Lost at sea or a new wave of innovation? Examining the effectiveness of the UK's wave energy innovation system since 2000

Hannon, M. J., van Diemen, R., Skea, J.

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Abstract

Since 2000 the UK has spent almost £200m of public funds on wave energy related innovation, however wave power still remains some distance away from commercialisation. This paper employs a technology innovation system (TIS) framework to examine: (1) how the UK wave energy innovation system (WEIS) has evolved since 2000; (2) how well it has performed against TIS functions; (3) and the structural factors responsible for supporting or undermining innovation performance. It employs a mixed-methodology, analysing a combination of qualitative data, (e.g. expert interviews, documentary evidence), and quantitative data (e.g. RD&D public grants, scientific publications, technology patents, installed capacity etc.).

The research finds that critical weaknesses in government policy and industrial strategy are largely responsible for wave power's slow progress to market. These include: (1) a premature emphasis from government and developers on commercialisation of wave power; (2) little coordination of RD&D funding and activities; (3) a lack of incentives and frameworks to facilitate knowledge exchange; and (4) an absence of test facilities to enable mid-to-late stage experimentation.

Following the failure of leading technology developers and the withdrawal of multi-national incumbents, substantial policy learning took place. This led to a reconfiguration of the WEIS in the mid-2010s, including a re-design of RD&D funding programmes that insulated wave from competition with more mature technologies and necessitated the sharing of intellectual property, as well as the commissioning of new mid-technology readiness level (TRL) test infrastructure and establishment of international knowledge exchange and coordinating networks.

Broader lessons include how the formation phase of a TIS does not necessarily follow a 'positive' linear path of structural accumulation but can undergo a variety of system dynamics, including phases of *disintegration, reconfiguration* and *stagnation*. We also uncover how technological innovation relies on synergistic innovation of other technologies, such as supporting test infrastructure, and the pitfalls of failing to nurturing niche markets prior to competing with incumbents' offerings in established markets. Finally, the case highlights how the governance of energy innovation is often distributed across different layers of government (i.e. regional, national and supra-national). This has the advantage of helping a TIS retain momentum should one government withdraw support from a technology but the disadvantage of resources being distributed across different governments, which in the absence of coordination can result in the delivery of contradictory or overlapping policies.

1 Introduction

The UK possesses wave power in abundance. Harnessing this indigenous low-carbon energy source could play a critical role in helping the UK meet its ambitious 2050 target of reducing greenhouse gas emissions by 80% compared to 1990 levels. Furthermore, as a UK-based industry with export potential, wave power could help to support economic growth, whilst reducing its dependence on imported fuels and technologies. Accounting for technical, economic and environmental constraints wave power from UK waters could potentially to provide up to 70 TWh/annum of electricity generation (AMEC & Carbon Trust 2012), equivalent to 21% of the UK's electricity supply in 2015 (BEIS 2016).

To capture this prize, the UK has invested heavily in wave energy, spending £200m of public funds on wave energy related research, development and deployment (RD&D) since 2000. However, despite this significant investment, wave power is not yet commercially viable. Consequently, this paper mobilizes a Technology Innovation System (TIS) framework to examine how well the UK has performed in accelerating wave energy technology since 2000 and the factors responsible for supporting or undermining wave energy innovation. It focuses specifically on whether its slow progress could also be attributed to governmental and industrial strategy to accelerate wave energy innovation. To answer these questions the research draws upon a combination of qualitative data, (e.g. expert interviews, documentary evidence), and quantitative data (e.g. RD&D public grants, scientific publications, technology patents, installed capacity etc.).

This paper is structured as follows. Section 2 outlines the paper's analytical framework and methodology, highlighting its contribution to the extant literature. Section 3 provides a brief overview of the technical aspects and history of wave power. Section 4 outlines the structure of the UK's wave energy innovation system (WEIS) and how this has evolved over time. Section 5 assesses the historical performance of the UK's WEIS. Section 6 examines the factors responsible for supporting or undermining its innovation performance. Section 7 discuss the contribution of the paper's findings to innovation studies. Section 8 presents the paper's conclusions.

2 Theoretical background and analytical framework

2.1 Technology Innovation System: structure, functions, drivers and barriers

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 comprised of a variety of core elements that perform a host of different functions that support technology innovation. These are broadly split across four dimensions (Jacobsson & Karltorp 2013; Hekkert et al. 2011):

- ***Actors*** – the organisations responsible for developing, diffusing and implementing new technologies, most commonly education institutes (e.g. universities), industry and market actors (e.g. technology developers, suppliers, customers), public bodies (e.g. regulators, government departments) and supporting organisations (e.g. venture capitalists).
- ***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, for example, through co-ordination and knowledge exchange. They typically centre upon scientific, industrial or governmental actors, or a combination of these. Examples may include trade associations or research networks.

- ***Technology and infrastructure*** – the technological systems and infrastructural networks that facilitate technology innovation. These commonly include test facilities, complementary technologies and distribution/transmission networks.

Mapping the structure of the TIS helps analysts to identify the presence and characteristics of key structural components before determining their capacity to stimulate innovation by performing key *functions* (Wieczorek & Hekkert 2012). TIS *functions* help diagnose the performance of an innovation system, highlighting the causal mechanisms between structure and performance (Jacobsson & Karltorp 2013), to help analysts scan the innovation system and identify systemic weaknesses that need addressing. In essence, if a TIS's functions are all performing strongly then, assuming basic viability of the technology and a supportive wider environment, it should steadily progress towards commercialisation. Each TIS function represents a specific interaction between structural components that has a positive bearing on the development, deployment and adoption of emerging technology (Hekkert & Negro 2009). Following a review of the literature seven TIS functions[1] outlined in Table 1 and employed as part of this study.

Table 1: Description of TIS functions

Function	Description
Knowledge development (F1)	The creation of technological variety achieved by a broadening and deepening of a codified knowledge[2] base via research and development (R&D).
Knowledge exchange (F2)	Exchange of information between actors facilitated by inter-actor networks.
Entrepreneurial experimentation (F3)	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.
Guidance of the search (F4)	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.
Resource mobilisation (F5)	Mobilisation of financial, human and physical resources critical to the technology innovation process.
Market formation (F6)	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.
Legitimation (F7)	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.

Unfulfilled system functions are considered a manifestation of structural problems within the TIS, 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), these are critical in helping to formulate interventions to improve TIS performance.

[1] Some scholars also include positive externalities as an additional function. These relate to indirect benefits or 'spillovers' derived from developments outside the focus TIS, such as advances in one technology providing new opportunities for another or one technology gaining public acceptance, which in turn raises the legitimacy of characteristically similar technologies (Bergek, Jacobsson, et al. 2008).

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

2.2 Analytical framework and methods

This study mobilises a TIS framework to map the evolution of the UK's WEIS, measure its performance and identify the factors responsible for shaping its performance. In line with previous TIS studies (see Hekkert et al. 2011), this study follows four sequential analytical steps:

Step 1 - Map the structure and evolution of the TIS.

Step 2 - Assess performance of the TIS against metrics coupled with specific TIS functions.

Step 3 - Identify factors supporting or hindering performance of the TIS.

Step 4 - Identify wider lessons for energy innovation strategies and TIS theory.

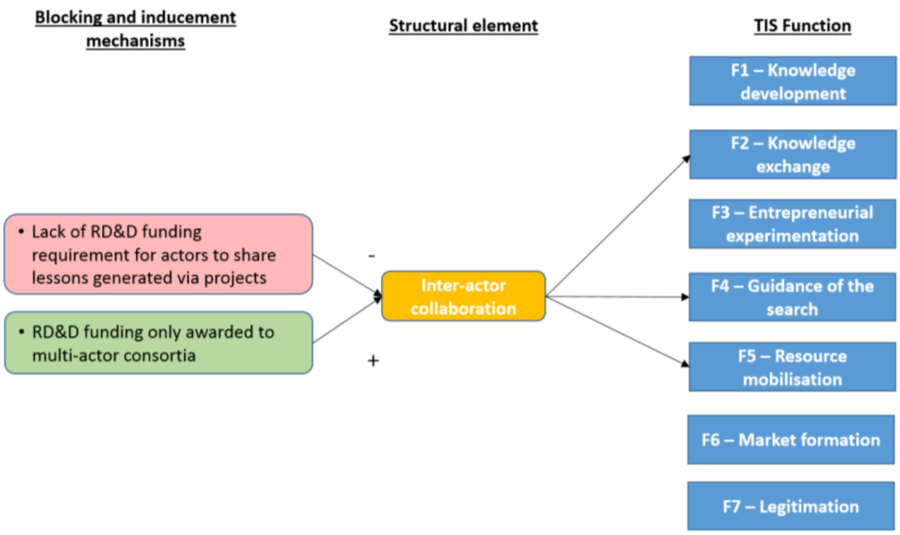
Building on these steps the paper employs a three-tiered approach (T1, T2, and T3) to diagnosing the factors responsible for shaping the performance of the UK's WEIS.

First, inducement and blocking mechanisms are identified that have served to support or undermine wave energy technology innovation (T1).

