CARBON TRUST

Making business sense of climate change

Accelerating marine energy

The potential for cost reduction – insights from the Carbon Trust Marine Energy Accelerator

July 2011

Contents

The Carbon Trust has worked with the following organisations during the Marine Energy Accelerator (MEA).

Innovators

Aquamarine Power
Aviation Enterprises Ltd
AWS Ocean Energy Ltd
Checkmate Sea Energy Ltd
Cranfield University Ltd
C Wave Ltd
Hammerfest Strøm
Joules Energy / Wavetrain UK Ltd
JP Kenny
Mac Taggart Scott
Marine Current Turbines
Minesto
Ocean Power Technology UK Ltd
Pelamis Wave Power Ltd
Promoor Ltd
Sea Energy Associates Ltd
SeaKinetics Ltd
Tension Technology International Ltd
Tidal Energy Ltd
TNEI Services Ltd
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Consultants

Black & Veatch
BMT Cordah Ltd
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J W G Consulting Ltd
Mojo Maritime Ltd
Nabarro LLP
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SeaRoc Group Ltd
WS Atkins PLC

Executive summary

The potential for wave and tidal stream to make a material contribution to the UK's energy mix is well recognised, and is reflected in the level of UK activity. As the industry moves from full-scale prototype stage to first arrays, the key challenge facing the marine energy industry is lowering the cost of energy generation. The Marine Energy Accelerator (MEA) has supported technology innovation over the past four years, and has set out clear pathways for future cost of energy reduction: with sufficient focus on innovation we believe the costs of energy from marine generators can be competitive with other renewable technologies by the mid 2020s.

Key findings

- The innovation supported by the Marine Energy Accelerator has shown that significant cost of energy reductions can be achieved, ultimately making wave and tidal stream technologies competitive with other renewables.
- The available resource is now better understood, and is significant – amounting to around 20% of the UK's electricity consumption.
- Cost of energy will fall as a result of experience and scale as installed capacity increases, and also from technology innovation.
- A continued focus on targeted innovation is required to bring costs down sufficiently, within a stable support environment.

The MEA was a £3.5 million programme to understand and accelerate the cost reduction of energy extracted from wave and tidal stream resources. The Accelerator has worked with industry leaders and technology innovators to progress key component technologies, develop offshore innovations and investigate the next generation of devices. The result is a deep understanding of device cost centres and a clearly defined pathway to achieve the cost of energy reduction needed to make these technologies competitive with other forms of renewable generation.

Innovation breakthroughs

Many of the direct cost reductions from the MEA projects have already been implemented, others are more applicable in the future since they relate more to the deployment of multi-device arrays. Cost of energy savings of 35% have been demonstrated through an innovative installation and recovery process for a leading wave energy device by reducing lifetime operation and maintenance costs, and increasing device availability. Significant cost of energy improvements have also been identified in component technologies. For example a better understanding of service conditions and the behaviour of carbon fibre tidal blades has resulted in a more optimised design, reducing the need for costly over-engineering.

Next generation of concepts

The most promising new device concepts representing the next generation of wave and tidal device technologies have also been identified and supported. Some of these have the potential for significantly reduced cost of energy in the future, and may also open up new areas of resource as economic. Concepts taken forward in the MEA include a dynamic tidal device that increases the flow speed through the turbine to increase energy yield at lower velocity sites and a wave attenuator with a novel power capture method that is made from rubber rather than steel or concrete.

Marine Energy Resource

A new hydrodynamic methodology used in the MEA study has shown that the total tidal resource is in line with estimates from the previous Carbon Trust assessment. For the first time we have also assessed the practical spatial constraints at the key tidal energy sites in UK waters, working in partnership with The Crown Estate. This has revealed that devices currently under development could practically and economically capture around 21 TWh of tidal resource per year[1]. Combined with the 50 TWh/yr of practically accessible wave resource previously assessed by the Carbon Trust, this gives a total of 70 TWh/yr, around 20% of current UK electricity demand[2].

The MEA work on tidal resource has also shown that a second generation of tidal devices will be needed to cope with the difficult and deep waters where much of the UK resource is located. Second generation tidal devices will solve these problems and might also include cost reducing innovations such as floating structures or multiple rotors on single foundations.

Costs can come down dramatically

As a backdrop for our analysis, and to assess the impact of the MEA, the Carbon Trust has calculated new benchmark costs for energy generated from first marine energy farms at typical sites. Our analysis places offshore wave cost of energy at 38-48p/kWh and tidal stream at 29-33p/kWh, both using a 15% discount rate[3]. These costs are higher than we previously projected in 2006, primarily because as an industry we now have a much better understanding of device performance and actual capital and operating costs. Details of the impact of site location on costs have also been considered for the first time, showing that farms at the best wave and tidal sites could produce electricity at lower cost than these baseline figures.

We set out the innovation steps required to deliver continued progress in reducing costs from this initial high level and conclude that, with sufficient effort on innovation, costs of energy will come down to around 28 p/KWh for wave and 16p/kWh for tidal stream by the time the industry is half way through developing the Pentland Firth and Orkney Waters licensed sites (that is, around 800MW of installed capacity). There is scope for marine costs of energy, particularly wave, to fall even faster if other countries install significant capacity as planned.

Focus areas

In the short term capital funding will be necessary to support the deployment of the first arrays of wave and tidal devices. Following on, a stable support mechanism is vital to encourage long-term investments by supply chain companies and offshore operations and maintenance contractors. Throughout this period, continued focus on innovation will ensure that the pace of cost reduction is sufficient to bring cost of energy down to competitive levels by the mid 2020s. For tidal stream technologies, future areas of focus will include installation techniques and equipment, along with continued efforts on foundations. Wave technologies will require focus on increasing energy capture – improving the interaction of the main structure with the waves – and optimised operations and maintenance strategies. Both wave and tidal stream technologies will place increased emphasis on proving reliability and on risk reduction as the resource is harnessed from inherently more difficult environments.

