Low
Carbon
Innovation
Coordination
Group

Technology Innovation Needs Assessment (TINA)

Marine Energy
Summary Report

August 2012

Background to Technology Innovation Needs Assessments

The TINAs are a collaborative effort of the Low Carbon Innovation Co-ordination Group (LCICG), which is the coordination vehicle for the UK's major public sector backed funding and delivery bodies in the area of 'low carbon innovation'. Its core members are the Department of Energy and Climate Change (DECC), the Department of Business, Innovation and Skills (BIS), the Engineering and Physical Sciences Research Council (EPSRC), the Energy Technologies Institute (ETI), the Technology Strategy Board (TSB), the Scottish Government, Scottish Enterprise, and the Carbon Trust. The LCICG also has a number of associate members, including the Governments of Wales, Northern Ireland, Ofgem, the Crown Estate, UKTI, the Department of Transport, the Department for Communities and Local Government, the Ministry of Defence, and the Department for Environment, Food and Rural Affairs.

The TINAs aim to identify and value the key innovation needs of specific low carbon technology families to inform the prioritisation of public sector investment in low carbon innovation. Beyond innovation there are other barriers and opportunities in planning, the supply chain, related infrastructure and finance. These are not explicitly considered in the TINA's conclusion since they are the focus of other Government initiatives, in particular those from the Office of Renewable Energy Deployment in DECC and from BIS.

This document summarises the Marine Energy TINA analysis and draws on a much more detailed TINA analysis pack which will be published separately.

The TINAs apply a consistent methodology across a diverse range of technologies, and a comparison of relative values across the different TINAs is as important as the examination of absolute values within each TINA.

The TINA analytical framework was developed and implemented by the Carbon Trust with contributions from all core LCICG members as well as input from numerous other expert individuals and organisations.

Key findings

Marine energy could make a meaningful contribution to the UK energy mix from around 2025. Cost of energy generated will need to reduce by 50-75% to around £100/MWh within this timeline if marine energy is to compete with offshore wind and other technologies. This pathway is ambitious but conceivable and only possible with significant innovation. If successful, innovation in Marine energy could save the energy system c.£3 - 8bn[1] and help create a UK industry that could contribute an estimated £1 - 4bn to GDP up to 2050[2]. Achieving this value requires continued support in prioritised innovation areas.

Potential role in the UK's energy system	• The UK has a large natural resource of marine energy – energy from waves and from tidal streams. • Successfully harnessing this energy has the potential to deliver over 75 TWh/y (which is over 10% of the UK's forecast electricity needs in 2050) whilst helping to meet our GHG emissions and renewable energy targets and reducing reliance on gas imports. • The eventual role of marine energy in the UK energy system is currently uncertain. Marine energy systems are still at the relatively early stages of technology development and demonstration, with significant uncertainty about their ultimate costs and risks. Deployment scenarios range from almost no marine energy to over 20GW in the UK by 2050. • Most deployment would occur post-2020, and levels of deployment this decade will not be sufficient to have a major impact on 2020 renewable energy or carbon emissions targets.
Cutting energy costs by innovating	• The cost of marine energy will need to reduce by 50-75% by around 2025 if it is to compete with offshore wind power and other technologies. Whilst whole arrays have not yet been developed, we estimate that the current costs of marine energy are of the order of £350-400/MWh for wave and £200-300/MWh for tidal. These compare to current offshore wind costs of £140-180/MWh with cost reduction pathways to £100/MWh by 2020 established and validated with key industry players. • This level of cost reduction of marine energy is ambitious but conceivable with significant economies of scale and innovation (combined with supply chain optimisation and appropriate financing). This assessment is based on a broad range of expert sources, in turn informed by what has been learnt from historical demonstrations and modelling of future arrays. It would require a large scale (at least 200MW) array installation to be deployed by 2025 and a significantly optimised marine energy system that incorporates multiple innovations, combining to deliver the maximum level of cost and risk reduction deemed possible. • If marine energy reaches parity on costs and risks with offshore wind by 2025, cost of energy generated (of both technologies) could potentially fall further to c.£60/MWh by 2050, which could make them cost competitive with nuclear, and fossil fuels with CCS. • Successfully implementing this innovation in marine energy could reduce deployment costs in the UK by between £3 - 8bn1.
Green growth opportunity	• There is similar uncertainty in the global market, with deployment scenarios ranging from almost no marine energy to over 180GW by 2050. • The UK is uniquely well positioned to capture market share, potentially c.15% of the global market, driven in particular by favourable resources and the current dominance of UK device developers. • If marine deploys globally and if the UK successfully competes in this global market to achieve the market share above, then marine energy could contribute £1.4 – 4.3bn[3] to UK GDP up to 2050.

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[1] Cumulative (2010-2050) present discounted values for medium-high deployment scenarios of 7 – 13GW in the UK by 2050. There would be no savings from innovation in a low/zero deployment scenario and up to £17bn in a very high scenario of 27GW in the UK by 2050. Depending on counterfactual methodology (see below), these values could be ~60% lower i.e., roughly £1-3bn (medium-high).

[2] Cumulative (2010-2050) present discounted values for medium-high scenarios.

[3] Medium – high deployment scenarios; Note that our low scenario is defined as zero Marine energy deployment.

The case for UK public sector intervention	• To unlock this opportunity there is a strong case for targeted public sector intervention to catalyse private sector investment – there are significant market failures to innovation and the UK cannot rely on other countries to develop the technologies within the required timescales: – There are on-going market failures, including demand uncertainty (*negative externalities),* infrastructure conditions (*public good effects*)*,* insufficient payback on early stage R&D and insufficient collaboration and knowledge sharing (*positive externalities, asymmetric information and IP spillover*). – The UK cannot rely on other countries to develop these technologies for us – marine energy will not achieve the required cost reduction within the window of opportunity outlined above without UK public sector intervention; it would take too long for other countries to catch up the UK. In addition, the UK requires specific technology solutions, in particular for foundations and installation systems, to address its specific resource conditions.
Potential priorities to deliver the greatest benefit to the UK	• Innovation support across various stages of technology development is needed to play a role in reducing cost of energy and risk, with the later stages having the highest innovation costs: – **Initial deployment of first arrays**: To demonstrate proof of value and a viable cost reduction pathway, support is required to move technologies beyond single device demonstration and into first arrays (c.5MW). In the longer term, first array development of second generation technologies may be required in order to prove solutions for more difficult conditions (e.g. deeper water). – **R&D to address the challenges identified in first arrays** such as cabling, multi-array deployment, device interactions, and the cost and risk reduction required to make first arrays viable. These areas are likely to provide opportunities for collaborative R&D. – **R&D for technologies at earlier stages of development**. For tidal energy, R&D is required on system integration and evolution of component level capabilities. For wave energy, as well as system level R&D, it is possible that new and better concepts will be required at the component and device level. This R&D is likely to be at relatively low cost compared to demonstration and deployment and will drive the step-change cost reductions required to meet the full cost reduction potential. – **Demonstration at full scale of devices that are currently in earlier stages of development** that prove their viability, although the extent of support required is uncertain. • Public intervention should focus on increasing collaboration and integration of RD&D to address the market failures outlined above. It should also join up innovation programmes with supply chain and infrastructure development. • Marine energy systems can be thought of in their sub-areas; the following sub-areas appear to have the greatest innovation potential: – Wave and tidal: system optimisation and installationWave only: the structure & prime mover (those aspects of the device that capture energy). • The LCICG members have provided significant support to marine energy in the UK. They expect to invest up to an estimated £60m-£80m[4] of public sector funding over the next 3-4 years, leveraging 1-3 times that from the private sector. • Achieving the full benefit from innovation over the following 4-10 years will require significant ongoing UK and European Union public sector funding, scaling up support for a prioritised set of technology innovations as they move from design to demonstration.