Second, these mechanisms are linked to specific structural elements relating to one of the four structural dimensions (*actors*, *institutions*, *networks* and *technology*) (T2). 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, indicated by arrows (T3). A worked example is provided below in Figure 1, focusing on inter-actor collaboration as a network related structural element.

Figure 1: Worked example of TIS structure–function analysis



To mobilise this framework, the analysis utilises a combination of quantitative (e.g. patents, bibliometrics, 444 marine energy UK public RD&D grants) and qualitative data (e.g. 33 expert interviews conducted in 2015, documentary evidence). Innovation performance is measured against a set of 15 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 (see Table 5).

2.3 Contribution to wider TIS literature

The paper seeks to address a number of important gaps in the TIS literature. The first relates to TIS evolution and how scholars have to date largely focused on the *formation, growth* and *stability* phases of a TIS (Jacobsson et al. 2004; Alkemade & Hekkert 2009; Hekkert et al. 2011), and more recently *decline* phases (Markard 2018). Here they have emphasised the differences in structural composition and functional performance. There is however a lack of insight into the detailed dynamics that characterize each phase, especially during the long-run formation phase (i.e. the period prior to the technology reaching market), which typically lasts for about 20 years (Bento & Wilson 2016). A particularly understudied area is the extent to which a TIS may endure periods of *disruption*, *stagnation, revitalisation* and *reconfiguration* during its development (see Markard 2018). Consequently, this paper examines the case of wave power, as it constitutes a TIS that has failed to move beyond its formation phase since the mid-20th Century and has been subject to periods of both growth and contraction.

The second is that TIS studies, especially 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 offers valuable insight into the types of barriers that could slow the progress of energy technology innovation.

Third, the TIS framework has been criticised for failing to acknowledge the influence of exogenous factors, or the TIS's wider environment, 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). As such 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), economic trends and high-level policy developments (e.g. climate change agreements).

In terms of methodological contributions, 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). In this context, this research employs a mixed-methods approach, using a combination of qualitative and quantitative data to enable data triangulation. TIS studies have also 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. 2008; Winskel et al. 2014; Wilson & Grübler 2014). Consequently, this study pays special attention to the chronology of events and how this has influenced changes to TIS structure and performance.

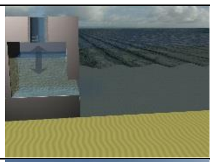
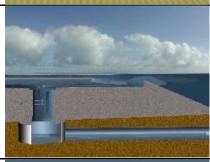
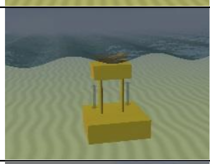
3 An introduction to wave power

3.1 Technological overview

Waves are generated when the wind blows over the ocean's surface, carrying both kinetic and gravitational potential energy, the level of which is a function of both the height and period of the wave. The Intergovernmental Panel on Climate Change (IPCC) estimates that the total theoretical wave energy potential is 32 PWh per annum (Mørk et al. 2010), roughly 30% greater than the global electricity supply of 2015 (24.3 PWh per annum).

Wave energy convertors are typically 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, *nearshore* devices are located in water where waves start breaking and shallow enough to allow them to be fixed to the seabed either via pinned pile foundations or gravity mass, and o*ffshore* devices are located in energy rich deep waters (10m plus) and tethered to the seabed using tight or slack moorings mass. Table 2 presents a selection of the most common device designs across these three regimes.

Table 2: Typical wave energy convertors (Magagna & Uihlein 2015; EMEC 2016b)(images from Aquaret 2012)

Typical Location	Device type	Illustration	Description
Onshore	Oscillating water column (OWC)		The water column rises with the wave, acting 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.
	Over-topping device		Waves breaking on a ramp are collected in a reservoir above the free water surface. This then flows through a low-head hydraulic turbine.
Nearshore	Oscillating wave surge converter		These devices exploit the surging motion of nearshore waves to induce the oscillatory motion of a flap in a horizontal direction.
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.
	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 Power Take Off (PTO)[3], either by pumping high-pressure fluids through a hydraulic motor or by operating a direct-drive generator.
	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 converter		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.

3.2 Historical background

Wave energy can be traced back to 1799 when Pierre Girard and his son filed the first wave energy patent in France (Ross 1996). Following the pioneering post-war work of Yoshio Masuda in Japan and Walton Bott in Mauritius wave energy innovation really gathered pace following the work of Stephen Salter on his device 'the Salter Duck' in the UK during the 1970s as part of the world's first major wave energy programme established in 1976, constituting an investment of £61m[4] (2018 value) over a 7 year period (1974-1983) (Mukora et al. 2008; Wilson 2012).

[3] Technology that converts kinetic energy into electricity, either directly via a rotary or linear electric generator or a hydraulic system (LCICG 2012).

[4] This has been re-calculated to 2018 values from the original £15m investment valued against 1981 currency

Slow progress in terms of expected cost reductions saw the UK programme halted in 1982 and was followed by a long period of very low investment from UK government, with this somewhat offset by investment flowing from EU RD&D programmes during the 1990s. This meant that the 1990s could be characterized as a period of stagnation, punctuated by a small number of demonstration projects. For example, the 2MW 'OSPREY' was launched in 1995, which suffered terminal damage from a storm while still undertaking installation (Ross 1996)(Figure 2).

Figure 2: The OSPREY wave energy device being prepared for installation off Dounreay, Scotland (source: Aquaterra)

It wasn't until the late 1990s that thoughts turned once again to the potential of wave power in the context of growing concerns about climate change, energy security and increasing oil prices. In this context it enjoyed a renaissance with new companies emerging, such as Pelamis (formerly known as Ocean Power Delivery), in reaction to a slew of renewable energy subsidies, some of which had an explicit focus on delivering a commercially viable wave energy device. This led to a new golden era for wave power innovation in the 2000s, which we explore in the following sections.

4 Structure of the innovation system

We now consider how the structure of the UK's WEIS has changed since 2000 across the four dimensions of *actors, institutions, networks* and *infrastructure*.

4.1 Actors

4.1.1 Commercial actors

Since 2000 the actor landscape witnessed an initial growth and subsequent contraction in the number and variety of actors. For example, the number of wave energy technology developers grew from 7 in 2000 to 30 by 2011, before dropping to 21 by 2017. A total of 14 of wave energy developers ceased trading during the period, representing a 41% failure rate. All these company failures came from 2011 onwards, with four firms folding in both 2014 and 2017. This occurred shortly after the financial crisis, with interviewees highlighting the difficulties of operating in a more difficult financial environment following the financial crisis. Most notably market leaders Pelamis and Aquamarine Power ceased trading, in 2014 and 2015. Together they accounted for 49% (£24.4m) of the £49.2m awarded to wave energy developers for experimental development or demonstration activities since 2000 and deployed the highest rated capacity devices of any UK developers (Section 5.3).

Similarly, Original Equipment Manufacturers (OEMs)[5], energy utilities and venture capitalists (VCs), entered in the 2000s and then withdrew during the 2010s; no longer considering wave energy to be an investment priority. For example, Voith acquired 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 in 2011 (Alstom 2011). However, in recent years OEMs have not been involved in any major mergers or acquisitions with wave companies and some have withdrawn from the sector, for example Voith closed Wavegen in 2013.

Like the OEMs, the energy utilities entered and retreated. Both E.On and Scottish Power purchased devices from Pelamis and tested these at EMEC in 2010 and 2012 respectively (EMEC 2016a). In partnership with Pelamis they provided the developer with valuable feedback from the perspective of the developers' target customer; the energy utility. Beyond testing, Scottish and Southern Energy (SSE) signed a joint venture agreement with AWS Ocean Energy and Alstom to develop large-scale wave farms, such as a 10MW array at Costa Head off the Orkney Isles (Alstom 2012). However, as part of their broader retrenchment to core business activities (e.g. energy retail) E.On withdrew in 2013 and Scottish Power sold its device to EMEC shortly afterwards (BBC 2013), whilst SSE never developed its planned wave farm.

4.1.2 Institutional actors

Since 2000 the governance structure of the UK wave energy TIS has become increasingly dispersed across three layers of government (i.e. EU, UK and devolved administrations), as powers have been devolved away from UK government. This has meant that alongside the Department of Business, Energy and Industrial Strategy (BEIS) and its predecessors, the EU Directorates General (DGs) have played an increasingly important role, responsible for managing the framework programmes for research and technological development that represent a major source of energy technology innovation funding. Furthermore, increasing powers has been devolved to Scottish Government through landmark legislation (e.g. Scotland Acts of 2012 and 2016), with many of its newly devolved powers directly relating to energy policy.

Another important development across the actor landscape since 2000 has been the emergence of new actors to perform roles previously missing. These include funding bodies providing mid-stage energy innovation support (e.g. InnovateUK and the Energy Technologies Institute (ETI)), international test facilities to develop industry standards and expert testing consultancy (e.g. European Marine Energy Centre (EMEC)), and physical centres to facilitate collaboration across academia, industry and government (e.g. Offshore Renewable Energy Catapult (OREC)). These are expanded upon in Table 3.