[1] New emerging devices, such as Minesto's dynamic 'kite' tidal generator which was supported in the MEA, could extend this resource assessment by accessing areas of tidal energy too diffuse to be included in the study.

[2] The Digest of United Kingdom Energy Statistics (2010) gives total UK electricity consumption of 379 TWh in 2009.

[3] These are projected 'first farm' costs, which are assumed to have a capacity of 10MW after around 10MW of previous installations.

1. Introduction

1.1 Status of the industry

The development of devices to generate electricity from waves or tidal currents goes through a number of stages, shown below. Now, as seen in *Figure 1*, leading developers are installing full-scale prototypes and working towards their first farms of devices.

In recent years the overall number of players in the industry has not changed significantly, and there are still numerous wave and tidal technology companies with only a few signs of consolidation within the industry. Demonstrable progress within this group has been limited to a handful of developers who have been able to secure both private and public funding. *Figure 1* shows that around eight devices are working at the full-scale demonstration stage.

Tidal stream energy extraction technology is currently more mature than wave technologies, and there are more developers at full-scale demonstration stage. Tidal devices are approaching a convergence of design, with most concepts based on a bottom-mounted horizontal axis turbine. A number of very different wave devices are under development, and little design convergence has taken place, although the leading developers are demonstrating full-scale devices.

Figure 1 *States in the development of a marine energy conversion device. Numerous device concepts exist for converting energy in tidal streams or waves to electricity; all are likely to pass through the following stages*

Technology journey

	Concept/tank testing	Part-scale demo	Full-scale at-sea demo	First farm deployment 5-10MW	Full 'commercial'
Indicative cost per project (£)		~£100-500k	~£10-30m	~£30m-100m	
No. of UK devices under development					
Wave	c. 10-15	c. 5-6	c. 3		
Tidal	c. 15-20	c. 8-10	c. 5		

***Figure 2** Indicative global wave and tidal activity*

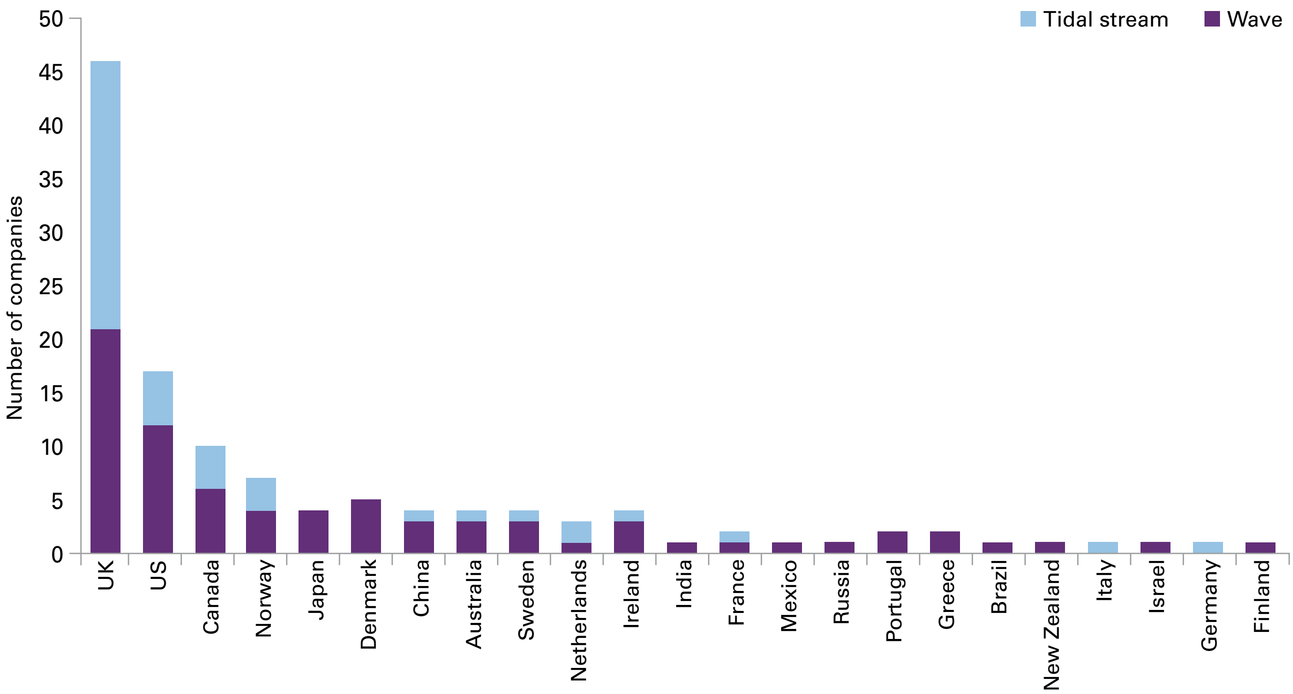


Figure 2 considers the global status of wave and tidal current energy technologies, showing the high level of activity in the UK relative to the rest of the world. These data include a number of very early stage concepts not included in *Figure 1*, some of which are being supported by other Carbon Trust schemes.

