a technological innovation (Smith & Raven 2012; Markard et al. 2015). As Bergek et al. (2015), explain, the 'structures and processes inside a focal TIS are generally well conceptualized in the literature … [but] what happens outside and across the system boundary has been less systematically worked out' (Bergek et al. 2015 p.53). In response to this criticism, this study is sensitive to factors strictly outside the UK's wave energy technology innovation system, such as the influence of other technologies (e.g. tidal stream, offshore wind) and high-level policy developments (e.g. climate change agreements).

Finally, TIS studies of energy technologies have been criticised for focusing predominantly on success stories rather than technology failures or those that have been slow to commercialise (Grübler & Wilson 2014). Consequently, our case study of wave energy, which has struggled to reach commercialisation, offers valuable insight into the types of barriers that could slow the progress of energy technology innovation.

In summary, this research makes an important contribution to state-of-the-art technology innovation studies, presenting an energy technology innovation case study that:

1. utilises a mixed-methods approach;
2. pays special attention to the sequence of historical developments over a long-term period;
3. is sensitive to wider landscape developments; and
4. examines a technology that has not yet reached market rather than an ex-post study of a success story.

4

Methodology

This section outlines the data collection methods that mobilise the analytical framework presented in Section 3, split between both qualitative (Section 4.1) and quantitative (Section 4.2) methods.

4.1 Qualitative methods

4.1.1 Industry expert interviews

In total, 33 interviews were conducted between March and October 2015 with a wide range of experts across the UK wave energy sector, including technology developers, consultants, test facility directors, government policy makers, senior researchers and trade association representatives. A full list of the interviews and their dates is provided in Appendix A. The interviews took a semi-structured approach, covering the factors shaping the structure, performance and evolution of the UK wave energy innovation system. They were fully transcribed and thematically analysed using the software NVivo.

4.1.2 Documentary analysis

Expert interviews and quantitative indicators were complemented with documentary evidence sourced via web searches such as official government policy, parliamentary committee reports, technology roadmaps and technology needs assessments. These are fully referenced wherever they are used as evidence.

4.2 Quantitative methods

4.2.1 UK marine energy RD&D public grant database

To offer a comparison of RD&D funding for wave energy against tidal stream, a database of 444 marine energy RD&D public grants covering 327 organisations operating in the UK between 2000 and 2017 was constructed, with awarded grants covered up to 1st June 2017. Data was drawn primarily from a combination of existing databases including the RCUK Gateway to Research (RCUK & InnovateUK 2017), UKERC data centre (UKERC 2017a) and EPSRC Grants on the Web (EPSRC 2017). Additional UK grant data was sourced from funding agency websites, such as Wave Energy Scotland (WES 2017b), InnovateUK (InnovateUK 2017), Welsh European Structural Funds (Welsh European Funding Office 2017) and the European Commission's Community Research and Development Information Service (CORDIS) database (European Commission 2017c).

The database covers only RD&D grants and not long-term revenue payments or investments made by public investment banks (e.g. Scottish Investment Bank's REIF, Green Investment Bank), aimed at supporting commercial deployment. Crucially, it covers awarded grants, not allocated budgets or actual grant expenditure from awardees. If we were to compare awarded funds against actual grant expenditure, we would likely find that some awarded grants may not have been paid to awardees in full or a portion of these grants going unspent, meaning that the total value for awarded grants will be higher than the actual public funds spent by awardees on wave energy RD&D. To help minimise this issue, any awarded grants known to have been rescinded because awardees failed to meet pre-defined criteria were omitted rom the analysis on the basis of information direct from government departments.

Grant values are adjusted for inflation, providing values in UK sterling (£) for 2015 using GDP deflators at market prices, taking the mid-point of the project grant as the reference year. Grant expenditure is distributed across the period of the project rather than just the year awarded.

Where cross-cutting offshore energy projects are only partially related to marine energy the total grant value is adjusted to approximate the proportion of work focused on marine energy. These weightings are taken from the grant database held by the UKERC Energy Data Centre (UKERC 2017b), which includes subjective assessments of the balance of each grant's technology focus using the IEA energy technology categorisation (IEA 2005). For grants not covered by the UKERC database, the authors made their own subjective judgement of the grant's weighting towards marine energy, taking the same approach.

For grants with multiple partners, the funding is split equally unless a detailed breakdown is provided by the funder. The awardees are categorised in terms of size and sub-sector using a combination of Companies House and LinkedIn databases. Where awardees have undergone mergers and acquisitions (M&A), the original company name is listed. Finally, the nationality of awardees is determined by where the head office is located.

The stage of innovation funding is categorised using a Technology Readiness Level[7] (TRL) framework that builds upon the Organisation for Economic Co-operation and Development's (OECD) Frascati Manual (OECD 2015), incorporating wave energy-specific activities relating to each TRL from Jeffrey et al. (2014). Six categories are applied: (1) basic or applied research; (2) experimental development; (3) demonstration; (4) test infrastructure; (5) knowledge exchange; and (6) training. The first three relate to RD&D activities at different stages along the innovation chain and the last three to non-RD&D activities that have an important bearing on the innovation process. For device level RD&D, the type of device is categorised using the European Marine Energy Centre (EMEC) device and developer categorisation as a guide (EMEC 2017g; EMEC 2017f).

The source of innovation funding is split into four main categories: (1) EU; (2) UK Government; (3) Scottish Government; and (4) Other. The latter includes funding from the Welsh Government, regional development agencies, county councils and local authorities. European structural funds managed by devolved administrations (e.g. the Welsh European Funding Office (WEFO)) are classed as EU funding.

4.2.2 Scientific publications

International wave energy-related scientific publications were searched using the database Scopus. The search query outlined below was used, limiting the search to between 2000 and 2016 and covering only journal articles including the terms 'wave energy' or 'wave power' alongside 'marine' or 'ocean' in the title, abstract or key words. Citations of these publications were also analysed, excluding self-citations by authors.

> (TITLE-ABS-KEY ("wave energy") OR TITLE-ABS-KEY ("wave power") AND TITLE-ABS-KEY (marine OR ocean)) AND PUBYEAR > 1999 AND PUBYEAR < 2017 AND (LIMIT-TO (SRCTYPE , "j")) AND (LIMIT-TO (DOCTYPE , "ar"))

4.2.3 Patents

Patent applications are taken from the 2017 spring edition of the European Patent Office (EPO) Worldwide Patent Statistical Database (PATSTAT) (EPO 2017). This study examines patents filed at the EPO between 1979 and 2013, the earliest and latest years for which complete data was available via PATSTAT. PATSTAT includes the Cooperative Patent Classification (CPC) scheme, which allows for the identification of climate change mitigation technologies under the category Y02E. This study examines patents categorised using the following classifications for wave energy: OWC (Y02E 10/32) and wave energy or tidal swell (Y02E 10/38).

The data is for patent applications or filings, rather than granted patents, meaning that some applications could have been rejected after filing. The date of the invention is assumed to be the 'priority date', the filing date of the very first patent application for a specific invention. Patent nationality is determined as the inventor's 'country of residence' and, where inventors from multiple countries are listed on the patent application, a fractional count method was used. Notably, patents are not the only proxy of technology 'know-how', such as trade secrets, and not all patents lead to operational technologies.

7 TRLs are a type of measurement system used to assess the maturity level of a particular technology, running from fundamental scientific research to full commercial application. A breakdown of these levels and the innovation activities they represent are provided in Appendix A.

4.2.4 Global marine energy installed capacity database

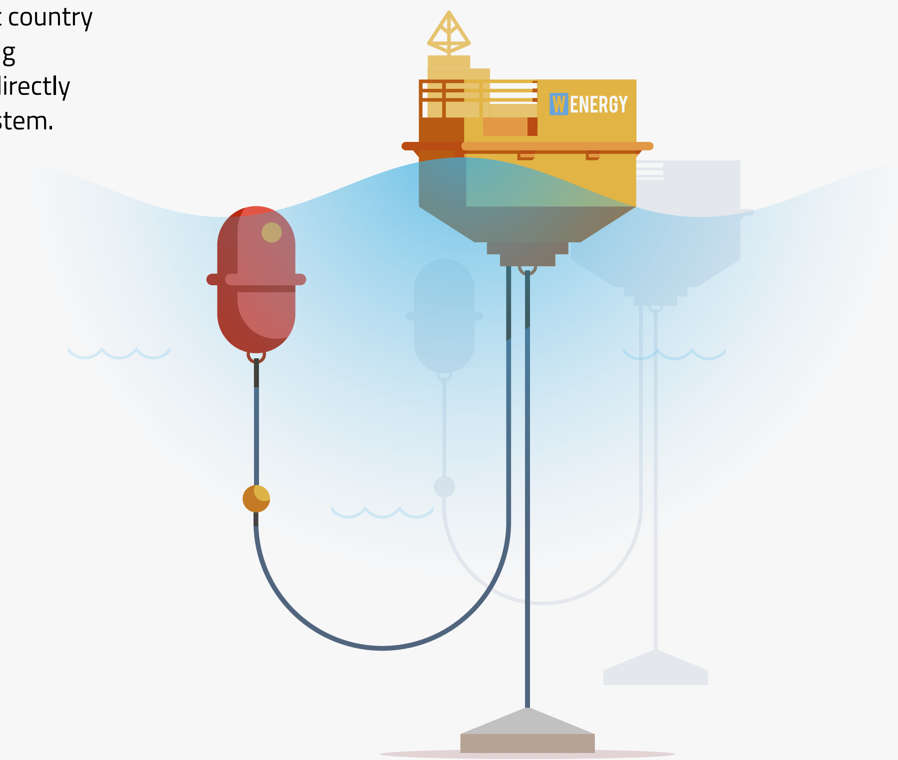
The installed capacity data includes 220 projects of both pre-commercial demonstration and commercial installations (i.e. TRLs 5 to 9), covering the period from 2007 to 2016. Project-specific data was sourced primarily from the IEA's Ocean Energy Systems (OES) GIS database (OES 2017b) and the OES annual reports dating from 2007 to 2016 (OES 2017a). By 2016, the OES programme had 25 members, each reporting data to varying degrees to these two databases.

This data was triangulated with data sourced from other online databases such as 4C Offshore (4COffshore 2017), Tethys (Tethys 2017) and the RenewableUK Marine Energy Database (RenewableUK 2017), as well as developer, test centre (e.g. EMEC), government and industry news (e.g. Tidal Energy Today) websites.

The nationality of the installed capacity is determined by the country in which the technology has been installed rather than the origin of the developer, meaning that some installations might have emerged from RD&D investments from other countries. However, nationality by host country was preferred because overseas developers testing their devices in the UK are still being directly or indirectly supported by the UK's wave energy innovation system.

4.2.5 Test facilities

A survey of UK wave energy test facilities covered: (1) wave energy test tanks; (2) land-based sub-component test facilities; and (3) open-ocean wave energy test facilities. Three databases were surveyed: the Marine Research Infrastructure Database (EUROcean_RID 2017), the Scottish Energy Laboratory: Test and Demonstration Facilities Directory (SEL 2014) and the UK Renewable Energy Facilities Directory (OREC 2017a). This data was supplemented with information from market leaders in wave tank design Edinburgh Designs (Edinburgh Designs 2017b) and test facility websites, as well as direct contact with test facility managers to request any missing data.



(Source: Shutterstock)

5

Mapping the structure and evolution of the UK's wave energy innovation system

This section describes the structure and evolution of the UK's wave energy innovation system, focusing specifically on the actors, institutions, networks and technology/infrastructure that make up the system. Each sub-section begins with an overview of how each structural dimension has evolved since 2000, followed by a more detailed breakdown.

(Source: Shutterstock)

5.1 Actors

The evolution of the UK wave energy innovation actor landscape is summarised in Figure 5, highlighting the four different actor categories of knowledge and education, industry, government and public bodies and supporting organisations. For government, we cover the EU, UK and Scotland.

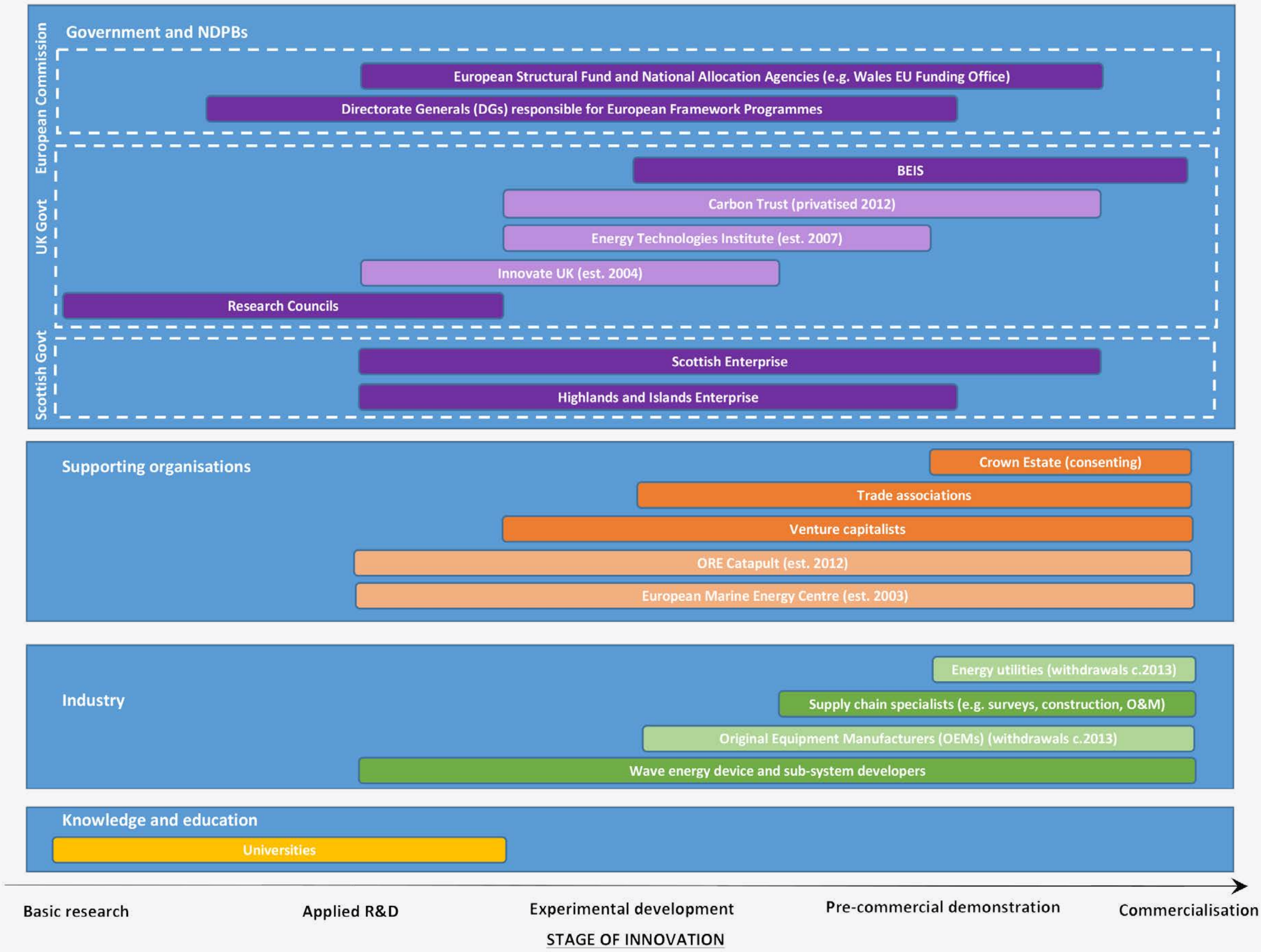
A review of the actor landscape presents a broadly positive picture, with a wealth of knowledge and education institutes in the form of world-class universities, a burgeoning supply chain that has leveraged existing expertise from other offshore energy sectors and a wide range of government, NDPB and other supporting organisations (e.g. test facilities, trade associations) offering support across the entire innovation chain.

Many important additions have been made to the actor landscape since 2000, with the introduction of two new funding bodies, InnovateUK and the Energy Technologies Institute (ETI)[8], concentrating on mid-stage TRL support, previously missing at UK level. Other important introductions include EMEC in 2003 and the Offshore Renewable Energy Catapult (OREC) in 2013. The former's role has grown beyond that of a test facility to incorporate other key activities, such as knowledge capture and the formation of industry standards, roles that were previously lacking in the sector.

In contrast, we find that some important actors have withdrawn rom the sector. These include various failed wave energy developers and the withdrawal of incumbent multi-national firms (e.g. original equipment manufacturers (OEMs), energy utilities and venture capitalists (VCs), who, at this stage do not consider wave energy as an investment priority.

8 The ETI will be discontinued in 2019 and further details are provided in Section 4.1.3.2.

Figure 5: UK wave energy innovation actor landscape (source: author)



NOTE: Lightly coloured actors indicate those that have been established or have fundamentally changed since 2000.

5.1.1 Knowledge and education

The major knowledge institutes and educational organisations for wave energy in the UK are universities, with the universities of Edinburgh and Southampton producing the largest number of marine energy scientific publications globally in 2011, each delivering 10% of the global share (Corsatea & Magagna 2014). To determine the most active universities in this sector, an analysis of public funding for wave energy related RD&D[9] between 2000 and 2017 found that the University of Edinburgh received the most funding, at £16.3m, followed by the Universities of Exeter (£7.1m), Swansea (£7.1m), Bangor (£6.5m) and Strathclyde (£5.9m). Approximately £20m[10] of university research funds were channeled through the UK's marine energy Supergen consortium (Section 5.3.1.1), accounting for almost a quarter of all university marine energy funding (£87m).

UK universities are also leaders in wave energy-related training and knowledge exchange, receiving significant funds to support these activities. We expand upon the breadth and depth of training in Section 5.3.1.5 and identify the large number of wave energy test facilities managed by universities in Section 5.4.1, further underlining the important role universities play n supporting wave energy innovation.

5.1.2 Industry actors

Drawing upon work undertaken by Highlands and Islands Enterprise (HIE) and Scottish Enterprise (2015), we disaggregate the UK wave energy supply chain into the following categories:

1. Technology development
2. Project development
3. Manufacturing, installation and construction
4. Operation and maintenance

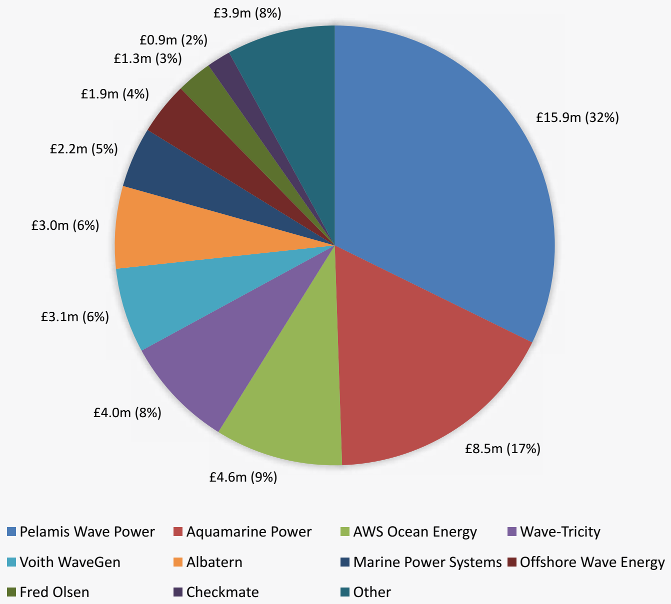
5.1.2.1 Technology development

5.1.2.1.1 Wave energy developers

Wave energy developers are the key actors in relation to wave energy technology development. Analysis of our public RD&D grants database and EMEC's own market analysis (EMEC 2017g) reveals that 34 wave energy developers operated in the UK between 2000 and 2017, with 23 developers drawing on public RD&D funds in 2017 (Section 6.6.1). Of these, Pelamis and Aquamarine Power were the most prominent, demonstrating WECs with the highest power rating (Section 6.3.2). Combined, they accounted for 49% (£24.4m) of the £49.2m awarded to wave energy developers for experimental development (TRL 5–6) or demonstration (TRL 7–8) of wave energy technology devices since 2000 (Figure 6).

9 Includes wave energy RD&D at all stages, as well as funding for knowledge exchange and training. Excludes test infrastructure.
10 Deflated to 2015 value.

Figure 6: Top 10 awardees of public mid- to late-stage wave energy RD&D funding (source: author)



NOTE: Covers only organisations with an explicit focus on developing a wave energy device in the UK.

Both Pelamis and Aquamarine Power ceased trading in the mid-2010s, with Pelamis going into administration in 2014 and Aquamarine Power in 2015. They were not, however, the only cases of company liquidation. Between 2000 and 2017, 14 of the 34 wave energy developers operating in the UK ceased trading, including WavePower, WaveBob, Wavegen, C-Wave and Orecon. This represents a 41% failure rate, substantially lower than the 54% failure rate for all professional, scientific and technical start-ups established in 2010 ,in the five years since they began operating (ONS 2016). All these company failures came from 2011 onwards, shortly after the financial crisis, with four firms folding in both 2014 and 2017.

5.1.2.1.2 Original Equipment Manufacturers

OEMs are companies that play an active role in the conceptualisation, design and assembly of complex technology systems (Sturgeon 2001). They have played an important role in wave energy technology development, and are responsible for the design and manufacturing of WEC sub-components such as PTO and generator systems (e.g. Bosch Rexroth, Siemens); electrical and automation controls (e.g. ABB); bearings (e.g. Hutchinson, Schaeffler); coatings (e.g. Hempel); and hydraulic components (e.g. Hunger Hydraulics).

OEMs have also been active in terms of mergers with and acquisitions of smaller wave energy developers. Examples include Voith's acquisition of Wavegen Ltd in 2005 (SDI 2007), ABB Technology Ventures' £8m investment in Aquamarine Power in 2010 (Aquamarine 2016) and Alstom's acquisition of a 40% stake in AWS Ocean Energy[12] in 2011 (Alstom 2011). Another approach used more recently to harness expertise from large multi-nationals is to engage them as project partners, as evidenced by Scottish Government's WES that has funded projects with energy utility (e.g. Iberdrola, GDF Suez), OEM (e.g. Siemens, Doosan Babcock, DuPont) and technical consultancy (e.g., Arup, Black and Veatch) partners.

Interest in the wave energy sector from large corporations has significantly declined in recent years, with a lack of recent investment and retrenchment from those who had already invested, such as Voith, who closed Wavegen in 2013. The UK tidal stream sector has witnessed a similar 'entry and withdrawal' pattern. However, large OEMs remain active in the sector unlike the wave sector. For example, Rolls Royce acquired Tidal Generation Ltd (TGL) in 2009. However, they subsequently withdrew, selling TGL to Alstom in 2012. Since 2016, this has been part of General Electric Power (PEI 2012), who have now discontinued their tidal stream activities. Similarly, Marine Current Turbines was acquired by Siemens in 2012, before Siemens withdrew and sold the company on to Atlantis Resources, another device developer (Atlantis Resources 2015).

11 Data for company failures take from Companies House. Some data for 2017 failures taken from company and industry websites as status not up-to-date on Companies House website.

5.1.2.1.3 Energy utilities

UK energy utilities have also been active in supporting wave energy technology development, attracted by the vast global wave energy resource, which is compatible with their vision of a low-carbon centralised electricity system. For example, the UK saw both E.On and Scottish Power purchase devices from Pelamis, which they subsequently tested at EMEC in 2010 and 2012 respectively, off the Orkney Isles (EMEC 2016b; EMEC 2016e). The utilities operated the devices in partnership with developers to provide feedback from the perspective of the developers' target customer. However, like the OEMs, the utilities have retreated in recent years. E.On withdrew in 2013 and Scottish Power sold its device to EMEC shortly afterwards (BBC 2013; EMEC 2017c)

5.1.2.2 Project development

The project development phase is concerned with project planning, surveying, consenting and preparation. These include geotechnical surveys for construction purposes that require divers, remote operated vehicles (ROVs) and specialist vessels (e.g. James Fisher Subsea), as well as resource surveys to measure wave energy potential (e.g. Partrac) and environmental surveys to assess the potential impact of wave energy device installation (e.g. Aquatera). Planning and consenting support is also important in acquiring rights to generate electricity offshore (e.g. SAMS Research Services Ltd), as well as project design to ensure optimal device layout and to maximise yield (e.g. The Northern Energy Initiative (TNEI)). Finally, independent comprehensive evaluation, verification and certification of wave energy devices and their sub-components is also important (e.g. DNV GL), playing an important role in giving potential investors and customers confidence that the technology in question will provide safe and reliable electricity generation. Much of this expertise can be usefully drawn from existing sectors such as the shipping, offshore wind and oil and gas sectors, given the overlapping offshore application.

5.1.2.3 Manufacturing, installation and construction

The manufacturing and construction phase includes the development and manufacturing of key supporting technologies such as foundations and moorings (e.g. Fugro Seacore, Mallaig Marine, Leask Marine), as well as electrical systems design and development (e.g. MacArtney, Ramboll, Atkins). It also includes the companies responsible for co-ordinating the installation of these supporting systems alongside the wave energy devices (e.g. Orcades Marine), as well as the fabrication of devices (e.g. Zeus Engineering Purepipe, Burntisland Fabrications, A&P Falmouth, BiFab) (Magagna & Uihlein 2015; HIE & Scottish Enterprise 2015).

5.1.2.4 Operation and maintenance

The third and final phase covers operation and maintenance and is concerned with ongoing generation during a project's anticipated lifespan, including activities such as dockside operations, performance monitoring and device inspection, as well as site decommissioning (e.g. Leask Marine).

5.1.3 Government and non-departmental public bodies

This sub-section explores the government bodies, NDPBs and royal chartered bodies responsible for supporting wave energy innovation at three levels of government: the EU, UK and Scotland.

12 AWS Ocean Energy also saw investment from the Shell Technology Ventures Fund in 2010, an affiliate of Royal Dutch Shell (Scottish Enterprise 2010a).

5.1.3.1 EU

Since the Lisbon Treaty in 2007, energy and innovation policy have both been areas of 'shared competence', between the EU and its member state governments (Gubb & Maclean 2015; Tosun et al. 2015). Consequently, the EC, the politically independent executive arm of the EU, has a shared mandate with member states to support energy technology innovation. The day-to-day running of EC business is managed by departments known as directorates general (DGs), such as the DG for Research and Innovation (R&I). These DGs are responsible for managing the framework programmes for research and technological development that represent a major source of energy technology innovation funding (Section 5.2.1.2).

5.1.3.2 UK

Prior to 2007, the Department of Trade and Industry (DTI) was largely responsible for energy technology innovation (Pearson & Watson 2012), followed by the Department for Business, Enterprise and Regulatory Reform (BERR) (2007–2009). However, from 2008/2009, the UK Government wave energy technology innovation policy was shared between the Department of Energy and Climate Change (DECC) (2008–2016) and the Department of Business, Innovation and Skills (2009–2016). DECC had direct control over pre-commercial demonstration and commercial deployment policies, whilst agenda setting and budgeting for earlier stage science and innovation funding was the responsibility of the Department of Business, Innovation and Skills. Since 2016, the Department of Business, Energy and Industrial Strategy has consolidated control over both energy and technology innovation policy making.

Beneath government sits a tier of arm's-length government-affiliated organisations with executive powers for further agenda setting and allocation of funds to support energy innovation. Funding for earliest stage research is allocated via the UK research councils, Royal Charter bodies that receive money direct from government, with most funds for wave energy managed through the Engineering and Physical Sciences Research Council (EPSRC), given its engineering focus. With a growing appetite for inter-disciplinary research, the research councils established the cross-council funded RCUK energy programme in 2002 with the aim of strategically planning and coordinating the councils' delivery of energy research, training and knowledge exchange in order to maximise its impact (RCUK 2017). Mid-stage wave energy innovation has been funded by InnovateUK[13], the UK's technology innovation delivery body, established in 2004, whose primary goal is to foster innovation to boost economic growth and employment.

A similar stage of innovation was supported by the ETI, a public–private partnership established in 2007 under the Limited Liability Partnership Act. This is due to close in 2019 and is currently delivering the remainder of its projects, with some functions due to be absorbed into the UK Catapult centres. It acts as a conduit between academia, industry and the government to accelerate the development of low-carbon technologies and is funded equally by the UK Government and industry, with industry funders (including BP, Caterpillar, EDF, Rolls Royce and Shell). Each private sector partner contributes the same funding of up to £5m per year[14], which is match funded by the UK Government (ETI 2016). The ownership and exploitation of IP arising from ETI-funded RD&D projects is negotiated specifically for each project, with bespoke agreements around how this is apportioned between project funding awardees and the ETI with appropriate licensing to its members (public and private). Alongside funding wave energy demonstration and the development of cross-cutting marine energy solutions (e.g. tools to predict marine energy array yields), the ETI has also produced marine energy roadmaps in conjunction with the UK Energy Research Centre (UKERC) (ETI & UKERC 2010; ETI & UKERC 2014).

13 Formerly the Technology Strategy Board and rebranded in 2014.

The Carbon Trust, founded in 2001 as a private company limited by guarantee to help it foster closer business relationships (NAO 2008) was originally funded by DECC to accelerate a low-carbon transition and was responsible for supporting various wave energy demonstration projects. In 2012, its core funding was cut by the UK Government and it now operates as a not-for-dividend company. It continues to play an active role in the wave energy sector; for example leading the work on the Low Carbon Innovation and Coordination Group's (LCICG)[15] technology innovation needs assessments (LCICG 2012) and advising on the management and design of government-funded marine energy programmes (Carbon Trust 2017).

5.1.3.3 Scotland

Since the establishment of the Scottish Parliament in 1999, an increasing degree of political power has been devolved from the UK Government to the Scottish Government through landmark legislation such as the Scotland Acts of 2012 and 2016. Whilst some areas of policy have remained explicitly 'reserved' for the UK Government and others 'devolved' to the Scottish Government, little clarity exists around which government is directly responsible for energy technology innovation policy, with energy policy and 'trade and industry' UK Government responsibilities but policies to promote renewable energy generation and economic development under Scottish Government control (Devolution Further Powers Committee 2016). Nonetheless, the Scottish Government has played an increasingly important role in supporting wave energy innovation, primarily through its two economic development arms, Scottish Enterprise and Highlands and Islands Enterprise (HIE).

5.1.4 Supporting organisations

Test centres such as EMEC play a very important supporting role. Whilst their test infrastructure capabilities are covered in Section 7.4.2, the centres also fulfil other roles. For example, EMEC provides assistance with grid connection, power purchase agreements, renewable obligations certificates (ROCs) accreditation and compliance with regulation, as well as real-time technology, resource and environmental monitoring (EMEC 2016d). EMEC is also recognised by the United Kingdom Accreditation Service (UKAS) as an accredited test laboratory for full-scale wave and tidal test facilities (ISO 17025) and environmental technology verification (ISO 17020), allowing it to provide independent, internationally recognised verification of the performance and environmental benefits of the devices they test (EMEC 2016a). EMEC has also helped to develop 12 different industry guides to ensure consistent and accurate comparison of performance between different WECs (EMEC 2017a). Finally, EMEC purchased a P2 wave energy device from Pelamis after it went into administration in 2014 to capture knowledge from the device following further examination, with WES performing a similar activity having purchased the other P2 device from Pelamis (EMEC 2016c).

In 2012, InnovateUK established the OREC (OREC 2017c), one of ten new UK Catapult centres that constitute 'physical centre[s] where the very best of the UK's businesses, scientists and engineers work side by side on late-stage research and development' (TSB 2014a). The centres rely on a 'thirds' funding model whereby competitively won private (1/3) and public (1/3) sector funds are complemented by core funding issued by InnovateUK (1/3) to tackle sectoral innovation challenges (TSB, 2013b). The OREC has managed joint-industry-enabling research projects, focusing on issues such as biofouling, component reliability and energy yield assessments (OREC 2017b). It is also responsible for managing marine energy test facilities (formerly NAREC) and the UK wave and tidal knowledge transfer network, as well as publishing reports on solutions to common industry issues such as financing solutions for marine energy (OREC 2014).

14 E.On was originally a member but subsequently exited the ETI.
15 See Section 4.3.3.2 for a description of its role.

The Crown Estate is also an important actor, granting leases for offshore renewable energy developments and, more recently, funding marine energy RD&D projects through its Enabling Actions Fund. It manages the commercial interests of the sovereign's public estate and is independent of government, although any surplus revenue from the estate is paid to the UK Treasury each year (Crown Estate 2017). Following the Scotland Act 2016, the Crown Estate's activities were devolved in Scotland, resulting in the formation of Crown Estate Scotland, with profits now going to Scottish Ministers rather than the UK Government (Crown Estate Scotland 2017).

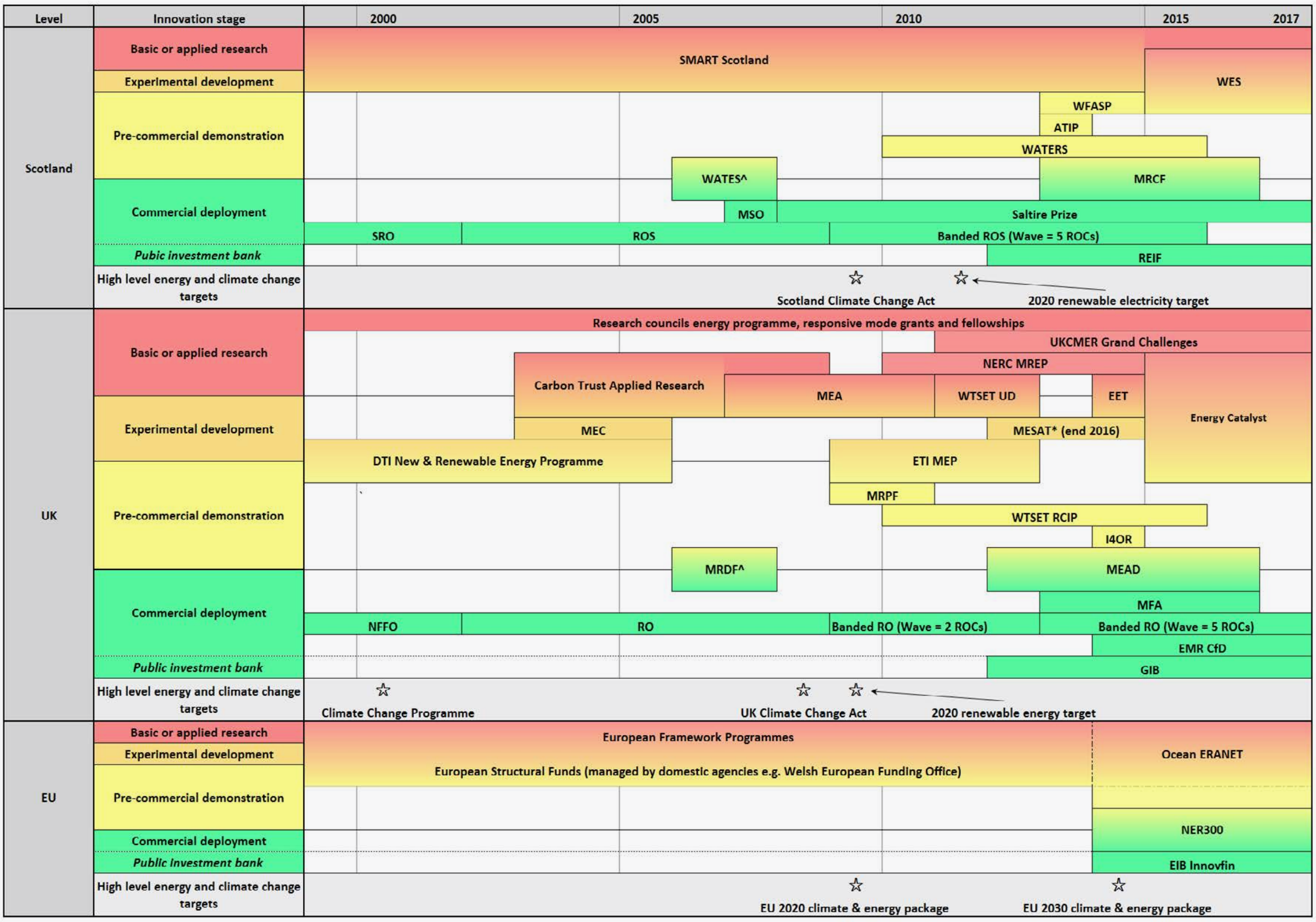
Finally, other important actors include investors, notably VCs, who have been instrumental in providing match funding for public grant schemes for mid- to late-stage TRL activities. Wave energy supporting trade associations also play a key role but are classified as networks for the purposes of this study and covered in Section 5.3.2.

5.2 Institutions

The evolution of UK wave energy innovation policy between 2000 and 2017 is presented in Figure 7. First, this reveals the complexity of the funding landscape, with technology developers facing a plethora of schemes simultaneously offering support from different departments or agencies operating at different levels of governance (i.e. EU, UK, Scotland). Second, it illustrates how fast the policy landscape has evolved, with a succession of new schemes emerging, each with their own submission application guidelines and objectives. Finally, it demonstrates the shift from commercially focused RD&D programmes in the mid-2000s and early 2010s (e.g. Scotland's WATES and MRCF and the UK's MRDF and MEAD), some of which had an explicit focus on arrays (e.g. MRCF, MEAD), to innovation programmes that supported much earlier stage development through to commercialisation (e.g. Scotland's WES and the UK's Energy Catalyst).

It is also important to note how these sector-specific policy developments have corresponded with higher level energy and climate change policy developments. Figure 7 illustrates two points in this regard. First, landmark energy and climate change legislation has been enacted at all three levels of government, especially during the late 2000s and early 2010s, followed by ambitious emissions reduction and renewable energy generation targets. Second, these high-level policy developments typically preceded a proliferation of new programmes to support wave energy innovation, suggesting that they laid the foundations for a renewed commitment to wave energy RD&D.

Figure 7: Overview of wave energy innovation support policies 1999–2017 (source: author)



NOTE: Dates refer to period of project funding. For revenue payment schemes (e.g. RO), dates relate to when funds were available. Some RD&D schemes that committed small sums when funding wave energy are omitted. Test facility access programmes (e.g. MARINET) are classified as networks and included in Section 5.3. * - MESAT partly funded by Scottish Government; ^ - Capital expenditure covered but also longer term offered revenue support payments.

5.2.1 EU

5.2.1.1 Over-arching energy policy landscape

Following the 2007 EU Lisbon Treaty, the EU member states adopted a set of EU-level 2020 policy targets, set in 2007 and enacted into EU legislation in 2009. The 2020 targets are a 20% cut in greenhouse gas emissions (from 1990 levels), 20% of the EU's total energy consumption to be met from renewables and a 20% improvement in energy efficiency. Linked to this, EU member states (including the UK) adopted binding national targets to raise the share of renewables in their energy consumption by 2020 under the Renewable Energy Directive (European Commission 2017a).

In 2014, the EU adopted a new policy framework setting an overall target of renewables accounting for a 27% share of energy consumption by 2030 to help deliver a 40% cut in greenhouse gas emissions on 1990 levels for the same year (European Commission 2017b). Importantly, this is an EU level target and there are no binding targets for individual member states.

In the context of these ambitious high-level energy and climate change targets and the EC's new energy and technology innovation policy making powers, the EC formulated its Strategic Energy Technologies plan (SET plan) in 2007, which is 'the principal decision-making support tool for European energy policy' (European Commission 2017f). The plan identifies priority actions for research and innovation to co-ordinate action across EU member states and other participating countries (Iceland, Norway, Switzerland and Turkey). Marine energy was incorporated into the SET plan in 2013.

5.2.1.2 Wave energy innovation support policies

5.2.1.2.1 Supply–push mechanisms

The EU has offered substantial support for technology innovation throughout the period examined in this study. Since 1984, the EU's framework programmes (FPs) for research and technological development have provided RD&D grants. The FPs aim to strengthen the scientific and technological base of European industry and to encourage its international competitiveness, whilst promoting research that supports EU policies (European Commission 2016). The FPs are the primary mechanism by which the EC supports technology RD&D with the current programme, Horizon2020, accounting for almost two thirds of EU R&D funding for the period 2014–2020 (Royal Society 2015). The funds are open not just to universities and research organisations but also to businesses and charities from qualifying European countries, covering both early and later stage innovation, such as technology demonstration.

Alongside the FPs, the EU also supports wave energy innovation via its structural and investment funds, through sub-schemes such as the European Regional Development Fund (ERDF). These represent 'funds targeted especially (though not exclusively) at building capacity in the least economically developed regions of the EU' (Royal Society 2015 p.8), with a specific focus on supporting technology innovation, small- to medium-sized enterprise (SME) competitiveness and the transition to a low-carbon economy (Reillon 2015). Whilst the structural funds typically support infrastructural investments, for the period 2014–2020, these structural funds will account for roughly one third of EC R&D investment (Royal Society 2015). The implementation of these structural funds is managed at regional/national level on behalf of the EC (e.g. WEFO).