[5] OEMs play an active role in the conceptualisation, design and assembly of complex technology systems

Table 3: Overview of new institutional actors since 2000

Actor	Year established	Overview of role
EMEC	2003	• Accredited test laboratory, offering internationally recognised verification of ocean energy device performance. • Assistance with grid connection, power purchase agreements, subsidy accreditation and compliance with regulation. • Formulated industry standards to ensure consistent and accurate comparison of performance between different devices. • Knowledge capture; purchased Pelamis's P2 device after it went into administration to enable forensic examination of its structure and performance.
InnovateUK	2004	• UK's technology innovation delivery body, focused on supporting mid-stage innovation, especially the transfer of knowledge from universities to commercial applications.
ETI	2007	• A public-private partnership to accelerate mid-to-late stage low-carbon energy innovation.
OREC	2013	• A physical centre that offers businesses, scientists and engineers an opportunity to work side by side on late-stage research and development to tackle industry-wide challenges affecting offshore renewable energy (e.g. biofouling, energy yield assessments). • Manages marine energy test facilities • Hosts UK wave and tidal knowledge transfer network • Publishes reports on solutions to common industry issues (e.g. financing solutions for marine energy).

4.2 Institutions

Since 2000 wave power technology has existed within an institutional landscape that has become increasingly supporting of low-carbon technologies. Landmark renewable energy and climate change legislation has been enacted at all three levels of government (Scotland, the UK and the EU). Under the 2008 UK Climate Change Act the UK was committed to reduce its emissions by 80% on 1990 levels by 2050. In parallel the EU introduced a set of legally binding 2020 emissions reduction and renewable energy targets, committing member states to reduce emissions by 20% on 1990 levels and supply 20% of their energy consumption from renewable sources[6]. These high-level policy developments have typically preceded a proliferation of new programmes to support wave energy innovation.

The UK's wave power policy framework has emerged in this context. It constitutes a highly complex landscape, characterised by a multitude of concurrent, overlapping RD&D programmes that are managed by organisations operating at different levels of governance (i.e. EU, UK, Scotland), with relatively little coordination between these. The policy landscape has also been extremely fast changing, characterised by a succession of new schemes, each with their own guidelines and objectives.

One important change has been in the focus of innovation funding. During the mid-2000s and early 2010s much of the funding for wave energy was focused on later stage demonstration and commercialisation. Examples include the UK's £42 Marine Renewables Deployment Fund (2006 – 2008) and Scottish Government's £13m Wave and Tidal Energy Scheme (WATES) (2006 – 2008). There was a subsequent move away from later to earlier stage innovation programmes seeing the share of funding for demonstration between 2000 and 2008 dropping from 43%, to 31% for the period 2008 to 2016 (Section 5.5).

[6] 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, which became legally binding in 2017 (European Commission 2018).

The best example of this shift has been the establishment of Scottish Government's Wave Energy Scotland (WES) in 2014, which represents a step-change in the way wave power innovation has been funded. The scheme had a much earlier stage focus, its role 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 April 2018, WES has awarded £28.8m, across 77 projects, 177 separate organisations and 13 different countries. It differs from its predecessors in a number of important ways:

- Offers 100% funding via a state-aid compliant procurement model, meaning no match funding from the private sector is required.
- Primarily funds sub-component development (e.g. PTOs, controls) rather than optimising a single device design[7].
- Employs a rigorous stage-gating model where developers must meet stringent criteria to progress to unlock funding at a higher TRL.
- Awards funds only to multi-party consortia and opens internationally to encourage knowledge exchange.
- WES reserves right to licence intellectual property (IP) generated from projects after a pre-determined period of time if projects-leads to not.
- Hosts and curates an on-line 'knowledge library' that shares results from previous RD&D projects that were not previously publicly available.

Whilst grant funding has played a key 'supply push' role, long-term revenue payments have provided a 'market pull', cultivating a greater demand for renewable energy amongst prospective customers (e.g. energy utilities). The three key policies are outlined below:

- **Renewable Obligation (2002 – 2017):** Required electricity suppliers to source a portion of their electricity from low-carbon sources. Generators were guaranteed a certain number of Renewable Obligation Certificates (ROCs)[8] per MWh from eligible technologies. From 2013 wave could receive ROCs per MWh (up to 30MW) across the UK, much higher greater than all other renewables apart from tidal stream. For example, onshore wind was eligible for only 0.9 ROCs and offshore wind 2 ROCs per MWh in 2013/14.
- **Contracts for Difference (CfD) (2015 – present):** The CfD eventually replaced the RO and wave was assigned to the 'less established technologies' pot, which included much cheaper technologies such as offshore wind. Successful projects were guaranteed a 'strike price' of £305 per MWh over a 15 year period but unlike the RO, generators were not guaranteed access to the subsidy as it was distributed via a cost competitive auction. To encourage marine energy, the first 100MW of marine schemes no larger than 30MW would each be guaranteed access to CfDs under the first allocation round in 2015, however no wave projects were awarded funding and this safeguard was removed for marine energy during the second CfD allocation round in 2017.

[7] It still retains a focus on device design via its novel wave energy converter call.

[8] ROCs were sold to suppliers to help them meet their obligations and enable them to avoid paying a 'buyout price' for every MWh they supplied without the necessary certification. 'Buyout' funds were distributed to ROC providers via 20-year-long revenue payments.

- **Saltire Prize (2008 – 2017):** A £10m prize to be awarded to the developer generating the greatest volume of electricity[9] from the ocean by June 2017. No party was successful in meeting the criteria and the prize money went unspent.

In addition to long-term subsidies government backed investment funds and banks have emerged during the 2010s to fill the gap left by the private sector's reluctance to invest in higher-risk low-carbon energy projects. Examples include the £103m Renewable Energy Investment Fund (REIF) launched in 2012, backed by the Scottish Investment Bank, which by 2016, it had provided £12.1m financing to four wave projects, including market leader Pelamis and Aquamarine (Ekosgen 2016). The UK government set up its Green Investment Bank[10] in 2012 and the European Commission and the European Investment Bank set up Innofin EIB in 2014, although neither has made investment in UK wave power technology to date.

4.3 Networks

The degree of connectivity across the UK's WEIS since 2000 is presented in Table 4

[9] Over a threshold of 100 GWh and a continuous two-year period. Open internationally.

[10] Privatised in 2017

Table 4, covering: 1) scientific, 2) industry, 3) government, 4) testing and 5) formal training networks. The first three are typically established to promote knowledge exchange, collaboration and coordination amongst their respective communities. Testing networks seek to facilitate access to wide range of test-facilities distributed across a large geographic area, whilst training networks facilitate lesson and skill sharing via formal training.

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 WEIS, as evidenced by a strong coverage of networks across all five domains at both regional, national and international levels.

We also find that the coverage of network functions[11] has significantly improved as the number and diversity of networks has increased. However, there is some evidence of overlapping networks, with multiple marine energy focused trade associations and centres for doctoral training (CDTs), raising the potential for a duplication of effort.

[11] Six key intermediary/network functions of: 1) Relationship building; 2) Capacity; 3) Knowledge transfer; 4) Technology foresighting; 5) RD&D coordination; and 6) Policy advocacy (see Kilelu et al. 2011).

Table 4: 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					
					Relation 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	X					X
		WES library	2017	N/A		X	X			
	UK	REA	2001	44	X					X
		RenewableUK	2004	N/A	X			X		X
		WT KTN	2013	N/A			X			
		ORJIP OE[3]	2014	87	X		X	X	X	
	EU	OEE	2006	115	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

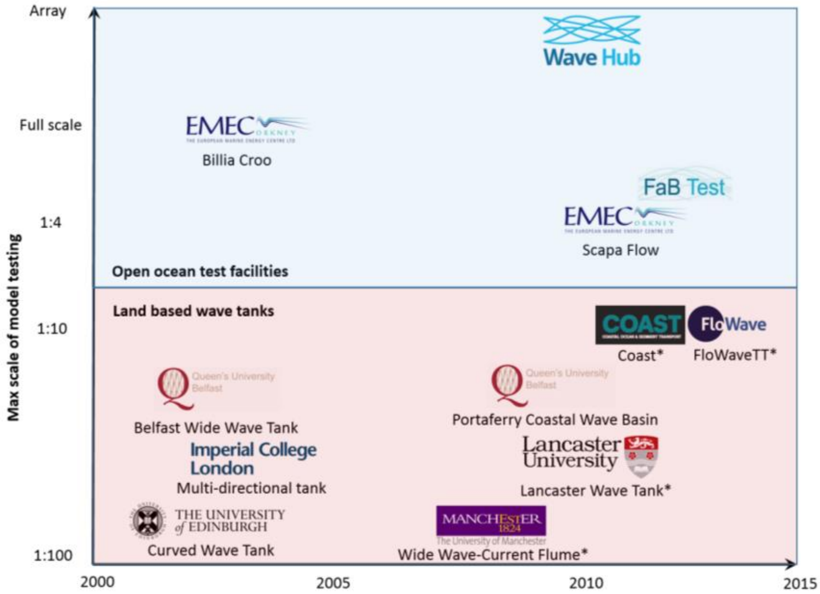
4.4 Infrastructure and technology

The UK's wave energy test facilities have undergone 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 innovation chain.