[4] This figure does not include devolved administration funding.

Chart 1 Marine energy value of innovation and key support needs – summary by sub-area

The critical innovation support needs (as outlined above) revolve around proving the scalability and value of full devices and arrays, with significant cost improvements expected from optimisation of the system as a whole (across sub-areas).With this in mind, we perform a rough breakdown across the sub-areas of marine energy technologies to identify those with the largest potential for improvement.

Sub-area	Value in meeting emissions targets at low cost £bn[5]	Value in business creation £bn[6]	Key needs for public sector innovation activity/investment
Structure & prime mover	1.2 (0 - 3.5)	0.4 (0 – 1.3)	• Use of alternative materials • Manufacturing methods • Evolution of component level capabilities e.g. high integrity tidal turbine blades • (Wave only) New and better design concepts and structural configurations
Power take-off	0.5 (0 - 1.5)	0.3 (0 – 1.0)	• Improved yield through control systems • Develop disruptive new technologies to advance approaches to drivetrain and power take-off systems
Foundations & moorings	0.1 (0 - 0.4)	0.1 (0 – 0.2)	• Moorings & seabed structures require design optimisation to improve durability & robustness and reduce costs, particularly for deep water tidal • Improved station-keeping technologies
Connection	0.1 (0 - 0.3)	0.1 (0- 0.4)	• Development of next generation cables, connectors and transformers, including using higher voltage HVAC or HVDC and developing wet mate connectors (connectors that allow connections and installation in wet conditions) for marine applications
Installation	0.5 (0 - 1.5)	0.2 (0 – 0.6)	• Installation techniques including vessels that are suited for deeper water and large scale installations at lower costs: ○ Wave: alternative intervention solutions which allow faster deployment using lighter weight (cheaper) vessels ○ Tidal: effective drilling techniques that are less prone to the fundamental challenges of operating in the tidal current
O&M	0.3 (0 - 0.7)	0.25 (0 – 0.75)	• Improved lifecycle design • Access technologies for O&M, retrieval rather than on-site intervention and remote monitoring
Total	**£2.8bn (0 – 8.0)**	**£1.4bn (0 – 4.3)**	**5 yr Investment: High tens to over one hundred million GBP, leveraging 1-3 times that in private investment**

Benefit of UK public sector activity/investment[7]	
	High
	Medium
	Low

N.B. Of the £2.8bn value in meeting emissions targets at low cost, £0.7bn comes from improvements in capacity factor, significantly driven by system optimisation.

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[5] 2010-2050 Medium deployment / High improvement (L/H – H/H)

[6] 2010-2050 with displacement; Medium deployment / High improvement (L/L – H/H)

[7] Taking into account the extent of market failure and opportunity to rely on another country but without considering the costs of innovation support

1. Marine energy could usefully contribute to the UK energy mix from the 2020s

Marine energy is defined for this TINA as two types of technology: extraction of energy from waves and from currents created by the ebb and flow of the tides around the UK shoreline.

From our best current knowledge the feasibly exploitable resource by 2050 could deliver around 40-50TWh/year of electricity for wave and 20-30TWh/year for tidal (although estimates vary significantly). This can be compared to current UK electricity consumption of around 360TWh/year and could meet over 10% of expected 2050[8] total UK electricity needs. The best resource is located in relatively inhospitable locations far off the North West Coast of Scotland for wave and in water deeper than 40m, with peak currents in excess of 4.5 metres/second, for tidal (for example in the Pentland Firth). Included in the totals are other lesser but still useful resources, for example in the Atlantic off the coast of Cornwall for wave or the Alderney races for tidal. Wave and tidal energy are variable; tidal energy is predictable though peak power delivery does not necessarily correspond with peak demand.

Marine energy technologies are not yet commercial. Only 6 technologies (2 wave, 4 tidal) have been deployed at full scale demonstration, with an additional 3 devices expected to do so over the next year (1 wave, 2 tidal). A further 10-17 developers are at early demonstration/scale testing and a further 25-35 developers are still at the applied research stage (completing tank testing; many of these technologies will never progress to full scale stage).

Designs for wave energy have not yet converged. There are a variety of device concepts including oscillating water columns, overtopping devices, point absorbers, terminators, attenuators as well as flexible structures. Tidal devices have converged to a greater extent, with most designs now based around horizontal axis turbines, which share some similarities to wind turbines. There are some earlier stage designs still looking at the potential for vertical axis turbines, hydrofoils and Venturi-effect devices, in some case for niche applications.

Given the relatively early stage of marine energy technology, there is some uncertainty about its eventual role. The TINA project used a number of energy model runs to develop potential UK deployment scenarios. These scenarios aim to capture the full range of feasible deployment scenarios, and are neither forecasts for the UK nor targets for policy makers[9].

The deployment scenarios were generated using CCC MARKAL runs for the fourth carbon budgets, DECC 2050 calculator scenarios, and customised runs of the ESME model. This determines how much capacity is required across the generation mix to meet energy demand and emissions reduction targets based on the constraints outlined above. From these, four were used in the course of the analysis:

- **Low scenario** (0GW by 2050): A significant number of model runs did not show any deployment of marine sources in the UK. These runs met energy requirements through nuclear, wind and CCS deployment, and significant energy efficiency gains. Such an outcome was not as a result of 'extreme' assumptions.
- **Medium scenario** (4GW wave/2.5GW tidal by 2050): This level of deployment was generated when assuming either heightened demand, or constraints on the effectiveness of renewable heat technologies (primarily heat pumps).
- **High scenario** (8GW wave/5GW tidal by 2050): This level of deployment was generated in a number of model runs. Assumptions include constraints on onshore wind (limited public acceptance), CCS (significantly delayed deployment, or much higher costs), bioenergy availability, and/or offshore wind (limited cost reduction) or accelerated improvement of marine technologies.
- **Very high scenario** (17GW wave/10GW tidal by 2050): This scenario assumes accelerated improvement of marine technologies accompanied by strict constraints on biomass availability and deployment of nuclear. This *did* involve a relatively 'extreme' combination of constraints compared to most other modelling runs.

The medium 4GW wave/2.5GW tidal by 2050 scenario is used in the analyses in sections 2 and 3, estimating the value from meeting targets at lowest cost and value to UK through business creation. It is appropriate as a proxy for a probability-weighted average of the potential capacity scenarios. In reality, it is more likely to be more a case of "all or nothing" – that either the industry will be successful at reducing costs and improving performance and achieve the higher scenarios or not be successful and achieve very little/no deployment rather than end up somewhere in-between.

Finally, given the high uncertainty for both wave and tidal, their relative deployments reflect a scenario where *both* succeed. Nevertheless, it is important to keep in mind that if one *or* the other were to succeed, its deployment would likely be closer to the high or very high deployment scenarios.

[8] Based on CCC scenarios of electricity demand

[9] By trying to capture the full range of uncertainty over the mid to long term to inform innovation policy, these indicative deployment levels were not precisely aligned with UK government short and mid-term targets

2. Cutting costs by innovating

Current costs

Marine energy technologies generate electricity and need to compete with other low carbon generation technologies on the cost of electricity and their other characteristics. Concepts for the design, operation and maintenance of whole arrays have not yet been developed, but we estimate that current costs are of the order of £200-300/MWh for tidal and £250-400/MWh for wave.