In 2012, the EC introduced a new scheme to support demonstration of innovative low-carbon energy demonstration projects called the New Entrants Reserve 300 (NER300). Funded by the sale of 300 million emission allowances from the NER (set up for the third phase of the EU emissions trading system (EU ETS)) (European Commission 2017e), the scheme awarded over €2.1bn to 38 renewable energy projects between 2012 and 2014 (European Commission 2017e). Whilst no UK wave energy projects were funded in the first two funding rounds, the scheme awarded Ireland's WestWave project with €19.8m (European Commission 2014; European Commission 2012).

5.2.1.2.2 Demand–pull mechanisms

In 2014, the EC, in conjunction with the European Investment Bank, established Innofin EIB. This initiative has made €24bn of financing available until 2020 for investments in research and innovation to help 'address the issue that the EU lags behind its global competitors in terms of both private and public investment in research and innovation' (Innovfin EIB 2017). Whilst no UK wave energy developers have been supported so far, Finnish company AW Energy received €10m in 2016 to demonstrate its 350kW WaveRoller in Portugal (Innovfin EIB 2016).

5.2.2 UK

5.2.2.1 Overarching energy policy landscape

Over the past 20 years, the UK energy policy landscape has been strongly influenced by the need to reduce carbon dioxide emissions whilst improving energy security and affordability. Following the 1997 Kyoto Protocol, the UK committed to reduce its emissions to 12.5% below 1990 levels over the period 2008–2012. This pledge was strengthened as part of its 2000 climate change programme, when it increased its non-binding commitment to reducing CO_2 emissions to 20% below 1990 levels by 2010 and 60% by 2050 (DETR 2000).

This ambition was formalised as part of the 2008 UK Climate Change Act, which committed the UK to reducing emissions by at least 80% in 2050 from 1990 levels (CCC 2016). The UK Government is required under the act to set legally binding 'carbon budgets', each relating to a limit on the amount of greenhouse gases that can be emitted in the UK over a five-year period (CCC 2016) (Table 4). In order to meet these carbon reduction targets and to comply with EU legislation, the UK set itself a legally binding target in 2009 that 15% of energy consumed in the UK should come from renewables by 2020, equating to approximately 30% of electricity demand (DECC 2009).

Table 4: UK carbon budgets and targets (Source: CCC 2017)

Budget	Carbon budget level	% reduction on 1990 carbon emissions
1st carbon budget (2008–2012)	3,018 $MtCO_2e$	25%
2nd carbon budget (2013–2017)	2,782 $MtCO_2e$	31%
3rd carbon budget (2018–2022)	2,544 $MtCO_2e$	37% by 2020
4th carbon budget (2023–2027)	1,950 $MtCO_2e$	51% by 2025
5th carbon budget (2028–2032)	1,725 $MtCO_2e$	57% by 2030

5.2.2.2 Wave energy innovation support policies

5.2.2.2.1 A renaissance in wave energy support (1999–2006)

Supply–push mechanisms

In this context of a need to deliver a low-carbon transition, the UK once again began to invest in wave energy technology RD&D via its new and renewable energy programme. Launched in 1999 by the DTI (DTI 2002), it funded demonstration projects for both Pelamis and Wavegen devices. Mid-stage RD&D was also supported a few years later by the Carbon Trust's applied research programme (2003–2008), funding 17 projects with a strong focus on wave energy device prototype development, including projects by Pelamis, Aquamarine and AWS Ocean Energy. In parallel, the Carbon Trust ran its Marine Energy Challenge (2003), which offered a platform where developers could collaborate with offshore engineering and power generation consultants to help build their capacity, independently validate their device's performance and drive down costs (Carbon Trust 2006). Much early-stage scientific research was supported by the research councils established by Marine Energy Supergen in 2003 (Section 5.3.1.1).

Demand–pull mechanisms

Turning to the other end of the innovation chain, the market–pull subsidy scheme entitled the Non-Fossil Fuel Obligation (NFFO) was replaced by the Renewables Obligation (RO) in 2002, requiring electricity suppliers to source a portion of their electricity from low-carbon sources. Renewable electricity generators were awarded one ROC per MWh of electricity generated from eligible technologies, including wave. ROCs could be sold to suppliers to help them meet their obligations and suppliers failing to meet their obligations had to pay the buyout price for every MWh they supplied without the necessary certification, with these funds distributed to the energy suppliers who submitted ROCs via 20-year-long revenue payments (Ofgem 2016; BERR 2009).

5.2.2.2.2 Strong push towards full-scale commercialisation (2007–2013)

Supply–push mechanisms

The period between 2007 and 2013 is characterised by a UK Government drive towards full-scale and even array-scale demonstration of wave energy devices. This is encapsulated by the DTI's Marine Renewable Deployment Fund (MRDF), launched in 2007, an ambitious £42m demonstration scheme[16]. It offered a combination of capital grant and revenue payment support, the latter a £100/MWh payment for a maximum of seven years, with support capped at £9m or 25% of total 'eligible costs'[17] per project. Unfortunately, developers struggled to meet the highly ambitious eligibility criteria, including three months full-scale device sea trial data, meaning no awards were made (HoCECCC 2012; DTI 2005).

With the acknowledgement that wave energy technology was not as advanced as first thought, a new £22.5m scheme was launched in 2009 called the Marine Renewables Proving Fund (MRPF), which shifted the focus back to short-term single device pre-commercial demonstration. The MRPF made two wave energy awards to Pelamis (£4.9m) and Aquamarine Power (£4.7m). In the same year the newly formed ETI (see Section 5.1.3.2) commenced its marine energy programme which, alongside cross-cutting challenges, also funded full-scale demonstration, again awarding funds to Pelamis (ETI 2017).

The UK Government once again re-focused its efforts on array-scale demonstration schemes in 2012 with its £20m Marine Energy Array Demonstrator (MEAD), to fund projects incorporating at least three generating devices with a combined capacity of no less than 3MW and generating at least 7GWh per annum (UK Government 2015b). No wave projects received funding, with funding instead going to two tidal stream projects (MeyGen and Skerries[18]) (DECC 2016b).

16 Another £8m was made available for infrastructure, environmental research and the development of protocols for developers to report their performance more accurately.
17 'Costs associated with the construction of the project over and above the cost of constructing a combined cycle gas turbine with the same average annual power' (DTI 2005 p.13).
18 Marine Current Turbines subsequently had their award withdrawn as they could not meet the generation deadline, with funding only drawn down by Atlantis for MeyGen.

Other array-focused schemes during the period included InnovateUK's £10.5m Marine Energy – Supporting Array Technologies (MESAT)[19] scheme (2012) to support the development of supporting array technologies such as sub-sea electrical connections, moorings, installation and maintenance vessels. Finally, funded through the OREC but managed by the Carbon Trust, the Marine Farm Accelerator (MFA)[20] was established in 2013, focused on tackling six common challenges associated with marine arrays: electrical systems, yield optimisation, installation methods, insurance, operations and maintenance and site characterisation (Carbon Trust 2016). It employed the same joint industry programme (JIP) model as the Offshore Wind Accelerator (OWA), bringing together 14 wave and tidal device developers, with two thirds funded through industry and one third from government (OES 2014; Carbon Trust 2016; Robertson 2014).

Whilst the period between 2007 and 2013 mostly saw later stage innovation investments, some earlier stage funding was still forthcoming. For example, the DTI established its £3.5m Marine Energy Accelerator (MEA) in 2007, which supported a comprehensive review of new device concepts and their potential to significantly lower marine energy costs (Carbon Trust 2011). Other important investments included NERC and Department for Environment, Farming and Rural Affairs' (DEFRA) joint £2.4m Marine Renewable Energy Programme (2010–2013) to examine the environmental benefits and risks of up-scaling marine energy schemes (NERC 2010). InnovateUK also launched its Wave and Tidal Stream Energy Technologies (WTSET) programme in 2010 to support the verification of device performance, improve device reliability and cost-effectiveness, and develop more robust installation and O&M methodologies (Technology Strategy Board 2010).

Demand–pull mechanisms

Further underpinning the UK's push towards commercialisation was the banding of its RO by technologies in 2009, designed to offer preferential revenue payments to less mature renewable energy technologies such as wave energy. Consequently, marine energy, along with some other less mature renewable technologies (e.g. geothermal, solar PV), was awarded two ROCs per MWh. This was increased to five[21] from 2013 (DECC 2013a), mirroring Scotland's support for wave energy since 2007 through its marine supply obligation (Section 5.2.3). Despite this increase, only three wave power stations have ever received ROCs, the first being the Claddach farm (2006) led by Wavegen using the Limpet device[22], and the others utilising Pelamis devices, namely E.On's Vagr Atferth project (2011) and Scottish Power Renewables' Orcadian wave project (2012) (Ofgem 2017).

5.2.2.2.3 UK Government steps back from marine energy (2014–present)

Supply–push mechanisms

From 2014, the UK Government slowly stepped down its support for wave energy, leading to an absence of any UK Government schemes explicitly designed to support wave energy innovation. Non-marine energy innovation schemes, however, committed support to wave energy, such as the Energy Catalyst in 2015. In a departure from most previous UK energy technology RD&D schemes, this is jointly funded by InnovateUK, EPSRC and DECC, and supports technologies from the early concept stage through to pre-commercial technology validation (InnovateUK 2014). It has funded three wave projects, together worth only £0.3m in funding, versus £2.3m for seven tidal projects.

19 Co-funded by Scottish Enterprise and Natural Environment Research Council (NERC).
20 The MFA was subsumed into the ocean energy strand of the Offshore Renewables Joint Industry Programme (ORJIP), which functions much more like a network than a funding programme (Section 4.3.2).
21 Five ROCs subject to 30 MW cap at each generating station. Two ROCs for any additional capacity added above 30 MW cap (DECC 2013a).
22 LIMPET stands for Land Installed Marine Power Energy Transmitter.

Demand–pull mechanisms

The UK's move away from wave energy is also evident in its demand–pull mechanisms, most notably via its Electricity Market Reform (EMR) Contracts for Difference (CfD), introduced in 2014 to replace the RO (Ofgem 2015). Under the CfD, both wave and tidal stream were in an allocation pot of £290m per annum (2021/2022 and 2022/2023) with other 'less established technologies', including offshore wind, advanced conversion technologies, anaerobic digestion, dedicated biomass with combined heat and power (CHP) and geothermal.

Eligible wave energy projects were to be awarded a 'strike price' of £305 per MWh (DECC 2013c), which was guaranteed regardless of fluctuations in the market price for electricity (EnergyUK 2016). However, should the cost of eligible projects exceed the total funding available for the 'less established technologies' pot, all CfDs for that pot are allocated via a cost competitive auction[24] (Clifford Chance 2015), where bids are 'accepted sequentially, from lowest to highest cost, up to the budget limit' (McNaught 2017).

To encourage marine energy, the UK Government legislated that the first 100MW of marine schemes would be guaranteed access[25] to CfDs until the end of the first delivery plan period in 2019 but that any capacity above this would have to compete against other technologies (HM Government 2015). However, this funding allocation minimum was removed for marine energy during the second CfD allocation round (post-2019), in turn removing the guarantee that up to 100MW of eligible marine energy projects would receive long-term revenue payments (BEIS 2016a).

5.2.3 Scotland

5.2.3.1 Overarching energy policy landscape

Following the UK's Climate Change Act 2008, Scotland passed equivalent legislation in 2009, committing itself to a 42% reduction in emissions by 2020 and an 80% reduction by 2050 on 1990 levels (CCC 2016). In 2011 this commitment was translated into a host of relevant energy targets including sourcing 100% electricity demand equivalent from renewables by 2020, with an interim target of 31% by 2011, which it achieved (Scottish Government 2012; Scottish Government 2011). The Scottish Government has recently published a provisional target that 50% of energy consumption is met by renewable energy by 2030 (Scottish Government 2017c).

5.2.3.2 Wave energy innovation support policies

5.2.3.2.1 Commencement of an ambitious marine energy strategy (2000–2013)

Supply–push mechanisms

The Scottish Government initiated their highly ambitious marine energy innovation programme in 2006, launching its £13m Wave and Tidal Energy Scheme (WATES). This was designed to support full-scale demonstration of marine energy devices and supporting technologies (e.g. foundations, moorings). Like the UK's MRDF scheme (Section 5.2.2.2.1), it had a strong commercial focus, offering a combination of grant funding and revenue payments, set as £100/MWh up to a maximum of five years from project commissioning (Scottish Government 2009b). Continuing this support for full-scale demonstration, Scotland introduced its £12m Wave and Tidal Energy: RD&D Support (WATERS) programme in 2010, running through three rounds to 2015. However, unlike its predecessor WATES, it did not include revenue payments, placing less pressure on long-term commercial deployment (Scottish Enterprise 2010b; Scottish Enterprise 2012).

Once again, the Scottish Government reignited its support for commercial marine energy deployment, launching the £18m Marine Renewables Commercialisation Fund (MRCF) in 2012. This aimed to deliver 3–10MW arrays of at least three devices already demonstrated at full scale (Blair 2013; Scottish Government 2014). Alex Salmond, then First Minister of Scotland, explained that the scheme was aimed at:

> 'those companies now at the verge of commercial deployment, to develop their prototype devices and forge ahead with the development of commercially viable arrays' (Scottish Enterprise 2012).

23 Another £8m was made available for infrastructure, environmental research and the development of protocols for developers to report their performance more accurately

24 When the auction is closed, all projects within that delivery year are awarded a final clearing price equal to the strike price of the last approved project … [which] is capped at the relevant Administrative Strike Price set for each technology' (McNaught 2017).

25 Wave and tidal technologies would receive 'first access to the less established technologies pot, without competition from other technologies' (Weightman 2014) but restricted to projects less than 30MW (RegenSW 2016).

Demand–pull mechanisms

Market–pull mechanism support for wave energy can be traced back to the third round of the Scottish Renewables Obligation (SRO) in 1999, which awarded contracts to three projects: Wavegen's LIMPET, Pelamis's P1 and Sea Power International's floating wave power vessel (House of Commons Science and Technology Committee 2001). However, despite the importance of this commitment from government, only LIMPET was commissioned in 2000, off the Isle of Islay in Scotland (DTI & DETR 2000).

In 2007, Scotland significantly increased its support for wave energy via its marine supply obligation (MSO), supplementing its Renewable Obligation Scotland (ROS), the Scottish version of the UK RO introduced in 2002 (Section 5.2.2.2). The MSO required electricity suppliers obligated under the RO to meet a proportion of that obligation with ROCs awarded for marine energy generation in Scottish waters or by paying a higher buyout price, initially set at £175/MWh for wave devices and £105/MWh for tidal devices, much higher than the standard RO buyout price of £35.76/MWh in 2008/2009 (Scottish Government 2017a). However, because of a lack of eligible capacity that suppliers could draw on to meet the obligation, the MSO was set at zero and discontinued in 2009 when the ROS offered five ROCs per MWh for wave energy (RenewableUK 2010; The Scottish Government 2008).

In 2008, Scotland launched another demand–pull policy, in the form of its £10m Saltire Prize. The prize was open internationally and was to be awarded to the developer generating the greatest volume of electricity from the ocean by June 2017, over a threshold of 100GWh and a continuous two-year period (Scottish Government 2009a). No party was successful in meeting the criteria and the prize money went unspent.

Finally, in 2012, Scotland launched its £103m Renewable Energy Investment Fund (REIF). Backed by the Scottish Investment Bank (Scottish Enterprise 2014), this offered low-cost loan and equity finance for renewable energy projects deemed too risky by institutional investors. By 2016, it had financed three wave projects, with Aquamarine and Pelamis together receiving £12m in investment, whilst Albatern received investment to harness wave energy for use in aquaculture (Ekosgen 2016).

5.2.3.2.2 Targeted support for wave energy innovation (2014–present)

Supply–push mechanisms

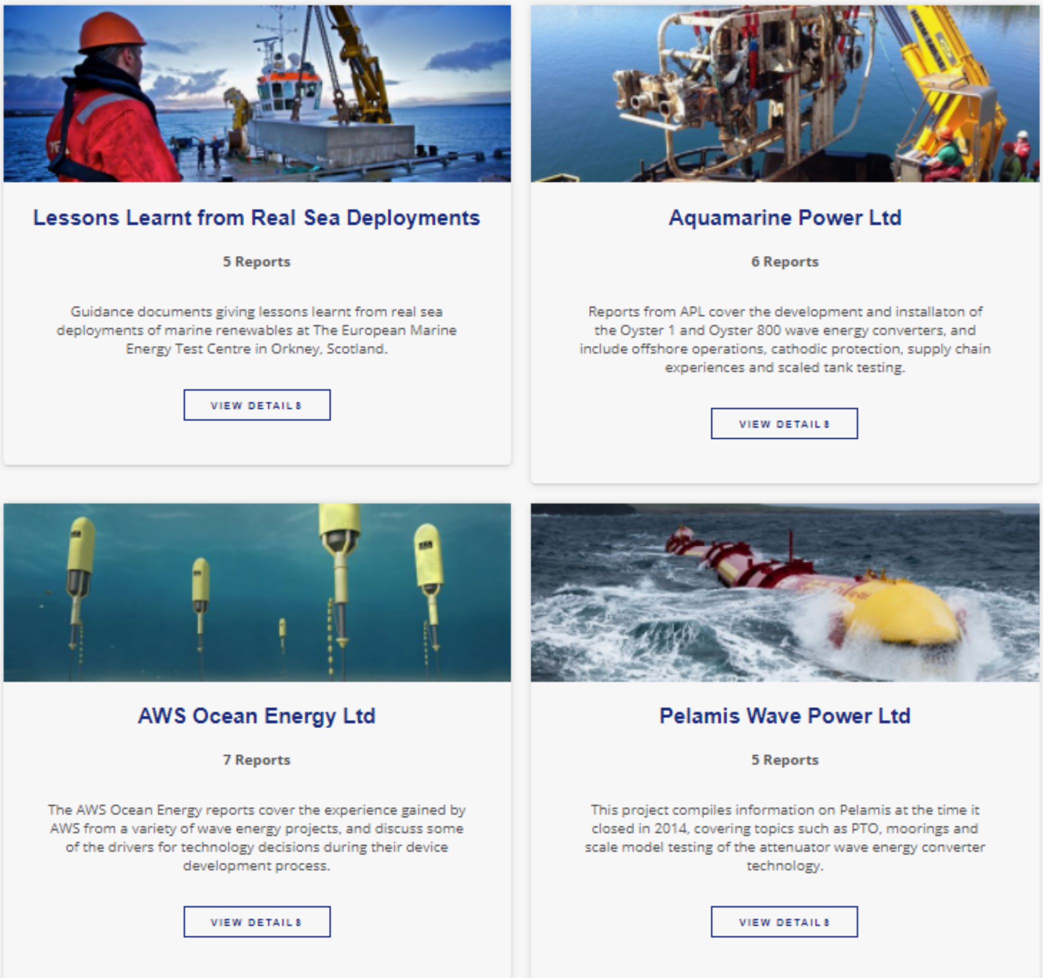
In 2013, there was an acknowledgement that 'wave array projects are not realistically able to be delivered within the MRCF time [2017] and spending constraints' (Blair 2013), whilst tidal stream had already received significant funding via other projects such as the EU's NER300 and the UK's MEAD. Consequently, the Scottish Government decided to recalibrate its support for marine energy, the first move being to compartmentalise RD&D funding for wave energy, splitting it from marine energy more broadly. For example, in 2014, it reconfigured its £18m MRCF programme, creating a stand-alone funding stream for wave, namely the £13m Wave First Array Support Programme. Two awards were made to Pelamis and Aquamarine but neither project reached fruition as both companies entered administration (The Carbon Trust 2014). The remaining £5m was committed to enabling technologies (e.g. moorings) and services (e.g. installation) to support deployments of marine energy arrays (i.e. the Array Technology Innovation Programme).

This trend towards offering discrete support for wave energy is, however, best encapsulated by its establishment of Wave Energy Scotland (WES) in 2014. The scheme's focus is to 'support wave energy technology development until the technical and commercial risks are low enough for private investment to re-enter the sector' (WES 2016 p.2). As of summer 2017, WES has awarded £24.6m across 56 projects and 150 organisations (Hurst 2017).

WES differs from most of its predecessors in a number of important ways. These include:

- Supporting activity across the innovation chain, from the concept characterisation and refinement stage (TRLs 1–3) through to small prototype development (TRLs 5–6).
- Employing a rigorous stage-gating model where developers must meet stringent criteria to progress to unlock funding at a higher TRL.
- Adopting a bottom-up approach, focusing on optimising sub-components (e.g. PTOs, controls, structural materials) and different device designs rather than optimising a single device design, although it still retains a focus on device design via its novel wave energy converter call.
- Encouraging the formation of consortia and has opened up funding to international developers as long as RD&D is conducted in Scotland.
- Offering 100% funding via a state aid compliant procurement model, meaning no match funding from the private sector is required.
- Imposing a requirement on developers to licence their intellectual property (IP) and, if they do not do this after a pre-determined period of time, WES has the right to do so on their behalf (WES 2016).
- Supporting lesson sharing through publication of open-access reports on project results. This is supplemented by a series of reports outlining lessons learnt over the past decade by the sector on key issues such as supply chain development, installation and O&M (WES 2017d), as well as knowledge generated by former leading developers such as Pelamis and Aquamarine Power (WES 2015) (Figure 8).

Figure 8: WES's knowledge capture portal (source: WES)

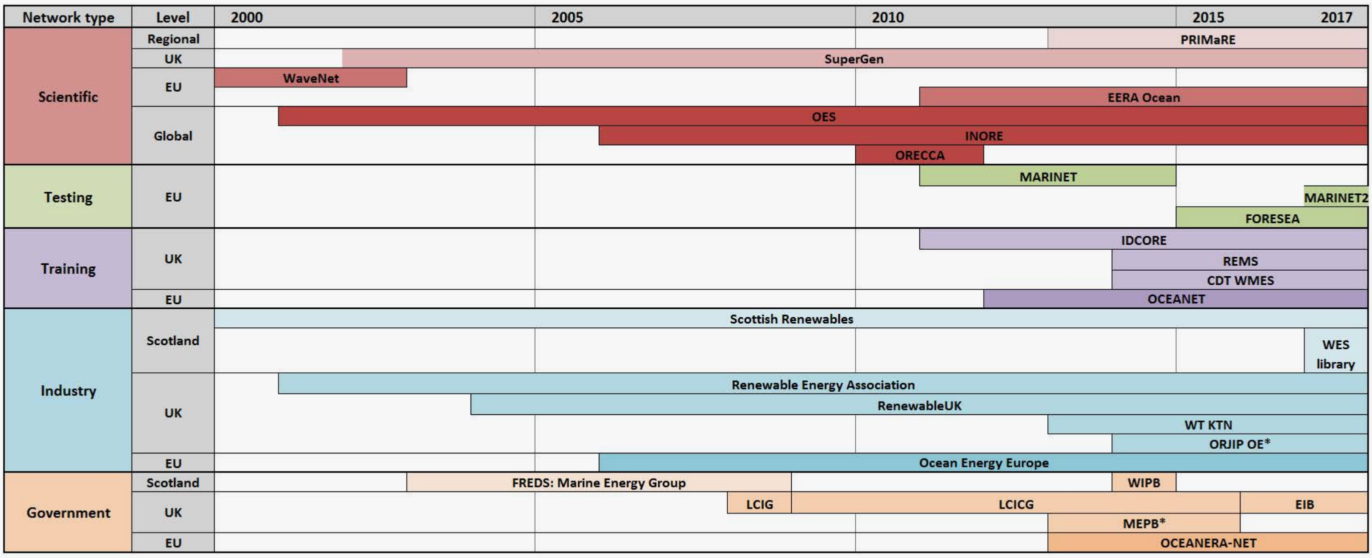


5.3 Networks

The evolution of the UK’s wave energy related scientific, industry and government networks is presented in Figure 9 and Table 5. First, we find that key scientific and industry networks have been present in one form or another since the early 2000s. However, networks co-ordinating test facility, training and government activities were much slower to form, mostly emerging after 2010. Since 2015, we can identify excellent connectivity across the UK wave energy innovation system, as evidenced by strong coverage of networks across the five domains of science, test facility, training, industry and government, with a good spread across regional, national and international levels.

Table 5 also indicates a good coverage not only exists across these five network domains but also across the six key intermediary/network functions, ranging from relationship building to policy advocacy[26]. Again, this coverage of network functions has significantly improved as the number and diversity of networks has increased. However, there is some evidence of overlapping networks, such as multiple trade associations and marine energy centres for doctoral training (CDTs). This could result in a duplication of efforts and dilute the overall impact of networks versus a single consolidated network for each of these discrete activities.

Figure 9: Timeline of wave energy innovation networks 2000–2017 (source: author)



26 These categories are adapted from a framework synthesised by Kilelu et al. (2011) on the functions of intermediary organisations, identifying six common functions they perform: 1) Relationship building – actor match-making and facilitation of long-term relationships; 2) Capacity building – improving actors’ innovation capabilities via training and experience sharing; 3) Knowledge transfer – strategic dissemination of knowledge between knowledge generators and users; 4) Technology foresighting – identification of priority RD&D areas and strategies to deliver these; 5) RD&D coordination – coordination of innovation activities across sectors; 6) Policy advocacy – promoting changes in institutional frameworks to support technology innovation.

Table 5: Summary of wave energy innovation networks and the activities they perform (source: author)

Type	Level	Network name	Established	Nos. of partners (and countries)	Intermediary activities					
					Relationship building	Capacity building	Knowledge exchange	Technology foresighting	RD&D coordination	Policy advocacy
Scientific (Research)	Regional	PRIMaRE	2013	7 (1)	X		X	X	X	
	UK	SuperGen	2003	15 (1)	X	X	X	X	X	
	European	WaveNet	2000–2003	14 (9)	X		X	X		
		EERA Ocean	2011	9 (9)	X		X	X	X	X
	Global	OES	2001	25 (25)	X		X	X	X	
		INORE	2006	N/A (76)	X	X	X			
		ORECCA[1]	2010–2011	28 (11)			X	X		
Scientific (Test facility)	European	MARINET[2]	2011–2015	39 (12)	X	X	X			
		MARINET2	2017–2021	57 (13)	X		X			
		FORESEA	2016–2019	4 (4)	X					
Scientific (Training)	UK	IDCORE	2011	5 (1)	X	X	X			
		REMS	2014	2 (1)	X	X	X			
		CDT WMES	2014	2 (1)	X	X	X			
	European	WaveTrain 1	2004–2008	11 (6)	X	X	X			
		WaveTrain 2	2008–2012	13 (8)	X	X	X			
		OCEANET	2013	13 (8)	X	X	X			
Industry	Scotland	Scottish Renewables	1996	53 (N/A)	X					X
		WES library	2017	N/A		X	X			
	UK	REA	2001	44 (N/A)	X					X
		RenewableUK	2004	N/A	X			X		X
		WT KTN	2013	N/A			X			
		ORJIP OE[3]	2014	87 (N/A)	X		X	X	X	
	EU	OEE	2006	115 (N/A)	X			X		X
Government	Scotland	FREDS[3]	2003–2009	N/A				X	X	X
		WIPB[4]	2014	N/A			X	X	X	X
	UK	LCICG/EIB	2008	8 (1)	X		X	X	X	X
		MEPB[3]	2013–2015	N/A	X		X	X	X	X
	European	OCEANERA-NET	2013	16 (8)	X				X	

NOTE: [1] An 18-month project; [2] 1 non-EU partner; [3] A combination of industry, government and third sector membership; [4] Disbanded in 2014

5.3.1 Scientific and educational networks

Knowledge and educational actors within the UK wave energy system are very well connected through a large number of extensive scientific networks, operating at global, European, UK and regional levels, performing a range of activities. We briefly review the development and content of these, categorising them by research, test facility and educational networks.

5.3.1.1 Research

The wave energy sector has a long tradition of international scientific research networks. The most significant is the IEA's Technology Collaboration Programme (TCP)[27] on ocean energy systems (OES) (OES 2016). From an initial three members in 2001 (the UK, Denmark and Portugal), its membership had grown to 25 by the end of 2016. Its over-arching aim is to drive marine energy innovation via international collaboration and it achieves this aim by co-ordinating different work R&D packages on issues such as testing protocols, grid integration and environmental impacts/monitoring, as well as reviewing the existing evidence base and disseminating this knowledge (OES 2015). The OES also produces a detailed review of global ocean energy sector developments and foresight reports offering a vision of a future ocean energy sector and co-ordinates the bi-annual International Conference on Ocean Energy (ICOE).

Another major international network was established in 2011, this time at European level, called the European Energy Research Alliance (EERA). Its aim is to accelerate new energy technology development through co-operation, bringing together more than 175 research organisations from 27 European countries, involved in 17 joint programmes. EERA is the public research pillar of the EU's SET plan. One of EERA's joint programmes is for ocean energy (EERA Ocean), involving nine organisations from nine countries. Its primary aim is to 'underpin the coordination of the emerging ocean energy sector in an effort to promote the incorporation of ocean energy into the SET plan' (Ocean Energy EERA 2015 p.5), which was achieved in 2013. Its primary role is to offer strategic leadership of ocean energy research, providing a 'co-ordinated voice towards the European Commission and the member states on medium- to long-term research priorities' (Ocean Energy EERA 2015 p.5).

A host of other international networks are outlined in Table 5, including: WaveNET (est. 2000), International Network on Offshore Renewable Energy (INORE) (est. 2006) and Offshore Renewable Energy Conversion platforms – Coordination Action (ORECCA) (est. 2013). The INORE exists specifically to support early-stage researchers of offshore renewable energy, bringing together over 1,400 individual members from over 76 countries via symposia and workshops (INORE 2017).

At the UK level, the most notable network is UK's Centre for Marine Energy Research (UKCMER), established in 2003 as part of the RCUK Supergen programme. Established primarily as a centre of research excellence to quantify the risk and return associated with marine energy and reduce uncertainty around the technology (UKERC 2007) it also performs important networking functions. For example it brings together a consortium of 15 UK universities, manages international and industry networks, as well as running residential training schools (Supergen UKCMER 2017). It is likely that the fourth phase of the UK Supergen programme will see marine energy merge with offshore wind as part of an offshore renewable energy hub following a recent review of the Supergen programme (RCUK 2016).

The other major network is the Partnership for Research in Marine Renewable Energy (PRIMARE) (est. 2009), bringing together seven world-class marine energy institutes in the south west of the UK. The network hosts an annual research conference, identifies priority research topics via workshops and maintains a directory of associated experts and projects to facilitate networks (PRIMARE 2017).

27 The IEA runs 38 TCPs, which represent 'independent, international groups of experts that enable governments and industries from around the world to lead programmes and projects on a wide range of energy technologies and related issues' (IEA 2016 p.1).

5.3.1.4 Test facilities

In addition to these inter-organisational RD&D networks, there are two major infrastructure testing networks: the Marine Renewables Infrastructure Network (MARINET) and Funding Ocean Renewable Energy through Strategic European Action (FORESEA). The primary aim of these schemes is to award periods of free access to allow developers to make use of a world-leading network of test centres across Europe that stretch from early- to late-stage TRLs, thus circumventing the very high costs these developers face in accessing facilities.

The first phase of EU-FP7-funded MARINET began in 2011 and has offered over 700 weeks of access to 39 test facilities across 12 countries for approximately 300 projects and 800 external users (Ocean Energy Europe 2017). Furthermore, MARINET has committed significant funding to other activities such as networking and training in the form of staff exchanges and training courses (e.g. numerical, experimental), as well as efforts to standardise test protocols and improve testing capabilities (MARINET 2015). A second phase of the scheme (MARINET2) commenced in 2017 under Horizon 2020, broadening the number of facilities to 57 test facilities across 13 countries, with no explicit focus on capacity building and networking. It should be noted that MARINET only funded researchers or developers to utilise test facilities outside their countries of residence.

In 2016, FORESEA, a similar initiative, was established under the EU-funded Interreg North-West Europe[28]. It brings together four test facilities across four countries, covering up to 100% of the costs of testing at these, including EMEC in the UK. Crucially, unlike MARINET, UK developers can apply for these funds to test free-of-charge in the UK and it funds the use of real-sea test facilities rather than onshore test facilities (e.g. wave tanks).

5.3.1.5 Training

The UK is also home to a host of important multi-university training networks for wave energy RD&D with three CDTs:

- **Industrial Doctorate Centre in Offshore Renewable Energy (IDCORE)** – established in 2011 between the Universities of Edinburgh, Strathclyde and Exeter, the Scottish Association for Marine Science and HR Wallingford. It is co-funded by the ETI and the EPSRC RCUK Energy programme.
- **Centre for Doctoral Training in Wind & Marine Energy Systems (WMES)** – established in 2014 between the Universities of Oxford and Cranfield and funded by EPSRC.
- **Centre for Doctoral Training in Renewable Energy Marine Structures (REMS)** – established in 2014 between the Universities of Edinburgh and Strathclyde and funded by EPSRC.

Both IDCORE and REMS offer engineering doctorates (EngDs), whilst WMES offers a PhD programme. The key difference between an EngD programme and a PhD programme is that the former offers a direct link with industry, with 'students spending 75% of their time working in their companies but will attend intensive training periods at the universities for taught modules, group project working and other activities' (REMS 2017). In addition to industrial placements and supervision, these programmes host regular events to support research dissemination, training and networking. It should also be noted that all three centres are funded by EPSRC but IDCORE has been co-funded by ETI, providing a very strong industrial focus.

European training networks have also been established, notably the two phases of WaveTrain, which ran from 2004 to 2012, bringing together a combination of universities and wave energy developers from eight countries, focused explicitly on creating a pool of specialised wave energy research professionals to support the emerging industry. OCEANET was established in 2013, bringing together 13 students across ten universities from eight countries, to develop the skills required for the design, implementation and operation of arrays, as well as develop supporting technologies (e.g. connectors, monitoring, O&M) (OCEANET 2017). As outlined in Section 5.3.1.4, test facility networks such as MARINET also offer training.

28 A European Territorial Co-operation Programme funded by the EC.

5.3.2 Industry networks

At the European level, the Ocean Energy Europe (OEE) association was established in 2006,[29] with 115 members across Europe. In addition to hosting networking activities, OEE plays a special role in defining research and innovation priorities for the ocean energy sector through its hosting of the European technology and innovation platform for ocean energy (TP Ocean), established in 2014 (ETIP Ocean 2017). Consequently, OEE is recognised by the EC as an advisory body to inform the design of the SET plan (TP Ocean 2016). It also hosts the annual Ocean Energy Europe Conference and Exhibition and produces periodic reports such as its Strategic Initiative for Ocean Energy (SI Ocean) series, which highlighted key priorities for technology development and a roadmap for commercial deployment.

5.3.2.2 UK

There are a few major trade associations at UK level, the oldest being Scottish Renewables (est. 1996), as well as the Renewable Energy Association (REA) (est. 2001) and RenewableUK (which included marine energy in its remit in 2004). Alongside the typical functions of lobbying government to develop favourable energy policy, these associations also host networking events (e.g. conferences), publish periodic foresight reports and invite members to shape the associations' response to government (e.g. policy consultations).

Several networks focus exclusively on knowledge exchange. The Wave & Tidal Knowledge Network (W&T KTN), originally established by the Crown Estate and DECC in 2013, is now managed by the ORE Catapult (ORE Catapult 2014). It provides an online repository of datasets and reports across the marine energy industry, as well as curating a newsfeed about sectoral developments (W&T KTN 2017). A similar function was established by WES in 2017 as part of their online library, presenting outputs from the projects and showcasing what IP has been generated, in a bid to foster collaboration and lesson sharing (WES 2017c). This is complemented by WES's knowledge-capturing initiatives (Section 5.2.3.2.2).

Finally, in 2014, toe Offshore Renewables Joint Industry Programme (ORJIP) was established, the aim of which is to reduce consenting risks for offshore energy projects. It does this by strategically coordinating RD&D funding and activity to address cross-industry challenge, bringing together industry, funders and researchers (ORJIP 2015).

5.3.3 Government networks

Various cross-government networks have also existed to improve the degree of policy co-ordination and effectiveness at different levels of government.

5.3.3.1 Europe

At the European level, OCEANERA-NET was formed in late 2013 to link 16 national and regional funding agencies from across the UK, Ireland, Sweden, Belgium, Netherlands, France, Spain and Portugal. The aim is to coordinate activity between European countries and regions to better support research and innovation in the ocean energy sector (OCEAN ERA-NET 2017). As part of its co-ordination activities, OCEANERA-NET has run joint funding calls, informed by member state representatives, as well as the European Energy Research Alliance Ocean Energy Joint Programme, Ocean Energy Forum and Technology Platform to develop a shared vision and co-ordinated action plan.

5.3.3.2 UK

At the UK level, the Marine Energy Programme Board (MEPB) was established in 2013 to bring together key stakeholders (60-plus members) from companies and trade associations from the marine energy sector to advise UK Government ministers about how best to meet the needs of the UK marine energy sector (UK Gov 2017). Special taskforces were established to tackle particular sectoral barriers and propose an evidence-based way forward (MEPB 2014). According to the UK Government's website it met twice, once in 2013 and 2014, with the Programme Management Board meeting another six times between 2013 and 2015 to ensure that the MEPB workgroups had met their objectives (UK Gov 2017).

29 Formerly the European Ocean Energy Association and rebranded in 2013.

In a bid to improve innovation policy co-ordination the UK Government recently announced the formation of UK Research and Innovation (UKRI) due for 2018, primarily to improve co-ordination between the research councils and InnovateUK. This followed the recommendations of the Nurse Review to 'support the Research Councils to collectively make up more than the sum of their parts' and develop a 'smoother pathway to more applied research' (UKRI 2017).

Efforts have also been made to improve co-ordination specifically of energy innovation across the UK and devolved administration governments. The Low Carbon Innovation Group (LCIG) was formed in 2008, later becoming the LCICG. Its core membership included the UK Government's DECC, BIS, the Carbon Trust, the ETI, EPSRC and TSB (now InnovateUK), as well as the Scottish Government and Scottish Enterprise. In addition to better aligning the activities of UK energy innovation funders by providing a forum for regular communication and co-ordination, the LCICG also published a series of foresighting exercises known as Technology Innovation Needs Assessments (TINAs) for different energy technology areas, including marine energy (published in 2012). These identified key innovation needs for low-carbon energy technologies and their associated benefits to help the UK plan its innovation support, compiled with significant input from industry and academia (LCICG 2014a).

The LCICG was discontinued in 2016 and replaced by the Energy Innovation Board (EIB), which provides strategic oversight of UK public programmes on energy innovation (EIB 2017). Unlike the LCICG, the EIB is made up of senior-level civil servants and chaired by the Chief Executive Designate of UKRI, Sir Mark Walport. Today, it has eight members (BEIS, InnovateUK, research councils, DCLG, DEFRA, DfID, DfT and Ofgem), one observer (HM Treasury) and the devolved administrations are invited to attend board meetings (EIB 2017).

5.3.3.3 Scotland

The Forum for Renewable Energy Development in Scotland (FREDS) was established in 2003, an advisory board made up of a mixture of industry, academia and government experts to help Scotland meet its 2020 targets under the Renewables Action Plan, containing a sub-group for marine energy (Scottish Government 2015; Scottish Government 2010). From 2009, this was subsumed into the Scottish Energy Advisory Board (SEAB), with no specific marine energy group but a Renewables Industry Leadership Group (Scottish Government 2017b).

Arguably, the most important development came in 2014, following the Wave Energy Summit organised by the Scottish Government's First Minister Alex Salmond in January 2014 in reaction to the withdrawal of private sector investment and the faltering of market leaders Pelamis and Aquamarine in the mid-2010s. As explained by one senior civil servant, the summit:

'brought utilities and other investors together in January 2014, and said to them, "What do you need the public sector to do, to keep you at the table?" and they said, "We want to see the technology working, so the public sector needs to focus on supporting technology development, rather than project development"' (I18)

A key outcome of the summit was an acknowledgement that efforts should focus on developing the technology first, and supporting technologies and processes second (e.g. grid connection, consenting), as well as the critical need for collaboration, a more stringent critique of device designs and a clear technology roadmap (Bannon 2017). The summit ultimately led to the establishment of the informal Wave Industry Programme Board in 2014 (see Section 7.3.4), which brought together multiple bodies to 'sit down and work out how we could produce a programme that would get over the previous problems of funding programmes that we'd had' (I17 – Senior public servant). Its membership included the Scottish Government, Scottish Enterprise, HIE, the Offshore Renewable Energy Catapult, the Carbon Trust, InnovateUK and DECC (now BEIS). It was from this that WES emerged (Section 5.2.3.2.2).