With regards to test tanks (i.e. onshore facilities that replicate ocean environments), clear improvements have taken place in capabilities over the past 40 years. They have evolved from mono-directional wave flumes offering small-scale testing of devices in mono-directional waves allowing for testing up to 1:100 scale (e.g. Narrow Tank at Edinburgh University in 1974) to highly complex facilities able to replicate real ocean environments with multi-directional waves and enable testing of devices up to 1:10 scale (e.g. FloWaveTT in 2014). These advances have enabled developers to test part-scale devices in a much less hostile and easier to manage environment than the open ocean (Figure 3).

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, where once there was a clear lack of test facilities offering testing between 1:10 and 1:4 scale; a critical stage for technology demonstration.

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



NOTE: Does not include all test tanks constructed during this period. Facilities with '*' that also have tidal current generation capability.

5 Innovation system performance assessment

This section considers how the WEIS's performance has changed since 2000 against 15 TIS function linked indicators. If we examine the long-term trends in performance by comparing the second half of the period against the first, we find that 13 of the 15 absolute quantitative indicators exhibit an improved performance, whilst seven of the nine normalised quantitative indicators show improved relative performance (Table 5). 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, with 10 of the 15 indicators showing an absolute increase in performance and five of the nine normalised indicators showing an improvement in relative performance. This suggests that wave energy innovation performance has overall been stronger in the second half of the period since 2000 but that performance in the last year has started to decline across some of these 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[12] (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 but other factors.

[12] With the exception of a significant decline in patenting between 2010 and 2013.

Table 5: Summary of UK wave energy innovation performance since 2000

TIS function	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	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 wave energy patents	2000 – 2013	8	↗↘	+97%	-28%	Share of global UK wave energy patents	11%	↗↘	-8%	-7%
F2 – Knowledge exchange	Average number of UK wave energy RD&D project partners	2000 – 2017	5.5	↗	+44%	+37%					
	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%
	Number of wave energy RD&D projects partners from other sectors	200 0– 2016	14	↗	+450%	+273%	Share of wave energy RD&D projects partners from other sectors	5%	↗	+2%	+2%
	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%
F3 – Entrepreneurial experimentation	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]	↗↘	-59%	-68%					
	Wave energy levelised cost of electricity ($/MWh)	2009 – 2017	498.5	↗→	+13%	+8%					
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	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%
F6 – Market	Number of UK wave energy	2000 –	24	↗↘	+83%	+17%					

TIS function	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
formation	developers	2016									
	Level of wave energy installed capacity in UK (MW)	2007 – 2016	0.7	↗↘	+117%	-64%	Share of UK marine industry[6]	6%	↘	-4%	-28%
F7 – Legitimation	Support outlined in public reports for wave energy	1999 – 2017		↗↘							
	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

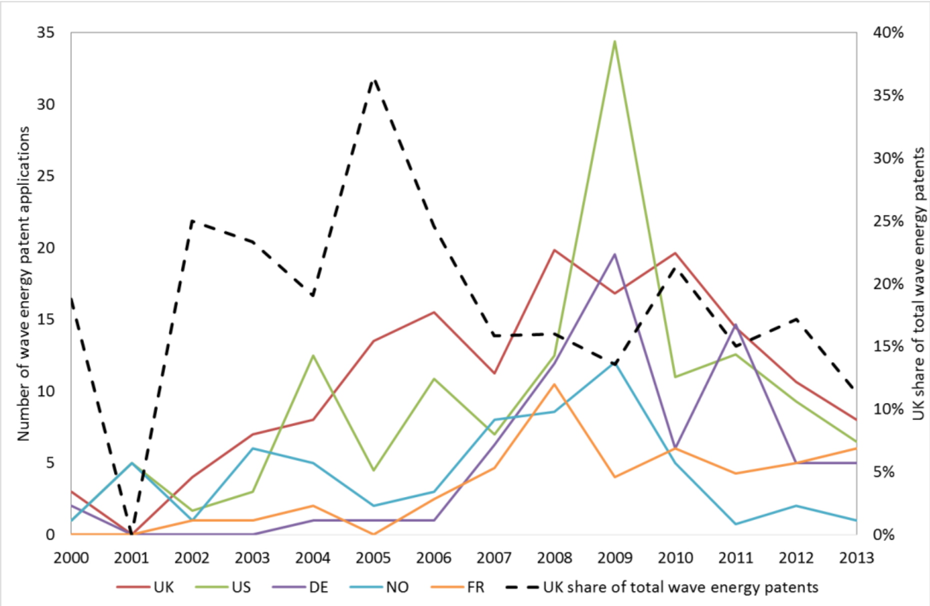
1. If period is an odd number of years then the two periods will overlap by a year to provide two periods of an equal number of years.
2. Mean excludes last year.
3. Average of past three years (2015–2017) taken against long-run averages to avoid bias towards devices only demonstrated in final year. 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.

5.1 Knowledge development (F1)

The UK published 21 times as many publications in 2016 versus 2000 and versus its international peers was second only to the US over the 16 year period. The UK accounted for an average of 15% of global publications; its share growing from 12% between 2000 and 2008 to 16% between 2008 and 2016 (Figure 4).

Patents followed a less positive trajectory, with a clear downturn in absolute terms since 2010, with the number of patents halving from 20 to 8 by 2013[13]. The UK's share of global wave energy patents began declining 5 years earlier from 2005, falling from 36% to 11% by 2013. Whilst the fall in absolute terms may be symptomatic of a broader downturn in the number of low-carbon energy patents since 2010 identified via the patent analysis, it cannot account for the UK's fall in its share of global wave energy patents.

Figure 4: 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.

5.2 Knowledge exchange (F2)

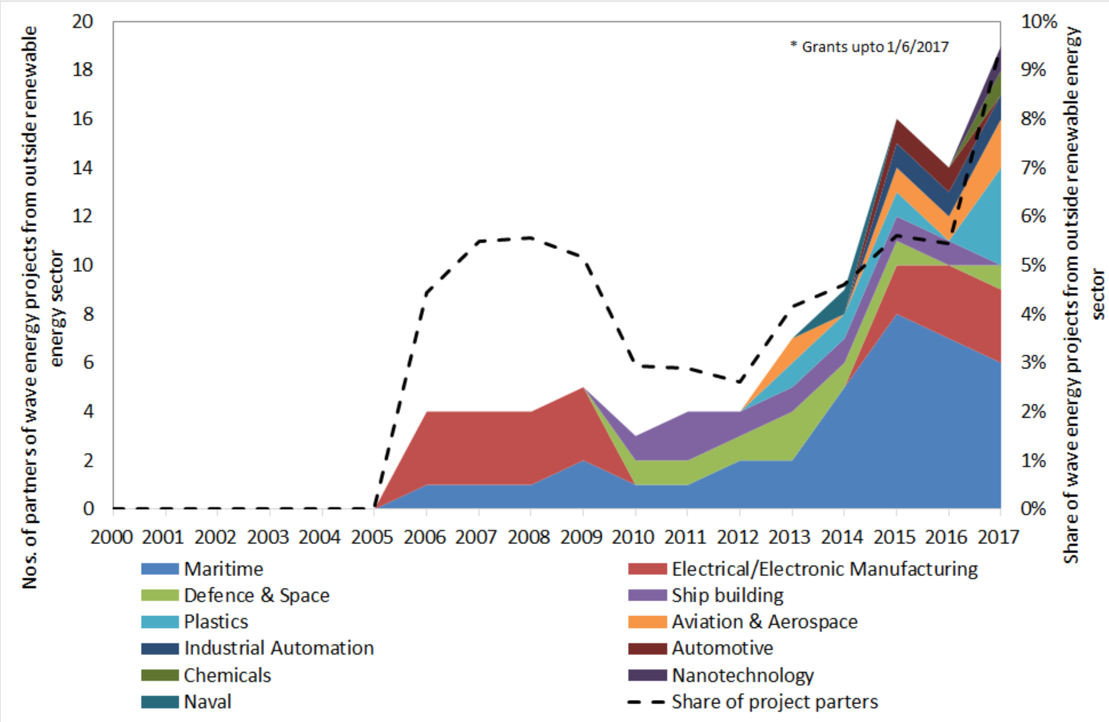
The average number of project partners involved has grown, increasing from three in the early 2000s to five during the late 2010s, suggesting a growing degree of collaboration. Similarly the number of projects being jointly led by industry and science organisations has grown, doubling from 9% in the 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. This evidences a growing exchange of knowledge between public and private sectors. Whilst the number of international project partners has grown the share of 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), peaking at 40% in 2016, there is less evidence to suggest that international collaboration has increased over time in terms of the share of scientific publications or patents.

Turning to cross-fertilisation an upward trend was also detected, in both absolute and relative terms, of projects involving partners from non-energy sectors. 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

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

almost 10%, with the entry of actors from sectors such as the automotive, aviation, aerospace, shipbuilding, nano-technology, chemicals and plastics industries (Figure 5).