In other words, tidal is currently cheaper than wave but both are still significantly in excess of other more proven technologies.

The cost of energy for marine energy systems can be attributed to a number of sub-areas: structure & prime mover, power take-off, connection, foundations & moorings, installation and O&M. For wave the structure & prime mover constitutes the largest share of costs (c.30%). For tidal, installation has the largest share (c.35%). (See Chart 2.)

Chart 2 Overview of marine energy sub-areas

Sub-area	Descriptions	% COE[10]	
		Wave	Tidal
Structure & prime mover	• The fluid mechanical process by which the device captures energy from the ocean. Can be through oscillation or rotation.	c.30%	c.15%
Power take-off	• Technology by which kinetic energy is converted to electrical energy. Can be directly to electricity, via a rotary electric generator or a linear electric generator, or via a hydraulic system.	c.20%	c.10%
Connection	• Method by which energy is transferred to shore. Can be an electrical connection (HVAC or HVDC) or, in some cases, a hydraulic connection.	c.5%	c.15%
Foundations & moorings	• Manner in which the device is held in place. Can be a moored, floating structure (moorings can be flexible or rigid) or a sea-bed structure, e.g. gravity-based or foundations.	c.10%	c.10%
Installation	• Process by which the device is installed. Will be influenced by the device location and station keeping method.	c.10%	c.35%
O&M	• Operation & maintenance of the device over its lifetime. This will also be influenced by the location of the device and its foundation.	c.25%	c.15%

Source: Marine Energy Challenge, Future Marine Energy, Carbon Trust Marine Energy Accelerator, Carbon Trust analysis

[10] Cost of Energy

Cost savings through economies of scale and innovation

In assessing the potential deployability of Marine, and its positive contribution to reducing the costs of a 'low carbon' energy system, we use offshore wind as our UK renewable benchmark. Offshore wind has been estimated to be capable of delivering power at £140/MWh for current sites and up to £180/MWh for future sites that are farther from shore, using current technologies. The path to offshore wind arrays which can generate at £100/MWh has been established and validated with key industry players and the UK has perhaps 900TWh/year of fixed and floating offshore wind resource, potentially accessible by 2050. There are further foreseeable innovations in offshore wind which could reduce costs to as low as £65/MWh over that time period[11]. It is therefore credible to believe that offshore wind could compete on a naked carbon price basis with nuclear fission and fossil fuels with CCS over the period.

If the marine energy technologies do not establish a path to generation costs of £100/MWh for first of a kind large scale (at least 200MW) array installation in typical UK resource locations by 2025, it is hard to see how any momentum could be sustained.

It is possible that wave or tidal will not succeed in meeting the challenge, and our current assessment is that success remains possible but very challenging and would be significantly more likely with carefully designed innovation support for developing robust and cost-effective systems. The TINA focuses on opportunities for innovation support, but it is important to note that overall success will also depend on building industry capacity and planning to make suitable infrastructure accessible on a timely and affordable basis.

Achieving this cost reduction pathway would require a large scale (at least 200MW) array installation deployed by 2025 with a significant optimised marine energy system that incorporates multiple innovations, combining to deliver the 50-75% reduction in cost of energy required by 2025. Our analysis has identified potential sources of cost reduction of this scale. Chart 3 details these, allocating the cost savings to each sub-area. Chart 3 also illustrates that some subareas, such as installation and foundations & moorings, have greater opportunities for cost reduction than others, such as connection and power take-off.

To achieve this level of innovation requires a combination of demonstration/deployment and targeted R&D:

Demonstration & Deployment

Six devices have been demonstrated at scale. The next stage for those that have been successful and that can make a strong case that their technologies can achieve the cost pathways outlined above is to build and demonstrate the first arrays (1-5MW). This will demonstrate proof of value and a viable cost reduction pathway, including:

- **Proving that multiple devices work in one location**: This means learning about the potential interaction of multiple devices in one location (such as turbulence effects)
- **Optimising energy yield**: Running back to back device trials allows the optimisation of control systems and strategies to maximise energy generation capabilities
- **Proving potential for achievable commercial cost level**: Deployment of multiple devices drives considerable learning with regards to cost efficiencies in construction and installation. In terms of construction, building multiple devices requires cost efficient procurement, and manufacturing processes (e.g. casting instead of welding). The need for cost efficiency drives similar learnings in installation (i.e. getting better and hence faster at installation)

Achieving the medium or higher deployment scenarios outlined above and achieving the necessary levels of scale economies would require the initial deployment of these first arrays to be completed by around 2015. The first commercial farms (10-15MW) would then need to be deployed by around 2017 and fully commercial farms (c.50MW) by 2019/2020.

This initial tranche of array deployment of fully demonstrated devices may or may not need to be followed by tranches of devices that are currently earlier on in their development, depending on how successful the initial tranche is and any breakthroughs the earlier devices might make.

[11] See the "Offshore Wind Power TINA".

Chart 3 Potential cost savings from innovation by subarea

Sub-area	Innovation impact – reduction in levelised costs, 2020/50[1]		Source cost reduction / rationale	Stage of develop-ment[2]
	Wave	Tidal		
Structure & prime mover	c.40%/c.70%	c.35%/c.55%	• Improved understanding of at-sea performance is expected to lead to design optimisation and especially reduction in mass of main structures • Innovations in manufacturing processes such as "batch production" of multiple units likely to reduce manufacturing costs and improve design through learning • Use of alterative materials such as GRP (glass-reinforced plastics), rubbers and concrete	Emerging
Power take-off	c.35%/c.65%	c.20%/c.35%	• Improvements in **control systems/software** will help drive yield improvements in marine applications • Innovation expected in **second generation power take-off technologies**	Emerging/ Evolving
Foundations & moorings	c.50%/c.85%	c.40%/c.60%	• Costs of foundations & moorings likely to reduce as **efficiencies** are made • Floating wave devices use conventional mooring systems with arguably little direct cost reduction potential. However, savings are nevertheless expected to stem **from improved deployability** (see installation)	Emerging
Connection	c.15%/c.30%	c.15%/c.30%	• Cost reductions likely to come from increasing use of **bespoke wet mate connectors** (connectors that allow connections and installation in wet conditions), more cost reductions as cable laying and DC connections are made more efficiently, and efficiency improvements in device and shoreline transformers	Evolving
Installation	c.45%/c.75%	c.55%/c.80%	• Wave cost reductions expected to come from development of alternative intervention solutions which allow **faster deployment using lower specification (cheaper) vessels** • Tidal cost reductions expected as gravity bases increasingly replaced by drilled structures. In particular drilling techniques expected which **negate the need for expensive and difficult jack up interventions** and are less prone to the challenges of operating in the tidal current	Emerging
O&M	c.50%/c.85%	c.35%/c.55%	• **Improved reliability** in design expected to reduce costs significantly • Development of new intervention techniques, with **retrieval** rather than on site-intervention. • **Better provision of ports and infrastructure** lead to lower servicing and transport costs	Emerging
Total cost reduction	c.40%/c.70%	c.45%/c.65%		
System yield improvement	6%	8%		

1 Based on learning curve analysis from Carbon Trust Marine Energy Accelerator studies in 2010, subsequently checked and validated in industry workshops

2 Stage of development follows the framework used by Jamasb, Tooraj (2007). "Technical Change Theory and Learning Curves", The Energy Journal 28(3). This defines technologies as ranging across the earliest stage (Emerging) through an intermediate stage (Evolving) through to a final stage (Mature)

3 Incorporated into levelised costs and allocated to sub-area reduction percentages above

Targeted R&D

Targeted R&D is required to realise the sources of cost reduction outlined in Chart 3.