5.4 Technology and infrastructure

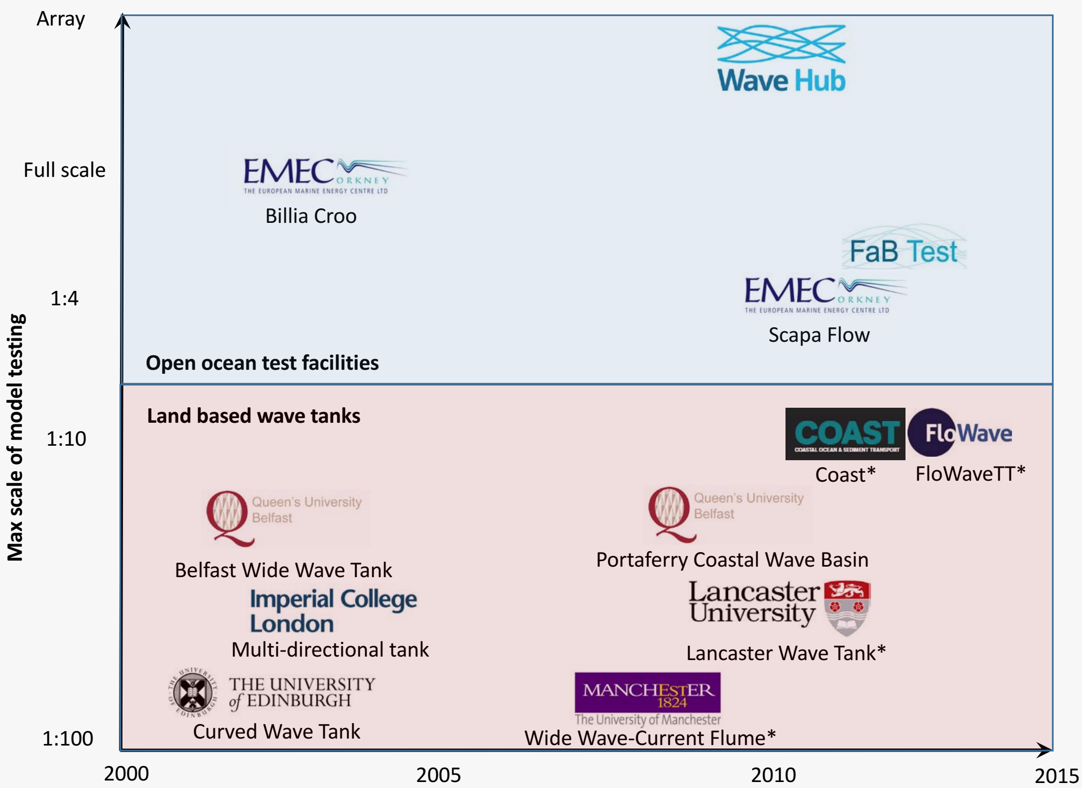
This section examines synergies with complementary technologies from other sectors and the presence and evolution of test infrastructure established to support wave energy RD&D.

With regards to technology, the review finds synergies across a number of already mature energy technologies, notably offshore wind and oil/gas sectors, as well as non-energy sectors such as aviation, defence, offshore construction, sub-sea mining and shipping.

A review of the UK's wave energy test facilities identifies a very clear progression across both land-based and open-ocean test facility capabilities, culminating today in a world-class suite of test facilities for wave energy developers and researchers stretching across the TRLs (Figure 10). With regards to test tanks, clear improvement has taken place in capabilities over the past 40 years (comprehensive list in Annex D). They have evolved from wave flumes offering small-scale testing of devices in mono-directional waves to highly complex facilities able to replicate real ocean environments and enable testing of devices up to 1:10 scale, thus enabling developers to test part-scale devices in a much less hostile and easier to manage environment than the open ocean.

In parallel, the UK has also grown its suite of open-ocean test facilities, beginning with full-scale grid-connected facilities and later expanding to earlier stage part-scale (1:4) nursery sites (e.g. Scapa Flow at EMEC) and multi-device array sites (e.g. WaveHub). Add to this the introduction of new sub-component test facilities, we find that the UK now offers a comprehensive suite of wave energy test facilities stretching across the innovation chain.

Figure 10: Evolution of land-based wave tanks and open-ocean test facilities since 2000 (source: author)



NOTE: Selection of facilities is for illustrative purposes and does not include all test tanks constructed during this period, which are included in Appendix D.
* – Facilities that also have tidal current generation capability

5.4.1 Complementary technologies

Wave energy represents a distinct class of technology but still shares a number of potential synergies with other technology sectors, which could offer valuable lessons to support wave energy innovation via cross-fertilisation. Drawing upon work conducted by the SI Ocean (2012) project, we find that wave energy could draw upon valuable technological and operational 'know-how' not just from energy sub-sectors, notably offshore wind and oil/gas, but a host of non-energy sub-sectors such as aviation, defence, offshore construction, sub-sea mining and shipping. Table 6 outlines the different sectors that could offer valuable lessons to inform the development of wave energy sub-components (e.g. PTO, structure/prime mover), supporting technologies (e.g. moorings, electrical connections) and processes (e.g. installation, O&M).

Table 6: Potential cross-fertilisation benefits for wave energy from other technology sectors (Source: SI Ocean 2012)

Sector	Examples of potential cross-fertilisation
Aviation and defence	Composites manufacture and automation of manufacturing processes
Offshore construction and sub-sea mining	Installation methods (e.g. seabed preparation, vessel usage) Hydrodynamic loading and degradation of structural materials
Offshore wind	Offshore installation and recovery techniques in tight weather windows Resource assessment and array layout optimisation PTO and sub-sea connection technology
Oil and gas	Offshore connections (e.g. wet mate connectors)
Shipping	Survivability of devices and components within the marine environment Mooring and foundations with both permanent and dynamic loading requirements

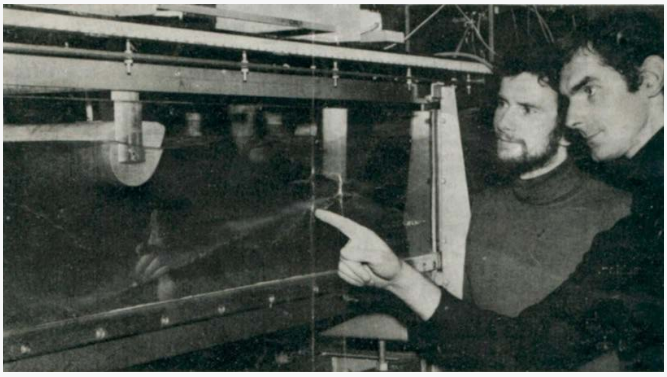
5.4.2 Wave energy test infrastructure

5.4.2.1 Wave tanks

Central to wave energy technology development has been the ability to test device prototypes in facilities that replicate ocean environments. At present, there are at least 30 wave energy generating test facilities or 'wave tanks' in the UK, the majority of which are operated by universities (e.g. Imperial College London, Plymouth, Edinburgh), with some others managed by former public sector R&D agencies (e.g. Qinetiq, HR Wallingford) (EUROcean_RID 2017; OREC 2017a; SEL 2014; Edinburgh Designs 2017b). These wave tanks use either a bottom-hinged paddle or horizontal motion piston-type wave generator across a contained body of water (Edinburgh Designs 2017d). Whilst wave energy devices are one of the most common uses of these facilities, they are also used for a variety of other research purposes such as exploring the effects on coastal and offshore structures and the transportation of sediment. Importantly, test tank technology has progressed in parallel with wave energy technology innovation, with each new generation of facility offering an even greater spectrum of conditions in which to test device prototypes.

The first generation of wave tanks took the form of narrow flumes such as Edinburgh's Narrow Tank (Figure 11), commissioned in 1974. It was 9m long, 0.3m wide and 0.6m deep, capable of generating waves up to 0.2m and frequencies of up to 2Hz. It represented: 'a 2D slice, with the model fully blocking the width of the tank … [with] waves and flow act in a plane' (Edinburgh Designs 2017c). If offered benefits such as excellent visibility and easy access but these facilities tended to be limited to very early stage experimentation.

Figure 11: Stephen Salter (right) testing the Salter Duck in an early wave flume (source: Edinburgh Wave Power Group)



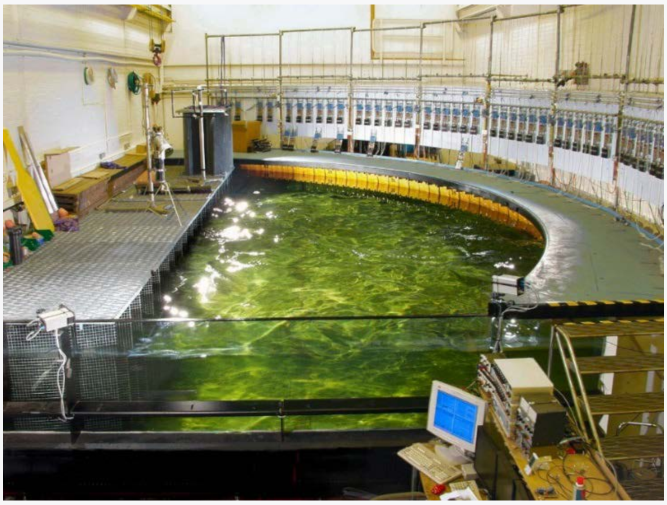
The next generation of tanks were wider rectangular tanks that included numerous flap- or piston-style wave makers with multi-directional capabilities to provide a wider spectrum of more complex and realistic sea states, demanding computer software control of individual paddles (Edinburgh Designs 2017b). Their larger size also meant that they could generate larger waves and thus test larger scale devices. For example, Edinburgh's Wide Tank (Figure 12), commissioned in 1977, was 11m long, 28m wide and 1.2m deep and capable of testing devices up to 100th scale. It included 89 absorbing wave makers[30] along one of the tank's sides, capable of producing waves up to 0.3m high and a rich variety of different sea states that differed in terms of 'amplitude, frequency, starting phase and angle relative to the line of wave makers' (Taylor et al. 2003).

Figure 12: University of Edinburgh researchers working with the Wide Tank (source: Edinburgh Wave Power Group)

The intervening years saw mostly narrow flumes commissioned. However, by the 1990s, a number of similar tanks were constructed, utilising a similar rectangular design. Examples include a 24-paddle tank at Heriot Watt University, Edinburgh, in 1996 (12m x 13m x 5m) and Imperial College London's 56-paddle tank (20m x 15m x 1.5m) in 2003. In general, these larger tanks could replicate larger waves and had sufficient space to test small-scale arrays.

The third generation of wave tanks offered the simulation of even more realistic sea states, this time by developing curved rather than rectangular tanks. Edinburgh was once again at the forefront, commissioning their curved tank in 2003 (Figure 13), with a depth of 1.2m and radius of 9m, sub-tending an angle of 96^{o} and incorporating 48 wave makers (Gyongy et al. 2014). Key advantages included removing parallel tank walls that could generate 'hard-to-damp' standing waves and that the curvature allows for greater multi-directional wave spread (up to 90^{o}), offering a greater workable area in the tank and extra power to be generated through focused waves (Edinburgh Wave Power Group 2009a). Together with 'a driven carriage or arm to give users easy access to the test area [and] to deploy wave measuring gauges' (Taylor et al. 2003), the curved tank could test devices up to 1:70 scale (University of Edinburgh 2016).

Figure 13: University of Edinburgh Curved Wave Tank (source: Edinburgh Wave Power Group)



30 Absorbing wave makers enable energy to be quickly absorbed to calm the water ready for a further testing (Edinburgh Wave Power Group 2009b).

Another important development was the construction of tanks enabling researchers to test the combined effects of waves, currents and wind. One of the first tanks to achieve this was Newcastle University's Wind Wave Current Tank in 2004, offering small-scale prototype testing in waves up to 0.12m high, as well as currents up to 1m/s and wind speeds up to 20m/s (Newcastle University 2014).

The latest generation of wave tanks appeared during the 2010s, including the University of Plymouth's 24-paddle COAST Ocean Wave Basin (35m x 15m x 3m), QinetiQ's 122-paddle Ocean Basin and Rotating Arm (122m x 61m x 4.4m) and HR Wallingford's 10-paddle Fast Flow Facility (F^3) (75m x 4m x 3m). However, the best example is the FloWaveTT (Figure 14) facility located in Edinburgh, constructed in 2014. This constitutes the first 360º tank in the UK, 25m in diameter, 2m deep and containing 168 wave paddles. Importantly, 'the circular design allows omni-directional wave and current generation', meaning that it is 'able to simulate any sea conditions around the British Isles' to part scale (Edinburgh Designs 2017a). It also incorporates 28 tidal current generators capable of generating currents up to 1.6m/s, a hydraulic floor to change water depth and a crane capable of lifting five tonnes. In culmination, the facility can test devices up to 1:10 scale and is large enough to test small arrays of devices (FloWaveTT 2016).

This evolution of test facilities over the past 40 years is illustrated by the case of the University of Edinburgh in Table 7.

Figure 14: University of Edinburgh FloWaveTT wave tank (Source: Dave Morris)

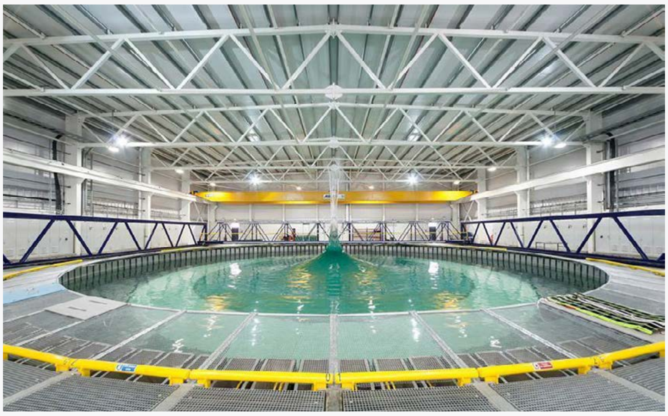


Table 7: Evolution of wave energy test tanks at the University of Edinburgh (source: see below)

	Narrow Tank	Wide Tank	Curved Tank	FloWaveTT
Date constructed	1974	1977	2003	2014
Geometry	Rectangular	Rectangular	Curved	Circular
Dimensions	L 9m x W 0.3m x D 0.6m	L 11m x W 28m x D 1.2m	Radius 9m x D 1.2m	Diameter 25m x D 2m
Actuator	1 absorbing, uni-directional, flap-type wave maker paddle	89 absorbing, uni-directional, flap-type wave maker paddles	48 absorbing, uni-directional, flap-type wave maker paddles	168 multi-directional wave makers 360º arc
Max. wave height	0.2m	0.3m	0.22m (at 1Hz)	0.7m
Frequency range	0.5–2Hz	0.5–2Hz	0.5–1.6Hz	0.3–1Hz
Max. current speed	-	-	-	1.6m/s
Scale of model testing	1:150–1:100	1:150–1:100	1:100–1:70	1:40–1:10
Key features	• Uni-directional waves	• Multi-directional waves	• Multi-directional waves (up to 90º)	• Omni-directional waves (360º) • 28 flow-drive submerged units simulate current • Overhead 5t crane for device transport • Rising tank floor to manipulate depth

NOTE: Table data taken from numerous sources (Taylor et al. 2003; EWPG 2009; University of Edinburgh 2016; Gyongy et al. 2014; Edinburgh Designs 2017a; FloWaveTT 2016) and peer reviewed by former University of Edinburgh researcher

In addition to these wave tank facilities, a wide range of other test facilities to support wave energy technology R&D also exist, focused primarily on sub-component RD&D. Examples include facilities to test the power output of PTOs (e.g. EMEC facility established in 2016), as well as the strength and durability of moorings (e.g. south west mooring test facility at the University of Exeter, established in 2009) and WEC components (e.g. dynamic marine component test facility at Exeter and Energy Technology Centre in East Kilbride) (University of Exeter 2017; Marine Energy Systems 2009; MARINET2 2017).

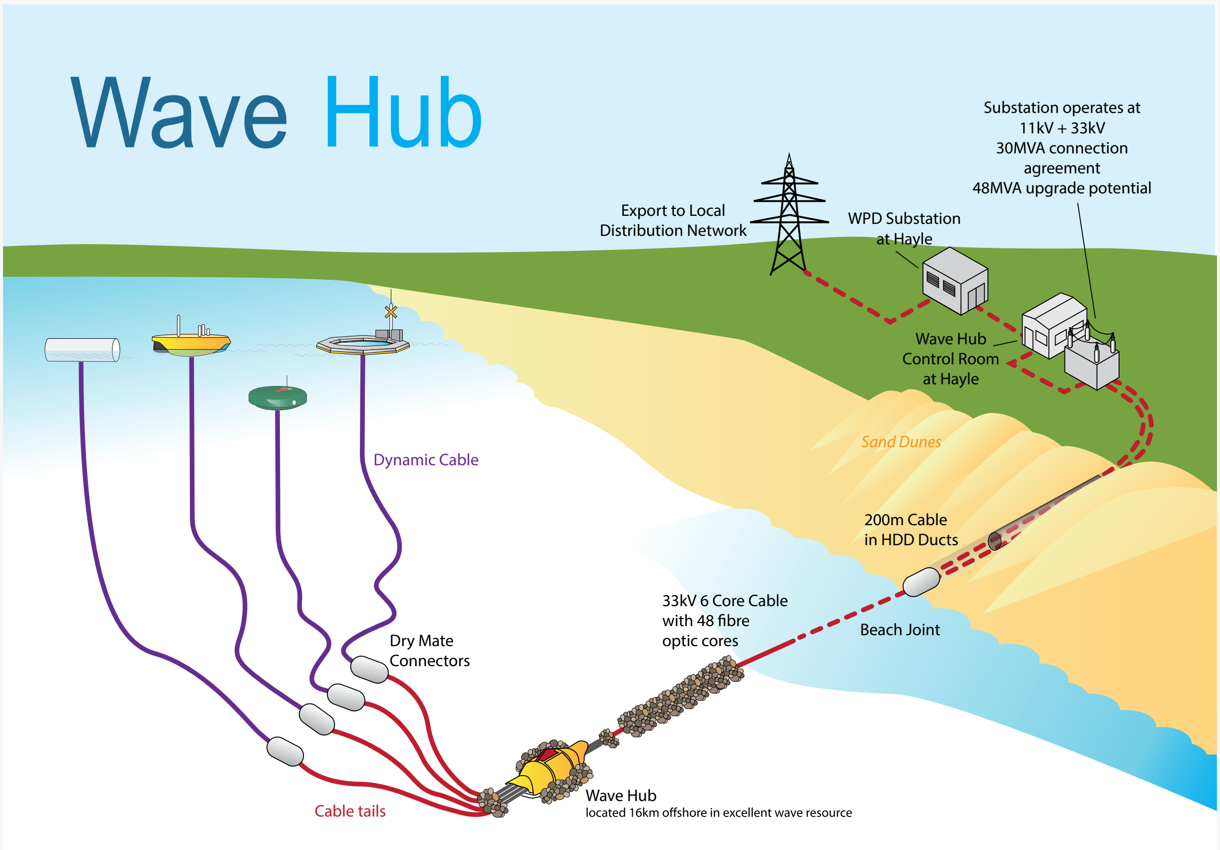
5.4.2.2 Open-sea facilities

To help support device demonstration, the UK has invested heavily in full-scale 'open-sea' test facilities, including EMEC in Scotland (test facility opened in 2004) and WaveHub (est. 2010) in England. Importantly, these sites offer rich wave energy resources, dock facilities to aid installation and maintenance, and a fully permitted space for the generation of wave power, avoiding the time and costs associated with securing permits. These facilities also offer electricity grid connection, meaning that any electricity generated can be sold to the grid and monitoring facilities installed, such as EMEC's integrated monitoring pod, which transmits real-time data from the seabed to provide improved characterisation of the high-energy marine environment, to 'assist in device design, enable more accurate assessment of device performance, and support operations and maintenance planning' (EMEC 2015).

These facilities do, however, differ in two key ways. First, unlike WaveHub, EMEC offers both full-scale test sites (e.g. EMEC's Billia Croo site) and nursery sites (e.g. EMEC's Scapa Flow) for testing of earlier stage, part-scale prototypes in less hostile conditions (MARINET2 2017). The nursery facility was opened in 2011, a few years after the full-scale Billia Croo test site (2004), to 'provide a more flexible sea space helping close the gap from tank testing, and acting as a stepping stone towards larger scale projects' (EMEC 2017d; EMEC 2017b). In reaction to this need, WaveHub partnered with FabTest, a nursery test site situated near Falmouth.

Second, whilst EMEC was established to offer single device testing via its five 2.2MW berths, the latter was established to enable deployment of offshore wave energy arrays via a 48MW sub-sea hub situated 16km offshore (WaveHub 2017) (Figure 15).

Figure 15: Schematic of WaveHub test facility (source: WaveHub)



6

Assessing wave energy innovation system performance

This section presents an assessment of UK wave energy innovation performance since 2000. It examines 22 predominantly quantitative indicators, each corresponding to one of seven different functions of TISs (Section 3.2). An overview of the results is presented below and in Table 8, with a detailed breakdown offered in the following sub-sections.

Since 2000, the UK's wave energy innovation system has exhibited a mixed performance. If we examine the long-term trends in performance by comparing the second half of the period against the first, we find that 14 of the 16 absolute quantitative indicators exhibit an improvement in performance, whilst nine of the 11 normalised quantitative indicators show improved relative performance.

Turning our attention to short-term trends by comparing the performance of the last year against the average for the whole period excluding the final year we find a slightly poorer performance versus the longer term trend, with 13 of the 18 indicators showing an absolute increase in performance and six of the 11 relative indicators showing an improvement in relative performance. This suggests that wave energy innovation performance has generally been much stronger in the second half of the period since 2000 than before but that performance has started to decline recently across some indicators, such as number of patents and level of installed capacity.

Over the period, performance was weakest against *entrepreneurial experimentation (F3)* and *market formation (F6)* and strongest against *knowledge development (F1)*, *knowledge exchange (F2)* and *resource mobilisation (F5)*. Overall, this indicates a weaker performance at the later stages of the innovation chain, which cannot be wholly attributed to a lack of scientific knowledge generation or public investment in innovation. We summarise the performance against each of the seven TIS functions.

Knowledge development (F1) – The UK's level of scientific publications and associated citations has improved over the period both in absolute and relative terms, the latter versus its international peers. However, the same cannot be said of patents, with a clear downturn in absolute terms since 2010 and as a share of global wave energy patents since 2005, suggesting that the UK is becoming less inventive and/or facing stiffer competition from other countries.

Knowledge exchange (F2) – We note an increasing trend in the number of project partners, an important proxy of collaboration. We also find that in both absolute and relative terms, a major increase in the number of projects, including partners from non-energy sectors and a combination of industry and science organisations, has taken place, evidencing both cross-fertilisation and cross-innovation collaboration. However, there is less evidence to support the notion that international collaboration has increased across scientific publications, patents or project partnership.

Entrepreneurial experimentation (F3) – Performance is very weak against all three indicators. Analysis of wave energy RD&D funding and installed capacity uncovers a divergence of technology design rather than a convergence. There is also little evidence of wave energy technology maturation given that the average rated capacity of devices fell by 56% in the second half of the period versus the first and the levelised cost of electricity (LCOE) of wave energy has increased since 2009 and remained very high compared to other renewable electricity technologies.

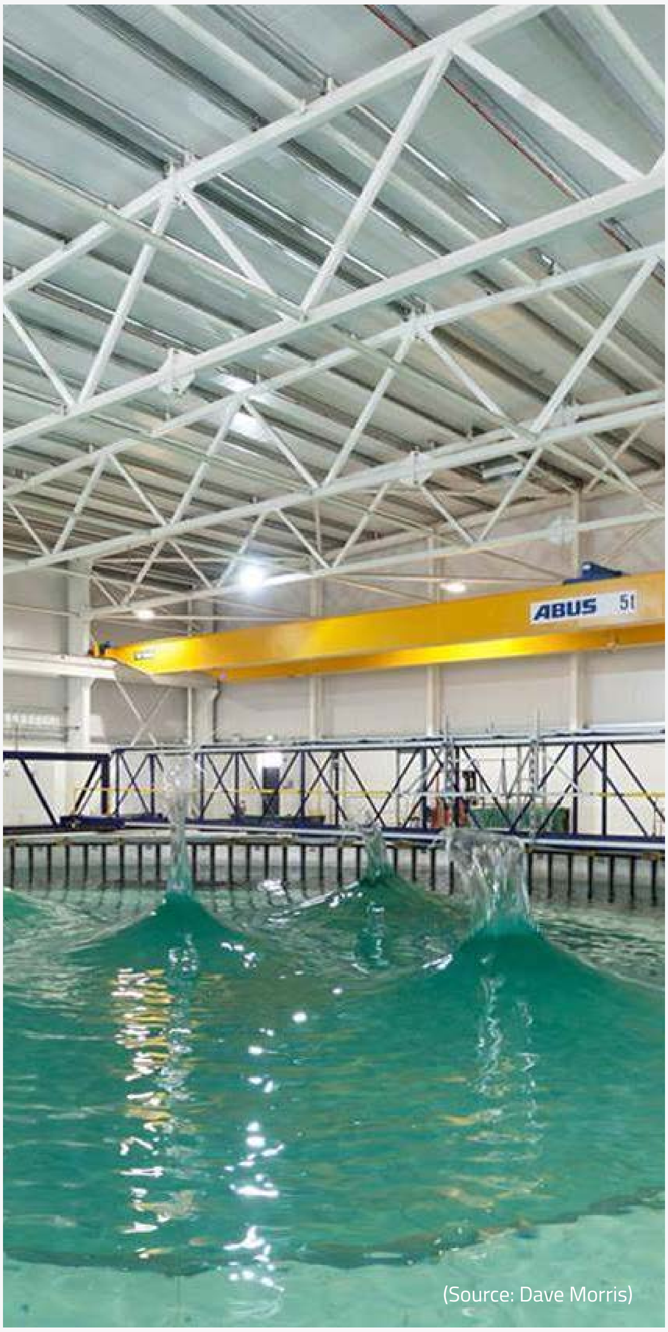
Guidance of the search (F4) – A review of wave energy-related foresight reports found a very strong guidance of the search and an increase has taken place in the number of these reports in recent years, albeit with a shift in focus from later stage demonstration and commercialisation to more fundamental experimentation. In parallel, explicit government targets for wave energy have steadily reduced in ambition, before they were removed altogether by the UK Government.

31 With the exception of a significant decline in patenting between 2010 and 2013.

Resource mobilisation (F5) – The UK wave energy sector has seen an increase in funding since 2000, with funding in the second half of the period 264% higher than the first half in real terms. The government budget for ocean energy RD&D as a share of that for all renewables has also grown during the period, up from 10% in the first half (2000-2007) to 15% in the second half (2007-2014). Human resources, measured as the number of higher education engineering degrees, remained steady, whilst the share of companies with over 50 employees involved in wave energy RD&D projects was 55% in 2016, slightly lower than the average for the period (64%).

Market formation (F6) – This category saw an initial improvement and then decline in performance across two indicators. The first was the number of wave energy developers, which steadily increased from seven in 2000 to 30 in 2011, before a steady decline to 24 in 2016, with 14 developers filing for administration since 2011, including market leaders Pelamis and Aquamarine Power. The other indicator was cumulative installed capacity, which grew from 0.5MW in 2008 to 3.5MW in 2012. However, between 2013 and 2016, this fell by two thirds, from 3.5MW to 1.2MW

Legitimation (F7) – Wave energy's legitimacy from the perspective of government grew in the first half of the period, with a host of white papers and parliamentary reports calling for increased support for wave energy RD&D. However, from the early 2010s, there was a clear change in direction, with a removal of formal wave energy deployment targets and an absence of official statements of support from government ministers. This downturn in perceived legitimacy was not however reflected by the general public, who have remained strong supporters of wave energy, averaging 74% since 2012, greater than support for onshore wind (67%) and biomass (62%), and on a par with offshore wind (74%).



(Source: Dave Morris)

Table 8: Summary of UK wave energy innovation performance since 2000

TIS function	Sub-theme	Absolute indicator	Time period	Latest year	Overall trend	Change between 1st and 2nd half of period[1]	Change on last year versus mean[2]	Relative indicator or benchmark	Latest year	Overall trend	Change in share between 1st and 2nd half of period	Change in share on last year versus mean
F1 – Knowledge development	Early TRL	Number of UK scientific wave energy publications	2000–2016	42	↗	+266%	+174%	Share of global UK wave energy scientific publications	16%	↗	+3%	+2%
		Number of UK scientific wave energy publication citations	2000–2016	720	↗	+1,201%	+379%	Share of global UK wave energy scientific citations	16%	↗	+3%	+2%
	Mid-TRL	Number of UK wave energy patents	2000–2013	8	↗↘	+97%	-28%	Share of global UK wave energy patents	11%	↗↘	-8%	-7%
F2 – Knowledge exchange	Generic	Average number of UK wave energy RD&D project partners	2000–2017	5.5	↗	+44%	+37%					
	International	Number of UK international co-authored wave energy scientific publications	2000–2016	18	↗	+303%	+134%	Share of UK international co-authored wave energy scientific publications	43%	→	+5%	-7%
		Number of UK international co-authored wave energy patents	2000–2013	0	↗↘	+1,500%	N/A	Share of UK international co-authored wave energy patents	0%	↗↘	+12%	N/A
		Number of non-UK wave energy RD&D project partners	2000–2016	36	↗	+269%	+279%	Share of non-UK wave energy RD&D project partners	34%	↗	+4%	+11%
	Cross-fertilisation	Number of wave energy RD&D projects partners from other sectors	2000–2016	14	↗	+450%	+273%	Share of wave energy RD&D projects partners from other sectors	5%	↗	+2%	+2%
	Industry–science	Number of joint industry–university wave energy-related projects	2000–2016	5	↗	+386%	+229%	Share of joint industry–university wave energy-related projects	24%	↗	+8%	+9%
		Number of wave energy university start-ups	1970–2017	–	→							
F3 – Entrepreneurial experimentation	Technological maturity	Largest share of funding awarded to single wave energy device design	2000–2017	23%	↘	-10%	-19%					
		Unit capacity of wave energy devices (MW)	2000–2017	0.12[3]	↗↘	-56%	-70%					
		Wave energy levelised cost of electricity ($/MWh)	2009–2017	498.5	↗→	+13%	+8%					

TIS function	Sub-theme	Absolute indicator	Time period	Latest year	Overall trend	Change between 1st and 2nd half of period[1]	Change on last year versus mean[2]	Relative indicator or benchmark	Latest year	Overall trend	Change in share between 1st and 2nd half of period	Change in share on last year versus mean
F4 – Guidance of the search	-	Number of wave energy technology foresight exercises	2000–2017	-	↗→							
		Number and ambition of wave energy deployment targets	2000–2017	-	↘							
F5 – Resource mobilisation	Financial	Level of public wave energy RD&D investment (£m 2015)[4]	2000–2016	19.4	↗	+264%	+123%	Share of UK renewables budget[5]	31%	↗	+5%	+19%
	Human	Number of engineering doctorates and higher degrees	2010–2016	17,550	→	+0.4%	+4%					
		Number of medium and large companies engaged in UK wave energy RD&D projects	2000–2016	51	↗	+271%	+178%	Share of medium and l arge companies engaged in UK wave energy RD&D projects	55%	↗	+2%	-8%
F6 – Market formation	-	Number of UK wave energy developers	2000–2016	24	↗↘	+83%	+17%					
		Level of wave energy installed capacity in UK (MW)	2007–2016	1.2	↗↘	+107%	-41%	Share of UK marine industry[6]	9%	↗↘	-6%	-25%
F7 – Legitimation	Government	Support outlined in public reports for wave energy	1999–2017	–	↗↘							
	Public	Public support for wave and tidal energy[7]	2012–2017	79%	↗	+2%	+5%					

NOTE: Where latest year values are provided as % shares, normally for relative indicators, then changes over period are given as changes in overall share not as % change on total

1. If period is an odd number of years then the two periods will overlap by a year to provide two periods of an equal number of years.
2. Mean excludes last year.
3. Average of past three years (2015–2017) taken against long-run averages to avoid bias towards devices only demonstrated in final year. 2017 includes two planned deployments at EMEC.
4. Change on base year for data drawn from RD&D funding database takes 2016 rather than 2017, as grants only taken up to 1/6/2017.
5. IEA data inclusive of all forms of ocean energy and data for 2008 is missing.
6. Data inclusive of tidal stream.
7. Covers both wave and tidal.

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The study finds that UK wave energy innovation performance was measurably stronger against most indicators in the second half of the period since 2000 (c. 2008–2016) than the first (c. 2000–2007) both in absolute and relative terms but that performance has started to decline in recent years across some of these indicators.

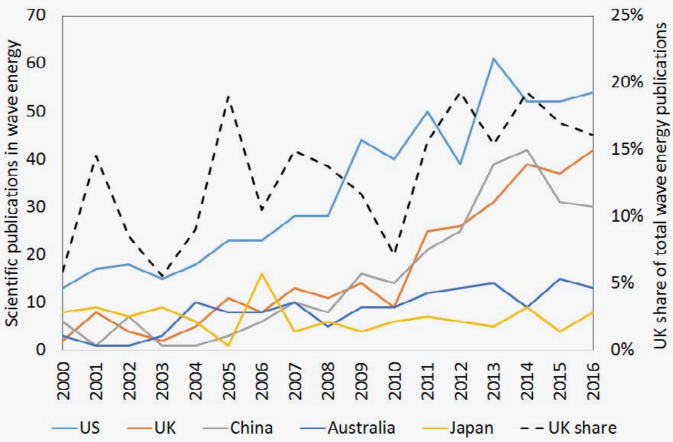
(Source: Jan Oelker)

6.1 Knowledge development

6.1.1 Number of scientific publications

An important proxy of knowledge development at the earlier TRLs is the number of scientific publications. Analysis of the period 2000–2016 finds that the UK has steadily increased its number of wave energy publications, publishing 21 times as many publications in 2016 versus 2000. In relative terms, the UK was second only to the US, with 287 scientific journal publications in wave energy (Figure 16). The UK also accounted for an average of 15% of global publications, with its share steadily increasing from 12% between 2000 and 2008 to 16% between 2008 and 2016. The analysis therefore indicates that the UK's level of knowledge generation at early TRLs has gradually increased over the past 15 years in both absolute and relative terms.

Figure 16: Top five countries for scientific journal publications in wave energy 2000–2016 (source: Scopus)

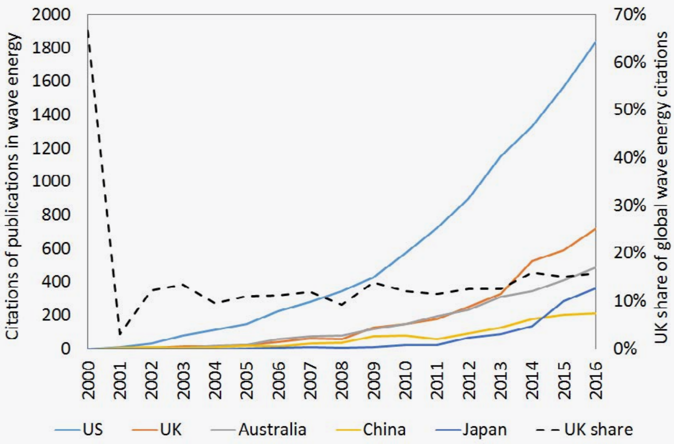


6.1.2 Number of scientific publication citations

Scientific publication citations are another useful indicator, acting as a proxy of publication quality. As Figure 17 illustrates, the UK has seen a strong year-on-year increase in citations of wave energy publications, growing from just two in 2000 to 720 in 2016. Its share of citations for the period was on average 14%, second only to the US, and the UK's share steadily increased from an average of 11% between 2000 and 2008 to 14% between 2008 and 2016.

Whilst this increase in citations can largely be accounted for by the increase in publications, we also see a major increase in the number of citations per publication, rising from four in the first half of the period to 13 in the latter. However, with an international trend towards more citations per publication, this could be a function of a growing propensity to cite other literature in journal papers rather than an increase in the quality of the knowledge being generated. Furthermore, with an average of 11 citations per publication, the UK is mid-ranking, behind some of its international peers such as the US (17) and Australia (22).

Figure 17: Top five countries for citations of scientific publications in wave energy 2000–2016 (source: Scopus)

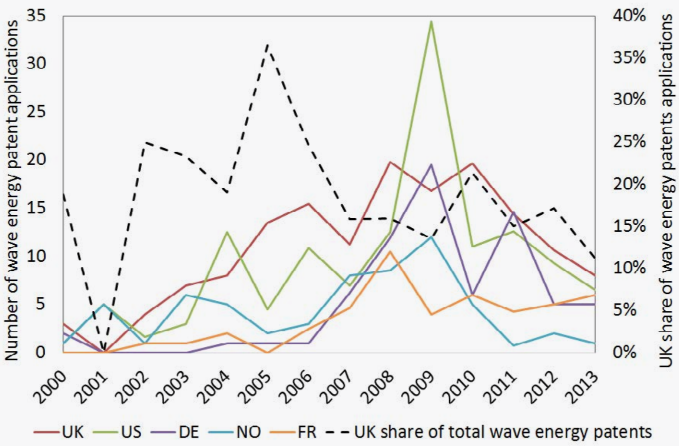


6.1.3 Patents

We take patents as another proxy of knowledge development, albeit at a later stage along the innovation chain than scientific publications. This is because patents are typically applied for at the applied research (TRL 3–4) and experimental development (5–6) stages of innovation, rather than earlier (i.e. fundamental research (TRL 1–2)) and later stages (i.e. technology demonstration (TRL 7–8)) (Abercrombie & Loebl 2014).

Between 2000 and 2013, the UK filed 152 wave energy patents. This followed an increasing trend, with the annual number of patents growing from three in 2000 to 20 in 2008. However, the number of UK wave energy patent filings has dropped significantly after 2010, with less than half the number of patents filed in 2013 (eight patents) than 2010 (20 patents). In terms of its global performance, the UK accounted for 18% of global wave energy patents during the period, more than any other country including the US (Figure 18). However, we find a declining trend in the UK's global share of wave energy patents, which fell from an average of 23% between 2000 and 2006 to 16% between 2007 and 2013.

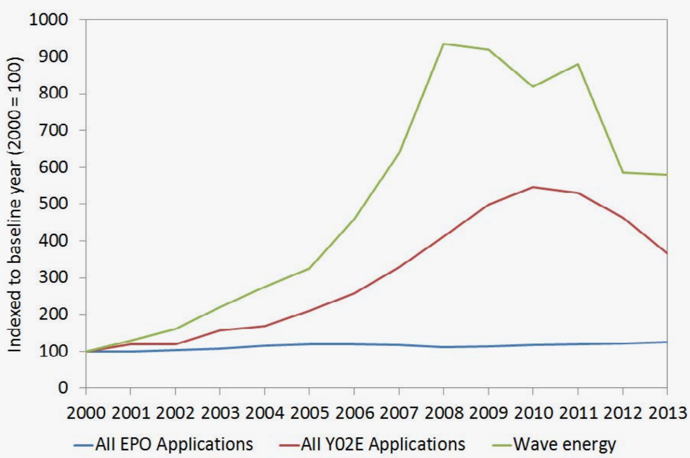
Figure 18: Top five countries for wave energy patents 2000–2013 (source: EPO)



NOTE: Covers patent classifications: OWC (Y02E 10/32) and/or (Y02E 10/38) wave energy or tidal swell.

Considering the steady increase in early- to mid-stage wave energy R&D during the 2000s (Section 6.5.1), and the typical lag of three years between RD&D expenditure and patenting (Kondo 1995; Margolis 1999), an increase in patent applications would be expected during this period rather than the observed decline. This could be the result of numerous factors. First, a fall in patenting could indicate that wave energy technology has moved beyond the early- to mid-TRL stages to later stage demonstration and commercialisation, which is not normally associated with patenting (Abercrombie & Loebl 2014). However, this is not supported by analysis of the other indicators, especially those indicating a lack of convergence around an optimal device design for wave energy (Section 6.3.1). Second, it could be a function of a wider global downward trend in wave energy patenting and/or low-carbon technology patents since 2000. This is supported by Figure 19, which identifies a global downturn in wave energy patenting since 2008 and low-carbon technology patents since 2010, in contrast to no relative change in the number of patents across all technologies since 2000. However, whilst this downturn in patenting could more widely account for the drop in the total number of wave energy patents, it does not account for the UK's fall in its share of global wave energy patents, which suggests that the UK has become less inventive in this area.