Figure 5: Number of organisations engaged in wave energy projects from other technology sectors 2000–2017 (source: author)

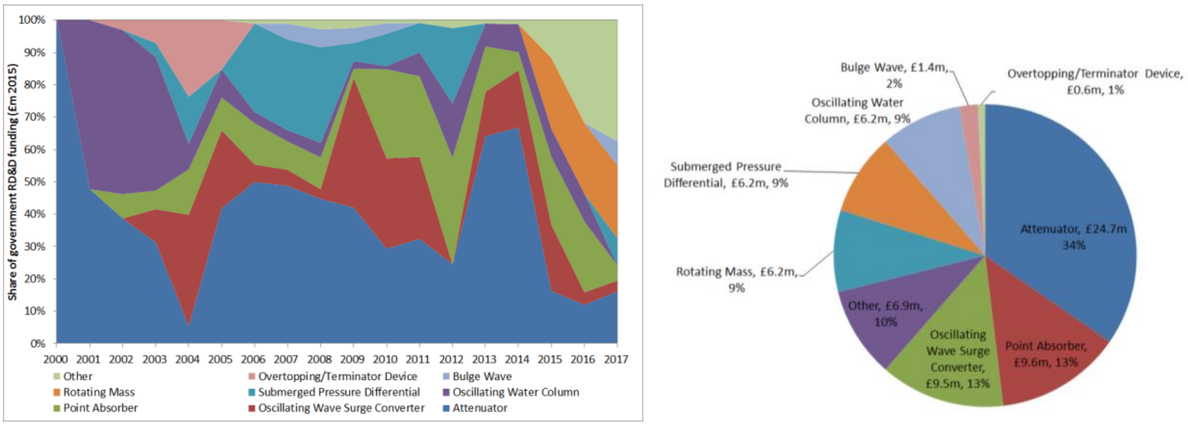


NOTE: Projects exclude those led by universities, research institutes and non-technology development-related service providers (e.g. accountancy, computer software), as well as knowledge exchange, training and test facility grants.

5.3 Entrepreneurial experimentation (F3)

Analysis of wave energy RD&D funding and installed capacity uncovers a divergence of technology design rather than a convergence. During the first half of the period (2000–2008) the most well-funded device design received 47% of RD&D funding, compared to just 35% in the second half (2009–2017), suggesting a weakening convergence of support around a single dominant design (Figure 6). This lack of convergence is also supported by the sheer variety of device designs deployed in UK waters (Figure 7).

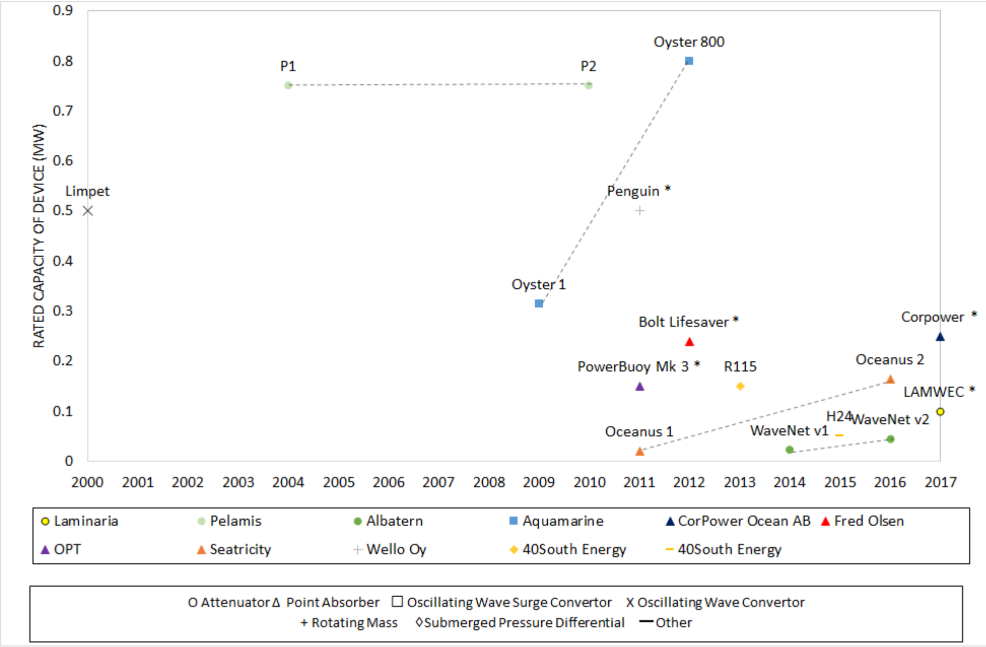
Figure 6: Share of RD&D funding committed to different wave energy device designs 2000–2017 (source: author)



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

Another indicator of energy technology maturity is the rate at which the average 'rated capacity' (i.e. maximum power output) of a technology increases over time (Figure 7). For wave energy devices deployed in UK waters was 70% lower during the period between 2015 add 2017 versus the remainder of the period (2000 to 2014). The period up to the early 2010s saw demonstration of devices pushing 1MW, with Pelamis' 750kW P2 (2010), WelloOy's 500kW Penguin device (2011) and Aquamarine Power's 800kW Oyster (2012). However, since Pelamis and Aquamarine ceased trading in the early 2010s the average power rating of devices demonstrated has fallen dramatically.

Figure 7: 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.

Finally, the levelised cost of electricity (LCOE) [14] of wave energy has increased since 2009 and remained very high compared to other renewable electricity technologies. It rose from $380/MWh in 2009 to $500/MWh by 2017, whilst solar PV has seen a fall of 73% ($292 to $80/MWh) and offshore wind 25% ($169 to $126/MWh) during the same period.

5.4 Guidance of the search (F4)

Between 1999 and 2017, 45 'foresight' reports were published that explicitly dealt with wave or marine energy innovation in the UK. These were delivered by a combination of government, government-affiliated bodies (e.g. non-departmental bodies, advisory groups) and non-governmental organisations (e.g. trade associations, research centres), across European, UK and devolved administration levels. The frequency of reports increased over time, evidencing a growing emphasis on the guidance of the search (F4).

There was also a clear shift in focus from later stage demonstration and commercialisation to more fundamental experimentation, with a noticeable 'downgrading' in the targeted installed capacity by

[14] LCOE data is taken from Bloomberg (2013) and includes 'capital costs, operating costs, the cost of finance and load factors. Where actual project cost data is incomplete the analysis uses Bloomberg New Energy Finance's trend analysis on technology and financing costs.

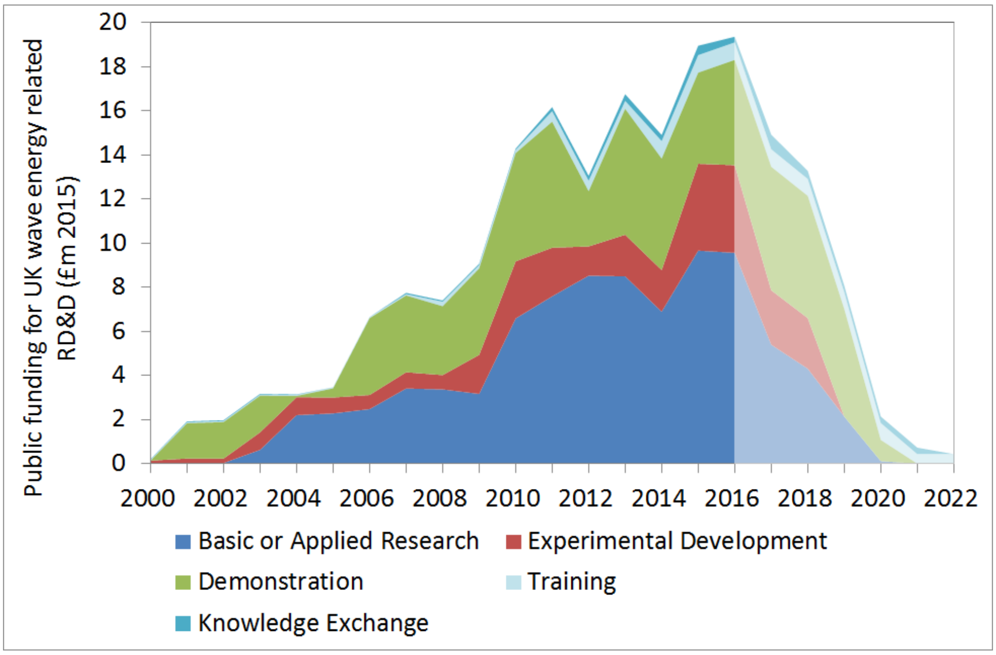
2020. For example, the DECC's 2009 Marine Energy Action Plan envisaged 1-2GW of wave and tidal stream by 2020, downgraded to 0.25GW in DECC's 2011 Renewable Action Plan, before targets were removed altogether by UK Government in subsequent whitepapers. A similar downgrading in the joint roadmaps from the UK Energy Research Centre (UKERC) and ETI, which downgraded their 2020 targets from 2GW (2008), to 1.5GW (2010) and finally 0.35GW (2014).