- **R&D is required to address the challenges identified in first arrays** such as cabling, multi-array deployment, device interactions, and the cost and risk reduction required to make first arrays viable; these areas are likely to provide opportunities for collaborative R&D.
- **R&D is required for technologies at earlier stages of development.** For tidal energy, R&D is required on system integration and evolution of component level capabilities. For wave energy, in addition to system integration it is possible that new and better concepts will be required at the component and device level. This R&D is likely to be at relatively low cost compared to demonstration and deployment and will drive the step-change cost reductions required to meet the full cost reduction potential. Successful earlier stage technologies will then need to demonstrated and deployed as outlined above.

Achieving the level of deployment and innovation above would put wave and tidal energy on the cost reduction pathways shown in Chart 4 below. The initial stage will be a ‘Proof of value’ stage during which levelised costs come down to ‘Point 1’ in the chart, the point at a critical mass of devices have been deployed and reached a potential subsidy level of approximately 2-3 ROCs (depending on electricity prices).

Once the technology has reached this point, the net benefit to the energy system can be estimated against two counterfactuals:

A: no further reduction is considered beyond the point of first commercialised costs; and

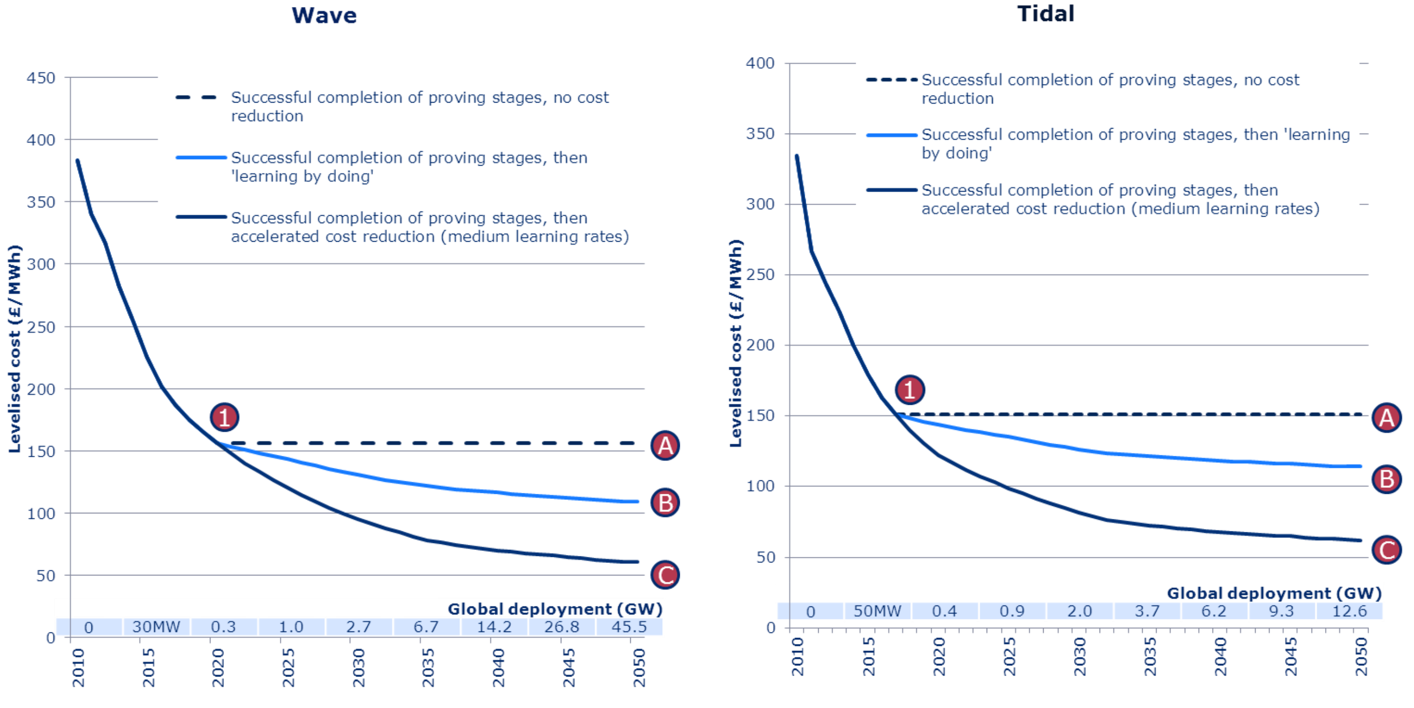
B: costs continue to fall in line with the expected improvements of alternative technologies e.g. offshore wind

The value of innovation can then be assessed as improvement beyond these two counterfactuals:

C: costs fall in line with additional technology innovation

N.B. Future costs are uncertain. The cost curves shown in Chart 4 are ‘aspirational but feasible’ scenarios of cost reduction. They are based on learning curve analysis, the results of which are consistent with marine energy achieving the path to £100/MWh by 2025 which is required to sustain future momentum.

Chart 4 Potential impact of innovation on levelised costs (medium global deployment)



1 ‘Proof of value’ point based on time at which a critical mass of devices have been deployed and reached a potential subsidy level of approximately 2-3 ROCs (depending on electricity prices)

2 Division between learning by research and learning by doing based on Jamasb, Tooraj (2007). "Technical Change Theory and Learning Curves", The Energy Journal 28(3)

Source: Cost reduction profiles based on results from Carbon Trust Marine Energy Accelerator studies, 2010, Carbon Trust analysis

Other non-innovation opportunities to reduce costs (e.g. greater competition / better developed supply chain / efficient financing) are likely to reduce costs further. Fluctuations in commodity costs and exchange rates could also decrease or increase costs considerably.

Value in meeting emissions and energy security targets at lowest cost

Based on our cost and efficiency improvements, and our scenarios for deployment (taking into account emissions and energy security constraints), we calculate the potential savings in energy system costs through innovation.

In our medium scenario, the identified innovation leads to a saving in deployment costs over 2010-2050 of £2.8bn, £1.6bn for wave and £1.2bn for tidal. The £2.8bn cost saving from RD&D is in addition to the base case £2.2bn cost saving from 'learning by doing'. These savings estimates use an 'inflexible deployment' counterfactual, which is most appropriate if we believe the feasibility of substitute technologies is low and/or deployment incentives are inflexible to changes in the relative cost-effectiveness of different technologies. This is more likely in a world in which other technology options are constrained e.g. due to a lack of public acceptance of nuclear and onshore wind, if CCS is delayed/higher cost or bioenergy availability is low. This is a high cost saving estimate.