In the recent economic downturn, a realisation of technology risk and the long time to market of early-stage devices has led to reduced venture capital and private investment in the sector. Public funding has increased to fill the gap somewhat, via initiatives such as the Marine Renewables Proving Fund, the WATERS fund in Scotland and initiatives by the Technology Strategy Board and the Energy Technologies Institute. There has been a shift away from reliance on VC money to fund the early stage of the industry, with major industrial companies and utilities taking equity stakes. Some key industrial players, including electricity utilities and equipment manufacturers, are developing in-house technologies, while others have bought into existing marine energy technology. The involvement of these key industry players, and the associated injection of significant funding, is an encouraging sign for the marine energy industry[4].

[4] Notable examples of direct investment by industrials in technology development companies include ABB and SSE's investments in Aquamarine Power, EDF Energy and Seimen's investment in Marine Current Turbines, Voith Hydro in-house development of hydro turbines, Rolls-Royce's purchase of Tidal Generation and Alstom acquiring stakes in AWS Ocean Energy and Clean Current power systems.

Recent progress

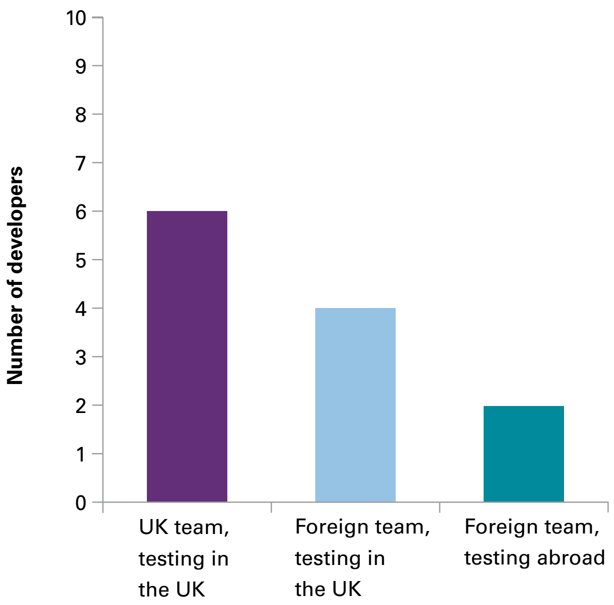
Since the Carbon Trust last reported on marine energy in 2006[5] a number of full-scale grid-connected prototypes have been installed. Marine Current Turbines (MCT) installed their 1.2MW prototype in Strangford Lough, Northern Ireland, in 2009. Open Hydro installed their prototype tidal turbine at the European Marine Energy Centre (EMEC) in Orkney in 2006 and have since installed a 1MW test device at Fundy Ocean Research Centre for Energy (FORCE) in Canada. In wave energy, Aquamarine Power installed their prototype 315kW Oyster 1 machine at EMEC in 2009 and are due to install the first of three connected ~800kW devices in 2011. In 2010 Pelamis Wave Power installed their 750KW P2 device in EMEC in association with Eon, and a further P2 device is planned for the same site, also built for Scottish Power.

Aquamarine, Pelamis and MCT are all installing full-scale prototypes with part-funding from the Marine Renewables Proving Fund, a £22.5 million Carbon Trust scheme funded by the Department for Energy and Climate Change (DECC) to prove device concepts at full-scale and in real sea conditions. Atlantis Resources, Hammerfest Strøm, and Voith Hydro are all also due to install full-scale devices at EMEC in 2011 with MRPF support.

In 2009 The Crown Estate ran a leasing competition for sites in the Pentland Firth and Orkney Waters Strategic Area. This area comprises sea near the north coast of Scotland and around Orkney. The Crown Estate has awarded leases for up to 1.6GW of wave and tidal devices at 11 sites that should be operating by 2020. Crucial to the success of the Pentland Firth leasing round was the completion of the Strategic Environmental Assessment (SEA) of the Scottish marine energy resource. This assessment, completed by the Scottish Government, is a European legal prerequisite under the SEA Directive for large-scale infrastructure projects. This assessment concluded that between 1GW and 2.6GW could be developed in Scottish waters with generally minor environmental effects[6].

The development of marine energy in English, Welsh and Northern Irish waters will also require additional SEAs. An SEA for Northern Ireland is due to be published in 2011 and a scoping report for England and Wales was published in March 2010[7].

Figure 3 *Proportion of wave and tidal technologies at large scale sea-testing stage that are being developed or tested in the UK (Carbon Trust analysis)*



A large proportion of the world's marine energy device developers are either based in the UK or conducting tests in UK waters as shown in *Figure 3*. This is a direct result of government support for the industry in the UK (MRDF, MRPF, MEA, ROC multipliers, EMEC, Wave Hub[8]) and the large indigenous resource, as well as indirect interventions such as proactive engagement from The Crown Estate regarding site leases and SEPA regarding Strategic Environmental Assessment.

So the UK outlook for marine energy remains positive. Many more devices, at all stages, are being developed in the UK than in any other country, and the vast majority of full-scale prototypes are being installed in UK waters. Leasing rounds totalling 1.6GW also demonstrate appetite and potential for significant commercial deployments. Finally, industrial companies are now beginning to invest in the sector, with a number of foreign companies developing technology in the UK.

[5] *Future Marine Energy* (CTC601).

[6] Scottish Marine Renewables Strategic Environmental Assessment (SEA), Scottish Executive, 2007.

[7] UK Offshore Energy Sea (UK OESEA2) Future Leasing/Licensing for Offshore Renewable Energy, Offshore Oil & Gas and Gas Storage and Associated Infrastructure, Scoping for Environmental Report, March 2010. UK Offshore Energy Sea, (UK OESEA2), Synthesis of Input to SEA Scoping, May 2010.

[8] These acronyms refer to: Marine Renewables Deployment Fund, Marine Renewables Proving Fund, Marine Energy Accelerator, Rewewables Obligation Certificates and European Marine Energy Centre.