Figure 19: Wave energy, low-carbon and all patents indexed to 2000 (source: EPO)



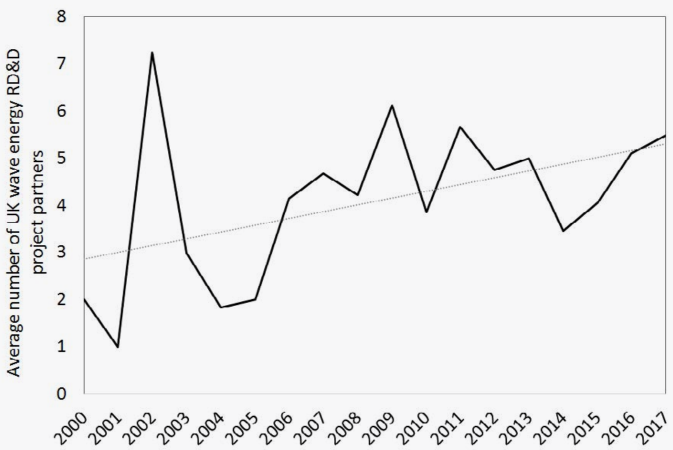
6.2 Knowledge exchange

6.2.1 Inter-organisational connectivity

6.2.1.1 Average number of project partners

Knowledge exchange is a difficult phenomenon to measure but the degree of connectivity between actors is a good indicator that knowledge is being exchanged. Analysis of the UK marine energy RD&D grants database reveals a trend towards a larger number of partners per project, increasing from three in the early 2000s to five during the late 2010s (Figure 20). This could be attributed to various factors such as a bottom-up move from researchers and developers to collaborate more with one another or a top-down requirement from funders for these actors to form larger consortia in order to be eligible for grant funding – the latter is discussed in detail in Section 7.3.1.4.

Figure 20: Average number of partners working UK on wave energy-related RD&D projects (source: author)



Note: Year of project represents project start date. Only RD&D project represented, not training, testing or knowledge exchange. Only projects included with a majority focus on ocean energy technology innovation.

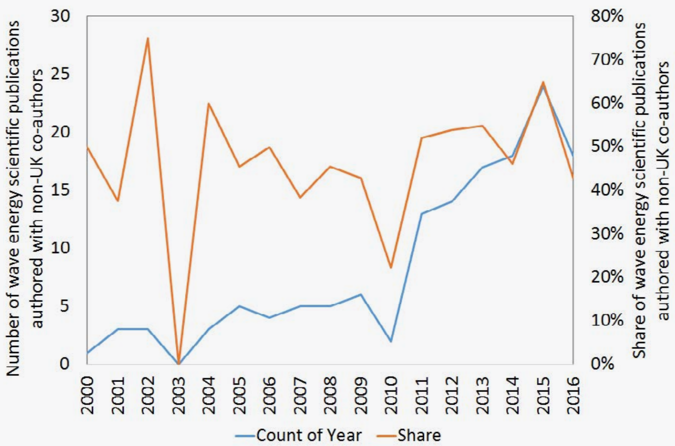
6.2.2 International collaboration

The number and breadth of international networks has increased dramatically since 2000 (Section 5.3). To assess the impact of these growing cross-country networks, we measure the degree of international collaboration across: 1) scientific publications; 2) patents; and 3) grants.

6.2.2.1 International co-authors of scientific publications

International collaboration between UK and non-UK authors of scientific articles on wave energy has been strong across the period, with 49% of all articles co-authored with international partners since 2000 (Figure 21). Whilst the total number of internationally co-authored publications has increased significantly in line with the overall increase in publications (Section 6.1.1), the share of publications authored with international partners has remained steady, with 45% of publications between 2000 and 2008 and 50% between 2008 and 2016. However, the low number of publications in the 2000s means that we cannot conclusively say that levels of international collaboration were already strong at the beginning of the period.

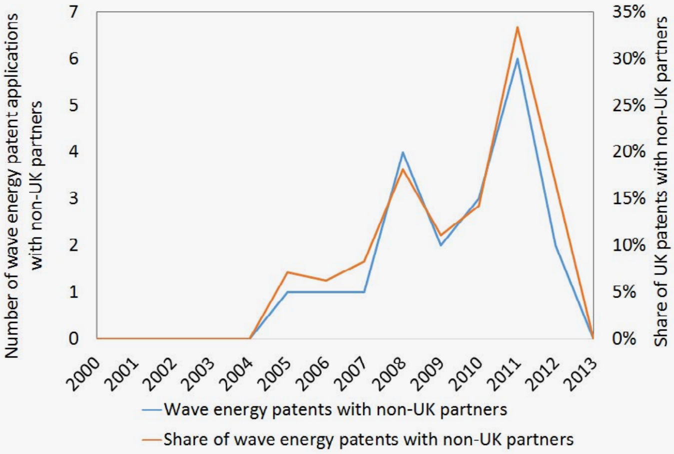
Figure 21: Number and share of UK wave energy scientific publications co-authored with non-UK partners (source: Scopus)



6.2.2.2 International co-authors of patents

Focusing further up the innovation chain, we examine the number and share of patents filed by both UK- and non-UK-based inventors (Figure 22). The total share of patents with non-UK partners steadily increased from zero in the early 2000s to a high of 33% in 2011, but dropped to zero by 2013, corresponding with an overall fall in wave energy patenting internationally. The average share of patents applied for with international partners was 12% for the period 2000 to 2013 and this share increased in the second versus the first half, growing from 4% between 2000 and 2006 to 16% between 2007 and 2013. The statistical significance of this analysis is low given the small numbers of wave energy patents filed with overseas partners.

Figure 22: Number and share of UK wave energy patents filed with non-UK partners 2000–2013 (Source: EPO)

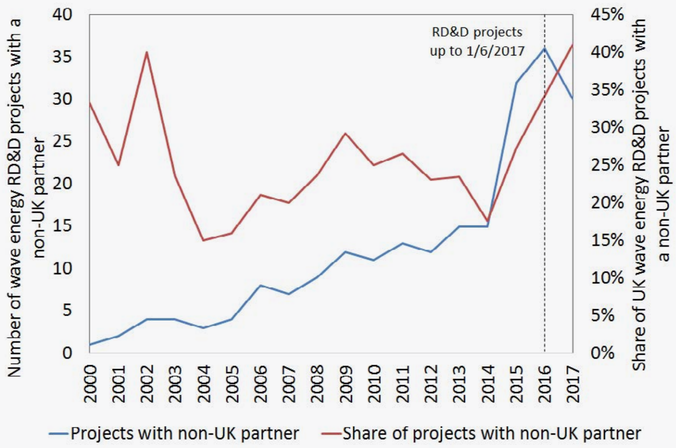


6.2.2.3 International project partners

International collaboration is also measured by analysing the number of publicly funded UK wave energy RD&D projects conducted with international partners. This takes account of UK and devolved administration grants, including international partners, but the majority of international projects stem from EU FP funds that demand partners from at least three different countries.

Overall, a significant increase has taken place in the number of non-UK partners, increasing from just one to 36 in 2016 (Figure 23), although this coincided with an overall increase in number of projects. However, the share of wave energy projects with a non-UK partner has gradually risen during the period from 22% during the first half (2000 to 2008) to 26% during the second half (2008 to 2016), suggesting a growing trend towards international collaboration. This latter trend corresponds with an overall reduction in the share of UK funding and an increase in EU and Scottish Government funding (Section 6.5.1), with the EU mandating international collaboration via its framework programme (e.g. H2020) and the Scottish Government encouraging such collaboration via its WES programme.

Figure 23: Number and share of non-UK partners in UK-based wave energy RD&D projects (source: author)



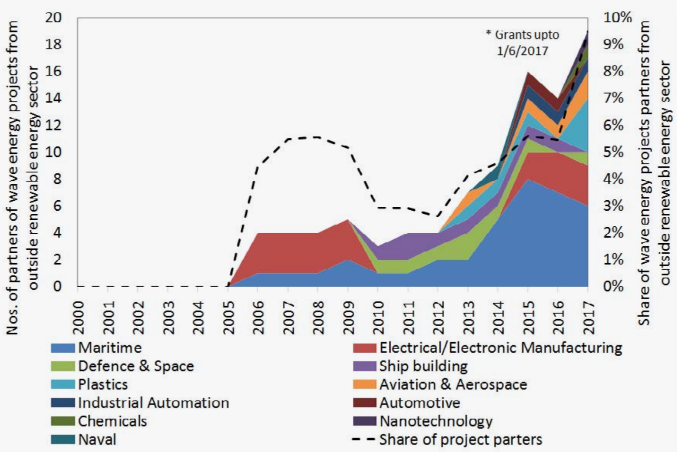
NOTE: Excludes test infrastructure grants

6.2.3 Cross-sectoral fertilisation

6.2.3.1 Project partners from outside energy sector

Another important form of knowledge exchange is the transfer of knowledge between actors from different sectors, often known as 'cross-sector fertilisation'. In the case of wave energy, a host of other technology sectors can offer useful insights to help commercialise wave power technology (Section 5.4.1). Figure 24 examines the number and proportion of companies involved in publicly funded UK wave energy projects operating primarily in other sectors. Between 2000 and 2005, projects involved firms exclusively focused on energy technology engineering. However, from 2006, the sector saw an influx of companies operating in different sectors. Initially, the move came from the maritime and electronic manufacturing sectors but, by the 2010s, the defence, aviation, plastics, nanotechnology and shipbuilding sectors had entered the industry. The level of cross-sector fertilisation was between 3% and 5% of project partners since the mid-2000s but in 2017 this roughly doubled to almost 10%. This trend corresponds with WES's funding of sub-components (e.g. PTO, structural materials and manufacturing processes) and novel device designs, with an emphasis on drafting ideas from outside the sector.

Figure 24: Number of organisations engaged in wave energy projects from other technology sectors 2000–2017 (source: author)



NOTE: Share of projects calculated as share of total wave energy-related projects, excluding universities, research institutes and non-technology development-related service providers (e.g. accountancy, computer software). Excludes knowledge exchange, training and test facility grants.

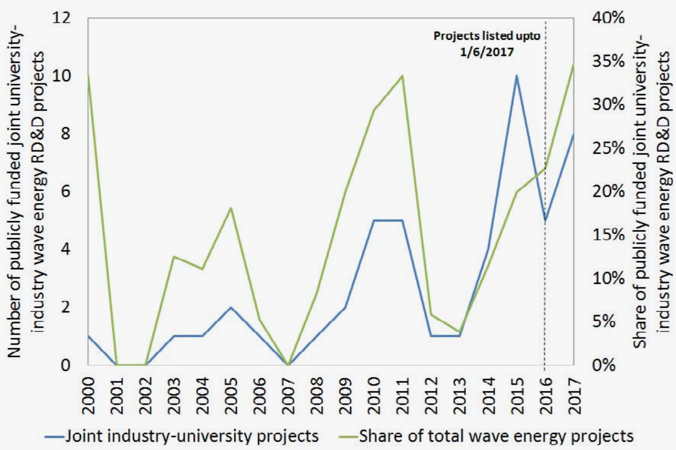
6.2.4 University–industry connectivity

This section considers both the number of publicly funded joint university and industry projects relating to wave energy (Section 6.2.4.1) and the number of university-affiliated start-up wave energy-related companies that have been established (Section 6.2.4.2).

6.2.4.1 Publicly funded joint university–industry projects

Since 2000, the number of new projects including both industry and university partners increased during the period, from just one or two in the early 2000s to between five and 10 in the mid-2010s. The share of joint projects also increased, doubling from 9% in the first half of the period (2000–2008) to 17% in the second half (2008–2016), with 35% of projects in 2017 involving actors from both science and industry (Figure 25). The picture is therefore one of an overall increase in the degree of collaboration between industry and science in the wave energy sector.

Figure 25: Number and share of joint industry–university wave energy related projects (source: author)



NOTE: Excludes test infrastructure grants. Third sector not-for-profit organisations not accounted for.

6.2.4.2 University-affiliated wave energy companies

Another important proxy for the degree of knowledge exchange across different stages of the innovation chain is the number of start-up firms emerged from universities. Four different wave energy device developers can be directly linked to the UK: Pelamis Wave Power, Aquamarine Power Ltd, The Bobber Company and Aqua Power Technologies, with the first two formerly industry leaders. In addition, four other wave energy-affiliated companies undertake component or test facility innovation, including Edinburgh Designs and Artemis Intelligent Power (Table 9).

The University of Edinburgh's wave power group has been at the epicentre of much of this spinout activity. The team, led by Prof. Stephen Salter, which created Salter's 'duck' to generate electricity from the waves in the 1970s, generated a wealth of knowledge relating to WEC design, high efficiency hydraulic transmission and the development of wave test tanks (University of Edinburgh 2017). Richard Yemm, a former PhD student of Prof. Salter, went on to found Ocean Power Delivery (later known as Pelamis Wave Power) in 1998 (The Engineer 2007).

Artemis Intelligent Power Ltd also emerged from Edinburgh, and was set up by Prof. Win Rampen and Prof. Salter in 1994. Its origins are in research relating to the design of the gyro Salter duck, which formed the basis for Artemis's digital displacement technology, which allowed for high-efficiency control and transmission of fluid power able to be applied to wave power (University of Edinburgh 2017; Taylor 2008). Another notable wave power spin-off company from Edinburgh is Edinburgh Designs, a world-leading wave tank developer with its roots in the work undertaken in Edinburgh in specifying and constructing wave tanks (Section 5.4.2.1). Finally, NGenTec is another Edinburgh spin-off, developing direct drive generators and the C-GEN Direct Drive PTO, which seeks higher levels of efficiency and reliability versus hydraulic systems (WES 2017a; SET Ventures 2017).

Beyond Edinburgh, the most high-profile company is Aquamarine Power, formed in 2005 by Allan Thomson to further develop the Oyster device, an oscillating wave surge convertor design first developed by a team at Queen's University Belfast[32], led by Prof. Trevor Whittaker (Queen's University Belfast 2012). Other wave energy-related spinouts include the University of Manchester's The Bobber Company (est. 2006), Brunel University's Aqua Power Technologies (est. 2014) and the University of Strathclyde's Synaptec (est. 2014).

Table 9: Number of wave energy-related companies that emerged from universities (source: adapted from New Company Finance)

Name	Established	Status	Universities	Area	RD&D focus
Artemis Intelligent Power	1977	Trading	University of Edinburgh	Sub-component	PTO (hydraulic)
Edinburgh Designs	1988	Trading	University of Edinburgh	Test infrastructure	Wave tanks
Pelamis Wave Power	1998	Ceased trading	University of Edinburgh	Device	Attenuator
Aquamarine Power Ltd	2005	Ceased trading	Queen's University Belfast	Device	Oscillating wave surge converter
The Bobber Company	2006	Ceased trading	University of Manches-ter	Device	Point absorber
NGenTec	2009	Trading	University of Edinburgh	Sub-component	PTO (direct drive)
Synaptec	2014	Trading	University of Strathclyde	Sub-component	Connections
Aqua Power Technologies	2014	Trading	Brunel University	Device	Attenuator (multi-axis)

32 Queen's University Belfast also initially devised the LIMPET device, which was developed further by Wavegen, commissioning a 75kW device in 1991 (QUB 2002).

6.3 Entrepreneurial experimentation

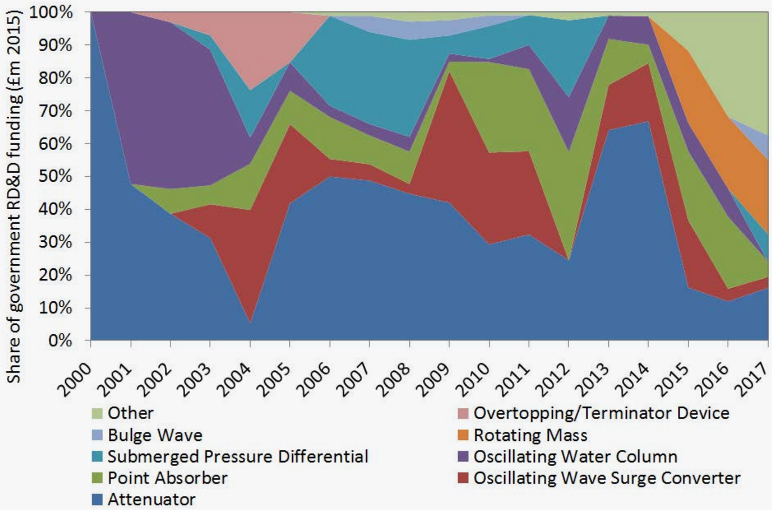
Entrepreneurial experimentation involves the reduction of risk associated with a technology through market-oriented experiments. One way of measuring this is through the extent to which technological convergence has taken place, evidencing a shift towards a common 'optimal' design proven to work. We measure this by examining trends in the concentration of funding (Section 6.3.1) and deployment (Section 6.3.2) of different device designs. We also examine the maturity of wave energy technology by examining the extent to which the device rated power capacity of wave energy devices has increased (Section 6.3.2) and its LCOE (Section 6.3.3). We compare wave energy's performance against tidal stream to help benchmark wave energy's progress.

6.3.1 Convergence around a single device design

Figure 26 and 27 highlight very clearly how funding has been distributed across a wide range of wave energy designs with a distinct lack of convergence (see Section 2.1 for an overview of designs). In the early 2000s, funding was largely split between attenuators (e.g. Pelamis's P1 and P2) and OWCs (e.g. Wavegen's LIMPET). Whilst attenuators continued to receive the most funding of any design, OWCs saw funding reduced with an influx of funds for overtopping/terminator (e.g. Wavedragon), submerged pressure differential (e.g. Checkmate's Anaconda) and oscillating wave surge convertor (e.g. Aquamarine Power's Oyster) devices amongst others. Post-2014 funding shifted again with a major fall in funds for traditional devices in favour of rotating mass devices (e.g. WelloOy's Penguin) and entirely novel device designs (see Other), the latter in part a function of WES's novel wave energy convertor funding call.

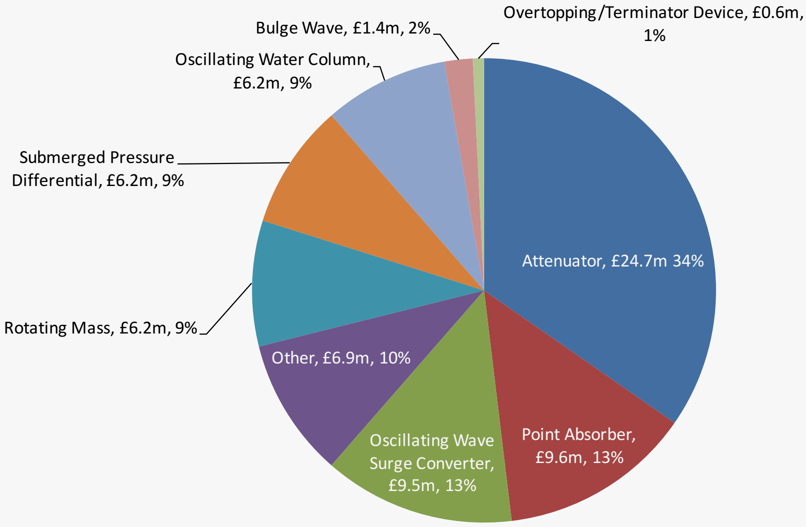
This lack of convergence can be illustrated by the fact that during the first half of the period (2000–2008) the most well-funded device design received a 47% share of of RD&D funding, compared to only 35% in the second half (2009–2017), suggesting a weakening convergence of support around a single dominant design.

Figure 26: Share of RD&D funding committed to different wave energy device designs 2000–2017 (source: author)



NOTE: Covers both experimental development (TRL 5–6) and demonstration (TRL 7–8), and grants up to 1st June 2017.

Figure 27: Share of wave energy RD&D funding by device design 2000–2017 (source: author)

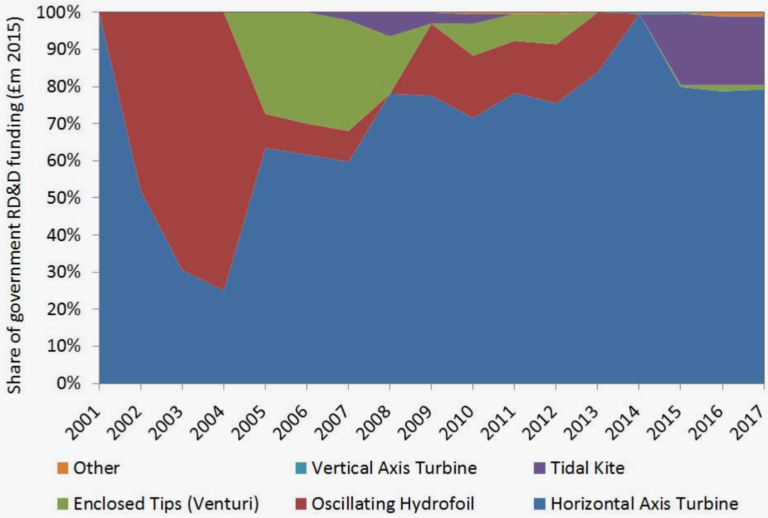


Whilst tidal stream has witnessed a convergence around a single device design, namely horizontal axis turbines, wave energy has exhibited the opposite.

(Source: Shutterstock)

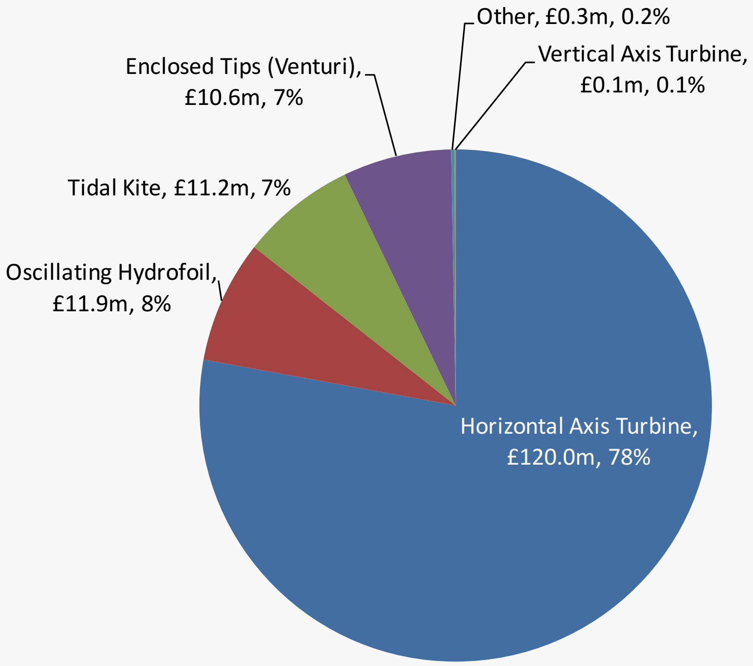
If we compare the technological convergence for wave against tidal stream (Figure 28 and 29) we find that during early 2000s saw funding for tidal devices split almost exclusively between horizontal axis turbines (e.g. Andritz Hydro Hammerfest, Atlantis) and oscillating hydrofoil devices (e.g. Pulse Tidal), with some funding committed to the enclosed tips (venturi) (e.g. DCNS Open Hydro) turbines by the mid-2000s. However, if we compare the first half of the period (2000 to 2008) versus the second half (2009 to 2017) we find that the share of funding awarded to horizontal axis turbines grew from 60% to 81%, demonstrating a strong degree of convergence around a single device design. Whilst we acknowledge that the heterogeneous nature of the ocean wave regime and he need for different device designs to best take advantage of the characteristically distinct onshore, nearshore and offshore environments (see Figure 2), the contrast in the degree of convergence between wave and tidal stream is stark.

Figure 28: Share of RD&D funding committed to different tidal stream device designs 2000–2017 (source: author)



NOTE: Covers both experimental development (TRL 5–6) and demonstration (TRL 7–8), and grants up to 1st June 2017.

Figure 29: Share of tidal stream energy RD&D funding by device design 2000–2017 (source: author)

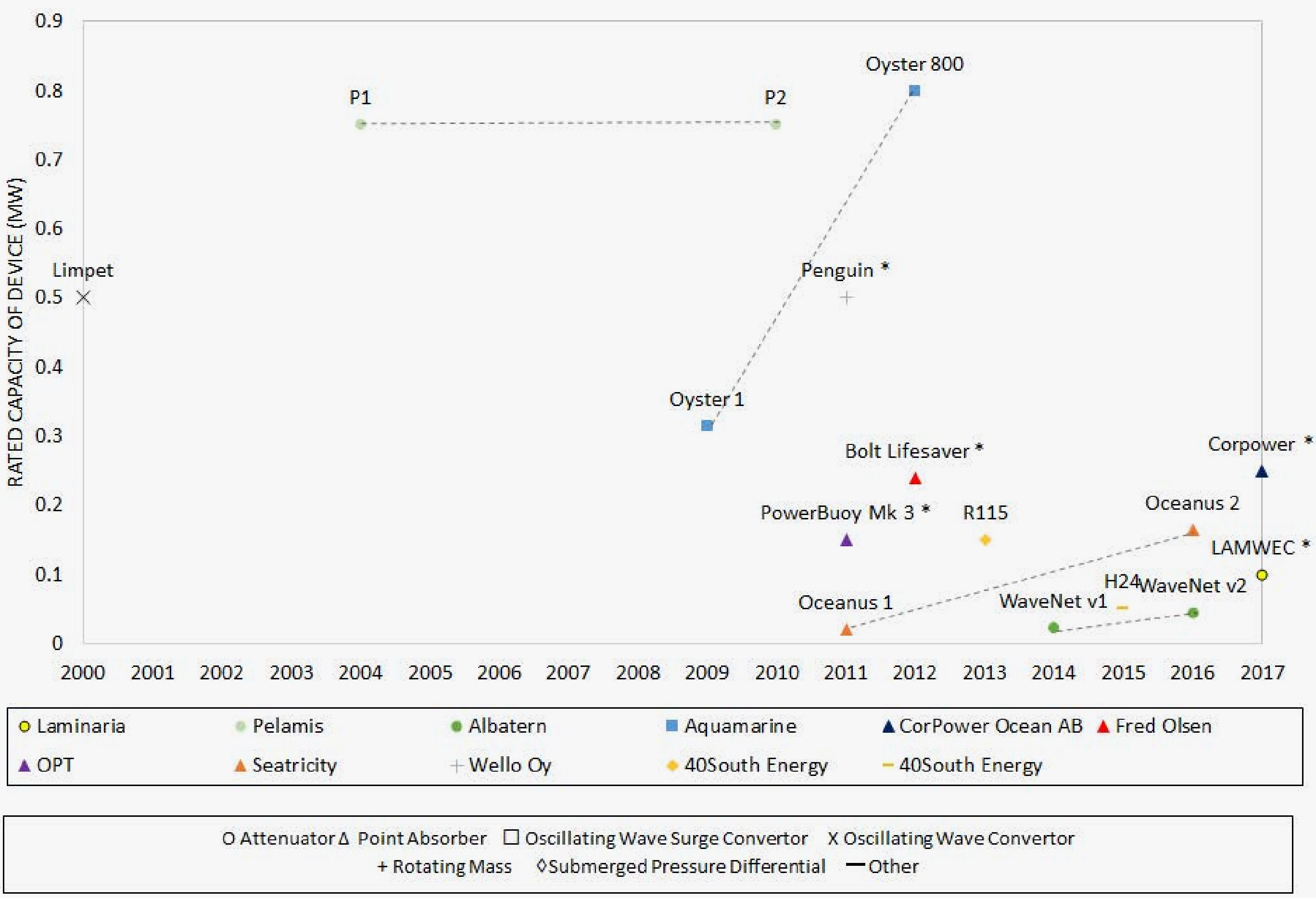


6.3.2 Rated power capacity

One indicator of energy technology maturity is the rate at which the rated capacity[33] of each device has increased over time. As Figure 30 illustrates, the rated capacity of new iterations of wave energy devices developed by UK developers or tested in UK waters has witnessed a decline over the past 15 years, with the average rated capacity of wave energy devices over the past 3 years (2015-2017) was 70% lower than the remainder of the period between 2000 and 2014.

The period up to the early 2010s saw demonstration of devices pushing 1MW, with Pelamis' 750kW P2, Aquamarine Power's 800kW Oyster and WelloOy's 500kW Penguin device. However, from the early 2010s onwards, when Pelamis and Aquamarine ceased trading, the average power rating of devices demonstrated fell dramatically, with the largest being CorPower's 250kW point absorber, due for deployment at EMEC in 2017. Figure 30 also illustrates the relative lack of convergence around a single device design, supporting the findings in Section 6.3.1.

Figure 30: Evolution of wave energy device capacity rating by developer and device type (source: author)



NOTE: * - Non-UK companies testing devices in the UK; ^ - Planned deployments at EMEC for 2017. Ignores redeployment of the same devices, instead listing new iterations of devices.

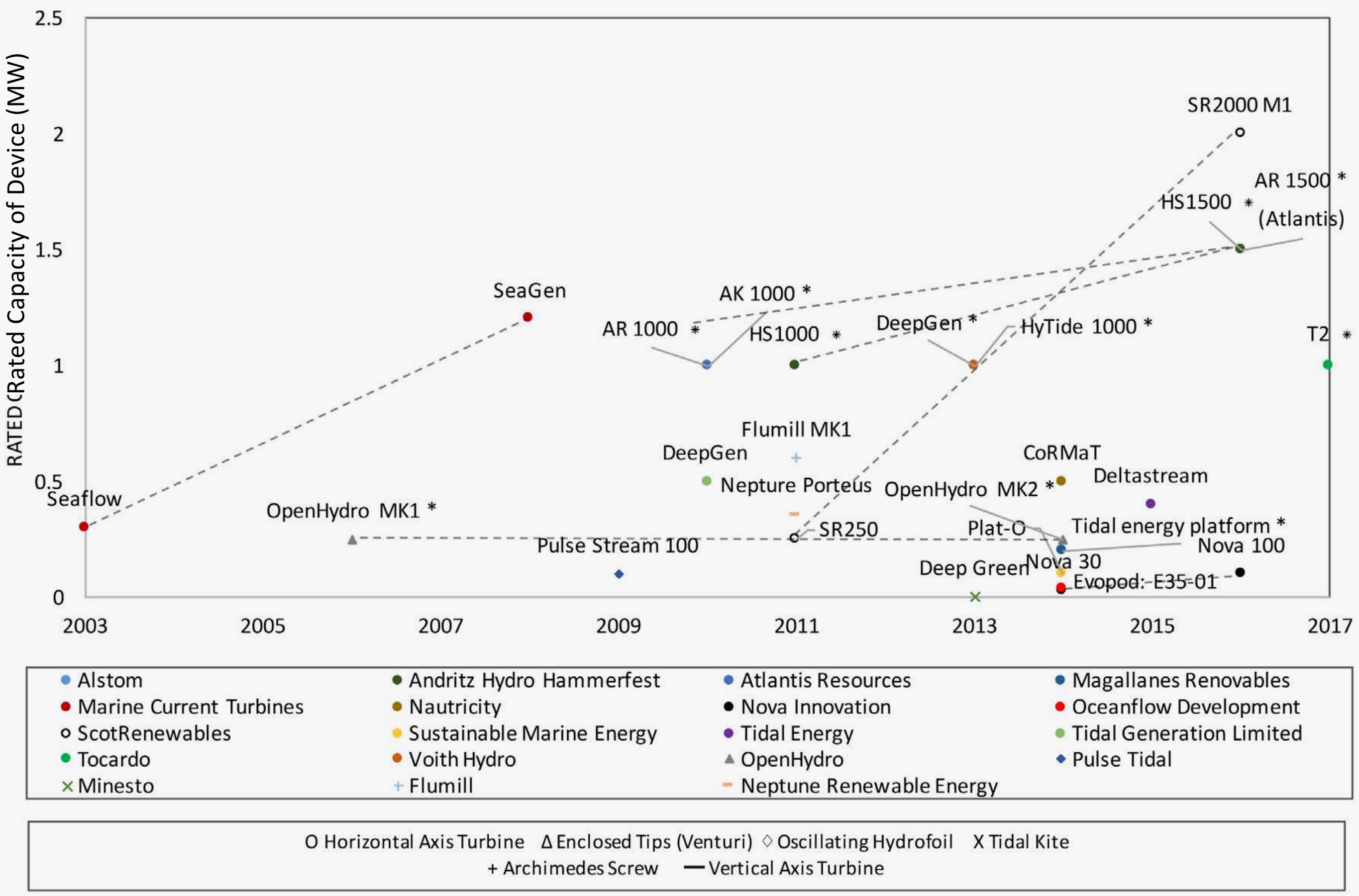
33 This relates to the rated capacity of the device, i.e. the maximum rather than the average power output.

The average rated capacity of wave energy devices over the past three years (2015-2017) was 70% lower than the remainder of the period between 2000 and 2014. In contrast tidal stream saw a 124% increase in the average rated capacity during the same period.

(Source: Shutterstock)

In contrast to wave energy, the tidal stream sector has witnessed a gradual convergence around the horizontal axis turbine design, representing 77% of demonstration projects between 2003 and 2017 tested by UK developers or in UK waters (Figure 31). Furthermore, during this period, the sector saw an increase in the rated capacity of tidal stream devices, growing from the 300kW Seaflow device to three devices being tested at over 1.5MW, namely the Hammerfest Strom's HS1500 (1.5MW), Atlantis' AR1500 (1.5MW)[34] and Scottish Renewables' SR2000 M1 (2MW)[35], suggesting that tidal stream technology is maturing at a much faster rate than wave technology. In contrast to wave energy tidal stream saw a 124% increase in the average rate capacity during the past three year (2015-2017) versus the remainder of the period (2000-2014).

Figure 31: Evolution of tidal stream device capacity rating by developer and device type (source: author)



NOTE: * - Non-UK companies testing devices in the UK

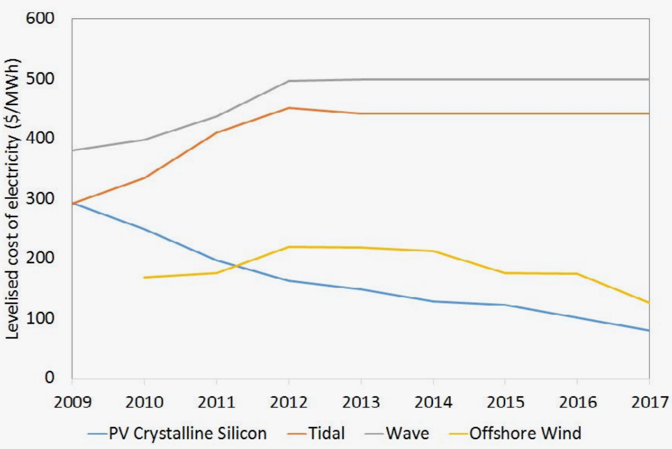
A different proxy of maturity that can be taken between wave and tidal stream energy is the total number of unit deployments of a technology (MacGillivray et al. 2015). Here, the UK has hosted 26 new iterations of tidal stream devices versus 16 for wave energy despite a greater degree of design convergence, suggesting a greater level of knowledge development and maturity overall. However, both marine technologies are some distance away from the hundreds or thousands of unit deployments observed for mature technologies such as steam, gas and wind turbines (MacGillivray et al. 2015).

34 Atlantis' AR 1500 co-developed with the US's Lockheed Martin.
35 ScotRenewables SR2000 M1 is two 1MW turbines on one floating structure.

6.3.3 Levelised cost of electricity

Finally, an important metric of entrepreneurial experimentation is a reduction in the cost of the technology developed, in this case electricity generated. As outlined in Figure 32, unlike solar PV (crystalline silicon) and to a lesser extent offshore wind, the LCOE[36] for wave energy has risen rather than fallen, from $380/MWh in 2009 to $500/MWh by 2012. Tidal stream energy has demonstrated a similar trend but sits at the lower cost of $442/MWh. In contrast, other renewable energy technologies' LCOE has fallen dramatically, for example, solar PV has seen a fall of two thirds.

Figure 32: Levelised cost of electricity generated by wave energy 2009–2017 (source: Bloomberg)



6.4 Guidance of the search

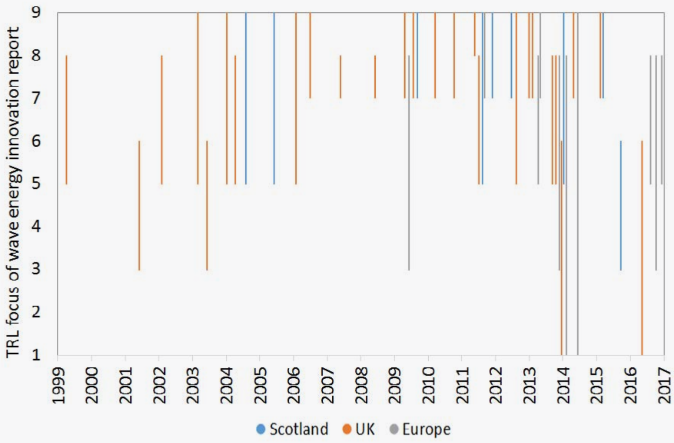
The 'guidance of the search' relates to the pressures that influence whether organisations commit resources to wave energy innovation and the focus of their efforts. To gauge the strength and direction of the 'guidance of the search' for wave energy, we examine the number and focus of foresight reports (e.g. policy strategies, roadmaps, technology innovation needs assessments) examining the potential role of wave energy in a future energy system and the steps that need to be taken to help it play this role. We also consider the ambition of targets for future deployment of wave energy.

6.4.1 Wave energy technology foresight reports

Between 1999 and 2017, our research identified 45 'foresight' reports explicitly dealing with wave or marine energy, with 27 delivered by UK organisations, ten by European organisations and seven by Scottish organisations (Figure 33). Most of these were delivered by governments (19), with a large number of non-governmental (e.g. trade associations, research centres) organisations (14) and government-affiliated (e.g. NDPBs, advisory groups) (12) reports. This indicates a relatively even split between the guidance of the search across different sectors and levels of governance (i.e. Scotland, the UK and the EU).

In addition, during the early 2010s, the frequency of reports increased over time and a gradual downgrading took place in the innovation stage targeted by these reports, with many influential reports suggesting that wave energy was only ten to 15 years away from large-scale commercial deployment during the mid-2000s before a gradual refocusing on earlier stage R&D (Figure 33).

Figure 33: Overview of wave energy-related technology foresight reports between 1999 and 2017 (source: author)



NOTE: Reports identified following rigorous literature review. However, there is potential for some reports to be missing if not identified by desk-based survey and expert elicitation. Excludes roadmaps with a global focus (e.g. OES). TRL focus relates to the report's primary focus for innovation over the forthcoming 20-year period.

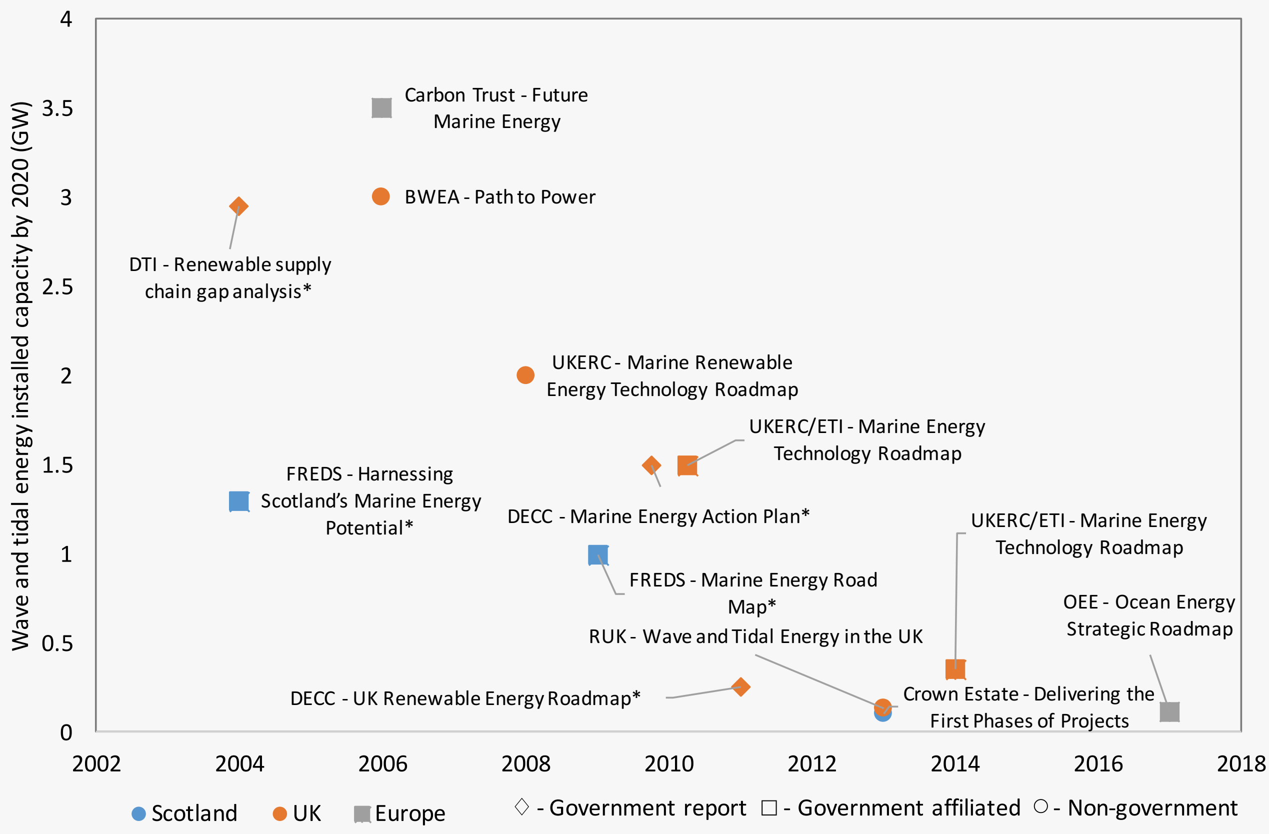
36 LCOE data is taken from Bloomberg, the methodology for which is outlined by Salvatore (2013): 'The calculation of LCOEs in this preliminary report is based on empirical data wherever possible. The data includes capital costs, operating costs, the cost of finance and load factors – either experienced or projected, and they are from actual projects that have been or are currently being built. Where actual project cost data is incomplete the analysis uses Bloomberg New Energy Finance's trend analysis on technology and financing costs' (p. 39).