Chart 5 Wave: Potential cost savings from 2010 to 2050 (discounted £bn) – assuming inflexible deployment (left-hand chart) or perfect system optimisation (right-hand chart)

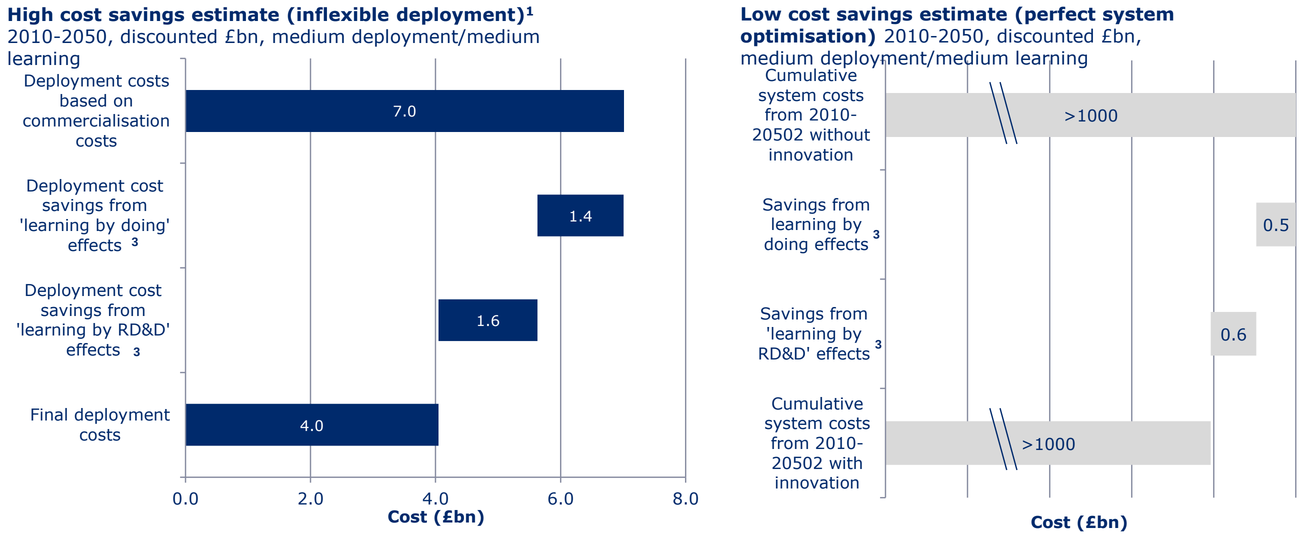
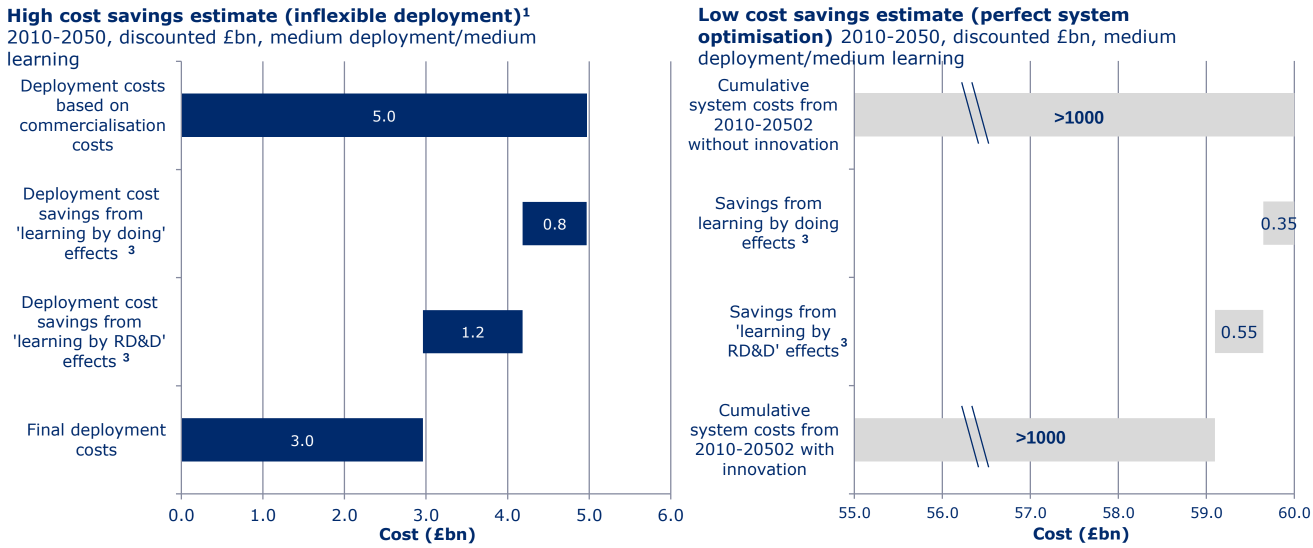


Chart 6 Tidal: Potential cost savings from 2010 to 2050 (discounted £bn) – assuming inflexible deployment (left-hand chart) or perfect system optimisation (right-hand chart)



1 Cumulative levelised cost of offshore wave capacity installed between 2010 and 2050 discounted to 2010 using the social discount rate
2 Cumulative system cost savings are as calculated by running one representative scenario in the ESME model (with TINA-specific assumptions) without cost improvements. Model assumes ~80% reduction in greenhouse gas emissions by 2050; The total cumulative system costs are highly sensitive to all assumptions in the model, and to avoid "false precision" we do not provide a precise figure
3 Savings from 'Proof of value' point onwards

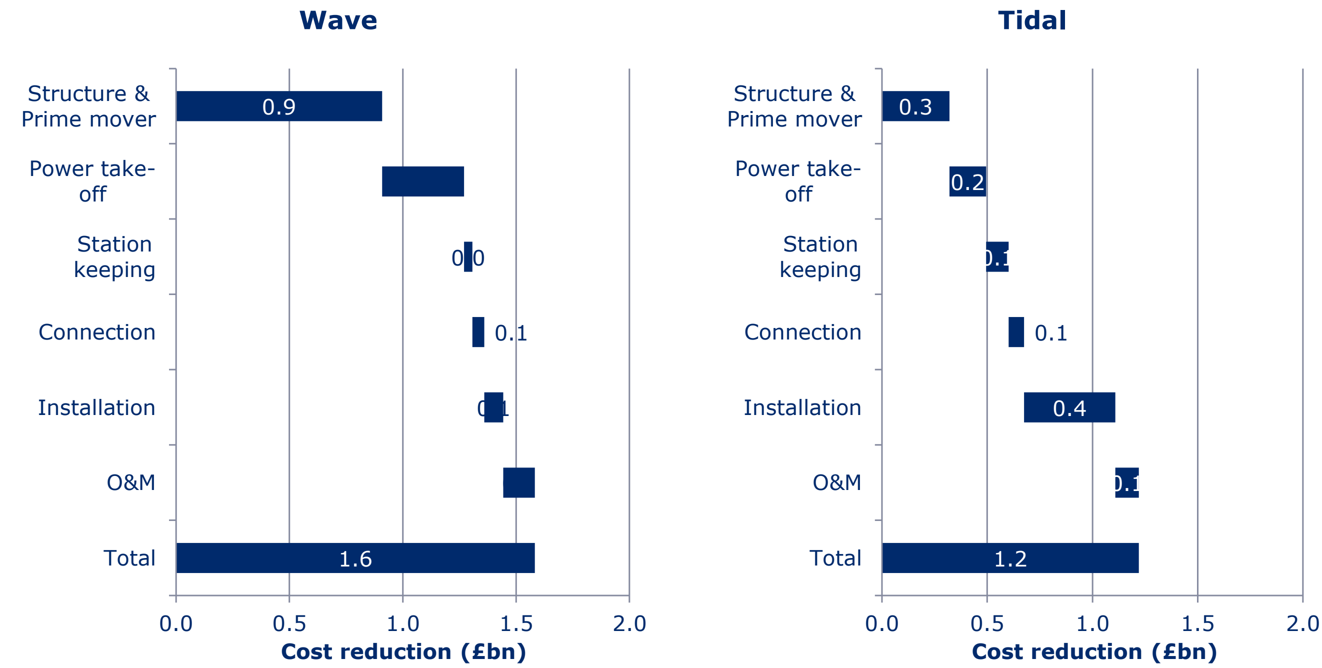
Source: Carbon Trust, MEA, ESME and CCC Markal, IEA, Carbon Trust analysis

An alternative counterfactual was also used assuming 'perfect system optimisation' whereby marine energy deployment could adjust significantly if cost improvements are not achieved, which is more appropriate when least cost alternatives are readily available and easily substitutable and deployment incentives adjust perfectly to changes in the relative cost-effectiveness. Under this counterfactual, our savings estimate would be about 65% lower for wave and 55% for tidal. The right hand sides of Chart 5 and Chart 6 illustrate the implied cost savings under perfect system optimisation.