1.2 The need for cost reduction

The £3.5 million Marine Energy Accelerator (MEA) was launched to explore cost reduction potential in marine energy. Since 2007 it has been working with the leading innovators in the field to progress technologies which have the potential to reduce the cost of wave and tidal stream energy extraction. The 2006 *Future Marine Energy* report[9] identified the following areas of innovation as having most potential for cost of energy (CoE) reductions, and as a result the MEA focused on these:

- Device components – Research into lowering costs and improving performance of specific components in existing marine energy devices.
- Installation, operation and maintenance – Developing strategies to enable marine energy devices to be installed, operated and maintained at a lower cost.
- Next generation concepts – Developing new device concepts that could significantly lower the costs of marine energy compared to current front runners.

The following chapters summarise the findings from the MEA's work in these three focus areas, as well as providing analysis and insights to suggest a pathway towards accelerated cost reduction in the marine energy industry.

Chapter 2 considers the UK resource and the likely costs of accessing that resource using today's technology. Chapter 3 details cost reductions already achieved by the strands of the MEA, as well as future cost reductions that have been made possible, and includes case studies of projects funded under the MEA. Chapter 4 looks ahead at priority areas for technology development in the industry, as well as introducing some 'next generation' concepts that have been developed further by the MEA. Finally, chapter 5 suggests next steps for various industry players – technology developers, array developers, suppliers, financiers and government – while drawing conclusions from the overall findings of the MEA.

[9] *Future Marine Energy* (CTC601).

2. UK resource and economics

While it is accepted that the UK is rich in wave and tidal resource, the exact size of the practically accessible resource has been the subject of much discussion. The costs of accessing this resource have also been debated at length, with estimates of cost of energy varying from less than 10p/kWh to more than 100p/kWh. This chapter assesses the size of the commercially extractable UK resource for tidal and wave devices, and discusses the likely costs of exploiting it, as well as discussing what the UK's resource characteristics will mean for future devices.

2.1 Accessible resource

Tidal

Advances in hydrodynamic understanding of tidal currents have enabled the Carbon Trust, with input from the University of Edinburgh, to update our estimates of the size of the UK's tidal resource. This work, compiled by Black & Veatch, divides tidal currents into three types, each driven by a different hydraulic mechanism: tidal

Tidal resource assessment methodology

The parametric tidal energy model uses hydrodynamic representations of three types of tidal current flow that were developed by the Institute for Energy Systems at Edinburgh University:

Hydraulic current: If two adjoining bodies of water are out of phase, or have different tidal ranges, a hydraulic current is set-up in response to the pressure gradient created by the difference in water level.

Tidal streaming: The physical response of the tidal system to maintenance of the continuity equation; when a current is forced through a constriction, the flow must accelerate.

Resonant basins: Resonant systems occur as a consequence of a standing wave being established, which arises when the incoming tidal wave and a reflected tidal wave constructively interfere.

The model calculates the effect of energy extraction on the tidal flow, which in all cases is a reduced flow velocity and/or a decreased tidal range.

This means that there is a maximum amount of energy that could theoretically be extracted from any tidal stream. More interesting, though, is the energy that can be extracted before there are significant environmental or economic impacts. The 'technical tidal resource' presented in this section is the amount of energy that can be extracted before there is a significant impact on the local environment (through reduced velocity or range of tidal flows) or a significant impact on the cost of energy extraction from the site (arising from a reduction in flow velocity, which would lead to more expensive power from all devices at the site)[10].

[10] The model used an iterative approach to adding tidal devices to a site, until a prescribed economic or environmental significant impact was reached. For more detail on this and the hydraulic mechanisms, see the Carbon Trust report on Tidal Current Resource and Economics, to be published in 2011.

streaming sites, hydraulic currents and resonant basins. For each type a hydraulic model was created that linked the amount of energy extracted by tidal devices with the impact on the downstream water flow.

The maximum extractable energy has been modelled for each of 30 UK sites, along with a 'technical' resource level – the energy that can be extracted within reasonable environmental and economic bounds[10].

The technical tidal current resource for waters around Great Britain, Northern Ireland and the Channel Islands is around 29TWh per year. The 29TWh of annual energy production is the middle of three scenarios and uses baseline assumptions on acceptable environmental and economic (cost of energy) impacts of extraction[11]. Optimistic and pessimistic assumptions give a technical UK resource of 38.4 and 16.4 TWh per year, respectively.

This technical resource is approximately 50% more than estimated previously (see *Future Marine Energy*, 2006). The new combined hydrodynamic-economic model better calculates the impact energy extraction has on the various types of tidal current sites. It should be noted that there is still a relatively high level of uncertainty due to a number of factors which still need to be investigated.

Practical constraints assessment

In order to understand how much of this resource is accessible in the real world, the Carbon Trust and The Crown Estate undertook a joint study to apply marine constraints to the technical resource identified above. This pulled together experts in the marine environment and marine energy extraction. We identified more than 50 constraints in The Crown Estate's Marine Resource System (MaRS) relevant to marine device deployment and operation, along with relevant exclusion zones.

In the end only three constraints were significant in the geographically small areas already identified as containing the technical resource: fishing, shipping and designated conservation sites. Fishing and shipping both reduced the total resource available, according to a weighting based on fishing value per year or ships per day. Conservation sites had a very significant weighting, applied according to what proportion of the site is designated, and how much scope there is for moving generation to outside the designated areas.

Practical constraints

The Carbon Trust, working closely with The Crown Estate, has also assessed real-world constraints that impact on the technical resource (see 'Practical constraints assessment'). Some of these, such as active cables, pipelines or protected wrecks, excluded any tidal energy extraction, whereas others, such as fishing and shipping, were treated as partial constraints.