This transition from encouraging demonstration and deployment to earlier stage experimentation is also supported by our analysis of the UK's 2020 visions and scenarios for marine energy deployment. From as early as the mid-2000s, reports from the DTI, British Wind Energy Association (BWEA) and Carbon Trust outlined lofty targets for the marine energy sector, with the DTI, for example, envisaging between 1.4 and 4.5GW of deployment by 2020 (DTI 2004) (Figure 34). This pressure to scale up continued during the late 2000s, evidenced by a series of reports with a very strong focus on later stage pre-commercial demonstration and commercial deployment, most notably the DECC's marine energy action plan (DECC 2010), which targeted approximately 1 to 2GW of marine energy by 2020, albeit with the target including tidal range.

This focus on relatively short-term commercial deployment began to dissipate with a recognition that wave energy was not advancing as quickly as first hoped, evident in a steady reduction in deployment targets for 2020 (Figure 34) and the increasing number of reports focusing on earlier stage innovation (Figure 33). This shift in expectation is best illustrated by the UK Government's target of between 1 and 2GW of deployment by 2020 (DECC 2010), falling to between 200 and 300MW in its 2011 UK renewable energy roadmap the following year (DECC 2011). Furthermore, the subsequent two updates of the roadmap (DECC 2012; DECC 2013d) did not specify a marine energy deployment target.

This downgrading of 2020 visions for deployment suggests that wave energy was making slower progress than expected. In this context, we would expect targets to drop as we advanced closer to 2020. However, importantly, these were not normally refreshed, with similarly ambitious targets for 2050 not put in place.

Figure 34: Wave and tidal stream 2020 deployment scenarios across Scotland, the UK and Europe (source: author)



NOTE: For consistency, the scenarios include deployment of just wave and tidal stream. Any targets that include other marine technology (e.g. tidal range) are omitted.

6.5 Resource mobilisation

This sub-section considers two forms of resource mobilisation, namely financial (Section 6.5.1) and human (Section 6.5.2), which both represent critical inputs into the wave energy innovation process.

6.5.1 Financial resources

Between 2000 and 2017, £545m of public grants were awarded to marine energy. Of the amount awarded to RD&D activities, tidal stream received 47% (£178m), followed by wave at 27% (£102m) and cross-cutting marine RD&D at 26% (£96m). If we take wave and cross-cutting marine energy RD&D together, £198m has been spent on wave energy-related projects (Table 10), with a further £170m awarded to the installation, operation and maintenance of marine test infrastructure.

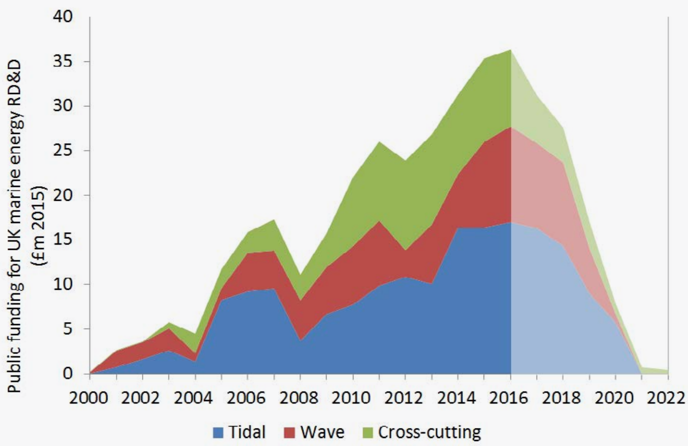
Table 10: Summary of public funds awarded for wave and tidal stream energy RD&D 2000–2017 (source: author)

RD&D area	Public funding (£m 2015)	Share
Wave	102.1	27%
Tidal stream	177.6	47%
Cross-cutting	95.8	26%
Sub-total	**375.5**	
Test infrastructure	169.4	
Total	**544.8**	

If we consider this split in funding over time (Figure 35), we find that in 2016 funding for wave energy-related RD&D (including cross-cutting but excluding tidal stream and test infrastructure) was running at more than double the long-run average between 2000 and 2015, representing a 123% increase. Taking a longer term view we find that funding for RD&D activity taking place during the second half of the period (2008 to 2016) stood at £130m, more than three times that of the first period (2000 to 2008), which was £36m.

From the mid-2000s, tidal stream energy also consistently received more RD&D funding than wave energy, although the share of funding for wave energy versus tidal has increased significantly in recent years following the formation of WES. Finally, a significant increase has also taken place in cross-cutting funding during the early 2010s, typically supporting either earlier stage research or later stage development of technologies (e.g. moorings, connections) and services (e.g. O&M, installation) relevant to both wave and tidal stream energy.

Figure 35: UK public RD&D funding for marine energy projects by research area 2000–2017 (source: author)



NOTE: Excludes test infrastructure. Funding for 2017 only for grants up to 1st June 2017.

It is also important to consider whether this increase in resources was indicative of a targeted bid from government to support wave energy innovation or a broader increase in renewable energy support. Analysis of the IEA data reveals that, between 2000 and 2014, the UK's ocean energy budget stood at £127.6m[37], accounting for 14% of the UK's total renewable energy RD&D budget and 4% of its RD&D budget for all forms of energy.

Ocean energy's share of the UK's renewable energy RD&D budget also increased during this period, accounting for £26m (10%) between 2000 and 2007, versus £107m (15%) between 2007 and 2014.[38] By 2014, ocean energy accounted for 31% of the UK's renewable energy RD&D budget and 6% of its total energy RD&D budget, illustrating that an increase in the funding allocation for wave energy in both absolute and relative terms.

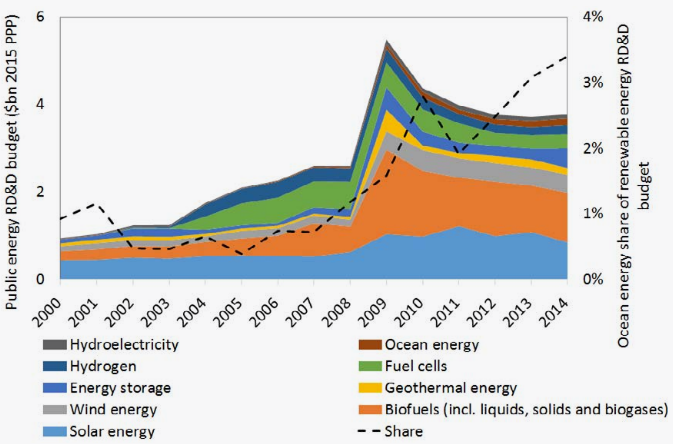
37 The total budget for ocean energy (£130m) is significantly lower than the actual awarded funds for wave and tidal stream energy (£552m). Both cover capital and current costs for basic research, applied R&D, experimental development and demonstration (IEA 2011). Reasons for the IEA value being significantly lower could include the IEA data not covering funding for 2015 to 2017 and some pre-commercial demonstration programmes (e.g. MRDF, MEAD) with a strong emphasis on array deployment being excluded because they were classified as deployment. The IEA value is surprisingly low considering that budgets for marine energy specific programmes total almost £200m (see Annex C), excluding EU funds and non-marine energy-specific programmes.

38 IEA data for 2008 UK ocean energy RD&D budget is missing.

It is also important to consider the level of RD&D funding committed to wave energy at a global level, considering that technology innovation represents a global phenomenon and developments outside the UK will dictate the pace at which wave energy progresses towards commercialisation.

Compared to other renewable and supporting technologies, ocean energy received a very small share of public support amongst the 29 countries (includes EC) (Figure 36). Overall, since 2000, $0.9bn has been committed by IEA countries to ocean energy,[39] accounting for 2% of the global renewables RD&D budget. Interestingly, its share remained very low during the early 2000s, sitting at between 0.5% and 1%, although this steadily increased from the mid-2000s, rising to almost 3.5% by 2014. However, the cumulative budget for ocean energy is dwarfed in comparison to the funding now committed to much more mature renewable electricity generation technologies such as solar PV $11bn (31%) and, to a lesser extent, wind, which received $4bn (11%). A similar dynamic exists if we go back to the early 1970s, with ocean energy receiving only $1.8bn (3%) versus $25bn (40%) for solar and $7.5bn (12%) for wind, suggesting that wave energy's failure to reach commercialisation could be linked to its level of funding.

Figure 36: Ocean energy's share of global public renewable energy RD&D budget 2000–2014 (source: IEA)

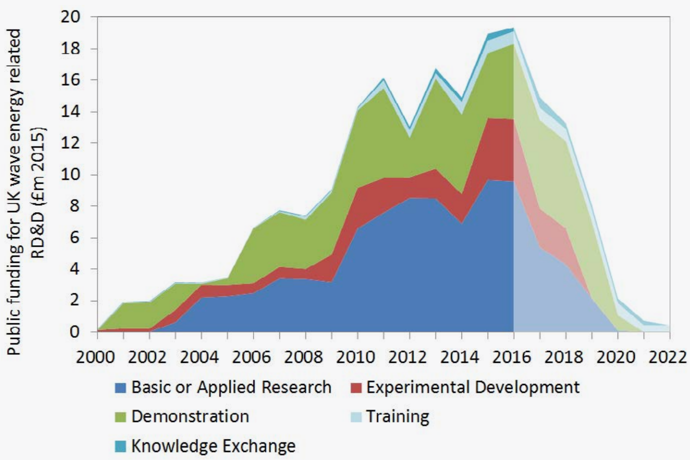


NOTE: IEA data excludes private sector investment and is for government budgets rather than actual spend.

6.5.1.1 Funding by stage of innovation

If we examine public funding of wave energy by innovation stage we find a clear shift away from an initial emphasis on demonstration, towards earlier stage innovation activities during the period. The first half of the period (2000 to 2008) saw 40% of public wave energy-related RD&D reserved for basic or applied research, 14% for experimental development and 43% for demonstration, with the remainder committed to training (2%) and knowledge transfer and exchange (1%) (Figure 37 and Table 11). If we compare this split against the second period (2008 to 2016) we find that the share committed to demonstration fell to 31%, whilst the combined share of funding awarded to basic research, applied R&D and experimental development rose from 54% to 65%, with the remainder given over to training and knowledge exchange. This gradual decline in later stage innovation in favour of earlier stage R&D is contrary to what we might normally expect for technology innovation, where greater sums of demonstration funding are awarded as the technology matures and moves closer to market.

Figure 37: UK public RD&D funding for wave energy-related projects by innovation stage 2000–2017 (source: author)



NOTE: Includes RD&D activity explicitly related to wave energy or cross-cutting marine energy. Excludes test infrastructure.

39 This includes all forms of ocean energy, such as tidal stream, tidal range, ocean thermal energy conversion and salinity gradient.

Table 11: Wave energy and cross-cutting marine energy innovation funding in the UK by innovation stage for projects taking place between 2000 and 2022 (source: author)

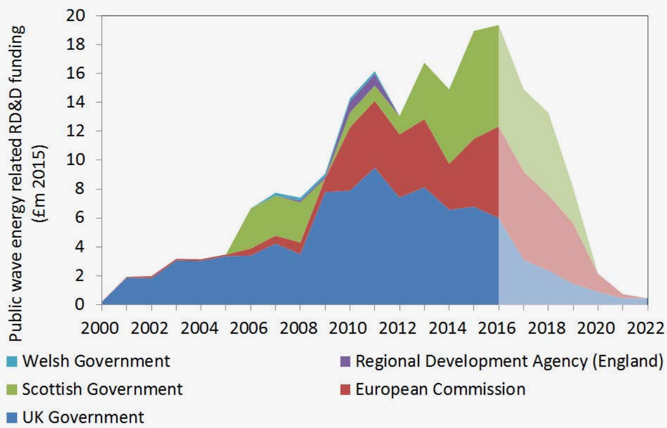
Stage or type of wave energy RD&D	2000–2008 (£m 2015)	Share	2008–2016 (£m 2015)	Share	2000–2022 (£m 2015)	Share
Basic or applied research	14.4	40%	63.9	49%	86.9	44%
Experimental development	4.9	14%	20.2	16%	29.3	15%
Demonstration	15.5	43%	39.8	31%	69.2	35%
Training	0.6	2%	4.2	3%	8.6	4%
Knowledge transfer and networking	0.3	1%	1.8	1%	3.9	2%
Total (exc. test facilities)	**35.7**		**130**		**197.9**	

6.5.1.2 Funding by government funder

Table 12 and Figure 38 present the total funding awarded between 2000 and 2017 to wave energy related RD&D by government funder, covering projects running to 2022. Overall, the UK Government was the largest funder, awarding £93m (47%), followed by the EU with £53m (27%), the Scottish Government with £49m (25%) and other devolved administrations with £2.9m (1%).

This funding mix has changed significantly over time, with the UK Government playing a significantly less important role in recent years, whilst the EU has played a significantly more important role. For example, the split of RD&D funding was 69% UK Government, 23% Scottish Government, 7% EU and 1% other devolved administrations in the period between 2000 and 2008. However, for projects between 2008 and 2016, the funding mix changed dramatically, with the UK Government accounting for 49% of awarded funding, the EU 26%, the Scottish Government 23% and other administrations 2%. Interestingly, a snapshot of funded projects in 2016 reveals that the UK government accounted for only 31% of awarded funds, whilst the EU stood at 33% and the Scottish Government 36%, further highlighting the UK's steady withdrawal compared to the EU and Scottish Government's growing commitment.

Figure 38: UK public RD&D funding for wave energy-related projects by funder 2000–2017 (source: author)



NOTE: Includes RD&D activity explicitly related to wave energy or cross-cutting marine energy. Excludes test infrastructure. Funding for 2017 only for grants up to 1st June 2017.

Table 12: Wave energy and cross-cutting marine energy innovation funding in the UK by government funder for projects taking place between 2000 and 2022

Level of government	2000–2008 (£m 2015)	Share	2008–2016 (£m 2015)	Share	2000–2022 (£m 2015)	Share
UK Government	24.5	69%	63.6	49%	93.2	47%
European Commission	2.4	7%	34.1	26%	52.7	27%
Scottish Government	8.3	23%	29.7	23%	49.1	25%
Regional Development Agency (England)	0.1	0%	1.9	1%	1.9	1%
Welsh Government	0.4	1%	0.8	1%	1.0	0%
Total (exc. test facilities)	**35.7**		**130**		**197.9**	

NOTE: Excludes test infrastructure. Funds from EC's structural funds (e.g. ERDF) classified under EC funds rather than devolved administrations (e.g. Welsh Government).

6.5.2 Human resources

We examine two proxies of human resources, the number of wave energy-related graduates (Section 6.5.2.1) and the number of employees working for companies involved in UK Government-funded wave energy projects (Section 6.5.2.2).

6.5.2.1 Number of higher education graduates

This report draws upon data from the HESA for higher education degrees obtained with relevance to wave energy technology. We take two subject categories – maritime technology, the closest to wave energy available, and engineering, which covers the various engineering subjects most relevant to wave energy (e.g. naval architecture, electronic and electrical engineering, mechanical engineering) – covering both doctorates and 'other higher degrees'[40] (Figure 39 and 40). We acknowledge that not all of these graduates will necessarily work in the wave energy sector. However, they are a proxy of the supply of relevant skilled individuals who could potentially work in the sector and therefore the level of appropriate human resource.

In 2016, the UK trained 20 maritime engineering doctorates and 185 students taking other higher degrees. The number of maritime doctorates remained steady during the period 2010 to 2016 apart from a spike in 2013, with the number of other higher degrees increasing by over 50%. Examining engineering more broadly in 2016, the UK trained 3,170 doctorates and 14,380 students taking other higher degrees. Together, the number of advanced engineering degrees has increased by 18% over the period. In summary, there appears to be a supply of highly trained individuals with the broad skills necessary to conduct wave energy RD&D and the number of engineers has climbed steadily over the past few years.

40 Higher degrees primarily relate to those after postgraduate studies (e.g. MSc), including doctorates (incorporating new route PhDs) and Master's degrees studied primarily through research (e.g. MRes).

Figure 39: Number of doctorates obtained in wave energy-related studies 2010–2016 (source: HESA)

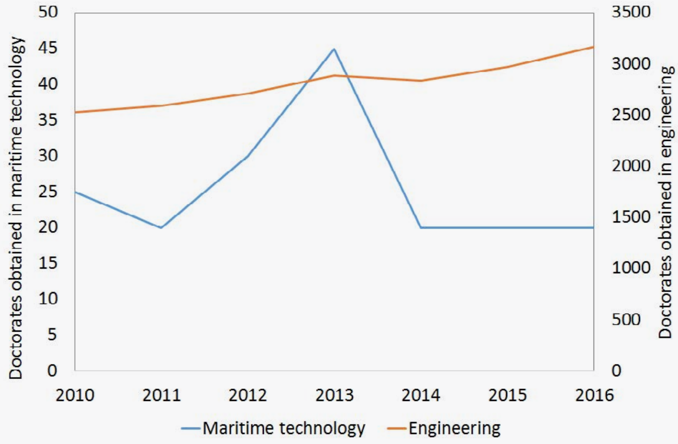
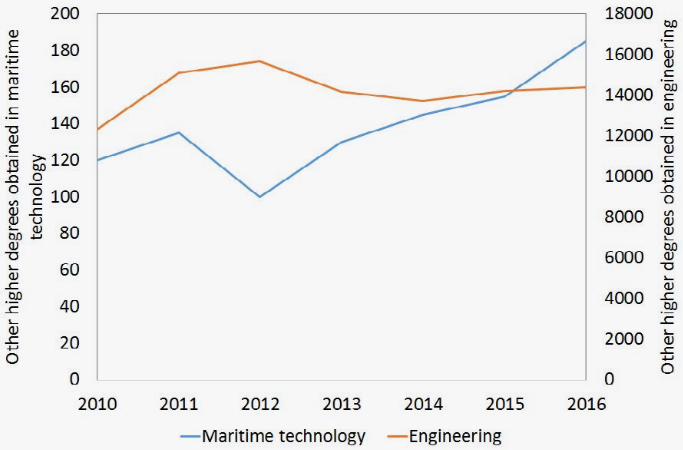


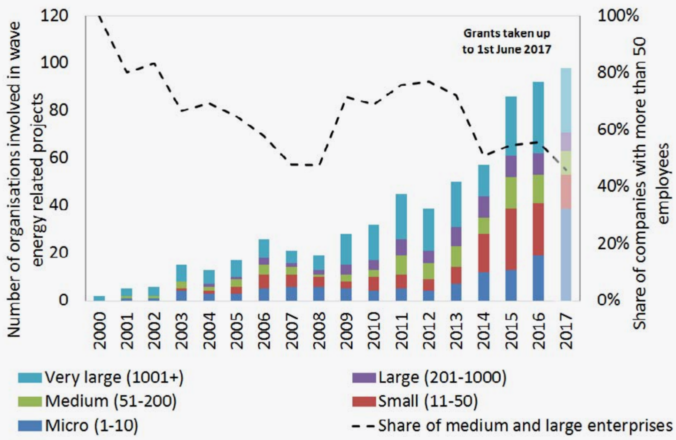
Figure 40: Number of higher degrees other than doctorates obtained in wave energy-related studies 2010–2016 (source: HESA)



6.5.2.2 Project partners' employee numbers

Another important proxy for human and also financial resources is the relative size of companies involved in UK wave energy projects. Figure 41 illustrates the mix of different sized companies, specifically the proportion of these made up of medium-sized companies or larger – i.e. more than 51 employees. Ignoring the very early years due to small number of projects, the proportion of these companies remained relatively high at between 50% and 65% in the mid-2000s, growing to between 70% and 80% in the late 2000s and early 2010s, before falling after 2013 to around 50%. Interestingly, despite the high-profile failures of leading wave energy developers in the mid-2010s, large corporations have remained active in the sector[41]. However, this masks the fact that 96% of wave energy developers funded since 2000 were micro, small or medium sized enterprises, with no more than 200 employees.[42]

Figure 41: Size of UK wave energy project partners by numbers of employees (source: author)



NOTE: Size of companies taken as of 2017 so does not account for growth or contraction during period.

41 The data is likely to be biased against the number of large corporations because these corporations may not target government funds as they are able to fund projects internally or via institutional investors.

42 This only takes into account developers for which we have employment data. The figure is likely to be much higher than 96% in reality as employee data was missing for some companies of very small sizes.

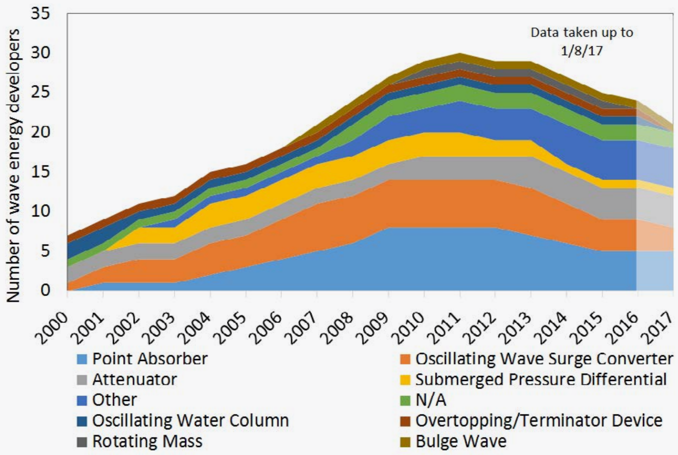
6.6 Market formation

We take two important proxies of market formation for the UK wave energy sector. These include the number of wave energy developers (Section 6.6.1) and the level of installed capacity (Section 6.6.2).

6.6.1 Number of wave energy developers

Figure 42 presents the number of wave energy developers active for any given year since 2000. Between 2000 and 2011, the number of developers more than quadrupled from seven to 30. However, since 2011, there has been a steady decline, with the number of operational developers dropping to 24 in 2016. In total, between 2011 and 2017, 14 developers filed for administration, including market leaders Pelamis and Aquamarine Power.

Figure 42: Number and device focus of wave energy developers operating in the UK 2000–2017 (source: author)

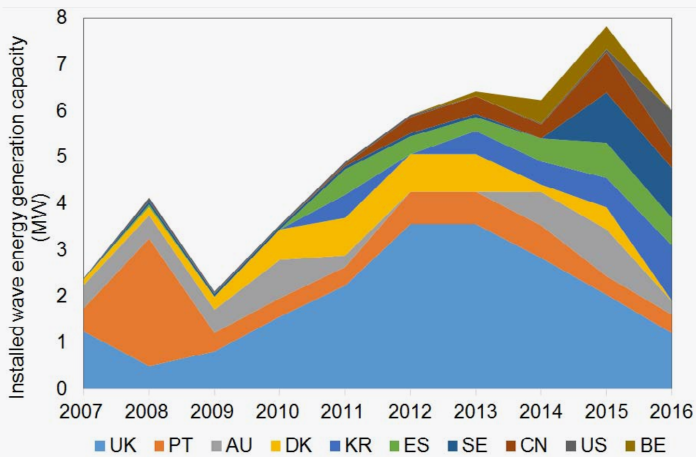


NOTE: Developers considered active or inactive primarily according to Companies House register. Developers identified via a combination of RD&D funding database, sectoral reports and expert interviews. Data correct up to 1st August 2017.

6.6.2 Installed capacity

Installed capacity is used as a proxy of the scale of market formation. Figure 43 illustrates the level of installed capacity between 2007 and 2016, taking nationality as the country hosting the installed capacity. The UK performed strongest during the period compared to other countries, with a major growth from 0.5MW in 2008 to 3.5MW in 2012. However, between 2013 and 2016, the capacity of operational devices dropped by two thirds, from 3.5MW to 1.2MW.[43] Notably, whilst UK capacity fell, other countries such as Sweden, China and Belgium also saw an increase in installed capacity.

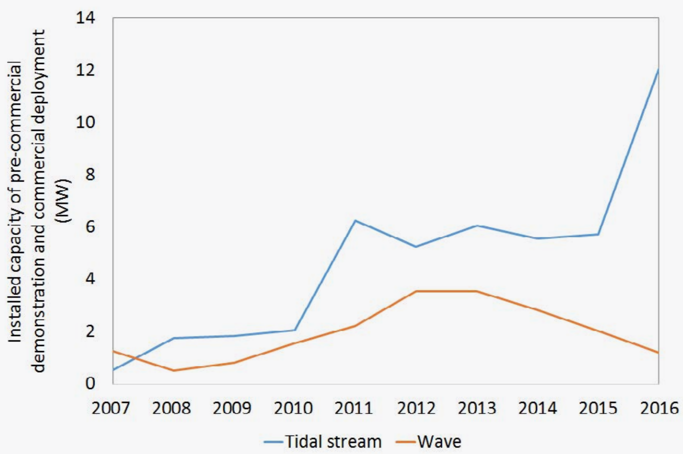
Figure 43: Top ten countries for installed capacity of wave energy generation by host nation 2007–2016 (source: adapted from OES)



Wave energy's decline in market size since 2013 is in contrast to tidal stream energy, which has witnessed a major increase since 2015, doubling from 6MW to 12MW (Figure 44). This was exclusively due to the commissioning of the four device Meygen array in the north of Scotland, with a combined capacity of 6MW. There is another 6MW of additional capacity approved for 2019.

43 The installed capacity data does not include installations by UK-based companies in other countries, such as Pelamis' three-device (2.25MW) wave farm in Aguçadoura, Portugal, in 2008 or 40SouthEnergy's two installations off the coast of Italy between 2013 and 2015. Importantly, the Pelamis array generated very little electricity before equipment failure and subsequent decommissioning.

Figure 44: Comparison of UK-installed capacity for wave and tidal stream energy 2007–2016 (source: adapted from OES)



6.7 Legitimation

Legitimation is the process of making something acceptable to a particular audience. The process of creating legitimacy for an energy technology is difficult to measure, however the degree of legitimacy attached to a technology is easier to gauge. Whilst the level of funding (Section 6.5.1) and the size of government deployment targets (Section 6.4.1) are important proxies of this, we focus on two different measures to illustrate the extent of wave energy's perceived legitimacy: the degree of political (Section 6.7.1) and public support (Section 6.7.2) for wave energy.

6.7.1 Government support for marine energy

A review of UK Government official reports uncovered six government white and green papers[44] and four UK parliamentary select committee reports with direct relevance to wave energy. Figure 45 demonstrates how both the UK Government and parliament were very much in support of developing wave energy during the 2000s and the early part of the 2010s. We summarise these developments below.

Following a number of influential reports highlighting the potential of wave energy and calling for additional support for wave energy innovation from the House of Lords Select Committee on the European Communities (1999), the Office of Science and Technology Foresight Report on marine energy was produced (Office of Science and Technology 1999) and the Royal Commission on Environmental Pollution (Royal Commission on Environmental Pollution 2000) and the House of Commons Science and Technology Committee conducted a special enquiry into wave and tidal energy in the UK. This concluded that there was a need for a reinstatement of wave energy innovation funding:

> 'It is extremely regrettable and surprising that the development of wave and tidal energy technologies has received so little support from the Government ... We welcome the growing recognition by Government of the energy potential of a range of offshore technologies. We hope it will lead to a coherent strategy for technology development and long-term investment' (House of Commons Science and Technology Committee 2001)

This recognition of wave energy's potential was underpinned by an update of the Government's own Energy Technology Support Unit's (ETSU)[45] report of the potential of wave energy: an independent review of the conflicting evidence and further evaluation of offshore wave power following the discontinuation of funding in the 1970s and 1980s. It concluded that:

> 'DTI's earlier review of wave energy found that the optimistic expectations for the original wave energy devices were unfounded. Nevertheless, the same review methodology now indicates that wave energy could become a useful source of energy' (Thorpe 1999 p.iii).

44 White papers are government policy initiatives and proposals for legislation, whilst green papers are government consultation documents (UK Parliament 2017).
45 Later known as AEA Technology.

Successive government white papers and parliamentary committee reports subsequently identified wave energy as a technology that could play an important role in the UK's low-carbon transition and as a priority for government support. One of the best examples is the House of Commons Committee on Energy and Climate Change's 2012 report on the future of marine renewables, which made the following recommendation:

> 'While we recognise that funding is limited in the current economic climate, we nevertheless feel that the Government's funding for marine renewables represents a modest investment for what is a world-leading industry with the potential to bring significant benefits to the UK' (HoCECCC 2012 p.13)

This commitment seemingly shifted in 2013. Greg Barker, then Minister of State for Climate Change, offered clear support during a speech in February 2013, emphasising that:

> 'This government supports wave and tidal 110% ... Now is the time for bold next steps – moving from individual projects to large-scale arrays' (DECC 2013b).

However, by the time the DECC published its renewable energy roadmap in November 2013, its confidence in wave energy had clearly diminished:

> 'In the 2011 roadmap we set out a profile of potential deployment by 2020 for wave and tidal stream energy. This suggests a range of between 200 and 300MW of deployed capacity. However, the delays in progressing to pre-commercial array demonstration and a better understanding of the challenges for both the wave and tidal stream sectors suggests that the actual levels of deployment may be lower than predicted' (DECC 2013d)

Evidence indicates that this crisis of confidence was closely aligned to market leaders such as Pelamis going into administration, as noted by then Minister of State for Climate Change Ed Davey in a speech in November 2014:

> 'Despite Government support ... it remains difficult to attract risk-averse funders. We have seen planned array projects which have been shelved or pushed to the right. And last week's sad news about Pelamis Wave Power filing for administration shows that risk aversion has real, and potentially devastating, effects on companies, their employees and families. This is always hugely disappointing for all concerned ... such recent developments are ... stark reminders of how fragile and young the industry is' (DECC 2014)

A clear change in government policy subsequently became clear with the formation of a new Conservative government in 2015, reflected in a speech by Amber Rudd int he same year, then Secretary of State for Energy and Climate Change. It focused on emphasising the importance of 'picking winners' and focusing on those technologies demonstrating the greatest potential or a low-carbon transition.

> 'Energy research and development has been neglected in recent years in favour of the mass deployment of all renewable technologies. We do not think this is right. We cannot support every technology. Our intervention has to be limited to where we can really make a difference – where the technology has the potential to scale up and to compete in a global market without subsidy' (UK Government 2015a)

No reference was made to either wave or marine energy, instead supporting other technologies such as energy storage, low-carbon transport fuels and energy-efficient lighting. This lack of support for wave energy was echoed in the Government's latest green paper outlining its industrial strategy (BEIS 2017a) and received only a passing mention in BEIS's recent Clean Growth Strategy, outlining that:

> 'More nascent technologies such as wave, tidal stream and tidal range, could also have a role in the long-term decarbonisation of the UK, but they will need to demonstrate how they can compete with other forms of generation' (BEIS 2017b p.99).

This shift in UK Government support is corroborated by analysis of UK Government policies (Figure 7) and funding (Figure 35) to support wave energy, as well as government targets for deployment (Figure 34).

Figure 45: UK government and parliamentary reports and statements on wave energy 1999–2017 (source: author)

UK Government

DTI Our Energy Future (2003)

'Wave and tidal technologies are rather further from commercialisation, with a number of competing designs … Determined that wave and tidal technologies should be given the opportunity to play the fullest part they can in the expansion of generation from renewables' (p.57)

DTI Meeting the Energy Challenge (2007)

'Potential to make a significant contribution towards our energy and climate change objectives … Even so, progress towards full commercialisation … has been slower than expected.' (p.226)

UK Gov – UK Renewable Energy (2009)

'Wave and tidal stream energy sources [have] the potential to make a significant contribution to our longer-term (2020-2050) energy and climate change goals by providing up to 20% of our electricity needs' (p.141)

DECC – Planning our electric future (2011)

'Wave and tidal energy technologies have proven themselves as dependable and are becoming significant means of generation' (p.24)

DECC – Greg Barker's opening speech RUK Wave and Tidal conference (2013)

'This government supports wave and tidal 110% ... Now is the time for bold next steps - moving from individual projects to large-scale arrays'

DECC – Amber Rudd's speech on the government's new direction for energy policy (2015)

No reference to wave energy

BEIS – Clean Growth Strategy (2017)

'More nascent technologies such as wave … could also have a role in the long-term decarbonisation of the UK, but they will need to demonstrate how they can compete with other forms of generation'

UK Parliamentary Committees

1999 **HoL Committee on the European Communities – Electricity from Renewables (1999)**

2000 *'The technology will not be able to make a substantial contribution to renewable energy supplies in the short and medium-term'*

HoC Science and Technology Committee - Wave and Tidal Energy (2001)

'Extremely regrettable and surprising that the development of wave and tidal energy technologies has received so little support from the Government'

HoL Science and Technology Committee - Renewable Energy: Practicalities and Energy Efficiency (2004)

2005 *'Recommend that there should be a co-ordinated programme of capital grants to encourage the establishment of pre-commercial wave and tidal power demonstration projects.' (p.11)*

2010

HoC Energy and Climate Change Committee – Future of Marine Renewables in the UK (2012)

'Government's funding for marine renewables represents a modest investment for what is a world leading industry with the potential to bring significant benefits to the UK.' (p.1)

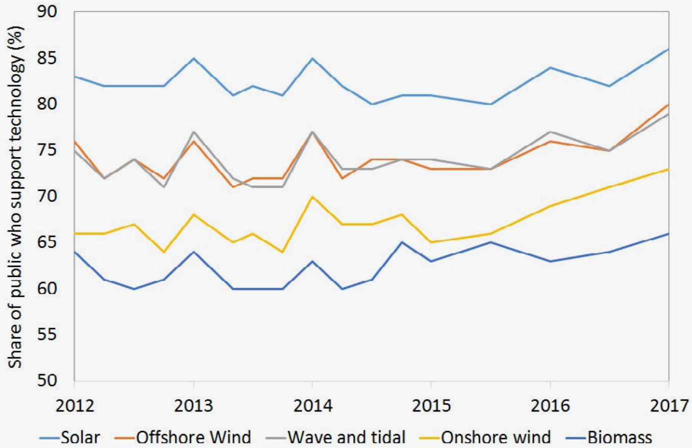
2015

2017

6.7.2 Public support for wave energy

Another measure of a technology's legitimacy is the degree of public support it attracts. Drawing upon official UK Government data, during the period 2012 to 2017, support for wave and tidal energy among the public has remained very high, tracking between 71% and 79%. On average, wave and tidal energy received 74% support, greater than onshore wind (67%) and biomass (62%), putting it on a par with offshore wind (74%), behind only solar PV (82%). Furthermore, support has grown slightly over the past two years, despite the challenges the sector has faced, although this is in line with a general increase in public support for renewables (Figure 46).

Figure 46: Public perception of wave and tidal energy in the UK 2012–2017 (source: BEIS)



7

Blocking and inducement mechanisms of wave energy innovation

This section considers the factors responsible for supporting or undermining wave energy technology innovation in the UK, categorising these according to the four structural dimensions of the UK wave energy innovation systems: actors, institutions, networks and technology/infrastructure. The findings are primarily drawn from 33 interviews conducted with UK wave energy industry experts.

7.1 Actors

This sub-section examines the actor-related factors responsible for supporting or undermining TIS functions and the underlying factors responsible for these. It considers the presence and capabilities of both private actors, namely technology developers (Section 7.1.1), the wider supply chain (Section 7.1.2) and market incumbents (Section 7.1.3), as well as public sector actors (Section 7.1.4), summarised in Figure 47.

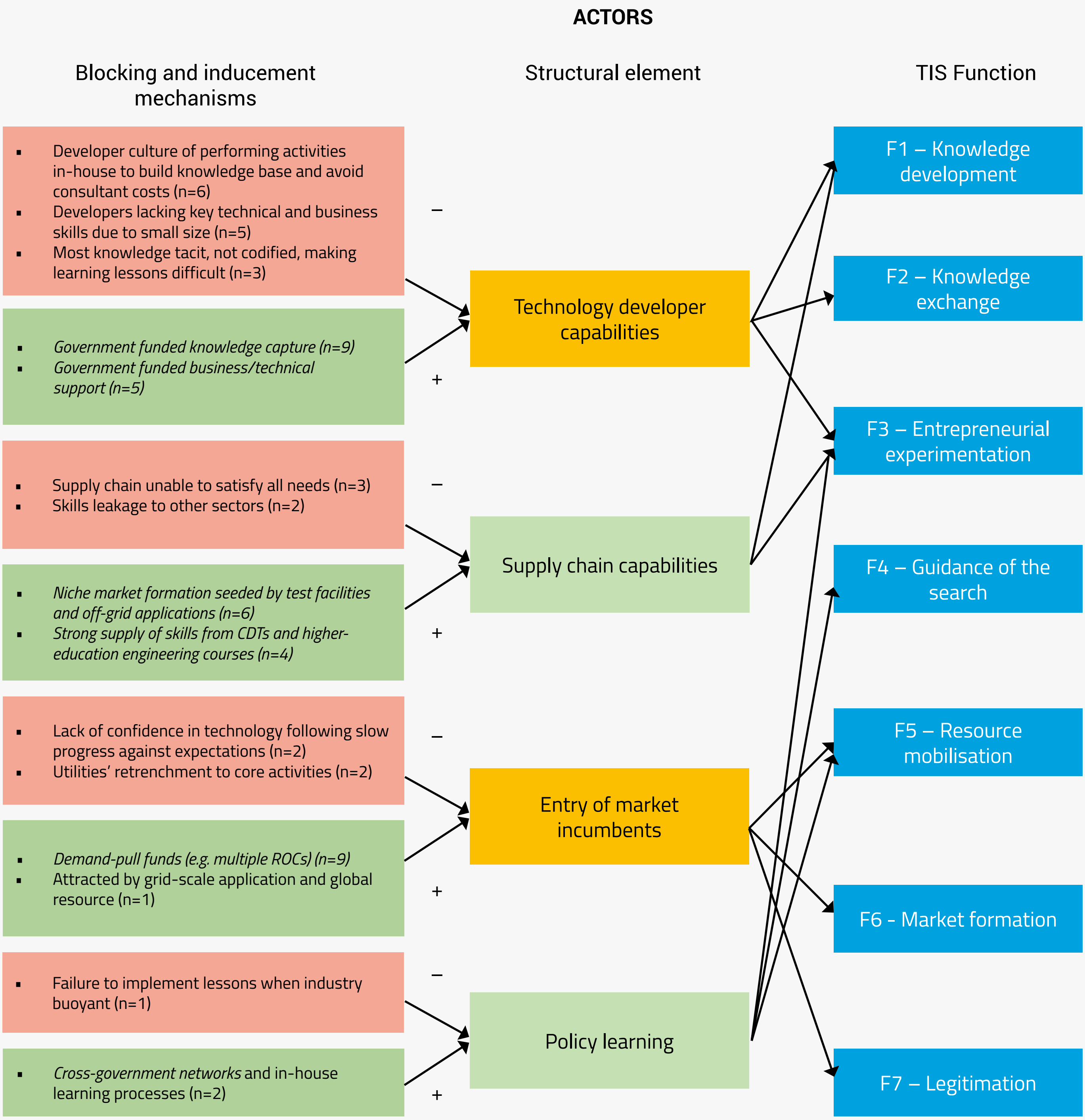
The research finds that the majority of UK wave energy developers were very small organisations lacking the full breadth of technical and business expertise *(resource mobilisation (F5))* needed to successfully commercialise wave energy via *knowledge development (F2)* and *entrepreneurial experimentation (F3)*, supporting previous research from the Renewables Advisory Board (RAB 2008). This was exacerbated by developers preferring to undertake most activities in-house because of a combination of a perceived culture that developers preferred to operate independently to avoid high consultancy costs and build up internal capabilities via 'learning-by-doing' and a belief that the wider supply chain could not satisfy all the developers' needs, especially for highly niche wave energy-related activities. Finally, *knowledge exchange (F2)* was hindered by a lack of actor-led codification of knowledge generated by RD&D projects, meaning knowledge remained tacit and was limited to the experiences of their staff rather than the wider sector. Investments in knowledge capture schemes and a requirement to licence IP, such as via Scotland's WES, have helped to address this problem.

Overall, the UK wave energy supply chain was considered strong, offering good support to developers. An excellent supply of skills from CDTs and higher education energy engineering was considered critical to supply chain development, as was the formation of niche markets, centred around off-grid market opportunities (e.g. islands, aquaculture) and the clustering afforded by UK test facilities such as EMEC. Concerns were, however, raised that intermittent funding and lack of a long-term strategy for wave energy has created a threat of skilled personnel moving outside the sector *(resource mobilisation (F5))*, echoing research from Vantoch-Wood (2012).