The actual cost savings are likely to be somewhere in between the inflexible deployment and the perfectly optimised system scenarios. We have shown the former estimates throughout this paper to give a clear indication of the upper limit of our estimates.

The savings opportunity can be attributed to each sub-area, as shown in Chart 7, including each sub-area's contribution to overall system cost reduction and yield improvement. These attributes are indicative but give a sense of relative importance to overall system cost reduction. The greatest cost savings within a sub-area for wave are from the structure & prime mover, followed by the power take off. For tidal they are from installation and then the structure & prime mover.

Chart 7 Total reduction in deployment costs by sub-area, 2010-2050 (medium deployment scenario)



Source B&V: Key Marine Energy Component Technologies for Cost Reduction R&D, May 2007; Carbon Trust expert interviews; Carbon Trust analysis

3. Green growth opportunity

The global marine energy market

IEA estimates for global marine energy range widely from no capacity to over 210GW by 2050 – a fifth of the offshore wind capacity under the equivalent scenario. The maximum estimate for 2020 is only 1.5GW globally. Wave is forecast to be the larger contributor to the marine market, with higher deployment levels reflecting greater known wave resource versus tidal. There is relatively scarce country level data about the potential size and location of markets.

- **Low scenario** (0GW wave/0GW tidal) if the world fails to remain on a path to 2 degrees Celsius and/or few constraints on nuclear and CCS, and/or electricity demand is relatively low
- **Medium scenario (IEA Blue Map)** (46GW wave/13GW tidal by 2050) the world keeps on a 2 degrees path and few constraints of nuclear and CCS
- **High scenario (IEA Blue Map HiRen)** (188GW wave/52GW tidal by 2050) the world keeps on a 2 degrees path and there are strong constraints on nuclear and CCS

The global market turnover in 2050 could grow to c.£3bn in wave and £1bn in tidal (under the medium scenario above).

The UK could be one of the market leaders

Our analysis would suggest that the UK is uniquely well positioned to capture market share, in particular due to its favourable resources (c.50% of available European wave resource, and c.25% of European tidal resource) and the strength of its supply base thanks to past support measures relative to other geographies. UK competitive advantage is estimated to be high or very high in nearly all areas with the exception of power take-off systems (a technology area dominated by larger electric engineering companies e.g. ABB), thanks to a strong research and development base, a strong share of leading device developers, and the experience from its offshore oil & gas and offshore wind industries.

The marine market is likely to be global for smaller subcomponents, vessels and design elements and regional for the larger components, with particularly strong regions in Europe, parts of SE Asia and the East Coast of North America.

With successful technology development, and the required build of infrastructure and industrial capacity, the UK could be a strong player, especially in regional markets. This would equate to a sizeable share of the global market, an estimated c.15%. The UK's global share in structures & prime movers could be c.25% reflecting today's dominance and with a c.25% of O&M reflecting its large local resource.

Up to £4bn contributed to the UK economy

If the UK successfully competes in a global market to achieve the market share described above, then under the medium deployment scenario marine energy could contribute c.£0.2bn[12] per annum to UK GDP by 2050, a cumulative contribution[13] of c.£1.4bn up to 2050. Cumulative contribution increases to c.£4bn under the high deployment scenario.

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[12] Accounting for typical displacement effects of c.50%

[13] Discounted at 3.5% to 2040, and 3.0% between 2040 and 2050, in line with HM Treasury guidelines

4. The case for UK public sector intervention

Public sector activity is required because there are significant market failures impeding innovation and because the UK cannot rely on other countries to overcome these market failures:

Market failures impeding innovation

Our analysis suggests that various market failures (that can only be overcome through public sector intervention) are preventing the development of marine technologies, with these impacting both the innovation path to bring marine technologies to commercial 'proof', and the innovation path for targeted R&D on the identified system sub-areas.

There are a number of overarching failures identified;

- **Uncertain and policy dependent market demand:** A missing market for carbon *(negative externalities)* and uncertainty about UK, EU and global commitments to targets raises risks and lowers returns, and means that investors are discouraged from entering the marine market
- **High capital expenditures requirements**, which tend to be outside the risk-reward profile of potential investors, exacerbate the uncertainty of market demand, and inhibit willingness to invest. The capital-intensive nature of the technology also requires more upfront finance and therefore convincing financial institutions to invest in areas they may know little about (asymmetric information)
- **Challenges to retaining the Intellectual Property (IP) benefits from R&D** (*knowledge spillover)* inhibit investment in innovation, especially at earlier stages. Moreover, they tend to limit collaboration and knowledge sharing to levels below what would be optimal from the public's perspective
- **Significant common infrastructure requirements** (*imperfect information)*, especially the need for increased certainty regarding the timings of grid availability for use with marine sources. This perceived uncertainty increases the difficulty of finance raising for both company and project finance.
- **Site planning and approval requirements**, owing to the use of public land or environmental protections also discourage market investment in the absence of clear and timely government action

In addition, some specific technology sub-areas or stages of innovation are particularly affected by market failures, and innovation on individual sub-area types are predominantly around the following areas:

- Uncertain market demand combined with high capital expenditure requirements have a particularly negative effective on the latter stages of innovation – **full scale demonstration** and **initial deployment of first arrays**
- Similarly **development in specific sub-areas** (especially prime mover) require significant capital expenditures and are relatively strongly affected by market failures
- The development of novel concepts is particularly inhibited by challenges to retaining the IP benefits from R&D
- Finally, activities with particular potential from knowledge sharing (such as installation, O&M and array effects) will also be inhibited by concerns about retaining the IP benefit from R&D

The UK cannot rely on other countries to drive innovation with the required focus and pace

Our analysis broadly concludes that the UK cannot rely on innovation by other countries, notably for the reason that the UK's leadership of the industry puts it noticeably ahead of its nearest competitors (Canada, US, Ireland) with twice as many devices and the most credible players. In addition, in the medium and high/very high deployment scenarios, the UK will require the technology well ahead of the rest of the world. In addition, the UK has specific requirements for foundations & moorings and, potentially, installation technologies, related to its geographical conditions (e.g. water depth in tidal, sea-bed conditions in wave).

5. Potential priorities to deliver the greatest benefit to the UK

The relative benefit of UK public sector activity /investment

Chart 8 brings together the analysis across all the sections above. In sections 2 and 3 we concluded that the value from innovation in marine energy is highly uncertain, from delivering almost no value – if marine does not become cost competitive in time to achieve commercial-scale deployment – to up to £8bn in value from meeting targets at reduced cost and enabling a £1.4bn–£4.3bn contribution to UK GDP (cumulatively up to 2050) if marine energy achieves medium to high deployment scenarios. In sections 3 and 4 we concluded that the UK has high to very high competitive advantage across all sub-areas, that there are significant market failures and that the UK cannot rely on someone else for most subareas.

Combining these analyses, the LCICG has also identified the relative benefit of UK public sector activity/investment across the innovation opportunities. The proving stages of initial deployment of the first arrays are critical to enabling all value and provide high benefit of UK public sector activity/investment. Applying this analysis to the sub-areas highlights that some provide greater benefit of UK public sector activity than others.