Shipping, fishing and designated areas were found to have the greatest influence on the UK's tidal stream resource. These removed around one third of the technical resource, particularly affecting the biggest site – the Pentland Firth Deep – which was reduced from over 10TWh/yr to around six. The 'practical' resource – the resource that is environmentally, economically and practically feasible to extract – has therefore been calculated for the first time. **The baseline figure for practical tidal resource is 20.6TWh per year**.

Figure 4 shows the practical resource at each tidal current site (purple) and the resource that has been constrained off. The resource in the Pentland Firth Deep site has been significantly reduced by the constraints assessment, but still makes up about 30% of all UK practical resource.

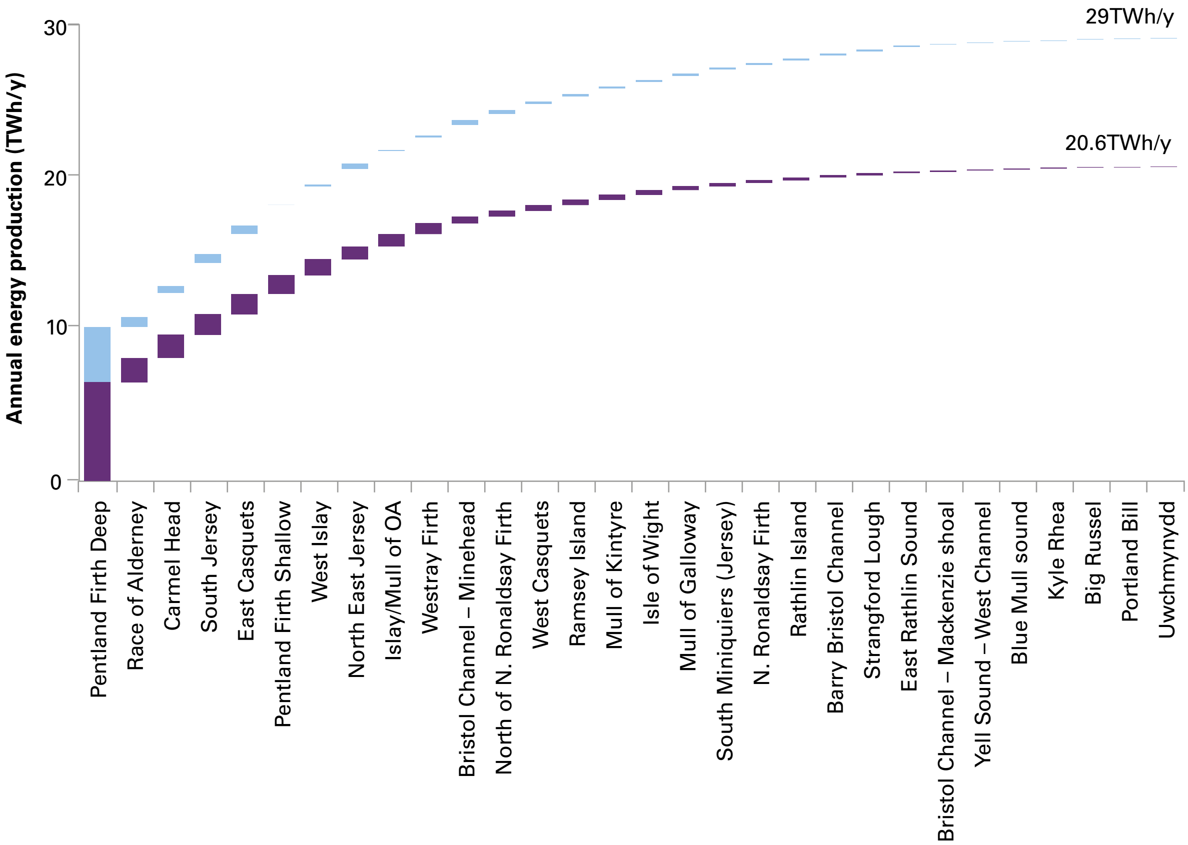
Figure 5 shows the locations and practical resource at each of the 30 sites considered. It is immediately clear that much of the resource is concentrated around the Pentland Firth and the Orkney Islands to the North, and around the Channel Islands in the South.

[11] The study investigated various combinations of tidal range, velocity and cost of energy limits, and sensitivity to changes in each. The base case numbers presented in this report use the following limits, which were chosen based on our understanding of project economics and the marine environment:

- Tidal amplitude variation limited to 0.1m (= tidal range reduction of 0.2m)
- Mid range tidal velocity reduction limited to 10%.
- Cost of energy increase limited to 20% (average CoE for whole site).

For more info see report on Tidal Current Resource and Economics, to be published in 2011.

***Figure 4** 'Practical Resource' at each tidal site is shown in purple, and the constrained resource is shown in light blue*



Wave resource

Estimates of the total wave resource hitting the UK waters vary between 250TWh/yr and 600TWh/yr[12 13]. Assessments of how much of this energy can practically be extracted depend on assumptions about mean power levels and the wave frontage available, as well as how many rows can be economically sited in a farm. They also make judgments on the space available, taking into account environmental designations, shipping lanes and other competing sea uses.

The Carbon Trust estimate of practical wave resource is 50TWh/yr, which is based on the 2000 study by the Energy Technologies Support Unit (ETSU) for the DTI[14].

Work is underway to redefine the UK wave resource estimates. The Carbon Trust, in collaboration with The Crown Estate, is updating the practical resource estimate based on a better understanding of wave farm layout and a more in-depth assessment of practical constraints. The results of this study will be published later in 2011.