5.5 Resource mobilisation (F5)

Between 2000 and 2017 wave power received £102m in public RD&D investment, with a further £96m was awarded to cross-cutting marine RD&D projects. A further £170m was awarded to the installation and maintenance of marine test infrastructure. Funding for wave energy has increased during the period between 2000 and 2017[15], with funds for wave and cross-cutting RD&D during the second half of the period 264% higher than the first half in real terms.

If we consider the TRL-focus of this innovation funding during the first half of the period (2000 to 2008) versus the second period (2008 to 2016) we find that the share for basic research, applied R&D and experimental development rose from 56% to 68%, whilst the share for demonstration fell from 44% to 32% (Figure 8). This decline in later stage innovation is contrary to what we would expect for a maturing technology, where greater sums of demonstration funding are awarded as the technology scales up and moves closer to market.

Figure 8: UK public RD&D funding for wave energy-related projects by innovation stage 2000–2017 (source: author)



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

We also note that wave energy RD&D funding was typically drawn from programmes that bundled wave and tidal stream together, with tidal consistently receiving a greater share of public RD&D funding versus wave, with tidal stream capturing £178m versus wave's £102m since 2000.

We also see a change in terms of the source of funding, with the UK Government playing a significantly less important role in recent years versus the EU and devolved administrations (e.g. Scotland). During the period 2000 to 2017 UK Government awarded £93m (47%), the EU £53m (27%), Scottish Government £49m (25%) and other devolved administrations £2.9m (1%). A

[15] Covering projects running to 2022

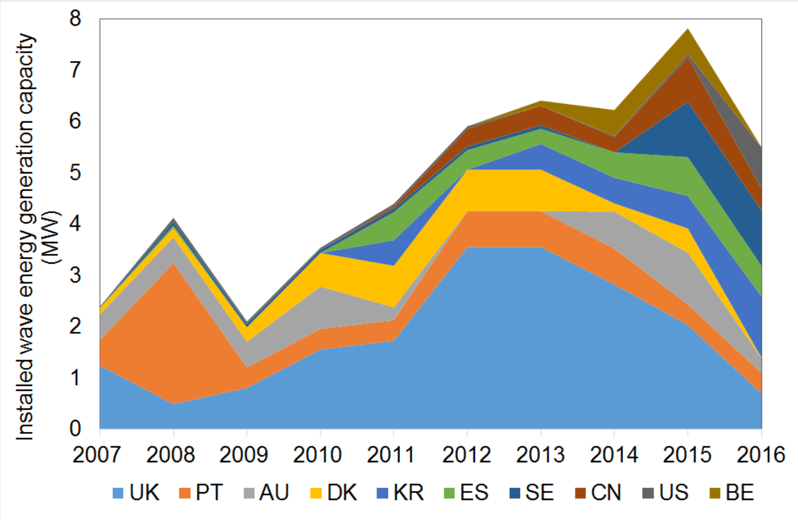
snapshot of 2016 reveals a much more balanced portfolio, with the UK accounting for 31%, the EU 33% and Scottish Government 36%. This has resulted in an innovation system whose governance has become increasingly dispersed across different spatial levels and one that is increasingly sensitive to regional and supra-national political developments such as Scottish Independence and Brexit.

5.6 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 13 developers filing for administration since 2011, including market leaders Pelamis and Aquamarine Power.

The other indicator of market formation is cumulative installed capacity in UK waters. Pelamis became the first company in the world to both generate electricity into a grid system from an offshore wave energy device in 2004 and deliver a wave energy array, installing 3 Pelamis devices (2.25MW total nominal rating) off the coast of Portugal at Aguacadora[16] in 2008. Overall, installed capacity grew from 0.5MW in 2008 to 3.5MW in 2012 (Figure 9). However, as less demonstration funding was awarded and leading developers ceased trading, installed capacity fell by 80% between 2013 and 2016, from 3.5MW to 0.7MW.

Figure 9: Top ten countries for installed capacity of wave energy generation by host nation 2007–2016 (source: adapted from OES)



5.7 Legitimation (F7)

A review was conducted of UK government white and green papers[17] and UK parliamentary select committee reports with direct relevance to wave energy since 1999 to gauge wave energy's legitimacy from the perspective of government. Prior to wave power becoming reinstated as a government priority in the 2000s, a suite of reports at the turn of millennium highlighted its potential and calling for additional innovation support (see Office of Science and Technology 1999; House of Lords Select Committee on European Communities 1999). A House of Commons Science and Technology Committee (2001) report emphasised that:

[16] In Figure 9 this installation is attributed to Portugal, not the UK.

[17] White papers are government policy initiatives and proposals for legislation, whilst green papers are government consultation documents.

> *'It is extremely regrettable and surprising that the development of wave and tidal energy technologies has received so little support from the Government'* and called for *'a coherent strategy for [wave] technology development and long-term investment'.*

Successive government white papers and parliamentary committee reports subsequently identified wave energy as a priority for government support, culminating in an increase in public. For example the House of Commons Committee on Energy and Climate Change's 2012 report (HoCECCC 2012) explained that:

> '*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'* (p.13)

The mid-2010s saw a steady retrenchment of formal support for wave energy, with a growing absence of deployment targets in white papers and voiced support from government ministers. For example, a speech in 2015 from Amber Rudd, then Secretary of State for Energy and Climate Change, emphasised the importance of 'picking winners' and focusing on those technologies demonstrating the greatest *'potential to scale up and to compete in a global market without subsidy'* (UK Government 2015); distancing government from large-scale investment in high-cost radical technologies like wave. This lack of support for wave energy was echoed 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 downturn in perceived legitimacy from government has not been reflected by the general public, whose support for marine energy has grown, from 73% between 2012 and 2014 to 75% between 2014 and 2017 (BEIS 2017a). During the period 2012 to 2017 marine energy's average support of 74% was greater than support for both onshore wind (67%) and biomass (62%), on a par with offshore wind (74%), and behind only solar PV (82%).

6 TIS blocking and inducement mechanisms

6.1 Actors

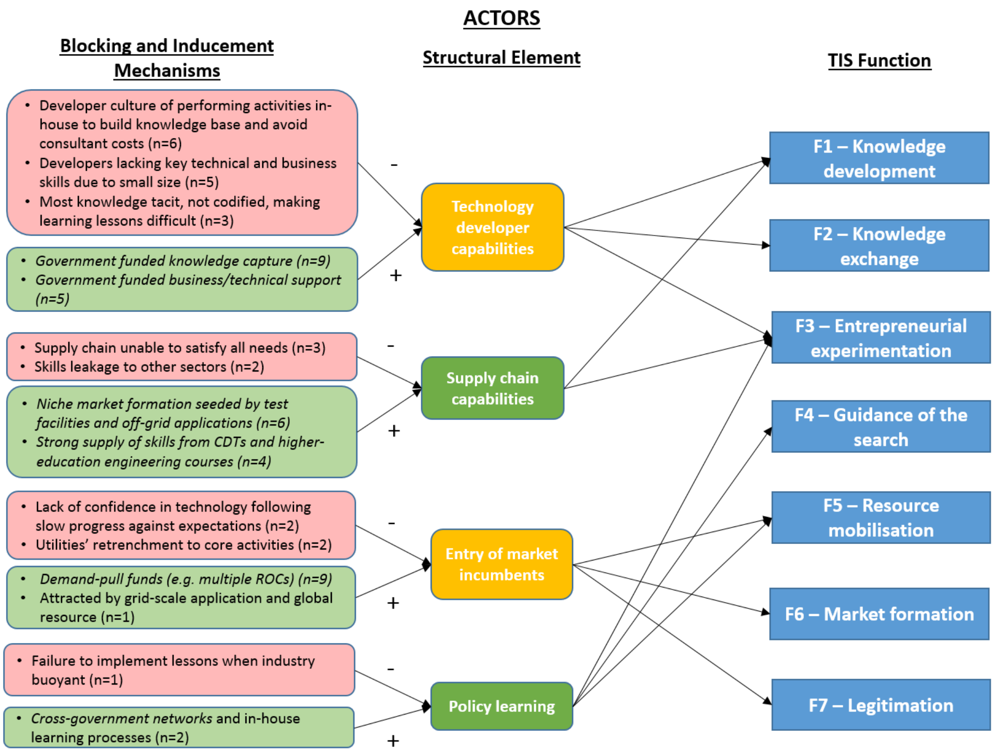
Knowledge exchange (F2) was hindered by a lack of knowledge codification, meaning that knowledge generated from RD&D projects remained tacit and was limited to the experiences of their staff rather than the wider sector (Figure 10). However, investments in knowledge capture schemes and a requirement to licence 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 WEIS, 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 and lack of partnership with larger multi-nationals, 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, interviewees emphasised that 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 also accumulated and then subsequently eroded following 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 and wave power's grid-scale potential but lost confidence in wave energy following a lack of technological progress against initial expectations and a retrenchment to their core business activities following the financial crisis.

Figure 10: 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. "n" refers to the number of interviewees who identified the mechanism.

6.2 Institutions

A major institutional barrier was the premature 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 11). This can be illustrated by the glut of pre-commercial demonstration focused schemes introduced during the mid to late 2000s (Sections 4.2 and 5.5).