The sub-areas with the greatest value are:

- Structure & prime mover and Installation, followed by
- Power take-off, Foundations & moorings and O&M, followed by
- Connection

It should be noted that whilst Connection provides the least benefit in and of itself, it is a critical enabler, particularly for tidal arrays. Sub-sea inter-array technologies represent a key uncertainty in multiple device projects, where the behaviour of the cables in the tidal stream environment is uncertain. Tidal streams provide a particular challenge to cables, with the rock bottom and movement of the cables in the steam causing fatigue, wear and scouring.

Given resources are limited; the UK may need to focus on these areas of greatest benefit. It will also need to take into account the costs of realising this benefit.

Chart 8 Benefit of UK public sector activity/investment by sub-area and technology type

Key: **Low** ○ ◔ ◑ ◕ ● **High**

Sub-area	Value in meeting targets, £bn Medium (Zero-high)[1]	Value in bus. creation, with displacement, £bn, Medium (Zero-high)[2]	Comp. adv.	Extent market failure	Opportunity to rely on someone else	Benefit of UK public sector activity/investment (without considering costs)[3]
Proving stages	Critical to enable all value		Very high	●	**NO** - Other countries active (US, Canada), but are significantly behind UK on innovation path	**HIGH -** No other country in position to drive technology to market readiness
Structure & prime mover	1.2 (0 - 3.5)	0.4 (0 – 1.3)	Very high	●	**NO** - Possibility of some development in Canada and USA in specific applications	**HIGH -** Intervention required for near and offshore applications
Power take-off	0.5 (0 - 1.5)	0.3 (0 – 1.0)	High	◑	**YES/NO** - Current technologies developed for established applications but need for second generation development	**MEDIUM -** Key innovation need for control systems and second gen power take-off technologies
Foundations & moorings	0.1 (0 - 0.4)	0.1 (0 – 0.2)	High	◑	**NO** - Few other countries placed to drive innovation; Some technology cross-over to come from offshore wind in deep water and off-shore applications	**MEDIUM -** Intervention required for near and offshore applications
Connection	0.1 (0 - 0.3)	0.1 (0- 0.4)	Med	◔	**YES/NO** - Grid and offshore wind likely to develop most requirements	**LOW -** Some intervention requirements in development of wet mate connectors
Installation	0.5 (0 - 1.5)	0.2 (0 – 0.6)	Very high	●	**NO** - Some industries such as offshore wind and O&G have relevant skill to draw on, but specific innovation needed	**HIGH -** Intervention required for near and offshore applications
O&M	0.3 (0 - 0.7)	0.25 (0 – 0.75)	Very high	●	**NO** - Some cross over in O&G, but unlikely to be sufficiently attractive in the early stages	**MEDIUM -** Intervention required for near and offshore applications
TOTAL	**£2.8bn (0 – 8.0)**	**£1.4bn (0 – 4.3)**				

Source: CT analysis

1 These values would be 55-65% lower according to a perfect system optimisation estimate

2 After displacement effects of 50%

3 These ratings compare relative opportunities between Marine energy innovation areas. They are NOT an absolute rating relative to other innovation opportunities in other technology areas

Current innovation support

Three types of public sector innovation support are required – a combination of **market pull** mechanisms (such as the Renewables Obligation), **technology push** mechanisms, such as grants and programmes that catalyse coordination and sharing of data and IP, as well as **enablers** such as grid and test infrastructure. Chart 9 illustrates the large amount of current UK public sector activity/investment across these three areas, including LCICG members' capital grant programmes and relatively complete testing infrastructure (sub-area testing at NaRec, prototype testing at EMEC, and array testing facilities recently completed at WaveHub).

Potential ongoing priorities for public sector innovation support

Short-term priorities – the next 3-4 years

Section 1 concluded that the innovation priorities over the next 3-4 years are a combination of initial deployment of first arrays and targeted R&D. The public sector support required for both these areas of innovation is outlined below.

Chart 9 Summary of current UK public sector activity/investment

Market pull (demand side)	**Technology push** (supply side)	**Enablers**
▪ Marine energy one of the 7 Low Carbon Industry areas singled out in **Low Carbon Industry Strategy** ▪ **Levy Exemption Certificates (LECs)** – As a renewable energy source marine energy qualifies for LECs ▪ **Saltire Prize** (Scottish Government) - £10m awarded to first device that can produce 100 GWh over 2 year period ▪ Revenue support through **Banded Renewables Obligation** - 2009 to 2017. Contract for Difference FIT expected from 2017. – Support levels for certain marine energy technologies will more than double from 2ROCs to 5ROCs per MWh, subject to a 30MW limit per generating station – In Scotland proposed support of 5 ROCs for wave and tidal (with no 30MW limit)	R&D grants: • **Supergen 2** – 2009 to 2012; Research Council led support for marine R&D at academic institutions. (£5.5m) • **Technology Strategy Board Marine Energy Programme** – £22m grants awarded since 2007 in device cost reduction and underpinning technologies Capital grants: • Offshore Renewable Energy Catapult - from summer 2012; up to £10m per annum over five years (£50m) from the Technology Strategy Board for offshore wind and marine energy. To be set up by a consortium of the Carbon Trust, Narec and Ocean Energy Innovation, headquartered in Glasgow with an operational centre in the North East of England (Northumberland) • Marine Energy Array Demonstrator (MEAD) – £20m from DECC to help fund the first marine arrays in the UK • Scottish Government £18m fund to help develop Scotland's first commercial wave and tidal power arrays • **ETI Marine Programme** - 2008 to 2018; R&D in sub-areas with cost reduction potential. Funding for projects is £21m (Funding in form of investments rather than grants) • **Wave and Tidal Energy: Research, Development and Demonstration Support fund (WATERS)** – 2010 onwards; Scottish government funding totalling £13m to support commercial demonstration	▪ Testing sites: – **NaREC** – New and Renewable Energy Centre; Tank and open sea test centre operated since 2002, with recent DECC/BIS funding (£10m) for marine drive train test rig (2009-11) – **EMEC** – European Marine Energy Centre, Orkney; Full scale open water test centre for marine energy prototypes. Government funding for EMEC to date c.£15m – **WaveHub** – from 2010; Offshore electrical grid connection point off North Cornwall coast to which wave energy devices can connect, c.£45m ▪ Permitting regime: – Crown Estate Pentland Firth and Orkney waters licencing round has provided 1.6GW of wave and tidal sites.

Initial deployment of first arrays

To demonstrate proof of value and a viable cost reduction pathway, support is required to move technologies beyond single device demonstration and into first arrays (c.5MW).

First, it is critical to ensure that these marine energy systems have the potential to reduce their costs at the rate required to become cost competitive with offshore wind and other technologies by 2025. Public sector support can facilitate identifying these system cost reduction opportunities through developing system models and helping to validate key assumptions across multiple stakeholders.

Public sector support is then required to provide:

- **Market pull** to overcome market demand failures. Existing market pull mechanisms (outlined in Chart 9) such as the Renewables Obligation provide revenue support once the arrays are generating electricity. Support levels for certain marine energy technologies will more than double from 2ROCs to 5ROCs per MWh, subject to a 30MW limit per generating station (with no limit in Scotland under current proposals).
- **Technology push**: Grants are required to enable developers to secure full finance of first arrays, given the large capital expenditures and associated market failures outlined above. Programmes can also catalyse coordination and sharing of common resourcing and testing data. To these ends, DECC and the Scottish Government have both recently announced additional public support. DECC has announced the Marine Energy Array Demonstrator (MEAD) with £20m of public sector funding. The Scottish Government has announced £18m to help Scotland's first commercial wave and tidal power arrays.
- **Enablers**: public sector funding could be required for array grid and testing infrastructure.