Figure 6 shows the distribution of wave energy around UK waters, from the 2008 Atlas of Marine Renewable Energy Resources (these data form the basis for all assessments of resource). The map shows that there is more resource further from shore, suggesting that there will be an economic trade-off between higher energy offshore and distance to grid and port, both of which will increase the cost of energy. The map also shows that the resource is focused off the north-west coast of Scotland, and off Cornwall (where the high energy seas are relatively far offshore).

[12] Winter, A.J.B. (1980). The UK wave energy resource, Nature, Vol. 287, October 1980.

[13] ETSU R-122 (2000). New and Renewable Energy: Prospects in the UK for the 21st Century: Supporting Analysis.

[14] Ibid.

Figure 5 *Practical Tidal Resource sites. The size of the circles represents practical annual energy potential – 33% of the resource is around the Pentland Firth; and 28% around the Channel Islands*

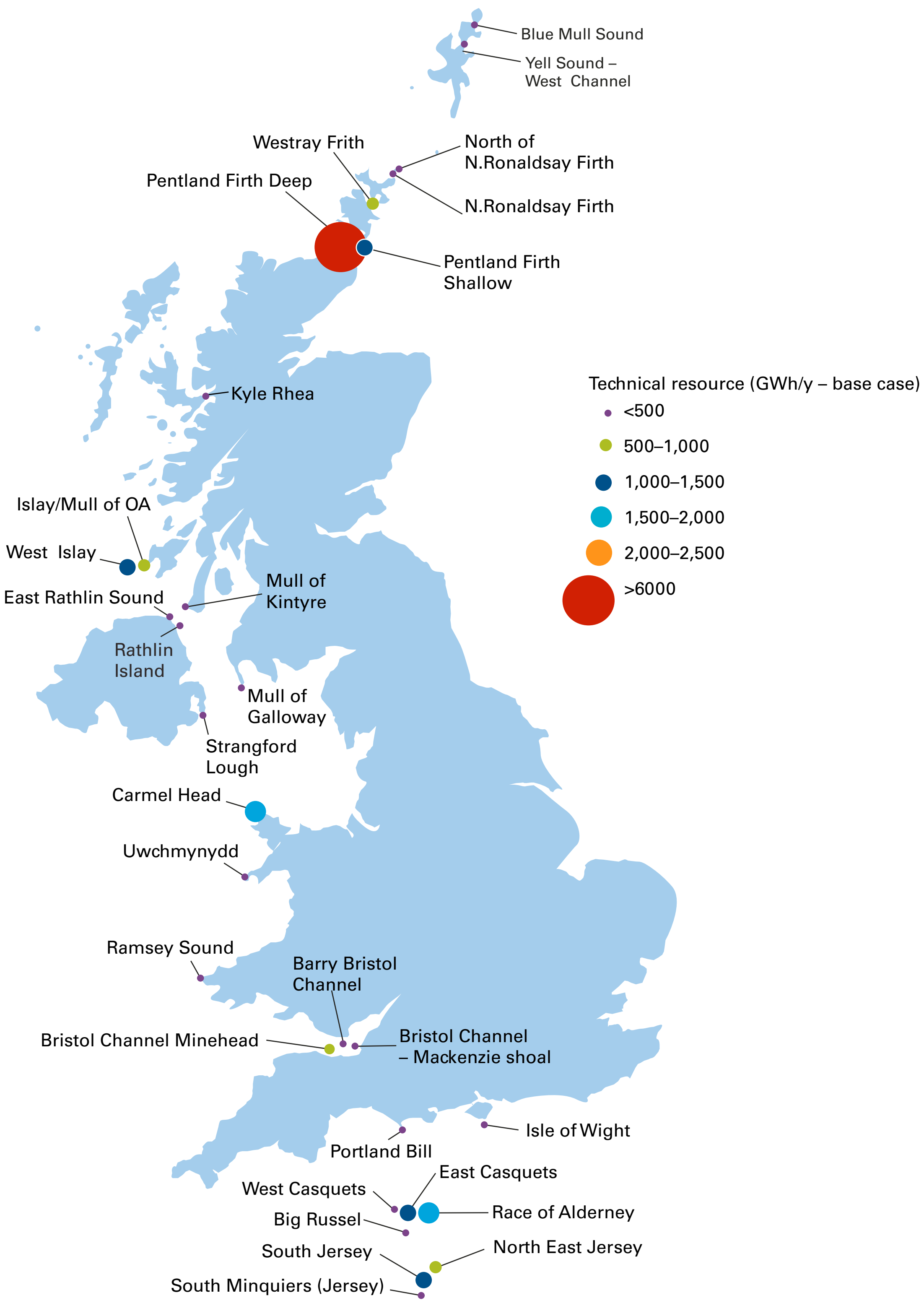
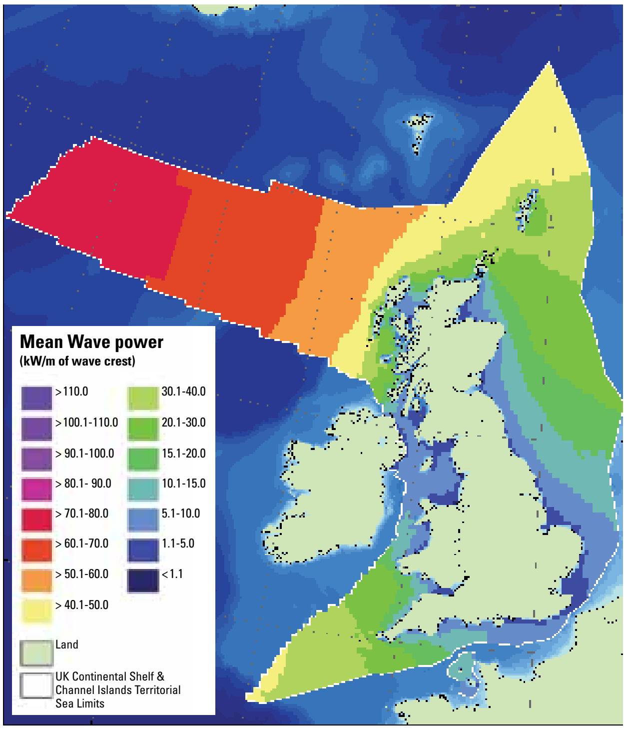