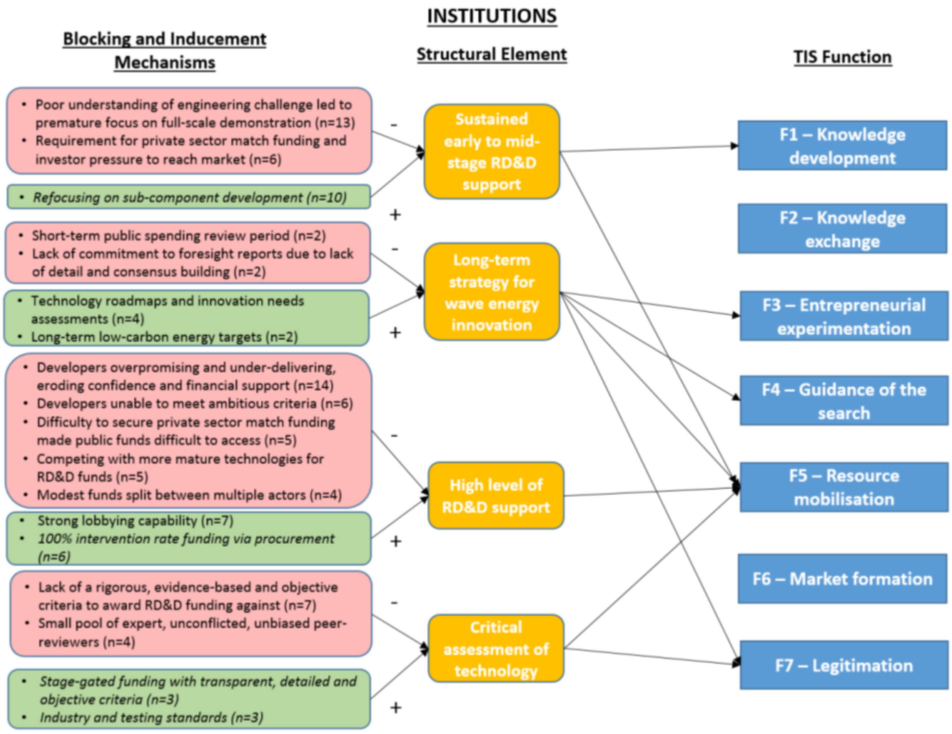
The wave energy industry was considered to be guilty of making over-optimistic claims about the speed with which wave energy would reach market, whilst public and private sector investors were responsible for believing the hype and subsequently making funds available to progress the technology as quickly as possible. The outcome was that developers 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)). This triggered the collapse of leading firms (e.g. Pelamis), further undermining the sector's legitimacy (F7).

Underpinning these developments was a poor understanding, from the perspective of both innovators and innovation funders, of the scale of the technical challenge and the associated time and resources required to overcome it. Also responsible was a lack of rigorous, objective procedures to review the credibility of funding proposals and the reliance on a relatively small pool of peer-reviewers with vested interests in competing device designs. Legitimacy has been improved somewhat with the development of more stringent stage-gating in new funding programmes (e.g. WES) and the development of new industry and testing protocols (see EMEC 2017).

Related to this over-ambitious wave energy strategy was that a large proportion of the UK's budget for wave energy RD&D went unspent because developers could not meet advanced funding criteria and/or struggled after the financial crisis to secure the necessary private sector match funding required to access these public funds. A separate issues was that financial resources (F5) were being channelled away from wave and towards more mature technologies. For example, 'supply push' innovation funding was bundled with the more mature tidal energy, whilst long-term 'market pull' subsidies (e.g. CfDs) were auctioned off against significantly cheaper renewables (e.g. offshore wind). To address both these 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.

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), the latter associated with a lack of consensus building and detail relating to next steps.

Figure 11: Overview of inducement and blocking mechanisms related to institutions (source: author)



6.3 Networks

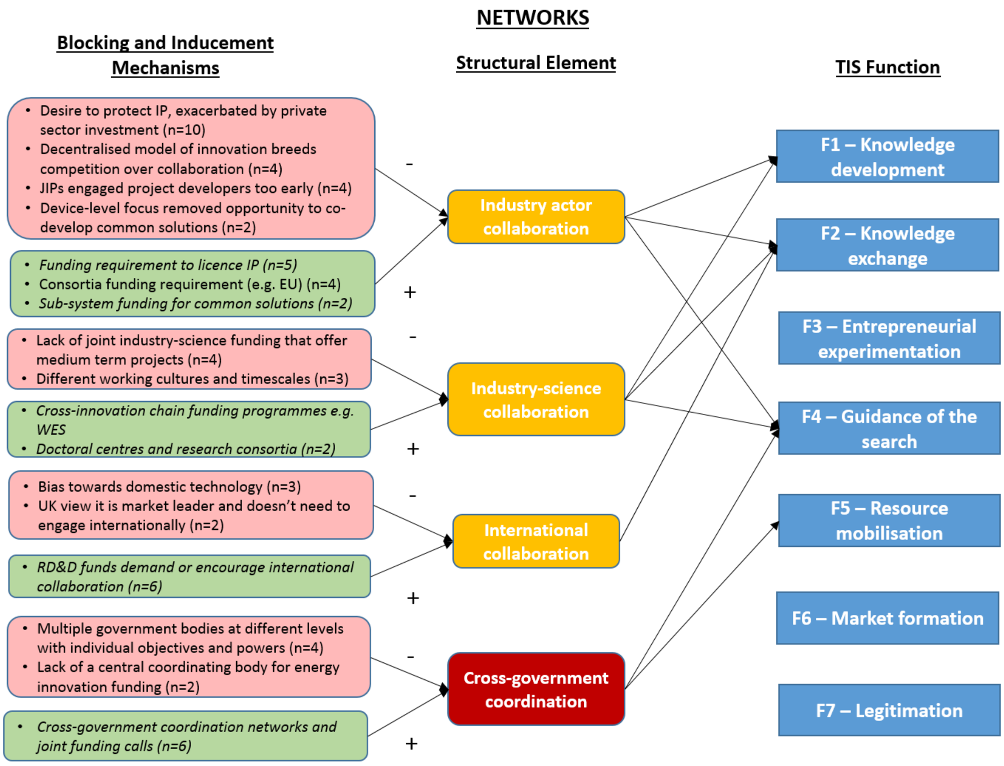
Actor knowledge exchange (F2) was considered to be constrained by a combination of: (1) a culture of developers operating secretively in order to protect IP; (2) the UK's decentralised model of innovation that prioritises competition over collaboration; and (3) a strong focus on device-level innovation funding, which removed the incentive for actors to develop common solutions to shared problems (Figure 12). Again, steps were taken to address these issues such as the WES programme imposing a requirement on awardees to licence their IP, publish results and form consortia.

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 industry–science projects (e.g. WES) 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 collaboration and communication was generally considered to be weak, resulting in a poorly coordinated 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)).

Figure 12: Overview of inducement and blocking mechanisms related to actor networks (source: author)



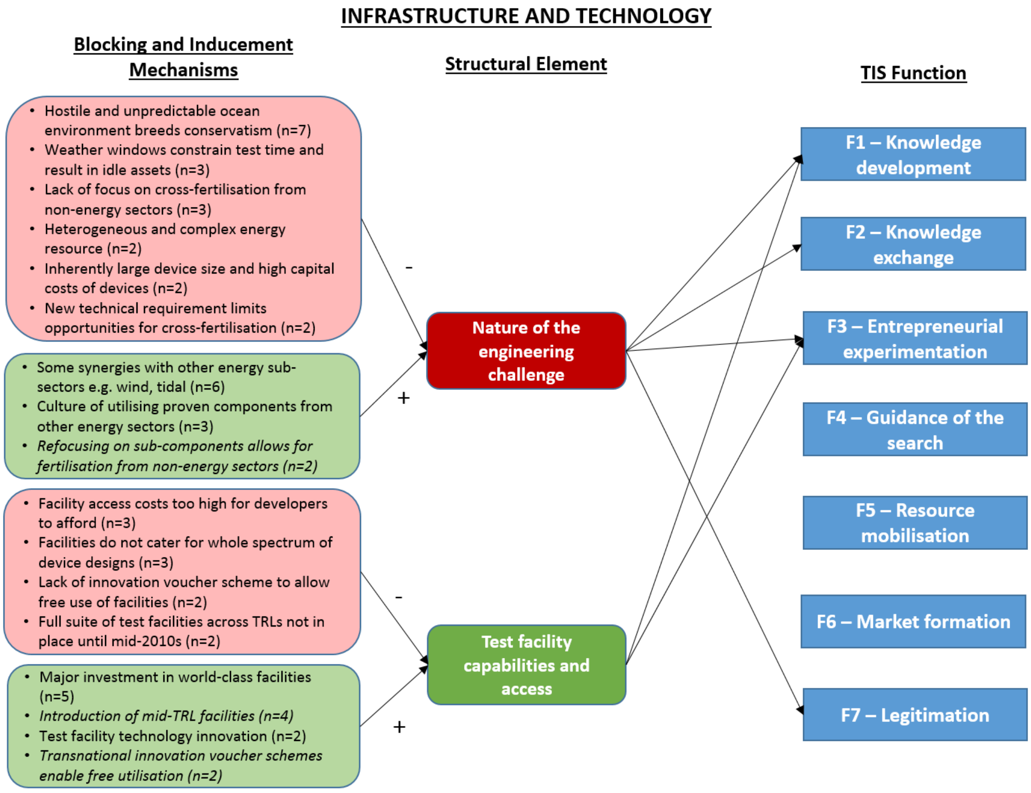
6.4 Infrastructure and technology

The UK's wave energy test facilities are amongst the best in the world. However, concerns were raised about the cost and ease of accessing these facilities, such as the lack of an innovation voucher scheme (Figure 13). The biggest barrier raised was the lack of test facilities filling the gap between testing at 1:10 to full-scale devices during the 2000s. 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) have helped to close this gap, with facilities now offering excellent coverage across the innovation chain.