Targeted R&D

Section 2 concluded that targeted R&D is required to address the challenges identified in the first arrays as well as for technologies at earlier stages of development:

- **R&D to address the challenges identified in first arrays**

  R&D is critical to address the challenges identified in first arrays to enable deployment, such as cabling, multi-array deployment, device interactions, as well as drive the cost and risk reduction required to make first arrays viable.

  Technology push public sector support is required. As well as grants to help fund the large capital costs of developing these components, particularly the prime mover, many of the challenges will be most efficiently addressed through increased collaboration. Public sector innovation programmes can catalyse this collaboration through creating governance, data and IP sharing models.

- **R&D for technologies at earlier stages of development**

  R&D is also required for technologies that are at earlier stages of development. These earlier stage technologies create optionality for step-change cost reduction and performance improvement should devices being deployed in arrays fail to come down their cost curves at a fast enough rate. For tidal energy, because there is a much larger consolidation around a single technology type (horizon axis turbine), R&D is required on system integration and evolution of component level capabilities. For wave energy, it is possible that new and better concepts will be required at the component and device level. This R&D is likely to be at relatively low cost compared to deployment and will drive the step-change cost reductions required to meet the full cost reduction potential. Again, this will require grants and coordination.

R&D should be targeted at the innovation priorities for the different sub-areas as outlined in Chart 10. The level of cost reduction is likely to require significant innovation across all sub-areas, but as explained above the benefit of UK public sector support is greater in some than others (as illustrated in the shading in Chart 10). This benefit will need to be weighed against the cost of support, with the indicative scale of funding also shown in Chart 10.

LCICG members expect to invest £20-30m of public sector funding into targeted R&D in marine energy over this period, leveraging 1-3 times that from the private sector.

Medium-long term priorities – the next 4-10 years

To realise the full benefit from innovation over the following 4-10 years will require significant ongoing UK and European Union public sector funding. This will enable the deployment of the first commercial-scale farms (c.10-15MW), on-going targeted R&D and potentially demonstration of full scale devices that are currently in earlier stages of development.

Deployment of first commercial-scale farms

In four years' time, if the first arrays have been successfully deployed and if marine energy is successfully maintaining the required cost reduction pathway, then the next step will be deployment of larger c.10-15MW arrays. These are likely to still require a combination of the three types of public sector support:

- **Market pull**: by 2017 likely to be through the proposed Contracts for Difference (CfD) Feed-in Tariff (FIT)
- **Technology push support:** capital investment support may still be desirable for further innovative R&D activities to reduce costs further. Whilst costs and risks will have been reduced they are likely to still not yet be attractive enough to commercial investors without public sector funding and/or de-risking of investment.
- **Enablers:** on-going testing and infrastructure support.

On-going targeted R&D

Public sector support to address the challenges outstanding from the initial deployment of the first arrays and the challenge in scaling up to the first commercial-size arrays, such as new manufacturing approaches to take advantage of economies of scale.

Demonstration at full scale of devices

By 2015, if the next tranche of devices provide significant additional cost reduction opportunities to those being deployed in arrays, then they should be demonstrated at scale to prove their viability. This will require grant support and use of testing sites.

Chart 10 Marine energy public sector activity/investment by stage of technology journey

Stage in technology journey	Potential innovation priorities	Estimated cost/time[1]	Current public sector activities/investments	Future potential activities
Early stage	• Funding to drive pipeline of most promising second generation concepts	Millions of pounds	• R&D grants such as Research councils – SuperGen £5.5m to 2012 • CT Entrepreneurs Fast Track • Technology Strategy Board Marine Energy Programme	• For tidal energy, provide support for system integration and evolution of component level capabilities • For wave energy, could also provide support for new and better concepts at the component and device level
Full scale demo	• Continuation funding is required to support the technologies which have just entered full scale demonstration stage • In addition a small pipeline of new technologies should be secured to keep the very best technologies progressing towards a second phase of full scale prototypes	Millions of pounds	• Renewables Proving Fund (MRPF) - £22.5m in grants, now fully allocated and expired March 2011 • Wave and Tidal Energy: Research, Development and Demonstration Support fund (WATERS) - £21m to 2018 – partially allocated • ETI marine programme - £13m to support commercial demonstration (earlier stage than scalability) • Technology Strategy Board Marine Energy Programme	• Future support in the next 4-10 years once early stage technologies have reached full scale demo stage leveraging existing facilities such as EMEC, NaREC and Wavehub
Initial deployment of first array	• Public support is required to secure full finance for first arrays. A well-defined support programme is required to provide longer term security around development paths • Leading developers such as Pelamis, MCT and Wavegen are planning now for first array developments; these projects are expected to be deployed from 2013 onwards, but constructed from late 2012	High tens to a hundred million pounds	• Marine Energy Demonstrator (MEAD) - £20m from DECC to help fund the first marine arrays in the UK • Scottish Government £18m fund to help develop Scotland's first commercial wave and tidal power arrays	• Compliment with targeted R&D focused on cost reduction and performance improvement through focusing on system optimisation and sub-areas outlined below

Chart 11 Marine energy public sector activity/investment to support targeted R&D by sub-area

System & sub-area	Potential innovation priorities	Scale of public funding	Current public sector activities/investments	Future potential activities
Structure & prime mover	Design, develop and coordinate R&D programme into targeted areas; • Lower cost and more resilient structures, for instance through the use of alternative materials such as glass reinforced plastic, rubbers and concrete • Evolution of component level capabilities e.g. high integrity tidal turbine blades • (Wave only) New and better design concepts and structural configurations Innovations in manufacturing processes such as "batch production" of multiple units Ensure participation of key stakeholders to pool knowledge Encourage stakeholder participation and funding through fiscal stimulus (i.e. maximise private leverage)	Tens of millions (5 years)	• ETI Marine Programme – £21m (funding in form of investments rather than grants) • Technology Strategy Board Marine Energy Programme – £5-10m • R&D grants such as Research councils – SuperGen £5.5m to 2012 • Offshore Renewable Energy Catapult (for offshore wind and marine energy) - up to £10m per annum over five years from 2012 (£50m)	• Targeted R&D in sub-area areas, focused on the most promising concepts and cost reduction areas • Central co-ordination to share knowledge in areas that are beneficial for the industry as a whole
Power take-off	Continued development of control systems and software to improve yield Develop disruptive new technologies to advance approaches to drivetrain and power take-off systems	Millions		
Foundations & moorings	Targeted R&D into moorings & seabed structures - require design optimisation to improve durability & robustness and reduce costs – particularly for deep water tidal Improved station-keeping technologies	Low tens of millions		
Connection	Development of next generation cables, connectors and transformers, including using higher voltage HVAC or HVDC and developing wet mate connectors for marine applications	Millions		
Installation	Installation techniques including vessels that are suited for deeper water and large scale installations at lower costs: • Wave: alternative intervention solutions which allow faster deployment using lower specification (cheaper) vessels • Tidal: effective drilling techniques that are less prone to the fundamental challenges of operating in the tidal current	Tens of millions		
O&M	Improved lifecycle design Access technologies for O&M, new intervention techniques (with retrieval rather than on-site intervention) and remote monitoring	Millions to over ten million		

Benefit of UK public sector activity/investment[14]	
	High
	Medium
	Low

[14] Also taking into account the extent of market failure and opportunity to rely on another country but without considering costs of the innovation support

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