Figure 6 *Average mean wave power (From the Atlas of Marine Renewable Energy Resources, published by BERR, 2008)*



2.2 Baseline cost of energy

The Carbon Trust worked with the leading industry developers to undertake a new bottom-up analysis of the costs of wave and tidal energy. This section gives a detailed breakdown of the current cost of energy from wave and tidal devices, and the expected costs of early farms. These cost estimates provide a benchmark against which to gauge progress towards achieving cost-competitive wave and tidal current energy in the near future.

In 2007 the Carbon Trust developed and published a cost of energy methodology which is considered a standard framework for the assessment of wave and tidal energy costs. The baseline costs for wave and tidal energy in this section refer to cost of energy (CoE) calculations using this framework, which takes into account all lifetime costs of a marine energy array, based on appropriate sites with good resource such as that off the West Coast of the Uists for wave and with average conditions for tidal[15]. Levelised cost of energy in pence per kWh (p/kWh) is shown for wave and tidal devices. These generic costs are based on current leading wave and tidal device concepts – later in the report, potential future generations of wave and tidal devices, some developed with assistance from the MEA, are considered.

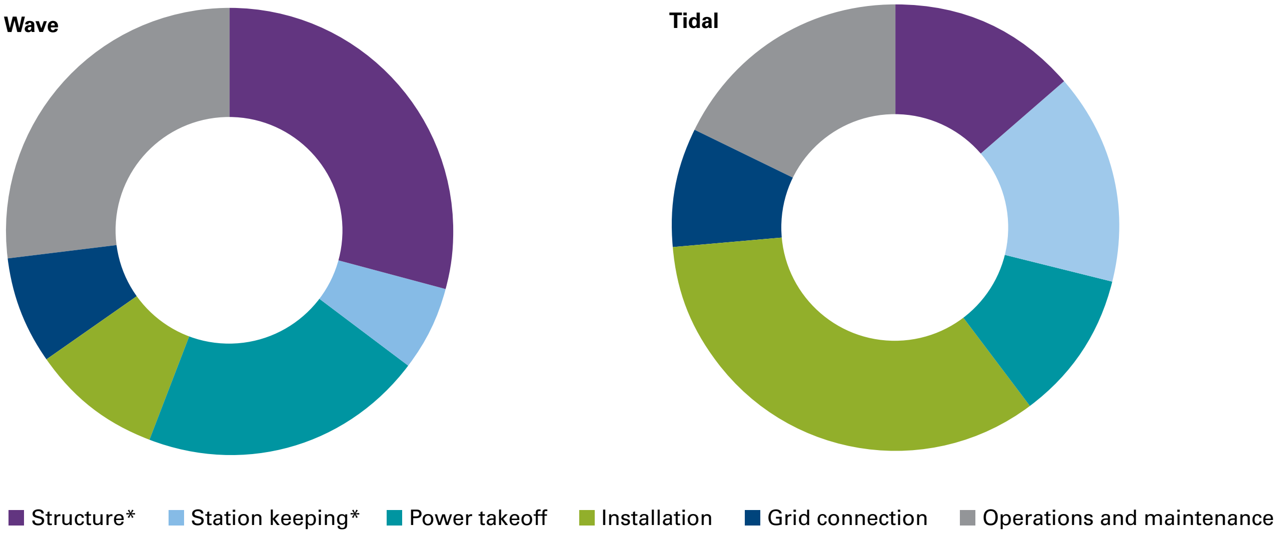
Levelised CoE is calculated by adding together the discounted lifetime costs of a device or farm, then dividing the total by the expected lifetime output. In this report we use a discount rate of 15% for the base case numbers, to take some account of the risk involved in a marine energy project. *Figure 7a* and *7b* shows the different costs involved in a marine energy generator.

These cost centres are common to all electricity generators[16], although the proportions of each segment, as well as the overall costs, will vary between technologies and sites. Lower discount rates, which would be expected as confidence in device and array performance improves, would increase the relative importance of operations and maintenance spend to the overall cost of energy. It should also be noted that the proportions shown here are for a floating wave device but a bottom-mounted tidal device. Installation costs could be higher for a bottom-mounted wave device, or lower for a floating tidal device.

[15] The cost of energy calculation includes all capital and operating costs associated directly with the array, including offshore electrical connections. It does not include contribution to any onshore grid upgrades that might be required.

[16] 'Station keeping' is a uniquely marine cost, but there are equivalents for land-based generators.

***Figure 7a and 7b** Indicative levelised cost of energy components for wave and tidal energy converters in an early commercial farm. The coloured segments are capital costs, while the grey segment represents O&M costs and includes all other spend including insurance and leases*



*Tidal Structures and Station Keeping may be combined in monopoile type designs.

2.2.1 Tidal device baseline costs

Estimates from the MEA put the baseline cost of energy for tidal at 29p–33p/kWh for the first farms[17]. This reflects the modelled cost of energy from leading tidal device concepts at medium and high energy sites with depths of around 30m. These costs represent a near doubling of the equivalent costs projected in 2006. The key difference between the figures presented here and those previously published is that the most recent figures are constructed from knowledge of real full-scale projects, rather than best estimates used in the 2006 study. The key reasons why the baseline costs from the MEA are higher than previous estimates are:

- a better understanding of device performance, in some cases based on real at-sea experience
- better understanding of post-installation costs for the first devices
- increases in material prices
- exposure to a fluctuating vessel market used for both deployment and maintenance
- a much better understanding of the challenges of deployment of tidal devices.