To further embellish the financial and human resources *(F5)* of the UK wave energy supply chain, a strong focus was placed on the need to attract market incumbents such as OEMs and energy utilities. Attractive market–pull mechanisms such as multiple ROCs were considered to have enticed these incumbents to enter the wave energy sector from the mid-2000s onwards, supporting previous research (Corsatea 2014; Allan et al. 2011; Jeffrey et al. 2014; Andersson et al. 2017). So too was wave energy's promise of grid-scale low-carbon electricity, which was compatible with these large companies centralised electricity generation business model. However, they began to exit during the early 2010s following a lack of technological progress against initial expectations and a focus on consolidating rather than diversifying their activities following the financial crisis. Their presence was considered very important in offering a combination of technical and financial *resource mobilisation (F5)*, *legitimacy (F7)* and *market information (F6)*, as previously identified by Andersson et al. (2017).

Finally, with respect to government, whilst it established a host of schemes that prematurely focused on full-scale demonstration, it in fact exhibited the capacity to learn from these mistakes resulting from a combination of in-house review mechanisms and cross-government networks. Importantly, however, this was mostly constrained to Scottish Government, encapsulated by its formation of WES; a programme designed around the lessons learnt from the successes and failures of its policy making over the previous 15 years.

Figure 47: Overview of inducement and blocking mechanisms related to actors (source: author)



NOTE: Blocking and inducement mechanisms in italics are those which emerged in the period since 2000.

7.1.1 Technology developer capabilities

There was a prevailing view that, whilst the UK typically funded wave energy developers to lead on wave energy RD&D, the developers alone did not have the full suite of capabilities necessary to deliver a commercial device (n=8; I1, 10, 14, 16, 19, 21, 25–26). Most developers are small companies, many with fewer than ten staff (Section 6.5.2.2). As such, they possess a narrow but highly specialised spectrum of skills relating to the development of wave energy devices, often lacking the full breadth of technical and business capabilities required to deliver a commercial device. In contrast, the UK was considered to have a strong overall marine energy supply chain (Section 7.1.2). We consider some of the factors supporting or undermining developers' ability to drive forward energy technology innovation.

7.1.1.1 Technology developers' culture of internalising majority of activities

There was a view that there was a culture amongst developers of choosing to do as much 'in-house' as possible (n=6 I1, 10, 14, 16, 21, 26). The logic underpinning this choice was a combination of external consultants being very expensive (I19) and a desire to build up as much capability in-house and retain any knowledge generated (I14, 26): 'if it's all done with consultants who don't stay involved with the project, then a lot of that knowledge works away and doesn't stay retained in the company' (I14 – Developer[46] CFO).

A view was also put forward that, despite being able to draw upon capabilities from offshore wind and oil/gas sectors, the UK marine energy supply chain could not cater for all of the needs of wave energy developers (n=3; I19, 28, 31), giving them no other option but to undertake some activities in-house: 'We did try and spin in the expertise of the supply chain … except where there wasn't a component that would do the job, then we had to take it on ourselves' (I31 – Consultant and former developer). One developer explained that they had chosen to develop their PTO in-house because they were more knowledgeable in this space than the wider supply chain (I19).

This view contrasted with those of other respondents who believed that developers were lacking some critical technical and business-related capabilities (n=5; I10, 23, 26, 28, 30). For example, with regard to PTOs, one respondent explained: 'they're not black belts in hydraulic power take off systems or linear generator, they're black belts in designing this elegant collector' (I16 – Researcher and former developer). Another example was device assembly (I10, 28), citing Pelamis as a company that established its own assembly facilities rather than outsourcing this activity to specialists. Consequently, the company failed to benefit from input offered by assembly specialists at an early stage about how to design the device in such a way as to minimise the manufacturing costs compatible with high-volume manufacturing capabilities. Furthermore, developers were also considered to lack the necessary business acumen (n=3 I23, 26, 30) to bring the device to market.

A negative impact of undertaking so many business activities in-house was that developers become overstretched, seeing resources diverted away from their core focus of developing a commercially viable wave energy device (n=4 I10, 23, 25-26). It also meant that they invested in staff and facilities to perform these activities, which saw them generate large overheads and exposed them to significant financial risk. Again, Pelamis was highlighted as an example of a company with a very large wage bill and their own assembly facility rather than outsourcing some core activities. As one respondent explained, they were 'trying to do it all themselves … I think Pelamis has come apart because of that' (I4 – Test facility director).

In reaction to this shortage of capabilities, government schemes were established to provide business and technical support (n=5; I8, 10, 11, 14, 26). For example, both Scottish Enterprise and the Carbon Trust offer high-value start-up business support (I11, 26), whilst technical support is offered by test facility managers at EMEC and FloWaveTT during the device testing phase on issues such as installation, testing and verification procedures (I10, 14) (Section 5.1.4): 'There's a lot of handholding that goes on, a lot of knowledge being imparted that isn't costed into that … [they] know much more about testing than the [developers] do' (I4 – Test facility director). Another example was the Marine Energy Challenge set up in 2004 to partner developers with leading engineering experts from major companies to help them understand how to improve the performance of their devices (I8).

46 The term 'developer' is used to refer to wave energy technology developers.

7.1.1.2 Lack of codified technology learning

There was a common belief that whilst wave energy had not yet reached commercialisation, the period since 2000 had delivered 'the biggest individual advancement of knowledge in the sector ever, by a long, long way' (I31 – Consultant and former developer), meaning that 'we know more than we ever knew, about what the challenge is ... and what type of solution will work' (I16, Researcher – former developer). However, a major concern was that much of this learning would not be taken advantage of because most knowledge remained tacit and had not been codified (n=3; I20, 26, 31), especially following the failure of market leaders Pelamis and Aquamarine Power:

> 'A lot of it is in [their] heads ... We have to rescue that so that we don't start from scratch again' (I20 – Senior researcher).

This situation was remarkably similar to the lack of codification and transferring of lessons learnt during the first phase of wave energy innovation in the 1970s and 1980s (I20).

To address this situation, efforts have been made to capture knowledge generated since 2000 through a variety of knowledge capture mechanisms (n=9; I3, 5, 10, 12, 15-16, 20, 31, 33), most notably via WES, which funded a company (Quoceant) founded by the former Pelamis CEO 'to harvest knowledge that otherwise might be lost, [much of] it is sitting in people's heads' (I20 – Senior researcher). It has also engaged with EMEC to develop an online library of reports outlining key lessons learnt by the sector over the past 15 years, with a specific focus on harvesting knowledge from companies such as Pelamis, Aquamarine Power and AWS Energy (Section 5.2.3.2.2). Another knowledge capture exercise involved the purchase of intellectual property and assets from former developers such as HIE and EMEC, each purchasing a Pelamis device (Findlay 2016; HIE 2015) to 'forensically examine the components to see what wear and tear has occurred and why' (I10 – Test facility director) and the impact on device performance. Despite these efforts, concerns were raised around the difficulty of codifying 'know-how' and the notion that some lessons will unfortunately be lost (I19, 26).

7.1.2 Supply chain capabilities

We consider the factors that have supported or undermined the development of the UK's wave energy supply chain, focusing on the availability of skills (Section 7.1.2.1) and niche market formation (Section 7.1.2.2).

7.1.2.1 Availability of skilled workers

Underpinning the UK's marine energy supply chain is a strong foundation of skills relevant to the wave energy sector (n=4 I14-15, 20, 31), in part evidenced by the strong training networks (Section 5.3.1.5) and number of engineering graduates (Section 6.5.2.1). The CDTs were credited with playing a leading role in developing skilled personnel for the wave energy sector, with excellent applied research skills and a strong understanding of how these can be applied in industry given that the EngD training model sees students spend 75% of their time in industry. Even so, another respondent expressed concern about a lack of skills, with many people working in the wave industry without a formal offshore engineering background (I1). A concern was also expressed that skilled staff were being lost to other sectors (e.g. offshore wind) because of intermittent investment and government support (n=2; I14, 26), often the result of redundancies:

> 'You're faced with the decision, can I get money raised or who do I lay off? If you lay them off, then those skills move outside the sector' (I14 – Developer CFO).

7.1.2.2 Niche market formation

Following the initial focus on grid-scale generation, there has, more recently, been a stronger focus on off-grid niche market formation (n=6; 9, 11; 14-15, 24), largely triggered by the withdrawal of the energy utilities and a need to identify an alternative strategy to grid-scale deployment. Furthermore, developers acknowledged that the formation of niche markets first could help to accelerate *market formation (F6)* and raise *legitimacy (F7)* by demonstrating operations in a real-world market environment. This strategy again drew comparisons with the wind industry where numerous variations of wind turbines were tested in niche markets, typically agricultural, helping to support design optimisation (I12, 24).

The niche market focus has, to date, been on island communities reliant on expensive oil-fired power generation because this typically presents a much more expensive form of electricity than grid-supplied electricity, meaning that island communities have usually been able to absorb a higher cost of electricity than their mainland, grid-connected counterparts who can source electricity much more cheaply. This has created an opportunity for the deployment of renewable technologies such as wave energy that would not have otherwise been able to compete with mature, grid-scale generation technologies such as gas and nuclear:

> 'I can make quite a lot of wave energy devices economically viable [with electricity costing] 60p a kilowatt hour, but I can't make many economically viable for 5p a kilowatt hour' (I15 – Senior researcher).

In addition, despite their modest wave energy resources, tropical islands were identified as attractive because hydraulic WECs could be adapted to offer desalinisation via osmotic pumping and pump cooler sea water onshore to provide thermal lift in ventilation systems and reduce air conditioning costs (I9). The aquaculture industry was also identified as another potential niche market, also reliant on expensive oil-fired generation (n=2; I14, 24).

Finally, a belief existed that the UK's test facilities had played an important role in the development of niche markets and the supply chain (n=4; 10, 21, 31-32). For example, at the height of marine energy funding testing in the late 2000s and early 2010s approximately 300 people were believed to be employed as part of the supply chain centred around EMEC in the Orkneys, creating a centre of excellence for wave energy innovation (I10):

> '[EMEC] was there to help to create a nucleus, a kind of focal point for the sector ... A whole body of experience and knowledge that has built up around that supply chain' (I32 – Senior public servant).

7.1.3 Entry of market incumbents

OEMs entered the UK wave energy market in the mid-2000s, with the utilities following suit in the early 2010s, although both subsequently stepped back in recent years (Section 5.1.2.1). The utilities were considered to offer a very important set of capabilities, most notably that they represented the target customer of wave energy developers and partnering with them on demonstration projects offered vital insights into the type of device they desired *(guidance of the search (F4))* and 'what [they] are going to have to do to sell these units in bulk to utilities in the future' (I24 – Consultant and former utility director). The utilities brought with them much needed financial and political capital given that they were multi-national companies (I16, 24).

In parallel the OEMs also entered the market, enticed by the interest shown by the energy utilities: 'You'd brought the utility ... bringing the customer then brought the OEMs' (I16 – Researcher and former developer). A key benefit of OEM involvement is their 'system integration' role, to improve the performance and reduce the cost of the device system (I14), as well as significant expertise in manufacturing and financial resources (I24), although they could potentially constrain the entrepreneurial spirit of some developers because 'they want to get into full manufacture quickly and lock down the design' (I24 – Consultant and former utility director). We consider the factors that triggered their entry and subsequent exit from the UK wave energy market.

7.1.3.1 Grid-scale potential and market–pull mechanisms

The entry of the utilities, such as E.On and Scottish Power, by purchasing devices from Pelamis, was attributed to their belief that wave energy had the potential to offer grid-scale low-carbon electricity generation:

> '[it] offers a potential scale that a utility desires ... it was seen as a great opportunity to diversify a renewables business, have something else alongside wind energy, that could go big' (I12).

Associated with this was the introduction of market–pull mechanisms designed to encourage grid-scale *market formation (F6)* (n=9, 5, 7, 10, 15-16, 19, 21, 23, 31), traced back to the inclusion of wave energy within the third round of the Scottish Renewables Obligation in 1997 (Section 5.2.3.2.1), which represented 'a signal … [that] this is no longer an academic curiosity; somebody wants this. The private sector people have got a future in this' (I31 – Consultant and former developer). This signal became much stronger with the inclusion of the MSO (Section 5.2.3.2.1), which 'brought in the utilities' (I16 – Researcher and former developer), putting an obligation on them to ensure a proportion of their electricity supply was from marine energy, followed by the provision of multiple ROCs for wave energy (Section 5.2.2.2.2). More broadly, government support for wave energy was considered to 'give confidence to our decision makers that they are doing something that is in line with government policy' (I24 – Consultant and former utility director).

The UK Crown Estate's consenting regime, granting developers rights to generate electricity offshore, was also considered important, offering a route to market in the eyes of the utilities (n=2; I23, 31), 'creating the market … a prize … they could see there's 300MW potential here at this site and 200 on that site' (I23 – Public estate NDPB). Despite attracting market incumbents, there was a feeling that these schemes were premature given that the technology was not ready for wide-scale demonstration or deployment (I14, 33):

> 'It doesn't matter whether it's 50 ROCs or 5 ROCs for wave … There aren't any projects in the water, so it's almost immaterial' (I14 – Developer CFO).

7.1.3.2 Lack of appetite for long technology lead time

During the early 2010s, the OEMs and the energy utilities began to withdraw from the wave energy sector because of a shift towards retrenchment and business consolidation following the financial crisis (I15, 33) and a lack of confidence in wave energy following slow progress against initial expectations (I20, 24):

> 'The utilities lost interest because they realised what we all knew, that this wasn't just around the corner, there was a lot, lot more that needed to be done' (I20 – Senior researcher).

Even so, there were some indications that these incumbents still have an appetite to re-invest should the technology show further promise through continued RD&D (I16–17, 24, 32): 'The message was loud and clear from industry … they're not going to put another penny on the table until they can … be certain that it will actually work' (I32 – Senior public servant). Providing this confidence is one of the core aims of WES, involving experts in sub-component design and performance to offer government and investors' confidence in the technology (I16).

7.1.4 Government policy learning

Government, predominantly the Scottish Government, was considered to have demonstrated a clear ability to learn from the successes and failure of past policies and incorporate these into future policy design (n=9; I11, 14, 16-18, 23, 25, 32-33). Examples included the shift from deployment focus programmes such as MRDF and WATES to single device demonstration schemes similar to MRPF and WATERS (see Section 5.2). Another was the unbundling of wave and tidal energy halfway through the Scottish Government's MRCF scheme because of a realisation that wave energy needed special support. However, the vast majority of these lessons came together in the design of WES, including a requirement for developers to licence IP and to form multi-actor consortia, as well as provide them with a 100% funding intervention rate to avoid the need for private match funding.

7.1.4.1 Cross-government networks and in-house learning procedures

Learning about the effectiveness of wave energy innovation policy was attributed to a combination of internal processes and cross-government networks (I11, 18) (Section 5.3.3). Nonetheless, concerns were raised that many of these important policy changes had come too late, delayed because at the time policy weaknesses were identified there was still sufficient private sector investment and political support for wave energy, meaning that recalibration was not considered a priority (I16). Additionally, there was a concern that some of the policy failures of the past could be repeated (I4, 20). Taking the example of WES again, one respondent explained that its design shared some similarities with the heavily criticised Intermediate Technology Institute (ITI) (Brown et al. 2016), such as its development of sub-components that were not immediately commercialisable on their own (I20) without integration in a larger device system..

7.2 Institutions

This sub-section examines the institutional and, specifically, the government policy-related factors responsible for supporting or undermining wave energy innovation. Specifically in relation to wave energy RD&D support, it examines the presence of a sustained focus on early- to mid-stage innovation (Section 7.2.1), long-term strategy (Section 7.2.2), high-level support (Section 7.2.3) and a rigorous and critical assessment of technologies (Section 7.2.4). These are summarised in Figure 48.

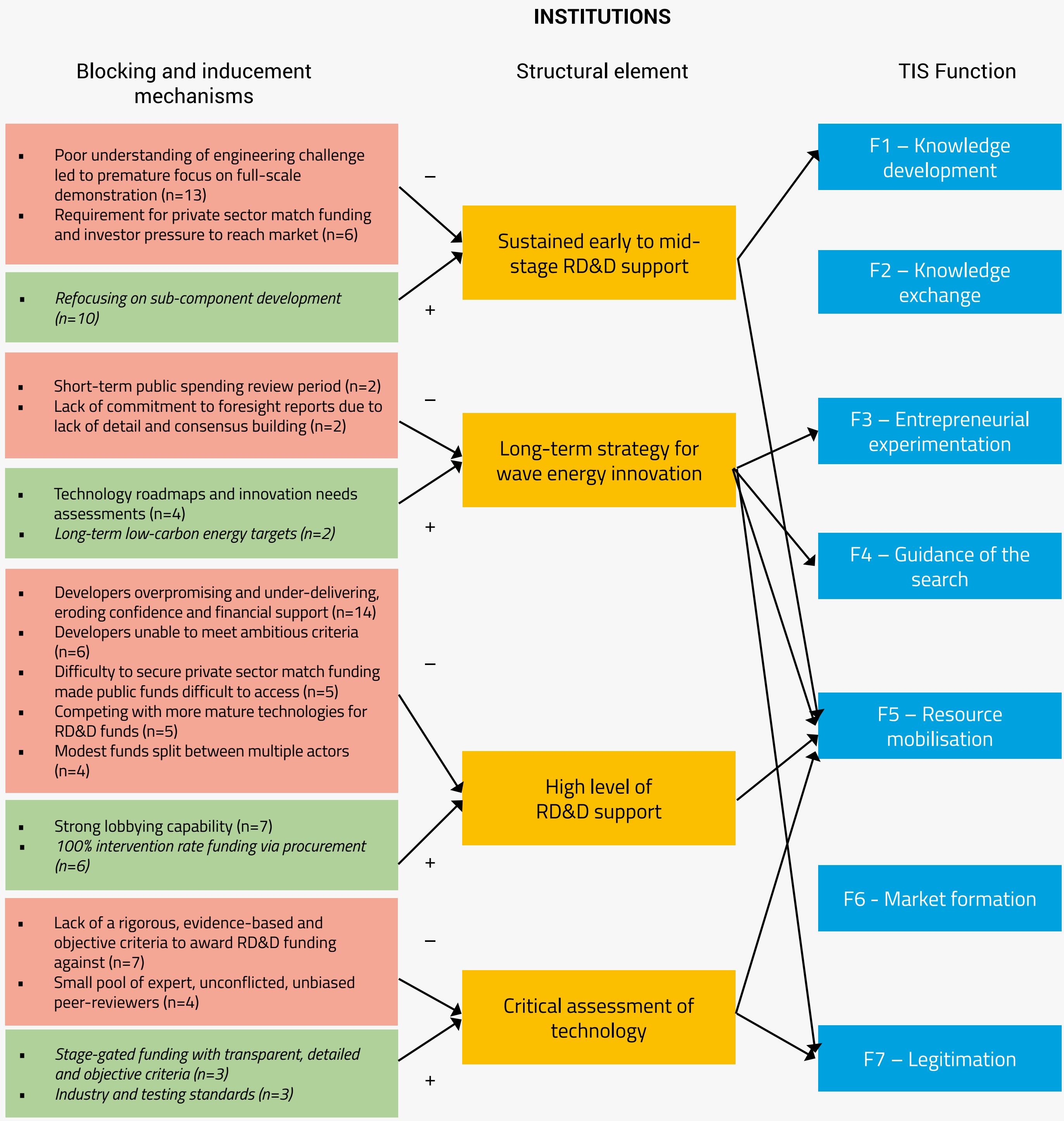
An overwhelming emphasis was placed on undertaking full-scale device demonstration, with a view to 'fast tracking' progress to commercial array-scale projects before the underpinning early- to mid-stage R&D had been performed *(knowledge development (F1))*, an issue also identified in previous studies (RAB 2008; Jeffrey et al. 2014; Jeffrey et al. 2013; Mclachlan 2010; HoCECCC 2012).

Numerous reasons were identified for the UK going 'too big, too soon'. From a developer's perspective developers were simply reacting to public and private sector funds made available to progress the technology as quickly as possible, the counter-argument being that funds were made available on the basis of developers' highly optimistic claims about the promise of wave energy. Underpinning either of these views was a poor understanding of the scale of the innovation challenge from both sides and the time and funds necessary to overcome it, as well as a lack of a rigorous, objective procedures to review the credibility of funding proposals. The outcome was that developers over-promised in order to secure funds and subsequently under-delivered in terms of technological progress *(F3)* and deployment *(F6)*, in turn eroding investors' confidence in wave energy and reducing their levels of investment *(resource mobilisation (F5))*, triggering the collapse of leading firms (e.g. Pelamis) and further undermining the sector's *legitimacy (F7)*.

Whilst the research finds that UK wave energy has been consistently and increasingly funded by the public sector since 2000 (Section 6.5.1), many respondents highlighted that a large proportion of the UK's budget for wave energy RD&D went unspent because developers could not meet over-ambitious funding criteria and/or struggled after the financial crisis to secure the necessary private sector match funding required to access these public funds. Finally, wave energy has competed with other forms of energy for funding, with grant RD&D programmes traditionally bundling wave with tidal energy and long-term revenue payments like the CfDs seeing wave competing against other renewables like offshore wind. The impact of this was that wave energy has struggled to compete with more mature renewable technologies on a cost basis, seeing these rival technologies crowding wave energy out and in turn receiving more funding. To help address these various funding issues, an explicitly wave energy focused, 100% funded, earlier stage innovation programme called WES was established, with an objective and transparent stage-gated funding allocation procedure.

As identified in previous studies (Andersson et al. 2017) a long-term strategy for wave energy innovation was considered critical to development of wave energy technology. However, the UK lacked such a long-term strategy, blamed on a combination of short-term public spending review periods and a lack of political commitment to foresight reports (e.g. roadmaps), the latter a consequence of a lack of detail and consensus building contained within these reports. However, these reports were still considered important 'signposting' exercises and helped to operationalise the Government's high-level energy and climate change targets.

Figure 48: Overview of inducement and blocking mechanisms related to institutions (source: author)



NOTE: Blocking and inducement mechanisms in italics are those which emerged during the period since 2000.

7.2.1 Sustained early- to mid-stage RD&D support

A major criticism of public support for UK wave energy innovation was that there was a premature focus on late-stage full-scale and multi-device array demonstration in open-sea conditions (n=9; I9, 12-13, 16-18, 22, 25, 31). A strong consensus existed that the wave energy sector had gone 'too big, too soon', trying to reach market before the necessary underpinning work had been undertaken:

> 'the way it's been funded to date over the long-term ... there has been this incessant push towards multi-megawatt arrays ... trying to run before you can walk' (I12 – Consultant).

This very early focus on full-scale demonstration is supported by Figures 7 and 35, which outline how demonstration funding formed the basis for UK wave energy support during the 2000s, through policies such as the UK's MRDF and MEAD and the Scottish Government's WATES, MRCF and Saltire Prize.

This haste to commercialise has had various negative impacts. Firstly, moving quickly to full-scale device demonstration without substantial early- to mid-TRL testing meant that lessons from these stages were never learnt *(knowledge development (F1))*. Furthermore, any lessons about the technology's fundamental design learnt at the demonstration stage could not easily be acted upon because at full scale the device design had already become 'locked-in' because of the sheer amount of time and money invested in it (I14, 16, 28). Additionally, the large size and cost of the machines meant developers were quite conservative in their approach to testing because of the associated costs of device failure (I12, 16), meaning that 'the results are never be as exciting as you would like' (I16 – Researcher and former developer), undermining the technology's *legitimacy (F7)*.

We examine some of the underlying factors responsible for this premature focus on commercialisation from both government and industry, as well as some of the actions taken to address this.

7.2.1.1 Poor understanding of the scale of the engineering challenge

A poor understanding of the scale of the engineering challenge (n=13 I1, 5, 8, 11-14, 16, 18, 20, 23, 25, 31) was identified as a major factor behind the UK's premature focus on commercialisation:

> 'There's been a history of wave and tidal of over-promising and under-delivering ... in part ... because people didn't quite understand the difficulty of the environment' (I13 – Test facility director)

This was in part attributed to a failure to transfer many of the lessons learnt during the first phase of innovation in the 1970s and 1980s (Section 7.1.1.2). Linked to this poor understanding was the commonly held belief that wave energy could emulate offshore wind's impressive deployment rate (n=3; I3, 12, 31), as illustrated in various foresight reports outlining the trajectory for wave power (FREDS Marine Energy Group 2004; Ocean Energy Forum 2016; Carbon Trust 2006; OEE 2013). The issue was the incorrect assumption that wave was at a similar stage of development to wind just before it enjoyed widespread deployment:

> 'There has been this incessant push towards multi-megawatt arrays ... that resulted from observing how things were done in offshore wind ... But we were effectively taking mature technology from the Danish wind industry' (I11 – Senior public servant)

Some respondents explained that developers' focus on full-scale demonstration was a response to government funds for later stage innovation (n=6; I9, 12, 16, 18, 22, 25). In parallel, the requirement for developers to secure private sector match funding to be awarded public funds brought with it intense investor pressure to reach commercialisation as quickly as possible (n=6; I11, 14, 16, 18, 23, 25):

> 'Developers have chased the money that's been available ... the money was there for demonstration projects ... and so the fault doesn't all just lie at the door of the developer ... the funding was designed to go too big, too soon' (I16 – Researcher and former developer).

However, others emphasised how, from the government's perspective, they were responding to the call from the wave energy community that their technology was now ready for full-scale demonstration (I14).

In light of the understanding that wave energy was some distance away from commercialisation, the Scottish Government refocused their support to an earlier stage of innovation on sub-component development (n=10; I5, 10, 16-19, 21, 24-25, 29, 32), specifically via programmes such as WES:

> '[It] removes the pressure of going, okay, [you] need an improvement to your power take off, but you've only got six months to sort it out and … it better be a reliable one because you're going to put it into a £5m machine' (I16 – Researcher and former developer).

Some respondents did, however, express concern about how the WES programme would eventually deliver a single commercial device by integrating the different sub-components together (n=5; I5, 19; 22, 25 29):

> 'What they're not looking at is the integration issues. Eventually they'll end up with a catalogue of different PTOs, mooring systems etc.' (I29 – Manager innovation NDPB).

However, informally, WES is actively considering what strategy it must take going forward to integrate these separate components into a commercially viable wave energy device.

7.2.2 Long-term strategy for wave energy innovation

A common criticism from the respondents was the UK's intermittent, stop–start funding regime, largely attributed to the lack of a long-term industrial strategy for UK wave energy (n=12; I10–11, 14, 17, 19, 21, 23, 26, 28, 31–32):

> 'there hasn't been sustained investment … you can't really grow an industry by funding it in fits and starts' (I18 – Senior civil servant).

Our analysis of UK RD&D funding found that funding had actually been awarded consistently since 2000 and increased annually on average (Figure 35). However, there was a very high turnover of different wave energy RD&D schemes, representing short-term gaps between schemes *(resource mobilisation (F5))* and a regular shift in the TRL focus of these schemes *(guidance of the search (F4))* (Figure 7), consistent with an intermittent and fast-changing funding landscape.

This negatively impacted upon developers' abilities to formulate a long-term, consistent strategy to develop their technology (n=4; I11, 17, 21, 26) *(entrepreneurial experimentation (F3))*, leading to their bidding opportunistically for whatever funds were available at that point in time and adapting their RD&D strategies accordingly:

> 'Developers said … "We're jumping from one grant to the next … It's quite difficult to have a consistent strategy for developing the technology when you have to change direction to get funding"' (I17 – Senior NDPB manager).

This fast-changing and short-term policy environment also led to increased uncertainty around the technology and negatively impacted the *legitimacy (F7)* of the sector (18, 24), as well as undermining the UK's retention of skilled personnel (Section 7.1.2.1) and its status as an international leader of wave energy technology (I10–11, 13, 19–20, 31), analogous to it losing its lead in wind to Denmark (I10, 13). We examine some of the factors responsible for this lack of long-term, consistent support for wave energy.

7.2.2.1 Short-term spending review period

The high level of policy turnover was attributed by some to the short-term budgetary periods of the UK and Scottish Government (n=2; I18, 25), meaning that they can only commit funding to specific areas a few years at a time.[47] This not only meant that government lacks the time horizon to plan long-term policies but that the RD&D funds are typically drawn down only halfway through these spending periods, applying pressure on developers to undertake projects in a relatively short period of time (I21, 25):

> 'The money pops up for a [five] year window but it's not actually secured and allocated until halfway through that' (I25 – Innovation NDPB manager).

47 The UK Government works to a five-year spending period and the Scottish Government to a three-year period.

7.2.2.2 Government low-carbon energy targets

In a bid to offer a commitment beyond the short-term spending review period, government has issued various carbon emission reduction and renewable electricity generation targets (n=2; I16, 31) (Section 5.2), considered critical to retaining a strong focus on supporting wave energy technology innovation. However, some respondents questioned whether there was sufficient political commitment to these targets and whether they have made a tangible difference to wave energy innovation (I8).

7.2.2.3 Technology roadmaps and innovation needs assessments

To help operationalise these low-carbon energy targets, a host of technology foresight reports were published that have informed the UK's *guidance of the search (F4)* (n=4; 16, 25, 28-29) (Section 6.4.1). These were considered important in terms of co-ordinating the wave energy community's actions so that actors worked in support of rather than against one another. Furthermore, they helped to retain a political commitment to wave energy, signposting a vision of wave energy's route to market, meaning that:

> 'Investors are able to see that there is a clear direction that can be followed for commercial exploitation … [it] is absolutely essential because it sets out what success looks like (I28 – Innovation NDPB Director).

Despite these benefits, a major criticism was that the recommendations of foresight reports were often not translated into action (n=2; I25, 28) because of a lack of detail about the nature and timing of specific actions (I25) and an insufficient commitment from government and industry to act upon their recommendations, linked to the lack of consensus building in formulating them (I28).

7.2.3 High-level RD&D support

Some respondents indicated a concern that, since support was initiated in the 1970s, wave energy had not yet received sufficient cumulative investment at a global level to enable it to reach commercialisation (n=3; I1, 21, 26) *(resource mobilisation (F5))*. This is supported by our comparison against other now mature renewables such as wind and solar PV, which received a significantly greater sum of support in the same period (Section 6.5.1). Nonetheless, investment in UK-based wave energy RD&D expenditure has steadily increased in real term since 2000 (Figure 35). However, a large proportion of the funds made available by the marine energy programmes outlined in Section 5.2 went under- or unspent (e.g. MRDF, MRCF). Consequently, we examine the factors that could have constrained the amount of the budget awarded to support wave energy RD&D in the UK.

7.2.3.1 Developers over-promising to secure private sector funds and under-delivering

Under EU law, all government funding must be state aid compliant, in order to avoid this government support distorting market competition by giving one or more parties an undue advantage over others. One implication of this is that UK wave energy RD&D funding schemes have limited the intensity or intervention rate of public funding programmes, achieved in part by requiring applicants to secure private sector match funding alongside public funds. Private sector investment was largely forthcoming during the 2000s, with one former developer explaining that they had 'spent hundreds of millions of pounds of primarily private investment, geared about five or six to one with public' (I31 – Consultant and former developer). However, to secure these funds, developers had to present an attractive investment case to private investors (e.g. OEMs and VCs) – typically for a technology able to enjoy wide-scale deployment and reach commercialisation in a relatively short period of time (I11, 14, 16). This often meant promising 1MW devices (I12) and a route to market that would take years, not decades, even if the developers were unsure whether these targets were realistic: 'You tell investors what they want to hear, whether it's the truth or not … Investors don't want a 10-year journey that involves a lot of preliminary testing' (I14 – Developer CFO).

The consequence was developers over-promising to secure investment and in turn under-delivering (n=14; 3, 5, 9, 11–13; 14, 16, 18, 20, 23, 31–33), significantly damaging investors' confidence in wave energy *(legitimacy (F7))* and precipitating a reduction in subsequent investment *(resource mobilisation (F5)).* This subsequently triggered the failure of firms such as Pelamis and Aquamarine, further undermining the sector's *legitimacy (F7)* (n=5; I14-15, 19-20, 26): 'With the demise of the larger companies that were leading the field, investors think, ''This is too difficult''' (I14 – Developer CFO).

The situation at the beginning of the 2010s was therefore that private sector investment was very hard to secure, with multi-nationals retrenching to their core activities following the 2008 financial crisis (Section 7.1.3.1) and VCs now questioning the technology's potential (I18, 33): 'Venture capitalists had got their fingers burned and wanted a way out' (I33 – Public investment bank director). Consequently, public funds became very difficult to secure because developers could not secure the necessary private sector match funding (n=5 I11, 14, 17, 32-33). As one developer explained:

> 'We've got a lot of support from government but can we find the private money in the quantities required to do it? No' (I14 – Developer CFO).

This is illustrated by the Scottish Government's WATERS funding scheme, where, by the third round in 2014, 'it was pretty clear that they were really going to struggle to raise the type of match funding that they would require for a grant' (I11 – Senior public servant). With the realisation that public funds for wave energy RD&D had become frozen by the lack of match funding, the Scottish Government established its WES programme with a 100% intervention rate, negating the need for private investment (n= 6, I11, 14-15, 17, 25, 33).

7.2.3.2 Competition with more mature renewable energy technologies

Funding for wave energy was often considered to be limited because it was competing directly with more mature technology (n=5; I7, 15, 18, 21, 25). As outlined in Section 5.2, funding for wave energy has typically been bundled with tidal stream energy (Section 5.2), resulting in tidal stream capturing 75% more RD&D funding than wave energy since 2000 (Figure 35). Some respondents attributed this to tidal stream being more mature than wave but being bundled together meant that they competed for the same funds (I18, 25). A good example is the £18m MRCF fund run by the Scottish Government, where the most eligible projects that came forward were for tidal energy (I25). Consequently, the Scottish Government reconfigured the scheme in 2013 with explicit sums of money made available only for wave energy (I18, 25) because 'they were at different stages ... two completely different industries' (I18 – Senior civil servant).

Wave energy has also had to compete against renewable energy technologies other than tidal stream as part of the CfD market–pull mechanism (Section 5.2.2.2.3). Its predecessor, the RO, offered wave energy preferential revenue payments. Whilst this did not provide certainty over the price wave energy generators would receive, it did guarantee that they would receive at least some revenue assuming their installation was accredited and generating electricity (Section 5.2.2.2.1) (I15). In contrast, the introduction of CfDs in 2014 provided certainty around the level of subsidy wave energy would receive if successful (i.e. 'strike price') but offered generators no certainty that they would actually secure any subsidy (I7, 15, 21). This is because wave must compete on a cost basis against other technologies from the same 'less established' pot (e.g. offshore wind) as part of an auction if there are more eligible projects than funding allocated. In the latest round of CfD allocation, the lowest strike price for offshore wind was at £57.50 per MWh (BEIS 2017b), significantly cheaper than wave power (Section 6.3.3).

To counter this, a minimum of 100MW of marine energy was included during the first allocation round, guaranteeing eligible wave projects a CfD at £305 per MWh. However, no projects received awards and this was removed during the second allocation round (DECC 2016a). Whilst one respondent welcomed this 'ring fencing', they explained that, in practice, 100MW of marine energy could never compete on cost with multiple GW of offshore wind because of economies of scale (I7).

7.2.3.3 Over-ambitious funding requirements

The premature emphasis on later-stage innovation of government policy meant that developers were often unable to meet the ambitious funding criteria (n=6; 15-18, 21, 25), resulting in government budget going unspent:

'you allocated all this money and then you can't spend it, because the industry couldn't meet the hurdles [or] the milestones, so we were not able to give them the funds' (I18 – Senior civil servant).

For example, the £42m from the MRDF scheme ring-fenced for wave energy technology RD&D went entirely unspent (Section 5.2.2.2.2) (I16–17, 25), including overly ambitious criteria such as requiring developers to have demonstrated three months of continuous generation, which 'didn't reflect the reality of anyone being able to put a device in first time and run it successfully [and] continuously for a long period. Basically no one could fulfil the criteria (I25 – Innovation NDPB manager). The £10m Saltire Prize launched in 2008 also went unspent, because it required developers to demonstrate a total electrical output of at least 100GWh over a continuous two-year period, equating to 'an array of about 20 devices' (I18 – Senior civil servant). Finally, one respondent explained that some stakeholders had perceived this lack of funding allocation as an indicator that wave energy was not progressing as quickly as first hoped but the reality was that it was actually symptomatic of inappropriate policy design (I15).

7.2.3.4 Decentralised funding model sees modest funding split between multiple bodies

The UK operates a decentralised model of innovation whereby numerous different developers compete for funding to develop rival technologies versus a centralised model whereby a single government-funded organisation such as a government R&D laboratory delivers a technological solution (e.g. Fraunhofer in Germany). This approach was identified as a factor limiting the level of investment in wave energy at firm level. Some respondents felt that the UK's relatively modest budget was being split between numerous developers, each of whom were progressing their own sub-components and covering their own overheads (e.g. staff, premises), resulting in a lack of a critical mass of investment in any one organisation to develop a viable wave energy device (n=4; I1, 8, 17, 26).

7.2.3.5 Lobbying capabilities

There was a strong consensus that the wave energy industry had helped to implement some supportive policies via strong lobbying capability (n=7; 14-16; 18; 24, 31, 33), helping to improve both r*esource mobilisation (F5)* and *legitimation (F7)*. For example, the introduction of multiple ROCs was attributed to industry pressure via trade associations (e.g. RenewableUK) and individual organisations (I24). Other favourable policy changes attributed to successful lobbying included wave energy being included in the EC's SET plan (Section 5.2.1.1) and the inclusion of a sub-system focus for wave energy innovation in the Horizon 2020 work programme (European Comission 2016) (I16, 18).

7.2.4 Critical assessment of technological potential

Objective peer reviews of different technological designs in accordance with a transparent set of criteria based on industry consensus were considered critical to the progress of wave energy development, in terms of framing the *guidance of the search (F4)* and lending *legitimacy (F7)* to wave energy. We consider some of the factors supporting or undermining this.

7.2.4.1 Lack of stringent RD&D peer review funding criteria

A lack of a rigorous, evidence-based and objective criteria to award RD&D funding was identified as a major issue (n=7, 1, 6, 8, 14-16, 22), with the view existing that some projects were awarded funds despite not necessarily exhibiting the greatest potential to reach commercialisation. For example, one respondent explained that funding had been awarded without the need for developers to present relevant evidence to support the theoretical performance of their device, such as a peer-reviewed paper or report (I8). Additionally, it was difficult for funders to compare the relative stages of innovation for different technologies without appropriate assessment protocol and industry standards (I22).

The lack of adequately experienced, unconflicted, unbiased experts to peer review funding applications was also cited as a cause of the lack of critical assessment (n=4 I1, 6, 14-15). The first issue was the relatively small pool of eligible peer reviewers because of the small size of the wave energy community and the trend towards multi-partner consortia, which increased the number of peer reviewers with a conflict of interests. Consequently, peer reviews came from a combination of more junior personnel or experts within other technology sectors (I14–15). The second issue was a lack of objectivity from peer reviewers, who were considered insufficiently critical of wave energy, either because they wanted to support the growth of their community and/or because they had insufficient experience of working in other energy technology sectors to draw comparisons with their standards of quality (n=2; I1, 6). Conversely, some reviewers were considered to be biased against some applications because they involved a rival technology to the one they were developing (I14).

In a bid to address these issues, a move was set in motion to implement a rigorous stage-gating procedure that objectively assesses the stage of development of each sub-component (n=3; I17–18, 31) as part of the WES programme, with clear quantitative objectives for each stage of funding:

'If you look at the calls that we've published, upfront, we've said what the criteria are ... We tell you how we're going to mark them, what marks we're going to give you for each of those' (I17 – Senior NDPB manager).

This stage-gated approach to funding ensures that promising concepts are guaranteed to access funding at a higher TRL, contingent on their meeting stringent stage-gating criteria:

> 'they don't need to worry about where's the next bit of funding from. They know that if they meet their milestones ... then they'll move to the next stage' (I17 – Senior NDPB manager).

Another important development was the formation of industry standards or guides to help ensure fair comparison between different designs (n=3; I4, 10, 21) developed by a range of actors. These were mainly developed by test centres such as EMEC, which constructed a suite of 12 guidelines covering issues such as testing, cross-device comparison, deployment and maintenance (EMEC 2017e) and major research consortia such as EQUIMAR, which established a suite of seven high-level protocols focused on ways to 'measure and compare the dozens of tidal and wave energy devices, proposed locations and management systems currently competing for funds, so governments can invest in the best ones and get marine energy on tap fast' (Equimar 2013).

7.3 Networks

This sub-section examines how networks involving private, public and third sector actors have served to support or undermine wave energy innovation and the underlying factors responsible for these. Section 7.3.1 considers interactions across industry and science, followed by a specific focus on industry–science (Section 7.3.2), international (Section 7.3.3) and governmental (Section 7.3.4) collaboration. The results are summarised in Figure 49.