The unique characteristics of wave energy technology were considered to have slowed down its innovation journey. For example, developers' conservative approach to testing was a reaction to a very hostile ocean environment, limited weather windows for testing and the need to construct large-scale devices that broadly matched the wavelength of ocean waves in order to operate cost-effectively, in turn making them very expensive.

Interviewees also emphasised that whilst many lessons could be learn around installation, operations and maintenance of wave power from established energy technologies (e.g. tidal power, offshore wind, oil/gas), the core functionality of wave power devices represent an overall new technical requirement. Consequently, the technology shares relatively few synergies with other technologies and little overlap with other TISs. This is in contrast to other ocean energy technologies like tidal stream, which has been able to share a number of important lessons from wind power by sharing a similar three-blade horizontal axis turbine design. Even so efforts have been taken to broaden the search for lessons from other sectors (e.g. shipping, aviation) via programmes such as WES that encourages engagement with other sectors by focusing on sub-component development, which opens up opportunities for specialist companies to engage with wave developers.

Figure 13: Overview of inducement and blocking mechanisms related to infrastructure and technology (source: author)



7 Discussion

7.1 TIS formation phase subject to disintegration, stagnation and reconfiguration

As outlined in Section 2.3 TIS evolution has traditionally been framed as following three phases of *formation*, *growth* and *stabilisation*, whereby the TIS steadily grows in size and complexity. Scholars have been keen to point out that a TIS may not necessarily move through all of these phases (Bergek, Jacobsson, et al. 2008; Markard 2018) and that ‘this sequence of phases is just one pattern for TIS development and alternative paths of transformation are possible’ (Markard 2018 p.23). Furthermore, the TIS may in fact move through a more complex series of dynamics that involve re-configuration or re-vitalization (Markard 2018).

The case of wave energy highlights supports this view, highlighting how even during its formation phase a TIS can endure both structural accumulation *and* disintegration. For example, the 1970s and 2000s represented a period of rapid expansion for the TIS but both were followed by periods of crisis and *disintegration* (early 1980s and 2010s), where the TIS subsequently contracted, seeing actors withdraw and funds dwindle. Other key phases included a period of *stagnation* during the 1990s, where investment was sufficient to retain some key aspects of the TIS (e.g. research institutes, test facilities) but insufficient to push the technology forward. Finally, we also see a period of *reconfiguration* during the mid-2010s where a concerted effort was made by the public sector to address major TIS blocking mechanisms, seeing significant changes across all four structural dimensions of the TIS.

7.2 Technology innovation relies on synergistic policy and infrastructural 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 is the iterative process of policy design, experimentation, ‘learning by doing’ and subsequent refinement based on lessons learnt, which draws analogies with the process of technology innovation. This process of policy innovation is reliant upon personnel possessing the capacity and appetite to develop innovative policies (i.e. policy entrepreneurs), intra- and inter-organisational networks that facilitate knowledge exchange and a culture that rewards policy innovation versus conservatism.

The research also identifies a co-evolutionary relationship between a technology and the test infrastructure that facilitates its experimentation and demonstration. This is in the sense that both constitute technologies that are subject to an innovation journey, in the case of this study wave power devices (the technology) and wave tanks/open sea testing sites (the infrastructure). They co-evolve in the sense that test facilities are designed around the key characteristics of emergent device designs, whilst devices are designed with the test facility’s capabilities in mind.

7.3 Devolution creates a complex but diverse innovation system

To date little work has examined how devolution impacts upon the evolution and performance of an energy innovation system. The case of UK wave energy is inextricably linked with devolution, 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 makes the co-ordination of innovation investment challenging. Consequently, inter-governmental coordinating networks are necessary to help avoid the duplication of resources or implementation of incompatible energy innovation strategies.

On the other, as governance powers are distributed across multiple layers of government, a TIS is somewhat insulated against the negative policy making of one government. For example, the UK Government’s move away from wave energy in the 1990s and 2010s did not entirely remove momentum from the TIS’s development, with support continuing to flow from other sources (e.g. EU, devolved administration). The *quid pro quo* is that, if we assume that aligning multiple layers of government is challenging, the total level of support channelled to one technology under a multi-level governance framework is likely to be less than if it were wholly supported by a single national government with the same budget. However, this ignores the non-financial benefits of trans-national collaboration that comes with multi-level governance, such as the exchange of tacit knowledge and sharing of test infrastructure.

7.4 Protected spaces help to nurture technology innovation

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 can be achieved by two means.

The first is the formation of ‘sheltered spaces’ or niche markets (see Schot & Geels 2008) that enable 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. Wave power focused prematurely on delivering devices capable of grid-scale generation versus application in emerging niche markets. Analogous to spacecraft for solar PV or public transport for electric vehicles wave energy developers have only recently identified the potential value of ‘scaling up’ through niche markets such as off-grid islands and aquaculture.

The second is to design innovation funding programmes so emerging technologies cannot be out-competed for subsidies on a cost basis when in direct competition with significantly more mature technologies. For example, wave power has struggled to attract long-term revenue payments (e.g. CfDs) when it has been in direct competition with cheaper technologies via auctions.

7.5 Characteristics of a technology influence its innovation journey

The pace of technology innovation is shaped by the characteristics of that technology. In the case of wave power the inherent need to demonstrate the technology in a very hostile ocean environment and the lack of synergies with established technologies was considered to have slowed its progress. This shares similarities with Nemet's (2014) work that identified how smaller, modular energy technologies (e.g. solar PV) have 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. It is therefore important that when comparing the innovation journeys of different energy technologies, their respective characteristics are taken into account because they can shape the pace and nature of their development trajectory.

8 Conclusions

Since 2000 the UK has spent almost £200m of public funds on wave energy related innovation, however wave power still remains some distance away from commercialisation. This paper employs a technology innovation system (TIS) framework to examine: (1) how the UK wave energy innovation system (WEIS) has evolved since 2000; (2) how well it has performed against TIS functions; (3) and the structural factors responsible for supporting or undermining innovation performance. It employs a mixed-methodology, analysing a combination of qualitative data, (e.g. expert interviews, documentary evidence), and quantitative data (e.g. RD&D public grants, scientific publications, technology patents, installed capacity etc.).

The research finds that critical weaknesses in government policy and industrial strategy are largely responsible for wave power's slow progress to market. These include: (1) a premature emphasis from government and developers on commercialisation of wave power; (2) little coordination of RD&D funding and activities; (3) a lack of incentives and frameworks to facilitate knowledge exchange; and (4) an absence of test facilities to enable mid-to-late stage experimentation. Following the failure of leading technology developers and the withdrawal of multi-national incumbents, substantial policy learning took place. This led to a reconfiguration of the WEIS in the mid-2010s, including a re-design of RD&D funding programmes that insulated wave from competition with more mature technologies and necessitated the sharing of intellectual property, as well as the commissioning of new mid-technology readiness level (TRL) test infrastructure and establishment of international knowledge exchange and coordinating networks.

Broader lessons include how the formation phase of a TIS does not necessarily follow a 'positive' linear path of structural accumulation but can undergo a variety of system dynamics, such as phases of *disintegration, reconfiguration* and *stagnation*. We also uncover how technological innovation relies on synergistic innovation of other technologies, such as supporting test infrastructure. It also identifies the pitfalls of failing to nurturing niche markets prior to competing with incumbents' offerings in established markets. Finally, the case highlights how the governance of energy innovation is often distributed across different layers of government (i.e. regional, national and supra-national). The advantage is that this can help a TIS retain momentum should one government withdraw support from a technology but the disadvantage of resources being distributed across different governments, which in the absence of coordination can result in the delivery of contradictory or overlapping policies.

Recommendations for future research include the need to consider the factors responsible for triggering changes in 'direction' of TISs, for example moving from a period of structural accumulation to disintegration. Another is to consider how and why TISs are re-configured and especially the role played by 'system builders' in both delivering and coordinating action. More broadly a crosstechnology study of different phases of TIS evolution would offer insight into both the sequence of phases but also the micro-dynamics of each phase, building especially on this paper's finding that the formation phase is subject to a wide range of positive and negative dynamics. Finally, more research is needed into the co-evolution of TISs, harbouring both synergistic *and* rival technologies, to understand how developments across two or more TISs mutually influence one another's evolution.

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