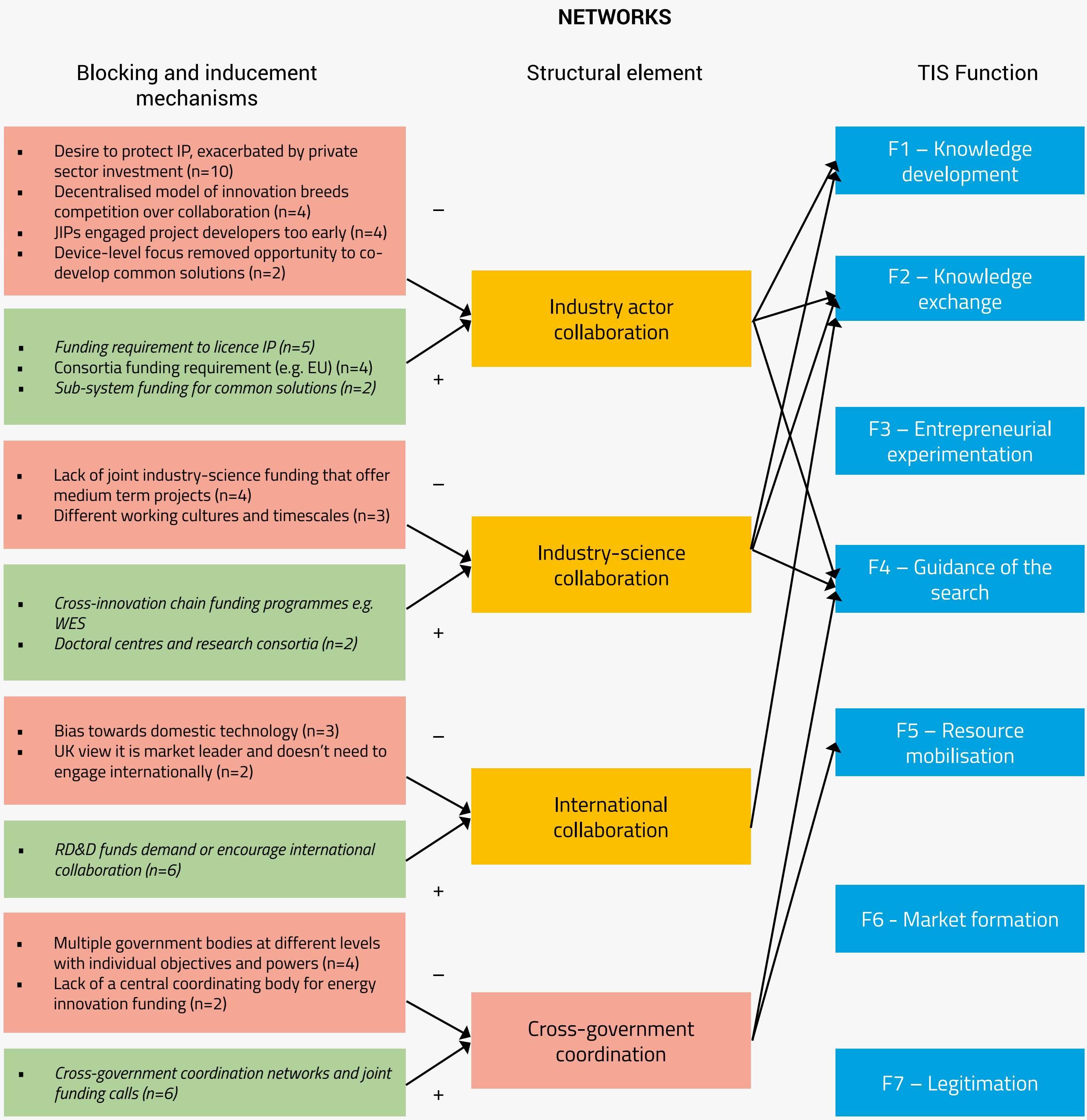
Traditionally, a number of factors constrained the degree of actor interaction, critical to both *knowledge development (F1)* and *exchange (F2)*. One responsible factor was the emphasis on protecting IP by operating secretively, an issue identified in previous research (Winskel 2007; LCICG 2012; Foxon et al. 2005; Mclachlan 2010). Other factors included the UK's decentralised model of innovation that prioritises competition over collaboration and a focus on device-level innovation funding, which removed the opportunity for actors to collaborate on developing common solutions to shared problems (e.g. sub-components). Again, steps were taken to address these issues – for example, WES imposed a requirement on awardees to licence their IPs, share lessons and formulate consortia in order to be awarded funds.

Industry–science collaboration was considered to be relatively weak but improving, critical to not just *knowledge development (F1)* and *exchange (F2)* but to formulating a shared view of priorities for wave energy innovation *(guidance of the search (F4))*. Barriers included a fundamental difference in working cultures and timeframes, supporting previous research from Winskel (2007), as well as a lack of joint industry–science funds offering a compromise between these to foster collaboration. Once again, positive interventions included cross-innovation chain stage-gated funding schemes (e.g. WES, Energy Catalyst), which opened up funds for joint science and industry projects, as well as industrially focused CDTs that saw doctoral students on industrial placements.

Similarly, international collaboration was considered to be relatively weak, undermined by a belief that the UK could tackle the wave energy challenge alone as a leader of wave energy and a perceived bias towards domestic wave technology. This was countered by funding schemes that help support the formation of international networks, for example by demanding international consortia (e.g. EU Horizon2020) or by opening up UK funds overseas (e.g. WES), supporting findings from previous work (Corsatea 2014; Vantoch-wood & Connor 2013).

The weakest area was cross-government coordination, which led to the duplication of funds that had a negative impact on *resource mobilisation (F5)* and the lack of a single, unified RD&D strategy across different funding bodies and layers of government, undermining the *guidance of the search (F4)*, issues previously identified by other studies (Jeffrey et al. 2014; HoCECCC 2012; A. R. Vantoch-Wood 2012; Mclachlan 2010; Andersson et al. 2017). The core issue was UK wave energy funding being split across three different layers of government (i.e. devolved administration, the UK and the EU), with numerous different autonomous bodies operating at each government level with distinct but often overlapping remits. The lack of a central co-ordinating body made for a highly complex and poorly co-ordinated policy landscape, despite efforts to improve coordination with the introduction of cross-government networks (e.g. LCICG).

Figure 49: Overview of inducement and blocking mechanisms related to actor networks (source: author)



NOTE: Blocking and inducement mechanisms in italics are those that emerged in the period since 2000.

7.3.1 Inter-actor collaboration

Transfer of knowledge across industry and science was considered critical to *knowledge exchange (F2)*, which in turn informed both *knowledge development (F1)* and the *guidance of the search (F4)*. We consider some of the factors that have supported or undermined this.

7.3.1.1 Protection of intellectual property

In the absence of a market to sell their devices, the main commodity of wave energy technology developers was the intellectual property (IP) of their technology (I32). Consequently, there was a culture amongst developers of secrecy in order to protect their IP, stifling collaboration (n=10; I1, 3, 6, 9–10, 15, 20, 29, 32–33). Consequently, little open and honest exchange of lessons learnt took place to inform the priorities for future innovation:

> 'They protect IP … [i.e.] knowledge. They've been secretive about failures … [so] the same mistakes have been repeatedly made because there hasn't been the exchange of information' (I20 – Senior researcher).

One example of this came from a former developer, who explained that they preferred not to patent their technology because it would expose their technical advantage to competitors once the patent was granted and made publicly available:

> 'You are in effect publishing … you're telling everybody what you're doing … You're actually much better … securing a loyal workforce who don't walk the ideas out of the building and keeping as much as you can in trade secrets ' (I31 – Consultant and former developer).

Exacerbating this secrecy was investors' desire that developers protect their IP (n=3; I3, 15, 33), which was commonplace because of the requirement of public funding to be matched by private sector investment (Section 7.2.3.1). As one respondent explained:

> 'if a private investor comes along and puts £1m into a company that's already had £10m worth of government funding … the price of that £1m investment is, ''You don't talk to anybody else''' (I15 – Senior researcher).

In an effort to address this lack of collaboration because of a desire to protect IP schemes such as WES, a condition was introduced whereby developers must licence their IP and share the findings of their project or WES can do so on their behalf (n=5; I3, 15, 17, 26) (Section 5.2.3.2.2), representing a radical departure from previous funding schemes that imposed no such demands on developers.

7.3.1.2 Decentralised model of innovation

The decentralised model of innovation the UK employs prioritises competition over collaboration from a very early TRL (n=4; I1,8, 15, 31) (Section 7.2.3.3), leading to wave energy developers competing against one another with rival technologies, the logic being that market forces would see the strongest device design emerge triumphantly. This is in contrast to a centralised approach where skilled personnel would pool their skills and experience within a government R&D lab to collaborate on a single technology. Respondents broadly agreed with the need for free-market competition to avoid championing of sub-optimal technologies but argued that the UK placed an emphasis on competition at too early a point along the innovation chain, again stifling collaboration that is critical at the early stages of a technology's development. As one former developer explained:

> 'The second phase was everyone for themselves … Government desperate to provide support to a bunch of private companies competing with each other before there was really a competition … It was pretty much, squash your neighbours, get to the top whether you were the cream or not' (I31 – Consultant and former developer).

7.3.1.3 Device versus sub-component focus of RD&D funding

The majority of funding was committed to the development of fully integrated devices (Figure 37), meaning that actors were funded to develop fully integrated devices. Consequently, little emphasis was placed on developing common sub-systems able to be utilised in a range of different device designs (n=2; I18, 31), such as PTOs, materials or control systems, which could have been co-developed by multiple developers. Again, the refocusing of efforts at the sub-component stage via WES has helped to encourage collaboration because of its aim to develop solutions to sub-systems to address industry-wide problems (n=2; I17-18). As one policy maker explained:

> 'Previously we funded companies to work in isolation [but] Wave Energy Scotland look[s] at where there are things that they have in common' (I18 – Senior civil servant).

Another model employed to foster industrial collaboration in the wave energy sector was the introduction of JIPs. Building on the UK's OWA, the MFA was established in 2013 (Section 5.2.2.2.2) to support the development of common solutions facing the development of marine energy arrays. Whilst the MFA encouraged industry actors to talk to one another, it was not ultimately deemed a success, mainly because the JIP prematurely engaged project developers (n=4; 1, 8, 22, 26) (e.g. Dong Energy, VattenFall, E.On) to develop common technologies and processes (e.g. cabling, foundations, O&M) capable of reducing the costs of commercial-scale wave energy arrays before a commercially viable wave energy technology had emerged. The JIP model continues to be employed for wave energy in the form of the Crown Estate's ORJIP, Ocean Energy and a host of other JIPs via the ORE Catapult, although the success of these remains to be seen.

7.3.1.4 Funding requirements for multi-actor consortia

Some funding schemes encouraged inter-actor collaboration by demanding the need for consortia (n=4; I1, 15, 17, 32). Examples of predominantly scientific funding include the EC's FPs, which have a requirement to fund consortia of multiple organisations across different European countries, and Scotland's WES programme, which has almost exclusively funded consortia to date, placing emphasis on drawing expertise from different sectors. Despite the perceived benefits of multi-actor consortia research projects, one respondent highlighted the challenges associated with managing large research consortia, noting that their own EU project involved 23 partners across 13 countries (I15).

7.3.2 Industry–science collaboration

Industry–science collaboration and knowledge exchange were overall considered to be weak in the UK wave energy sector. This trend is, to some extent, supported by our quantitative analysis of UK RD&D funding, which found relatively little industry–science engagement across projects but identified a clear improving trend following the introduction of cross-innovation chain programmes such as WES and the Energy Catalyst. A host of factors were identified as responsible.

7.3.2.1 Mismatching cultures – working between science and industry

A key barrier to collaboration between science and industry was the mismatch between the ways the two communities worked (n=3; I20, 22, 27). The first issue was that academia considered there to be a significant amount of fundamental research on wave energy still needed, whilst industry sought to commercialise technology as soon as possible:

> 'Academia was having to convince their funders that the questions were still being uncovered ... Meanwhile industry ... needed to convince their private investors that the questions were all answered' (I20 – Senior researcher).

Second, universities were incentivised to generate outputs, such as research papers and PhDs, via frameworks such as the Research Excellence Framework, which do not necessarily chime with what industry wants (I27). Third, there was considered to be a mismatch in timescales to which academia and industry work (n=2; I22, 27), with research typically spanning years compared to industry's much shorter timeframe, meaning that research outputs were interesting to industry but not generated quickly enough. Finally, from the perspective of industry, universities were difficult to engage with because they did not employ a standardised approach when collaborating with industry, meaning that bespoke contractual arrangements were required for each university and resulting in additional time and costs (I27).

An associated barrier with the lack of industry–science collaboration was the lack of funding for joint science and industry projects (n=4; 1, 15, 20, 22). As one senior researcher explained, government 'funded companies to put things in the water and they funded universities to do underpinning research but they didn't fund the two together' (I20 - Senior researcher). Another related issue was the lack of medium-term funding programmes able to give universities and industry a timeframe to which they could both work, given that universities took a long-term approach and industry a short-term view, something the establishment of the OREC sought to address with its JIPs (I27). Looking forward, one respondent explained that it was essential that policy makers acknowledge the differences in the ways in which industry and science work when designing schemes to bring the two together, highlighting how the ETI had treated universities as commercial entities, 'thereby wiping out their attractiveness in the process' (I20 – Senior researcher), because it imposed commercial law constraints on them and limited their intellectual freedom.

7.3.2.2 Industry–science networks

Some respondents identified the importance of formal networks in facilitating industry–science collaboration (n=2; I15, 22). In particular, CDT (Section 5.3.1.5) were identified as important, building a strong link between industry and universities by offering EngD programmes that saw students spend 75% of their time in industry (I15). The UK's Marine Supergen was also identified as important, whose annual assembly and advisory group include a combination of industry and science attendees (I15), although another respondent questioned whether it had achieved genuine industry–science exchange: 'the exchange of ideas from this sector … and academia was far, far less than it ever should've been' (I20 – Senior researcher).

7.3.3 International collaboration

Section 6.2.2 identified that international collaboration during the period from 2000 remained fairly steady across scientific publications, patents and projects, without a dramatic increase. This view was mirrored by the interviewees, who also identified the potential for much more international collaboration (n=4; 1, 19, 28, 31). We explore some of the underlying factors below.

7.3.3.1 UK culture of working independently and being inward-looking

An important barrier identified was the UK's perception that it was a world leader of wave energy technology innovation, meaning that it sought to tackle the wave energy challenge alone (n=2; I15, 16). This was reinforced by a culture of being inward-looking and failing to learn lessons from other countries and bias towards the merits of its own technology (n=3; 19, 28, 31). As one respondent explained:

> 'Scotland had an inward focus up until recently whereby it was all about, it must be invented [and] developed in Scotland … The challenge really has been that transition in mentality from 'not invented here' to embracing development worldwide and leveraging it' (I19 – Developer).

7.3.3.2 Funding programmes encouraging international collaboration

To tackle this inward-looking culture, RD&D funding schemes were established to encourage international collaboration (n=6, 3, 18-19, 26, 28, 32). For example, the EC's FP supported a significant amount of wave energy RD&D (Section 5.2.1.2) but to secure these funds a consortium must include at least three different legal entities from three different eligible countries (European Commission 2017d). Another example is the Scottish Government's WES, open to international applicants as it is 'about getting the best technology, no matter where it comes from' (I32 – Senior public servant). The caveat is that testing must happen in Scotland and there was a view that some companies were prepared to locate their operations in the UK and collaborate with UK firms to access these funds:

> 'A lot of these guys have said, "Well okay, we're based in Denmark, in Sweden, in the US, but ... We'll get this money, we'll move to the UK' (I28 – Innovation NDPB director).

A concern did however exist that Scotland faced a major challenge embedding the skills and knowledge generated by projects with international partners domestically, given the lack of requirement for these companies to remain active in the UK after the project (I19, 32):

> 'They pay to go into EMEC and they are gone. Not a lot of knowledge is retained in the UK as a result of that project' (I19 – Developer).

7.3.4 Inter-governmental coordination and knowledge exchange

A common criticism of the UK's wave energy innovation system was how complex and poorly co-ordinated the funding landscape was (n=9; I1, 10-11, 14; 17, 20, 22, 26, 31). Associated issues included a duplication of resources (n=3; I10-11, 14) *(resource mobilisation (F5))*: 'It's all been a bit fragmented and perhaps we've seen different schemes popping up, more or less trying to do the same' (I11 – Senior public servant). This is a view supported by our analysis of the UK policy landscape (Figure 7), which sees analogous initiatives established in parallel to support the same stage of innovation by both the UK and Scottish Governments. Examples includes MEAD and MRCF, as well as MRDF and WATES, the former supported by both the UK and Scottish Governments. This complex, fast-changing and poorly co-ordinated landscape also saw actors committing significant human resources simply to navigate it and identify suitable funding schemes, deflecting resources away from *knowledge development (F1)* and *entrepreneurial experimentation (F3)*. As one developer explained:

> 'How does a team of three people keep up to date with five or six different sources of funding, from DECC, [InnovateUK], Scottish Government etc.?' (I14 – Developer CFO)

7.3.4.1 Lack of a central over-arching body for energy technology innovation

An important reason for this lack of coordination was the lack of a central, over-arching funding body to channel and co-ordinate all UK energy innovation (n=2; I14, 26). Instead, the UK finds its wave energy RD&D funding split across numerous public bodies, operating across different geographies (i.e. regional, national, European), each with their own distinct set of objectives (n=4; I10-11, 17, 25) (Figure 7). In addition, funding agencies and government bodies were considered to be sufficiently autonomous that they had little imperative to work jointly with other bodies to achieve their objectives (I10–11): 'There is a lot they can do themselves. Therefore, why ... get embroiled in multi-partner collaborative structures, which can raise their own issues'? (I11 – Senior public servant). It was felt that devolution reinforced this dynamic in the UK, especially in Scotland (I10, 18, 31), splitting innovation funding powers across an even greater number of public bodies.

In a bid to improve the degree of co-ordination across governing bodies of wave energy innovation a host of cross-government co-ordinating networks have been established (n=6; 11, 14, 18 21-22, 32) (see Section 5.3.3). Of these the Wave Industry Programme Board was considered to have the most impact on wave energy support (see Section 5.3.3.3). As one board member explained, the convening of the WIPB led to the formation of WES: 'the culmination of an awful lot of learning' (I32 – Senior public servant).

There were examples of policy makers communicating directly with different layers of government when developing their own schemes, such as the Scottish Government, who invited a UK Government representative responsible for managing an array-focused demonstration scheme (i.e. MEAD) to sit on their advisory board for their own array demonstration scheme (i.e. MRCF) (I18). One respondent linked this desire for greater co-ordination to the increased pressure on government to make the most of public investment in innovation following public sector cutbacks in the aftermath of the financial crisis (I11). The overall consensus was neatly summarised by one policy maker, who explained that whilst there is:

> 'Still more to be done to provide a real coherent platform of different programmes and being clear about who is doing what … I think that it's fair to say that across the UK … all the major funding bodies have worked fairly close together … that allows cross-learning to go on' (I11 – Senior public servant)

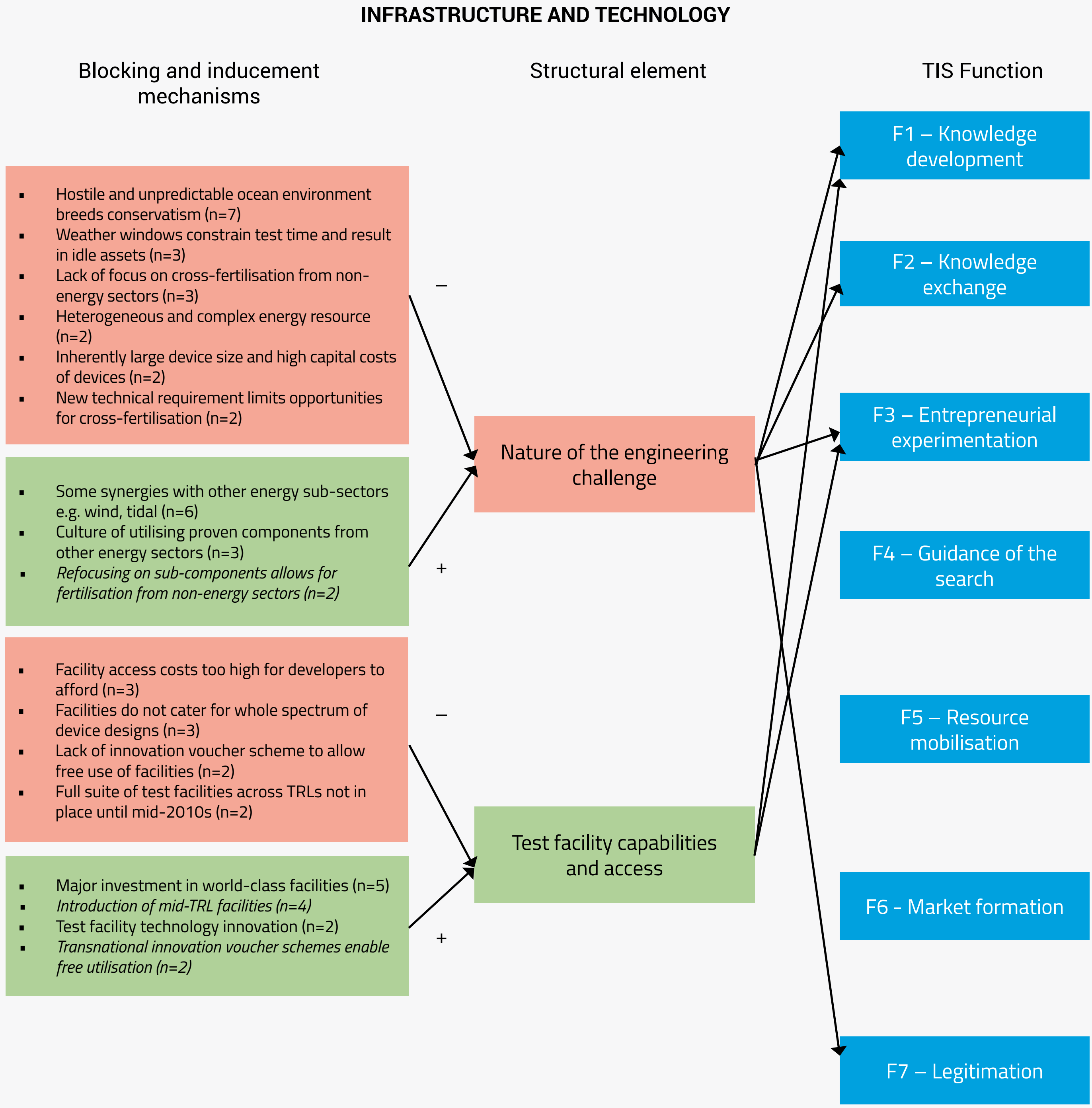
7.4 Technology and infrastructure

This sub-section examines how the technological characteristics of wave energy (Section 7.4.1) and test facility infrastructure (Section 7.4.2) served to support or undermine wave energy innovation and the underlying factors responsible for these, summarised in Figure 50.

The research finds that the unique characteristics of wave energy technology have, on balance, slowed the innovation journey, with developers having to work to tight weather windows and operate conservatively in hostile ocean environments *(knowledge development (F1))*; *entrepreneurial experimentation (F3))*. Additionally, despite efforts from companies such as Pelamis to integrate proven sub-components, wave energy represents a radically new form of energy technology and one that has therefore struggled to benefit from advances from other sectors to date, negatively impacting upon both *knowledge exchange (F2)* and the technology's *legitimacy (F7)*. Efforts are now being made to broaden the direction of the search and integrate expertise from non-energy sectors (e.g. automotive, materials science, commercial shipping, defence), primarily via WES.

UK wave energy test facilities were considered to be amongst the best in the world and underpinned many of the advances in wave energy technology *(knowledge development (F1))* and *(entrepreneurial experimentation (F3))*, echoing previous research (Jeffrey et al. 2014; Mclachlan 2010; Corsatea 2014). However, concerns were raised about the costs of accessing these facilities and the in-built bias of some facilities towards certain device designs. The biggest barrier raised was the lack of test facilities that filled the mid-TRL gap between small-scale prototypes and full-scale devices. In reaction to this state-of-the-art new generation wave tanks (e.g. FloWaveTT in Edinburgh) and open-ocean 'nursery' test sites offering less hostile conditions were commissioned to help fill this gap, meaning that today the UK has excellent test facility coverage across the innovation chain.

Figure 50: Overview of inducement and blocking mechanisms related to infrastructure and technology (source: author)



NOTE: Blocking and inducement mechanisms in italics are those which emerged in the period since 2000.

7.4.1 Technological characteristics and cross-fertilisation

This section considers how the unique characteristics of wave energy technology (see Section 2) pose a distinct set of innovation challenges compared to other energy technologies, both in terms of experimentation (Section 7.4.1.1), and technological cross-fertilisation (Section 7.4.1.2).

7.4.1.1 Inherent challenges of wave energy RD&D

A strong consensus existed that wave energy poses a unique and extremely difficult engineering challenge (n=11; I3, 5, 10, 12, 14, 19, 21, 24, 28-29, 31). At the broadest level, wave energy was considered to present a much more difficult engineering challenge than other technologies such as wind or tidal stream energy given the multi-dimensional forces at play:

> 'Wind and tidal are basically two-dimensional laminar flows, and so they've ended up with a propeller or a kite as the methods of energy capture. Wave is a circular particle motion, so it is more complex' (I14 – Developer CFO).

The heterogeneous wave energy resource across the onshore, nearshore and offshore environments was also identified as a challenge, each requiring a different device design to maximise resource capture (I3). The dimensions of WECs were also considered to be naturally very large, in turn making them very expensive, as they needed to match the wavelength of ocean waves to operate cost-effectively (n=2; I5, 24).

The most common issue identified was experimenting in such a hostile and unpredictable open-ocean environment (n=7; 10, 12, 14, 19, 21, 29, 31): 'That's the nature of the waves, you can't switch them off; they are destructive, and that makes it very challenging' (I12 – Consultant). This hostile environment was considered to make experimentation very costly for a number of reasons. First, devices must be engineered to withstand extreme conditions, constructing devices, for example, from high-cost durable materials such as steel. Second, the changeable and hostile conditions constrain testing to short 'weather windows' (n=3; I10, 19, 23), meaning that experimentation is limited to short periods of time and incurs 'stranded asset' costs when personnel and equipment (e.g. vessels) is idling. Referring to an analogous tidal stream installation, one interviewee explained that:

> 'The cable vessel was holed up for six weeks with the cable on board, waiting for a weather window to lay it ... [We] wasted probably the thick end of eight or nine months and £1m' (I10 – Test facility director).

Finally, the high-risk ocean environment was considered to breed a conservative approach towards device demonstration (n=3; 12, 14, 31) in a bid to avoid damage to very expensive prototypes. As one former developer explained:

> 'We just didn't let them see anything bigger than 10m waves. They're still big waves, but we made a risk-based decision not to do it because it was too likely they would all would get smashed up' (I31 – Consultant and former developer).

Again, comparisons were drawn with onshore wind, explaining that it had benefitted from much more extensive experimentation in the early years than wave energy because:

> 'pioneers were effectively able to build their prototype, put it up on a pole, test it the same week and break it. That would cost them the price of the materials' (I12 – Consultant).

7.4.1.2 Wave energy characteristically distinct from other technologies

Technologies such as tidal stream energy, offshore wind and offshore oil and gas, were identified as an important source of cross-fertilisation (n=6, I4, 9, 16, 19, 22, 30), a view echoed by technology needs assessments (Carbon Trust 2006; Ocean Energy Forum 2016; FREDS Marine Energy Group 2004; OEE 2013), especially in relation to enabling technologies (e.g. foundations) and operational methods (e.g. installation). However, wave energy was considered to be so distinct from other technologies that cross-fertilisation was difficult (n=2; I12, 31):

> 'We've looked at the benefits that can be applied from the outside ... but there is a new overall technical requirement here' (I31 – consultant and former developer).

In contrast, tidal stream energy was considered to have enjoyed a much stronger degree of cross-fertilisation, particularly from offshore wind given the analogous horizontal-axis turbine design. With reference to tidal stream developers, one respondent explained:

> 'These guys are able to learn from what's already been done in the wind industry, so there's a much more rapid sense of convergence. They're standing on the shoulders of giants you could say really, whereas in the wave industry it's very hard to find a parallel' (I12 – Consultant).

Strong efforts to harness learning from other energy sub-sectors were identified, most notably in the shift away from the approach in the 1970s and 1980s of developing a suite of bespoke sub-components and integrating these into a novel device focusing on integrating existing proven components into a novel device during the 2000s and 2010s (n=3; I5, 9, 31). This in turn helped to improve the *legitimacy (F7)* of wave energy by de-risking it because 'the stuff inside is more or less what's been used in the North Sea, in your vacuum cleaner or in your car' (I5 – Consultant). However, one interviewee did explain that developers had integrated existing components into devices not originally designed for the marine environment, and this contributed to underwhelming results or even device failures (I10).

Despite these efforts to harness lessons from other sectors, there was a view that wave energy did not fully take advantage of learning from non-energy sectors (n=3; I9, 22, 28), most notably the ICT, automotive, materials, science, shipbuilding and heavy manufacturing sectors, in part because of the 'siloed' approach of the UK to developing energy technologies.

In reaction to this, some technology foresighting exercises (SI Ocean 2012; Huckerby et al. 2011) identified potential synergies with other non-energy sectors and the establishment of WES explicitly sought to bring in expertise from these non-energy sectors, organising RD&D at sub-component versus device level (I26, 32), opening up potential collaboration with experts to develop sub-systems with relevance to other sectors (e.g. PTOs, materials, controls) (Section 7.3.1.3): 'WES is about getting the best technology, no matter where it comes from' (I32 – Senior public servant). Examples from WES include: (1) DuPont, a leading chemical company, partnering a project to assess the potential of using high performance thermoplastic elastomers for wave energy device structures; (2) Griffon Hoverwork, a hovercraft manufacturer, testing the use of deformable fabric/elastomeric structures for wave energy conversion; and (3) Romax Technology, a developer of gearbox, bearings and driveline systems for aerospace and transport sectors, helping deliver a PTO comprising a gearbox and generator for wave energy.

7.4.2 Marine energy test infrastructure

This section considers the capabilities of wave energy test facilities outlined in Section 5.4.1 and how developers' engagement with these has impacted upon the wave energy innovation process, especially with regards to *knowledge development (F1)* and *entrepreneurial experimentation (F3)*.

7.4.2.1 Test facility access costs

There was a view that some developers felt the costs to access wave energy test facilities were too high for developers to cover (n=3; I12, 14, 32): 'I would say the costs of testing at EMEC are very high … So typically at the moment it will cost you £300,000 I think to get a mooring, if I'm right' (I12 – Consultant). In contrast, other respondents explained that UK developers received excellent value for money considering that the alternative to establishing communal test facilities was for developers to construct their own facilities and cultivate their own testing expertise (n=3; I19, 21, 32), such as in Australia, where Carnegie Clean Energy had to establish their Fremantle wave energy research facility (Carnegie Clean Energy 2017):

> 'The cost of the developer doing it themselves is probably about £3m to get their own site ready, with grid connection … substantially more that it costs them to go to EMEC' (I32 – Senior public servant).

Associated with the costs of accessing these facilities was a criticism of the lack of an 'innovation voucher' scheme (n=2; I13, 15), providing developers with a pre-determined period of test facility time to test their device, such as the US wave energy prize, which provided time at a test facility as part of their funding award (I13). In the absence of such a scheme, UK developers had to secure public funds via open competitions and the associated levels of private sector match funding in order to cover both their device development and testing costs, entailing significant amounts of time that could be spent developing their technology (I13–14). Consequently, some developers struggled to secure the necessary private sector funds to utilise test facilities after the financial crisis (Section 7.2.3.1) (I14). This model was attributed more widely to the UK Government's willingness to provide capital expenditure (CAPEX) to establish the test facilities but not the operational expenditure (OPEX) (I13, 32), likened to 'the batteries aren't included' (I13 – Test facility director) philosophy, an issue identified in previous research (Skea et al. 2013).

The lack of an innovation voucher scheme was in part attributed to the EU State Aid 'de minimus' rules[48] (Section 7.2.3.1) which limit the amount of government-funded 'test time' government can offer developers (I13). It was also attributed to the fact that the test facilities were set up by government as private sector entities to insulate government from financial risk, meaning that they were not legally incorporated to offer government subsidised testing (I14, 32).

Europe-wide voucher schemes for marine energy test facilities were established to help address this issue, including MARINET and FORESEA (Section 5.3.1.4), which provide eligible developers from across Europe with free access to facilities in other countries (n=2; I13, 15). However, through MARINET, developers cannot access infrastructure in their own country of work (Healy 2013) (I15), meaning that UK-based companies cannot test their devices in UK facilities, which rank amongst the best in the world. In contrast, FORESEA does allow UK developers to access UK facilities but operates a relatively small budget and does not cover on-shore test facilities (e.g. test tanks) (FORESEA 2017).

7.4.2.2 Coverage of facilities across innovation chain

Overall, the UK's marine test facilities were generally considered to be world-class (n=5; I9, 13–14, 22, 29, 32), offering wave energy developers unparalleled technical support to develop their technologies, both in simulated environments via test tanks (e.g. FloWaveTT) and open-sea test centres (e.g. EMEC, WaveHub) (Section 5.4.1). Despite these strengths a common criticism was the lack of test tank facilities to enable onshore testing in simulated ocean environments of mid-TRL devices during the 2000s and early 2010s, in turn leading to very costly failures during open-ocean testing that seriously undermined investor confidence in the technology:

> 'People had no choice, [they] went to a … big rectangular tank with a one directional wave … then they cut steel and built something to go in the water and it broke' (I13 – Test facility director).

To fill the gap between test tanks offering 1:50 scale testing and open-ocean facilities offering full-scale testing, more advanced onshore facilities were commissioned to larger scale testing (n=4; I13-14, 20, 32), such as FloWaveTT in Edinburgh in 2014, which offered testing up to 1:10 scale, and the opening of nursery open-ocean sites, at, for example, EMEC in 2011, offering part-scale testing (approx. 1:4 scale) (Section 5.4.1). The view was that with the introduction of these intermediate TRL test facilities, 'all the stepping stones are [now] in place … facilities like FloWave are a last step before you step off the beach … EMEC is the place you go to next' (I13 – Test facility director).

48 State aid is limited to less than €200,000 over three years (BIS 2015a) and aid intensity (i.e. intervention rate) to between 25% and 80%, depending on the organisation's size (BIS 2015b).

Despite these new facilities being welcomed, there was a view that a significant delay had taken place in delivering these intermediate stage test facilities (n=2; I20, 25), especially given that these had followed rather than preceded full-scale test facilities (Figure 10): 'So we've got the TRL 1–4 facilities and infrastructure coming online ... a decade after the full scale at sea testing facilities came on line' (I25 – Innovation NDPB manager). To help explain this delay, one respondent explained how test facilities such as FloWaveTT are themselves an outcome of a technology innovation journey that has run in parallel to wave energy (Section 5.4.2.1) (I5, 13). As one former researcher who had worked with Stephen Salter, a pioneer of wave energy, during the first phase of wave energy innovation in the 1970s and 1980s, explained:

> '[He] quickly realised that he needed to invent some other things in order to make the research possible. One of those things was wave tanks ... If it occurred now, you would already have facilities ... because we developed them' (I5 – Consultant)

7.4.2.3 Coverage of different device designs

Despite the world-class capabilities of UK test facilities, some concerns existed that the test facilities did not suit the whole spectrum of technological variants (n=3; I9-10, 14). For example, WaveHub's facility offers an underwater electrical hub and cable system that requires devices to generate electricity offshore rather than pump pressurised fluids onshore to then drive a turbine; a process that Carnegie, Seatricity and Aquamarine devices employ (I9). Another example was the hostility of the conditions to which devices were subject at the UK's test facilities, which suited some devices but not others (I10, 14). One respondent explained that the two wave regimes of the full-scale and nursery sites at EMEC were not best suited to their device, highlighting that the full-scale test facility offered:

> 'very big waves [that] our current device is not built to withstand', whilst the nursery site offered 'a relatively sheltered location [that] gives us the kind of wave conditions that we want to test less than 5% of the time' (I14 – Developer CFO)

As one respondent explained, it was very difficult to design a test facility when 'there was no clear idea of what it needed to look like' (I32 – Senior public servant), given that there was no consensus amongst developers about what the dominant device design was going to be, meaning that design decisions had to be made that were inevitably biased towards or against certain device designs (I14).

8

Conclusions and policy recommendations

8.1 Synopsis

Almost 20 years after the UK's first wave energy innovation programme came to an end in the 1980s, a new programme to accelerate the development of wave energy technology was launched at the turn of the century. This was grounded in the belief that wave energy could play a central role in helping to deliver a low-carbon, secure and affordable energy system, as well as provide an important boost to the UK's economy through the growth of a new domestic industry. However, despite investment of almost £200m of public funds in UK-based wave energy-related RD&D since 2000, the technology remains some distance away from commercialisation. In this context, this report examines the extent to which this failure to reach commercialisation can be attributed to weaknesses in both government and industry's strategy to support wave energy innovation in the UK.

By mobilising a Technology Innovation System (TIS) analytical framework this report finds that wave energy's failure to reach market can, in part, be attributed to weaknesses in both government and industry's approach to supporting wave energy innovation in the UK. However, a concerted effort to learn from past policy mistakes, led primarily by the Scottish Government, has resulted in a major reconfiguration of the wave energy innovation system that has helped to address many of these issues. Consequently, today, we find an innovation support framework that is much better placed to deliver a commercial wave energy device. Even so, this newly configured system is likely to face severe disruption in the face of the UK's withdrawal from the EU and the UK Government's shift away from supporting wave energy, both of which are likely to have a major impact on the level and type of RD&D support on offer for wave energy.

8.2 Key findings

Looking back, one of the most critical barriers to wave energy innovation was a fundamentally over-optimistic view, on the part of government and industry, of how quickly wave energy could be commercialised. As a result, the wave energy sector sought to 'fast track' wave energy technology towards commercialisation, focusing its efforts on later stage innovation. This can be illustrated by the raft of government RD&D funding schemes and test facilities that emerged during the mid-2000s, shortly after the UK had re-established its wave energy programme, which were geared explicitly towards full-scale demonstration. The implication was that, whilst almost £200m has been committed to wave energy-related RD&D since 2000 excluding test infrastructure, and over a third of this (£69m) was awarded to support late-stage technology demonstration rather than earlier stage R&D.

This strong focus on quickly commercialising wave energy was exacerbated by the entry of market incumbents from the mid-2000s onwards, including the energy utilities, OEMs and VCs, who were attracted by wave energy's potential to deliver grid-scale low-carbon electricity generation and be exported internationally as it utilised a global renewable energy resource. In a bid to secure the private sector match funding they needed to access public subsidies, developers presented an over-optimistic view of how quickly wave energy could reach commercial application to market incumbents in order to attract investment. In turn, many developers failed to fulfil investors' expectations against the ambitious targets, seriously damaging the legitimacy of wave energy technology. Examples of slow progress include a lack of convergence around a single design, as well as a recent decline in the level of installed capacity and the power rating of wave energy devices.

As investors and government lost confidence in the technology and the financial climate became more challenging following the 2008 financial crisis, funds were withdrawn. This is especially true in the case of the UK Government, which saw its funding fall by over a third in 2016 from its peak in 2011. These factors presented wave energy developers with an increasingly difficult financial environment within which to operate. Consequently, both Pelamis and Aquamarine Power, the two market leaders at the time, ceased trading between 2014 and 2015 respectively, further damaging the legitimacy of the sector. From this point, the UK Government began to step back from wave energy, leading to its share of funding dropping from an average of 47% between 2000 and 2016 to just 31% in 2016. In contrast, the EU and the Scottish Government continued to increase their share of support for the technology.

Crucially, the failure of leading developers also triggered a major structural reconfiguration of the wave energy innovation system, informed by the lessons learnt since 2000 about which policy approaches were deemed successes and failures. This included the introduction of new test infrastructure to enable mid-TRL testing (e.g. FloWaveTT), transnational free access to test facilities (e.g. MARINET), centres for industry–science excellence (e.g. OREC), doctoral training networks (e.g. IDCORE) and cross-innovation chain funding programmes (e.g. EC).

The most significant change has been the introduction of WES by the Scottish Government, designed to explicitly address many of the weaknesses associated with previous government policy. For example, a requirement was placed on developers to licence IP and a sub-component focus was brought in to promote collaboration, with investment made in knowledge capture to learn lessons from the past, and a stand-alone stream for wave energy funding set up to avoid the sector being crowded out by more mature technologies. A 100% intervention rate was also introduced to avoid the pressures associated with wave energy developers having to secure before private sector investment. Together, these structural changes to the UK wave energy innovation system demonstrate a clear ability and willingness from government to act upon lessons generated from evidence-based policy learning.

Whilst some key policy-related issues continue to face wave energy innovation, such as lack of policy co-ordination between funding bodies across different layers of government (i.e. devolved administrations, the UK and EU) and lack of a clear long-term strategy to deliver a commercial device, our analysis finds that this reconfiguration of the UK's support for wave energy created a system much better placed to deliver a commercial technology than before. For example, a measurable improvement across some key innovation indicators has already been detected, such as the degree of technology cross-fertilisation and industry–science collaboration. However, time lags between cause and effect mean the overall impact of this reconfiguration on the UK's wave energy innovation performance will not be evident for a few years, especially for indicators such as installed capacity and cost of electricity. This emphasises the importance of ongoing monitoring of the UK's wave energy innovation performance.

Given that it will take time for the impact of this innovation system reconfiguration to take effect, the focus for policy makers should be on consolidating this newly configured innovation system and avoiding a major overhaul until it has had time to take effect. This will, however, be challenging given that Brexit could halt the UK's access to EU RD&D funding programmes, which has accounted for a third of UK wave energy RD&D funding since 2010. This, coupled with the UK's recent shift towards supporting RD&D for technologies other than wave energy, means that Scotland faces the very real possibility of leading the development of wave energy alone. Should this situation arise, it is unlikely to deliver the critical mass of financial and political support required to commercialise wave energy, especially when we consider the relatively small RD&D budget the Scottish Government controls and the billions of dollars of global investment it has required to commercialise other enewable energy technologies such as wind energy and solar PV.

8.3 Policy recommendations

In light of the research's key findings, we present ten policy recommendations to help improve the effectiveness of the UK's future support for wave energy innovation and help accelerate the technology's journey towards commercialisation.

1. **Retain access to EU innovation funding post-Brexit** – Brexit poses a major risk to EU wave energy funding, accounting for 27% (£53m) of all wave energy-related RD&D committed since 2000, and in 2016 EU funding (£6.3m) was greater than that from the UK Government (£6m). It is essential that the UK retains access to EU innovation funds following Brexit negotiations, especially EU Framework Programmes (FPs) (i.e. Horizon2020). Exiting from the EU will also remove the UK's primary platform for international RD&D collaboration, making it necessary to identify alternative ways to collaborate internationally to achieve the critical mass of resources and expertise necessary to commercialise wave energy, possibly via new international platforms such as Mission Innovation.[2]

2. **Allow time for new UK wave energy innovation policy landscape to take effect** – The UK wave energy innovation system has undergone a major reconfiguration over the past few years and the effects of this have not yet been fully felt. This new configuration must be given time to take effect before its efficacy is critiqued and decisions made to engage in any additional wide-scale restructuring.

3. **Develop a long-term Scottish wave energy strategy in a new political order** – With the UK Government significantly reducing its support for wave energy and the threat of EU funds being withdrawn after Brexit, the Scottish Government could find itself acting alone in developing wave energy technology. Consequently, a strategy must be put in place that presents a credible path towards delivering a commercial wave energy device in Scotland that is resilient to the potential withdrawal of UK Government and/or EU funds. This should situate the development of wave energy in the context of a wider portfolio of energy technologies that the Scottish Government has identified as playing a key role in the future as part of its recent energy strategy (Scottish Government 2017c) and outline the steps required to integrate the various sub-components developed by the WES programme into a single, commercial device.

4. **Improve co-ordination of UK energy innovation policy landscape** – There are still significant opportunities to improve the degree of co-ordination of wave energy RD&D support both within and across different levels of government. It remains to be seen how effective the UK's newly formed EIB and UKRI will be in co-ordinating energy RD&D investment at UK level. It is recommended that, to ensure co-ordination with bodies operating at different levels of government, these new networks engage closely with both the devolved administrations (e.g. the Scottish Government) and the EU. Furthermore, a top-down body responsible for wave energy at UK level, similar to Scotland's WES model, could also improve co-ordination of wave energy RD&D.

5. **Share and synthesise lessons from past and present wave energy innovation programmes** – Outputs from publicly funded later stage wave energy RD&D projects have not traditionally been made available for public consumption because of issues around IP protection and private sector match funding. In contrast, the Scottish Government's WES programme and the EU's FPs require awardees to share their key findings via project reports, enabling the wider sector to learn lessons from past projects and avoid making the same mistakes. It is critical that this approach is applied across all future publicly funded wave energy RD&D programmes in the UK and efforts should also be made to capture knowledge generated from past public RD&D projects, expanding upon WES's current knowledge capture exercise.

6. **Acknowledge that support for wave energy has been historically low and intermittent** – Since 1974, ocean energy has been allocated approximately $1.8bn[3] of IEA members' public energy RD&D budget versus $25bn for solar PV and $7.5bn for wind energy. Furthermore, funding for wave energy has been much more intermittent than most other energy technologies, split across two phases during the 1970s and 1980s and the 2000s and 2010s, increasing the likelihood of significant knowledge depreciation between these periods of concentrated investment. In this context, key policy decisions should

49 Through Mission Innovation, 22 countries and the EU are taking action to double their public clean energy R&D investment over five years. In addition, Mission Innovation members encourage collaboration among partner countries, share information and co-ordinate with businesses and investors.
50 Includes all forms of ocean energy, not just wave energy.

be made against the backdrop that wave energy has not enjoyed the same level or consistency of RD&D support in comparison to more mature renewables such as wind and solar energy.

7. **Avoid competition for subsidies with established low-carbon energy technologies** – Emerging technologies, such as wave energy, can be out-competed for subsidies on a cost basis when in direct competition with significantly more mature technologies. Specific examples include separating wave energy from the same EMR CfD allocation as significantly cheaper technologies such as offshore wind energy and avoiding wave energy becoming bundled into wider marine energy RD&D programmes where it must compete with more mature technologies such as tidal range and tidal stream.

8. **Avoid need for private sector match funding to support wave energy RD&D** – The need to secure private sector investment to be awarded public grants has placed intense pressure on wave energy developers to 'fast track' their innovation timeline and avoid knowledge exchange in a bid to protect their IP. Furthermore, the financial crisis and wave energy's slow progress saw private sector funds become more difficult to secure, in turn making access to public funds difficult. State aid compliant procurement frameworks such as WES can avoid the need for private sector match funding, offering a 100% intervention rate. Opportunities should be explored to apply this procurement model more widely, not just for wave but for other energy technologies.

9. **Support wave energy niche market formation** – A shift towards demonstrating wave energy devices in niche markets (e.g. off-grid islands, aquaculture) enables developers to learn valuable lessons through 'learning by doing' in both real-world ocean and market environments, as well as providing both government and investors with greater confidence in the technology's prospects. When wave energy is ready for full-scale demonstration, funds for wave energy RD&D should facilitate deployment in 'real-world' niche markets. However, funds should be awarded to developers that present an evidence-based roadmap that outlines how their technology can progress beyond small-scale niche application and towards wide-scale deployment.

10. **Enable easy access to wave energy test facilities** – Access to the UK's world-class test facilities has required developers to secure public sector funds via open competitions, and the corresponding levels of private sector match funding. This process involves significant time and effort, channelling developers' resources away from RD&D. To ensure developers can quickly and easily access these facilities, a state aid compliant UK-wide 'innovation voucher' scheme should be established to enable 'free at the point of use' access to those that have passed through preliminary stage-gated phases of development with independently verified positive results, building upon lessons learnt from the Europe-wide est infrastructure access schemes such as FORESEA and MARINET.

8.4 Wider lessons to support energy technology innovation

We draw a number of broader lessons from the case of UK wave energy innovation in order to improve our understanding of how energy technology innovation unfolds and how it can best be supported. This will help to inform both the design of energy innovation policy and development of innovation theory.

1. **Innovation systems can become destabilised and reconfigured** – Traditionally, TIS evolution has been considered to follow a broadly linear and positive development trajectory, incorporating two main phases: *formation and growth* (Bergek, Jacobsson, et al. 2008a). The case of wave energy highlights how a TIS may indeed follow a non-linear and more challenging development path involving distinct phases such as: (1) *disintegration*, in the face of destabilising forces such as the failure of market leaders and the withdrawal of government funds; (2) *reconfiguration* of structural elements potentially in a concerted effort to improve the efficacy of the TIS in reaction to system failures; and/or (3) *stagnation*, where a prolonged period of little investment results in low levels of activity, possibly inducing knowledge depreciation, but where investment is sufficiently high to preserve some key aspects of the TIS (e.g. research institutes, test facilities).

2. **Test infrastructure innovation co-evolves with energy technology innovation** – To date, the role of infrastructure in the technology innovation process has normally been characterised as one enabling technology deployment – for example, via integration with existing electricity networks (Gallagher et al. 2006). However, this research identifies the key role test facilities play in enabling technology innovation. Furthermore, the research finds that test infrastructure is subject to a process of innovation similar to that of the technologies of which it enables testing (e.g. wave energy). Crucially, test infrastructure also co-evolves with the technologies it is designed to test. Devices are designed with test facility capabilities in mind, whilst test facilities are designed around the key characteristics of emergent device designs.

3. **Technology innovation relies on policy innovation** – The research finds that government reflected upon and learned lessons from the successes and failures of past wave energy policy, using these to inform the design of its current policy framework. Paramount to successful energy innovation policy making is the iterative process of policy design, experimentation, 'learning by doing' and subsequent refinement based on lessons learnt, which represents its own discrete form of innovation (Petmesidou & Gonz 2015; Mintrom 1997). This process of policy innovation is reliant upon the presence of personnel with the capacity and appetite to develop innovative policies (i.e. policy entrepreneurs) (Petmesidou & Gonz 2015), as well as intra- and inter-organisational networks that enable knowledge exchange and a culture that rewards policy innovation rather than discouraging it.

4. **Devolution creates a complex but diverse innovation system** – Whilst research has considered how innovation policy unfolds in regions subject to multiple layers of governance (Sotarauta & Kautonen 2007; Kuhlmann 2001) little work has examined how devolution impacts upon the evolution and performance of an energy innovation system. The case of wave energy is inextricably linked with devolution in the UK both upwards to the EU and downwards to devolved administrations such as the Scottish Government. On the one hand, devolution has led to a complex, multi-level energy innovation governance framework that has created difficulties in terms of co-ordination and policy landscape navigation. On the other, it has created diversity, meaning that the UK Government's move away from wave energy has not entirely dictated the fortunes of wave energy, with support continuing to flow from the EU and Scottish Government. Furthermore, Scottish Government, the smallest and most agile of the three governments, demonstrated the strongest ability to learn from past policy performance and translate this into action.

5. **Innovation relies on the capture and codification of tacit knowledge** – The case of wave energy identifies that, too often, tacit knowledge (i.e. 'know-how') was lost when companies ceased trading, personnel moved on or knowledge was stockpiled due to confidentiality issues. Successful technology innovation relies on tacit knowledge being codified and, wherever possible, shared. However, it should be acknowledged that some tacit knowledge cannot easily be codified, making it difficult to transfer or 'sticky' (Hippel 1994; Brodbeck & Polanyi 1960). Finally, codification can help protect against knowledge depreciation during periods of relatively low RD&D funding (Wilson & Grübler 2014), as was the case for UK wave energy during the 1980s and 1990s.

6. **Competition and collaboration must be balanced according to stage of innovation** – The case of wave energy supports the need for a balance between competition and collaboration or closed and open innovation (Chesbrough 2003). It points to the need for a stronger emphasis on collaboration during the earlier TRLs to ensure technology developers do not operate in isolation but instead benefit from knowledge sharing and the pooling of human and financial resources. As the technology moves closer to market, the emphasis may gradually shift towards competition in a bid to encourage convergence around a single optimal device design. Even so, it is important that areas for collaboration are clearly demarcated and built on sectoral consensus, with suitable platforms put in place to facilitate collaboration (e.g. JIPs).

7. **Regional innovation clusters offer a locus for market formation** – A growing body of literature points to the importance of 'regional innovation clusters', which constitute a geographical concentration of key structural elements underpinning innovation (e.g. actors, institutions, networks, infrastructure), facilitating key innovation functions such as knowledge exchange and market formation (Muro & Katz 2010). The wave energy case study supports this view in the examples of the EMEC and the University of Edinburgh, which have formed centres of excellence with their own entrepreneurial ecosystems. Consideration must therefore be given to where and how regional energy innovation clusters will be established and opportunities to build these around test facilities, which already see a high concentration of actors, resources and infrastructure (e.g. grid connection).

8. **Protected spaces help to shield emerging technologies from competition against mature technologies** – To avoid emerging technologies becoming 'crowded out', it is essential that they are not in direct competition with more established technologies for the same RD&D funding. This finding supports the view outlined in the socio-technical transitions and strategic niche management literature that emerging technologies should be protected by the formation of 'sheltered spaces' such as niche markets (Schot & Geels 2008), enabling gradual technological maturation through 'learning by doing' and 'learning by using', as well as improving stakeholders' confidence in the technology via successful real-world deployment.

9. **Characteristics of technology influence its innovation journey** – The case of wave energy points to the unique technical challenges it has faced, such as the need to test in a very hostile ocean environment and the lack of synergies with established technologies. It is critical that, when comparing the progress of different energy technologies, their respective characteristics are acknowledged because these will shape the pace and nature of their development trajectory. This echoes research by Nemet (2014) who identified how smaller, modular energy technologies (e.g. solar PV) tended to benefit from a faster rate of learning versus large, site-assembled technologies (e.g. nuclear) because they underwent a much larger number of iterations due to their lower costs and build times.

8.5 Recommendations for future work

We highlight a number of priorities for future research, beginning with wave and marine energy-specific work, before turning to research on energy technology innovation more broadly.

8.5.1 Wave and marine energy innovation

First, in light of the major structural changes to the UK's wave energy innovation system, it is important that the UK's innovation performance is closely monitored over the coming years to assess whether these changes have resulted in a net positive or negative impact on performance. Quantitative assessment is the first step in measuring changes in innovation performance, and should be complemented by qualitative research to identify the factors underlying these changes and the extent to which they are coupled with the observed structural developments.

Second, this report has adopted a sectoral-level focus and future research would benefit from comparing and contrasting a host of detailed firm-level case studies of wave energy developers , both past and present. This would offer valuable insight into how and why developers took the strategic decisions they did within the context of wider sectoral developments (e.g. political, economic).

Third, the research has drawn some valuable comparisons between the progress of both wave and tidal stream energy in the UK. Future work would usefully examine, in similar detail to this report, how and why the UK's tidal stream sector has grown. It would offer a complementary focus to wave energy as tidal stream is generally considered to be at a more advanced stage, and would offer useful insights into the challenges facing a technology closer to commercialisation, such as securing large-scale project finance and array deployment.

Finally, this report has focused explicitly on UK wave energy RD&D, with little attention paid to developments internationally. It is essential that, to identify best practice wave energy innovation policy, this study of the UK's wave energy innovation system is compared with those of other countries. This should involve an international quantitative assessment of wave energy performance, followed by a series of mixed-method country case studies which examine why some countries are performing better than others in both absolute and relative terms, in turn helping to inform policy design. This would build upon the excellent work conducted by the EC's Joint Research Council (Magagna et al. 2016; Magagna & Uihlein 2015)

8.5.2 Energy technology innovation

This study has examined the development of just one energy technology within one country. However, to identify best practice energy innovation policy, it is essential that a systematic comparison of a range of different energy technology case studies across different countries is conducted, utilising a standardised methodology to enable cross-case comparison. Building upon the methodology employed in this study, and the valuable work conducted by Wilson and Grübler (2014), this should mobilise a mixed-method approach with a robust analytical framework that adopts a long-time horizon to ensure that long-term trends in energy technology innovation are accounted for.

Second, another valuable strand of research would be to utilise quantitative energy innovation indicator sets (see Bento & Wilson 2016; Hillman et al. 2011; Hu et al. 2017) to offer a cost-benefit analysis of innovation policy frameworks, comparing innovation inputs (e.g. RD&D investment) and outputs (e.g. levelised cost of electricity, unit cost, installed capacity) and/or outcomes (e.g. CO_2 emission reduction, job creation). If this economic assessment was conducted internationally, it might be possible to identify the countries with the most effective innovation systems for certain energy technologies, as demonstrated by Hannon and Van Diemen (2016) for ocean energy, in turn presenting a focus for more detailed case study research. It is essential that any such analysis goes beyond this study, taking into account both public and private RD&D investment, utilising private RD&D investment available from datasets such as Bloomberg New Energy Finance.

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Appendix A – List of interviewees

Interviewee number	Position	Organisation	Former role	Date
1	Senior researcher	University	Engineer at wave tank manufacturer	03/03/2015
2	Director	Wave energy technology developer	-	01/04/2015
3	Researcher	University	Engineer at energy utility	01/04/2015
4	Senior researcher	University	-	01/04/2015
5	Director	Consultancy	University researcher	16/04/2015
6	-	-	Senior public servant	16/04/2015
7	Manager	Renewable energy trade association	-	21/04/2015
8	Director	Multi-national oil and gas company	Energy innovation NDPB manager	13/05/2015
9	Manager	Wave energy technology developer	-	13/05/2015
10	Director	Marine energy test facility	Former engineer at oil and gas company	05/08/2015
11	Senior public servant	Government development agency	-	09/09/2015
12	Managing director	Consultancy	Engineer at energy utility	11/09/2015
13	CEO	Marine energy test facility	Engineer at technical consultancy	14/09/2015
14	CFO	Wave energy technology developer	Finance director	14/09/2015
15	Senior researcher	University	-	14/09/2015
16	Senior researcher	University	Engineer at wave energy technology developer	14/09/2015
17	Director	Energy innovation NDPB	-	16/09/2015
18	Senior civil servant	Government	-	16/09/2015
19	CEO	Wave energy technology developer	Environmental consultant	16/09/2015
20	Senior researcher	University	-	18/09/2015
21	Managing director	Consultancy	Director at wave energy technology developer	18/09/2015
22	Manager	Energy innovation NDPB	Employee of energy utility	18/09/2015
23	Manager	Public estate agency	-	18/09/2015
24	Director	Consultancy	Director at energy utility	19/09/2015
25	Manager	Energy innovation NDPB	Manager at energy utility	19/09/2015
26	Manager	Energy innovation NDPB	-	19/09/2015
27	Director	Energy innovation NDPB	-	19/09/2015
28	Director	Energy innovation NDPB	Engineer at OEM	23/09/2015
29	Director	Energy innovation NDPB	Consultant in defence sector	23/09/2015
30	CEO	Wave energy technology developer	Entrepreneur	23/09/2015
31	Managing director	Consultancy	Director of wave energy technology developer	28/09/2015
32	Senior public servant	Government development agency	-	02/10/2015
33	Director	Government investment bank	-	02/10/2015

Appendix B – Breakdown of technology innovation chain

Technology innovation activity	TRL description	TRL	Description of wave energy-relevant RD&D activities
Basic research	Experimental or theoretical work undertaken primarily to acquire new knowledge of the underlying foundations of phenomena and observable facts, without any particular application or use in view.	1	**Basic principles observed and reported** - Lowest level of technology readiness. Scientific research begins to be translated into applied research and development.
		2	**Concept and/or application formulated** - Once basic principles are observed, practical applications can be invented. Applications are speculative and there may be no proof or detailed analysis to support the assumptions.
Applied research	Original investigation undertaken to acquire new knowledge. It is, however, directed primarily towards a specific, practical aim or objective.	3	**Analytic proof of concept and small-scale experimental** - Active research and development is initiated, including analytical, engineering and laboratory studies to physically validate analytical predictions of separate elements of the technology.
		4	**Functional proof of concept** - Basic technological components are integrated at a smaller scale to validate design predictions and system level functionality.
Experimental development	Systematic work, drawing on knowledge gained from research and practical experience and producing additional knowledge, directed to producing new products or processes or to improving existing products or processes.	5	**Component/sub-system/system integration, testing and validation** - Basic technological components are integrated to establish that they will work together so the system can be tested in a simulated environment.
		6	**Prototype model test facility** - Validation. Representative model or prototype system, well beyond that of TRL5, tested in a relevant environment. Represents a major step up in a technology's demonstrated readiness.
Demonstration	Design, construction and operation of a prototype of a technology at or near commercial scale with the purpose of providing technical, economic and environmental information to industrialists, financiers, regulators and policy makers.	7	**Open-water system test and validation** - Prototype near, or at, planned operational system. Represents a major step up from TRL6, requiring demonstration of an actual system prototype in an operational environment.
		8	**System demonstration/operational verification** - Technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development.
Deployment	System ready for full-scale commercial deployment.	9	**Actual system proven through successful operations** - Actual application of the technology in its final form and under mission conditions, such as those encountered in operational test and evaluation.
Test infrastructure	-	-	Full-scale test centre infrastructure to facilitate the testing and verification of technologies in an open-ocean environment.
Knowledge exchange	-	-	Initiatives to promote knowledge transfer specifically focused on supporting the development of the sector (e.g. research networks).
Training	-	-	Initiatives to promote training specifically focused on supporting the development of the sector (e.g. CDTs)

NOTE: Generic TRL descriptions are taken from the Frascati Manual (OECD 2015) and the wave energy-specific activities relating to each TRL from Jeffrey et al. (2014).

Appendix C – List of major UK-eligible public funding programmes for wave energy innovation

Innovation Stage	Programme	Level of government	Funding body	Coverage	Start of funding	End of funding	Funding Type	Public budget[1]
Early	Marine Renewable Energy Programme (NERC MREP)	UK	NERC and DEFRA	Marine energy	2010	2014	Supply push – grant	£2.4m
Early	UK Centre for Marine Energy Research Centre Grand Challenges (UKCMER)	UK	EPSRC	Marine energy	2011	2017	Supply push – grant	£6m
Early	Small Business Research Initiative Greenius	UK	InnovateUK	Sustainable development	2013	2013	Supply push – grant	N/A
Early to mid	SMART Scotland	Scotland	Scottish Enterprise	Economy wide	1999	Ongoing	Supply push – grant	N/A
Early to mid	Carbon Trust Applied Research	UK	Carbon Trust	Energy	2003	2008	Supply push – grant	N/A
Early to mid	Marine Energy Challenge (MEC)	UK	Carbon Trust	Marine energy	2004	2006	Supply push – grant	£3m
Early to mid	Marine Energy Accelerator (MEA)	UK	Carbon Trust	Marine energy	2007	2010	Supply push – grant	£3.5m
Early to mid	Innovation Vouchers	UK	InnovateUK	Economy wide	2013	Ongoing	Supply push – grant	N/A
Early to mid	Emerging Energy Technologies (EET)	UK	InnovateUK; EPSRC	Energy	2014	2014	Supply push – grant	N/A
Early to late	Wave Energy Scotland (WES)[2]	Scotland	Highlands and Islands Enterprise	Wave energy	2015	Ongoing	Supply push – grant	£24.6m
Early to late	Wave and Tidal Stream Energy Technologies: Underpinning Deployment (WTSET UD)	UK	InnovateUK	Marine energy	2011	2013	Supply push – grant	£3m
Early to late	Energy Catalyst	UK	Innovate UK; EPSRC; DECC/ BEIS	Energy	2015	Ongoing	Supply push – grant	N/A
Early to late	European Structural Funds	EU	European Commission	Economy wide	1958	Ongoing	Supply push – grant	N/A
Early to late	European Framework Programmes	EU	European Commission	Economy wide	1984	Ongoing	Supply push – grant	N/A

Innovation Stage	Programme	Level of government	Funding body	Coverage	Start of funding	End of funding	Funding Type	Public budget[1]
Mid	Marine Energy: Supporting Array Technologies (MESAT)	UK	InnovateUK; NERC	Marine energy	2012	2016	Supply push – grant	£10.5m
Mid to Late	New and Renewable Energy Programme	UK	DTI	Energy	1999	2005	Supply push – grant	N/A
Mid to late	Energy Technology Institute Marine Energy Programme (ETI MEP)	UK	DECC/BEIS and industry	Marine energy	2007	Ongoing	Supply push – grant	£17.1m
Mid to late	Wave and Tidal Stream Energy Technologies: Reducing Costs & Improving Performance (WTSET RCIP)	UK	InnovateUK	Marine energy	2010	2016	Supply push – grant	N/A
Mid to late	Energy Entrepreneurs Fund	UK	DECC/BEIS	Energy	2012	Ongoing	Supply push – grant	N/A
Late	Wave and Tidal Energy: RD&D Support (WATERS)	Scotland	Scottish Enterprise	Marine energy	2010	2016	Supply push – grant	£12m
Late	Marine Farm Accelerator (MFA)	UK	UK Government	Marine energy	2013	2016	Demand pull – Joint Industry Project	N/A
Late	Infrastructure for Offshore Renewables (I4OR)	UK	InnovateUK	Offshore renewable energy	2014	2014	Supply push – grant	N/A
Late	Ocean ERA-NET	EU	European Commission	Marine energy	2014	Ongoing	Supply push – grant	€24m
Late	New Entrants Reserve 300 (NER300)	EU	European Commission	Energy	2014	Ongoing	Supply push – grant	N/A
Late to commercial	Wave and Tidal Energy Scheme (WATES)	Scotland	Scottish Enterprise	Marine energy	2006	2008	Supply push and demand pull – grant plus revenue payment	£13m
Late to commercial	Marine Renewable Commercialisation Fund (MRCF)	Scotland	Scottish Government	Marine energy	2013	2016	Supply push – grant	£18m
Late to commercial	Marine Renewable Deployment Fund (MRDF)	UK	DECC/BEIS	Marine energy	2006	2008	Supply push and demand pull – grant plus revenue payment	£50m

Innovation Stage	Programme	Level of government	Funding body	Coverage	Start of funding	End of funding	Funding Type	Public budget[1]
Late to commercial	Marine Energy Array Demonstrator (MEAD)	UK	DECC/BEIS	Marine energy	2012	2016	Supply push – grant	£20m
Commercial	Marine Supply Obligation (MSO)	Scotland	Scottish Government	Energy	2007	2007	Demand pull – revenue payment	N/A
Commercial	Saltire Prize	Scotland	Scottish Government	Marine energy	2008	2017	Demand pull – prize	£10m
Commercial	Renewable Energy Investment Fund (REIF)	Scotland	Scottish Enterprise	Energy	2012	Ongoing	Demand pull – low-cost finance	N/A
Commercial	Non-Fossil Fuel Obligation/Scottish Renewable Obligation (NFFO)	UK	Scottish Government/ UK Government	Energy	1990	2002	Demand pull – revenue payment	N/A
Commercial	Renewables Obligation (RO)	UK	UK Government	Energy	2002	2002	Demand pull – financial incentive	N/A
Commercial	Green Investment Bank (GIB)	UK	-	Sustainable development	2012	Ongoing	Demand pull – low-cost finance	N/A
Commercial	Electricity Market Reform Contracts for Difference (EMR CFD)	UK	DECC/BEIS	Energy	2014	Ongoing	Demand pull – revenue payment	N/A
Commercial	InnovFin European Investment Bank	EU	European Commission/ EIB	Economy wide	2014	Ongoing	Demand pull – low-cost finance	N/A

NOTE: [1] - Unadjusted for inflation; [2] - Budget is actual expenditure up to summer 2017.

Appendix D – List of major wave energy test tanks

Name	Operator	Length (m)	Width (m)	Depth (m)	Nos. of wave generators	Max wave height (m)	Max. tidal flow (m/s)	Max. frequency (Hz)	Max. scale of model testing	Multi-directional	Year of commissioning	Latest known upgrade
Narrow tank	University of Edinburgh	10	0.3	0.6	1	0.2	-	2	1:100	No	1974	1974
Wide tank	University of Edinburgh	11	28	1.2	89	0.3	-	2	1:100	Yes	1977	1977
Cadnam wide tank	UK Department of Energy	-	-	-	60	-	-	-	-	-	1982	1982
Double-ended narrow tank	Heriot Watt University	-	-	-	-	-	-	-	-	-	1987	1987
Narrow tank	City University	-	0.9	0.5	-	-	-	-	-	-	1988	1988
Narrow tank	Heriot Watt University	-	-	-	-	-	-	-	-	-	1988	1988
Narrow tank	Heriot Watt University	-	0.75	0.9	-	-	-	-	-	-	1991	1991
Wave basin E	HR Wallingford	54	27	1.2	-	0.3	0.14	1.25	1:50	Yes	1993	1993
Narrow tank	City University	-	0.4	0.7	-	-	-	-	-	-	1994	1994
Narrow tank	Heriot Watt University	-	0.5	1.2	-	-	-	-	-	-	1994	1994
Towing tank	qinetiq	270	12.2	5.4	2	0.37	Towing	1	-	No	1932	1995
Narrow tank	Queen's University Belfast	-	0.35	1	1	-	-	-	-	-	1995	1995
Wave basin	Heriot Watt University	12.4	12	3	24	-	-	2.5	-	-	1996	1996
Narrow tank	Applied Research and Technology	18	3.5	1	1	-	-	-	1:40	-	1996	1996
Narrow tank	UCL	-	0.45	0.5	2	-	-	-	-	-	1997	1997
Narrow tank	Wavegen	20	6	-	8	-	-	-	-	-	2001	2001
Belfast wide wave tank	Queen's University Belfast	18	4.8	0.8	6	0.55	-	1	1:20	Yes	2002	2002
Narrow tank	University of Brighton	-	0.5	-	1	-	-	-	-	-	2002	2002
Multi-directional wave basin	Imperial College London	20	15	1.5	56	0.3	-	2	1:50	Yes	2003	2003
Wide wave flume	Imperial College London	62	2.8	2.15	4	0.3	-	2	1:50	No	2003	2003
Coastal flume	Imperial College London	23	0.6	0.8	1	0.3	0.6-1.25	2	1:50	No	2003	2003
Double-ended wave and current flume	Imperial College London	27	0.3	0.7	1	0.3	1.4	2	1:100	No	2003	2003
Wave evolution flume	Imperial College London	60	0.3	0.5	1	0.15	-	2	1:100	No	2003	2003
Wind wave current tank	University of Newcastle	11	1.8	1	3	0.12	1	1.25	-	-	2004	2004
Re-circulating coastal flume tank	UCL	20	1.2	0.7	2	0.45m at 0.55Hz	6	2	-	Yes	2005	2005

Name	Operator	Length (m)	Width (m)	Depth (m)	Nos. of wave generators	Max wave height (m)	Max. tidal flow (m/s)	Max. frequency (Hz)	Max. scale of model testing	Multi-directional	Year of commissioning	Latest known upgrade
Towing tank	University of Newcastle	37	3.5	1.3	8	0.12	Towing	2	-	-	1951	2008
Portaferry coastal wave basin	Queen's University Belfast	18	16	0.7	24	0.55	-	1	1:20	Yes	2008	2008
University of Manchester wide wave current flume	University of Manchester	20	5	0.5	8	0.15	0.5	2	-	No	2009	2009
Lancaster wave tank	University of Lancaster	11	2.5	1	7	0.25	1	1.5	1:50	-	2003	2010
COAST sediment wave flume	University of Plymouth	35	0.6	0.8	1	0.35	1	2	1:20	No	2012	2012
COAST ocean wave basin	University of Plymouth	35	15	3	24	1 at 0.45 Hz	0.3	2	1:8	Yes	2012	2012
COAST coastal basin	University of Plymouth	16	10	0.5	20	0.32	0.5	2	1:20	Yes	2012	2012
Aberdeen University Random Wave Flume	University of Aberdeen	20	0.5	0.9	1	0.3 at 0.9Hz	-	2	1:50	No	1991	2013
COAST tilting flume	University of Plymouth	20	0.6	0.6	1	0.35	1	2	1:20	No	2013	2013
Curved Wave Tank	University of Edinburgh	12 (9m radius)	6	1.2	48	0.22 at 1 Hz	-	1.6	1:70	Yes	2002	2014
FloWave Ocean Energy Research Facility	University of Edinburgh	25 (diameter)	25 (diameter)	2	168	0.7	1.6	1	1:10	Yes	2014	2014
F³ – the Fast Flow Facility	HR Wallingford	75	4	3	10	1	2	1.25	-	No	2014	2014
Ocean Basin and Rotating Arm	qinetiq	122	61	4.4	122	0.75	-	1.25	-	Yes	1961	2014
UCL ocean towing tank	UCL	20	2.5	1	7	0.35m at 0.7Hz	Towing	2	-	Yes	2005	2016
Tow tank	Southampton Solent University	60	3.7	1.8	-	0.18	Towing	2	-	-	2016	2016
Towing tank	University of Southampton	138	6	3.5	12	0.7	Towing	2	-	Yes	2017	2017
Wide flow tank	Imperial College London	26.9	6	1	8	0.3	0.05-0.3	2	1:50	Yes	2017	2017
Kelvin Hydrodynamics Laboratory	University of Strathclyde	76	4.6	2.5	4	0.5	Towing	1.2	1:4	No	1960s	c. 2017
OREC wave flume	Offshore Renewable Energy Catapult	55	5	7	-	1.2	-	-	-	-	N/A	N/A
OEC tank test	Orion Energy Centre	20	6	1.5	-	0.45	-	-	1:20	-	N/A	N/A

NOTE: [1] Formerly UK Coastal Research Facility

Appendix E – List of major wave energy foresight reports

Date	Title	Organisation	Country level	Author type	Time horizon	Deployment targets for wave energy	TRL focus
1999	Energies from the sea – towards 2020. A marine foresight panel report	Office of Science and Technology	UK	Government	2020	■ None set	5–8
2001	DTI technology roadmap – wave energy	DTI	UK	Government	2010	■ None set	3–6
2002	The energy review – a performance and innovation unit report	Cabinet Office – Performance and Innovation Unit	UK	Government	2050	■ None set	
2003	Our energy future – creating a low carbon economy	DTI	UK	Government	2020	■ Large arrays (10MW+) from 2015	5–9
	Status and research and development priorities: wave and marine current energy	AEA Technology on behalf of DTI	Global	Government	N/A	■ None set	3–6
2004	Harnessing Scotland's marine energy potential	FREDS	Scotland	Government-affiliated	2020	■ 1.3GW by 2020 in Scotland, generating 4000 GWh/year	5–9
	The renewables innovation review	DTI and Carbon Trust	UK	Government	2050	■ 220GW globally of wave	5–8
	Renewable supply chain gap analysis	DTI & Scottish Government	UK	Government	2020	■ 1.4-4.5GW by 2020	5–9
2005	Scotland's renewable energy potential: realising the 2020 target	FREDS	Scotland	Government-affiliated	2020	■ None set	5–9
2006	Path to power	British Wind Energy Association	UK	Non-government	2020	■ Large arrays (10MW+) from 2010 ■ 600MW by 2015 ■ 3GW by 2020	7–9
	Future marine energy	Carbon Trust	UK	Government-affiliated	2020	■ 1–2.5GW across Europe installed by 2020 for wave	5–9
2007	Meeting the energy challenge	DIT	UK	Government	2020	■ None set	7–8
2008	Marine renewable energy technology roadmap	UKERC	UK	Non-government	2020	■ Small arrays (up to 10MW) from 2008 ■ Large arrays (10MW+) from 2012 ■ 2GW by 2020	7–9

Date	Title	Organisation	Country level	Author type	Time horizon	Deployment targets for wave energy	TRL focus
2009	Marine energy road map	FREDS	Scotland	Government-affiliated	2050	■ 150MW marine by 2013 (medium scenario) ■ 1GW by 2020 (medium scenario)	7–9
	The UK renewable energy strategy	HM Government	UK	Government	2020	■ 1.5GW by 2020 (includes tidal range)	7–9
	The UK low carbon transition plan: national strategy for climate & energy	HM Government	UK	Government	2020	■ Large arrays (10MW+) from 2014	7–9
	Research priorities for renewable energy technology by 2020 and beyond	Europe Renewable Energy Research Centres Agency	European	Government-affiliated	N/A	■ None set	3–8
2010	Marine energy action plan 2010	DECC	UK	Government	2030	■ Small arrays (up to 10MW) from 2010 ■ Large arrays (10MW+) by 2014 ■ 1–2 GW marine by 2020	7–9
	Marine energy technology roadmap	ETI & UKERC	UK	Government-affiliated	2020	■ Small arrays (up to 10MW) from 2013 ■ Large arrays (10MW+) from 2017 ■ 1–2 GW marine by 2020 ■ 10–20 GW by 2050	7–9
2011	2020 route map for renewable Energy in Scotland	Scottish Government	Scotland	Government	2020	■ No clear marine target	5–9
	Accelerating marine energy. The potential for cost reduction – insights from the carbon trust marine energy accelerator	Carbon Trust	UK	Government-affiliated	N/A	■ 0.3GW by 2020 global ■ 46.5GW by 2050 global	5–8
	UK renewable energy roadmap	DECC	UK	Government	2020	■ 200–300 MW (0.9 TWh) by 2020	7–9
	Wave and tidal energy in the Pentland Firth and Orkney waters: how the projects could be built	Crown Estate	UK	Government-affiliated	2020	■ 1.6GW by 2020 (Orkneys & Pentland Firth)	8–9
	European offshore renewable energy roadmap	ORECCA	Europe	Non-government	2030	■ Large arrays (10MW+) from 2014 ■ 188 GW by 2050 across Europe	7–9
2012	Marine energy action plan	FREDS	Scotland	Government-affiliated	N/A	■ None set	7–9
	Technology innovation needs assessment (TINA) marine	LCICG	UK	Government-affiliated	2050	■ Small arrays (up to 10MW) from 2015 ■ Large-scale arrays (10MW+) from 2017 ■ 40–50TWh/year of electricity for wave ■ 4GW wave/2.5GW tidal by 2050 (medium)	5–9
	UK renewable energy roadmap (update)	DECC	UK	Government	2020	■ 27GW by 2050 (includes range)	7–9

Date	Title	Organisation	Country level	Author type	Time horizon	Deployment targets for wave energy	TRL focus
2013	2020 route map for renewable Energy in Scotland – update 2013	Scottish Government	Scotland	Government	2020	■ None set	5-9
	UK renewable energy roadmap (update)	DECC	UK	Government	2020	■ No target outlined and cast doubt on 2011 roadmap marine target	5–8
	Energy research and training prospectus: wind, wave and tidal energy	RCUK Energy Programme	UK	Non-government	N/A	■ None set	1–6
	Wave and tidal energy in the Pentland Firth and Orkney waters. Delivering the first phases of projects	Crown Estate	UK	Government-affiliated	2020	■ Small arrays (up to 10MW) from 2015 ■ 100 MW in Pentland Firth and Orkney waters by 2020	5–8
	Wave and tidal energy in the UK Conquering challenges, generating growth	RenewableUK	UK	Non-government	N/A	■ Small arrays (up to 10MW) from 2016 ■ ~60MW by 2020	7–9
	Overcoming research challenges for ocean renewable energy	Energy Research Knowledge Centre	Europe	Government-affiliated	N/A	■ 3.6 GW by 2020 and ■ leap to nearly 188 GW by 2050 in Europe (includes all ocean energy)	5–9
	Ocean energy technology: gaps and barriers	SIOCean	Europe	Non-government	N/A	■ None set	3–8
	Industry vision paper	European Ocean Energy	Europe	Non-government	2050	■ Small arrays (up to 10MW) from 2015 ■ Large-scale arrays (10MW+) from 2020 ■ 200–300 MW by 2020 in UK ■ 100GW by 2050 across Europe by 2050	7–9
2014	Marine energy technology roadmap 2014	UKERC & ETI	UK	Government-affiliated	2050	■ Large arrays (10-100 MW) from 2019 ■ 200–500 MW by 2020 ■ 10–20GW by 2050	7–9
	Wave and tidal: energy strategic technology agenda	SIOCean	Europe	Non-government	N/A	■ None set	1–8
	Wave and tidal energy market deployment strategy for Europe	SIOCean	Europe	Non-government	2050	■ 10 small arrays (up to 10MW) by 2020 ■ 100GW by 2050 across Europe (may include tidal range)	1–9

Date	Title	Organisation	Country level	Author type	Time horizon	Deployment targets for wave energy	TRL focus
2015	2020 route map for renewable Energy in Scotland – update 2015	Scottish Government	Scotland	Government	2020	■ None set	3–6
	Marine energy: seizing the supply chain opportunity	HIE and Scottish Enterprise	Scotland	Government	N/A	■ None set	7–9
	Wave and tidal supply chain development plan: supply chain capability and enabling action recommendations	BVG Associates	UK/ Scotland	Non-government	N/A	■ None set	7–9
2016	Energy research and training prospectus: follow up workshop on wave energy	RCUK Energy Programme	UK	Non-government	N/A	■ None set	1–6
	Transforming the European energy system through innovation	European Commission	Europe	Government	N/A	■ None set	5–8
	Strategic research agenda for ocean energy	TPOcean	Europe	Government-affiliated	N/A	■ None set	3–8
	Ocean energy strategic roadmap - Building ocean energy for Europe	Ocean Energy Europe	Europe	Non-government	2050	■ Small arrays (up to 10MW) by 2025 (wave) ■ 850MW by 2020 (ocean) ■ 10MW by 2020 (wave) ■ 100MW by 2025 (wave) ■ 100MW by 2020 (tidal stream) ■ 100GW (350TWh) by 2050 in Europe (may include all marine)	5–8

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