The increases in CoE estimates since the MEC four years ago reflect a trend seen in other industries, notably offshore wind although there are some market driven effects which make offshore wind subtly different. It also reflects an over-optimism about future technology costs that is common in many early stage industries[18]. The costs published in this report are the result of a bottom-up analysis of leading wave and tidal devices, and have been tested against estimates made by device and project developers. The Carbon Trust believes that this significantly better new evidence base is more representative of likely first farm costs of wave and tidal energy than those previously published.

It should be noted, however, that these baseline costs are for first farms of devices – small-scale arrays of around 10MW. The cost of energy from future farms is likely to drop significantly, which is discussed in more detail in chapters 3 and 4 of this report. The cost of accessing most of the UK's wave and tidal resource will therefore be significantly lower than these baseline costs. It is also important to recognise that very high energy sites (such as the Pentland Firth) could provide energy at below the 29-33p/kWh range if it was technically possible to site early farms there (see Section 2.3).

[17] First farms are modelled specifically as 10MW farms after 10MW of previously installed capacity. The range represents baseline costs at medium and high energy sites. Pessimistic and optimistic assumptions on technology performance and costs extend the range significantly (see 2.2.3).

[18] For example, see UKERC (2010): Great Expectations- the cost of offshore wind in UK waters. Understanding the past and projecting the future. At http://www.ukerc.ac.uk/support/tiki-index.php?page=tpa%20overview. For an analysis of why offshore wind costs are currently higher than initially predicted, as well as reference to optimism-bias.

2.2.2 Wave device baseline costs

Research as part of the MEA to normalise the cost of energy assumptions from a number of wave energy devices has suggested considerable variation in CoE from different devices (see *Figure 8*) as well as significant uncertainty around performance, this is in part due to the lack of a commonality in design approach for wave energy converters. Analysis of wave energy costs is more difficult than tidal, because wave technology companies are in many cases developing entirely different energy extraction concepts and it is often difficult to model the energy performance of these new concepts with any certainty. Only a handful of device developers have an accurate idea of costs for their full-scale machines, so it is these devices which have formed the basis for this study.

Estimates from the MEA put the baseline cost of energy from the first wave farms at 38p/kWh to 48p/kWh[19]. These costs are significantly higher than first farm wave costs estimated in the MEC for similar reasons to those mentioned above for tidal energy – the most recent figures are based around real costs rather than estimates.

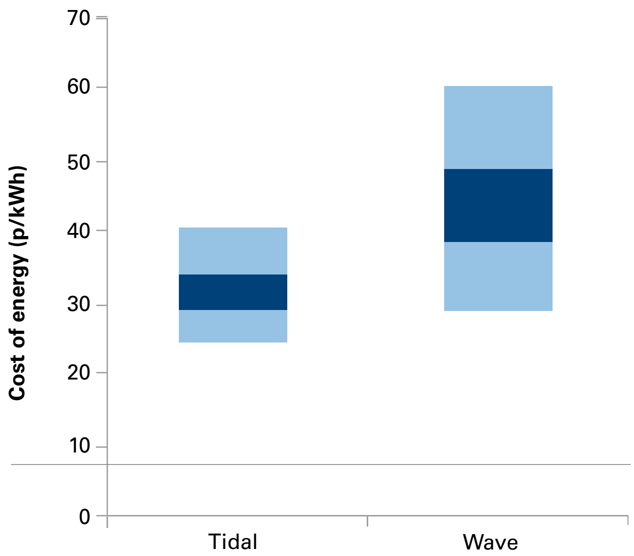
2.2.3 Cost uncertainties

The chart in *Figure 8* shows the variations around the baseline costs of energy for wave and tidal current energy when different assumptions are made on costs, resource, and device performance. These costs are for 'first farms' of wave or tidal devices at around 10MW installed capacity; the bands do not represent any learning or scale effects other than those associated with buying ~10 machines.

The chart shows that the estimated first farm costs of wave energy are currently higher than those for tidal energy. It also shows significantly more uncertainty around the costs of wave energy devices. This is largely because the energy capture concepts behind wave devices are less well understood, making them more difficult to model than the axial-flow turbines that are the basis of most leading tidal devices. We do believe, though, that the power capture of wave devices will increase with scale of the devices, leading to the potential for a levelised cost of energy as low as tidal stream in the long-term. This is discussed in chapters 3 and 4 of this report.

The following section and chapters apply the base case cost of energy assumptions to the variable tidal and wave resource around the UK. They also introduce the concept of reducing cost of energy as arrays get bigger and as cumulative experience increases, from volume and experience effects, and also from targeted interventions to encourage marine energy innovation.

***Figure 8** Baseline costs for benchmark first farm wave and tidal devices. These costs assume a discount rate of 15% and a lifetime of 20 years. The dark bars represent CoE at medium energy (upper bound) and high energy (lower bound) sites, using base case cost and performance assumptions; while the outer bars add optimistic and pessimistic cost and technical assumptions to these limits. Thus the lowest costs represent optimistic case cost and performance assumptions for devices sited in energetic locations*



[19] As with tidal, 'first farm' is specifically a 10MW farm after 10MW of previously installed capacity. The range represents baseline costs at medium and high energy sites. Pessimistic and optimistic assumptions on technology performance and costs extend the range significantly (see 2.2.3).

2.3 UK resource costs

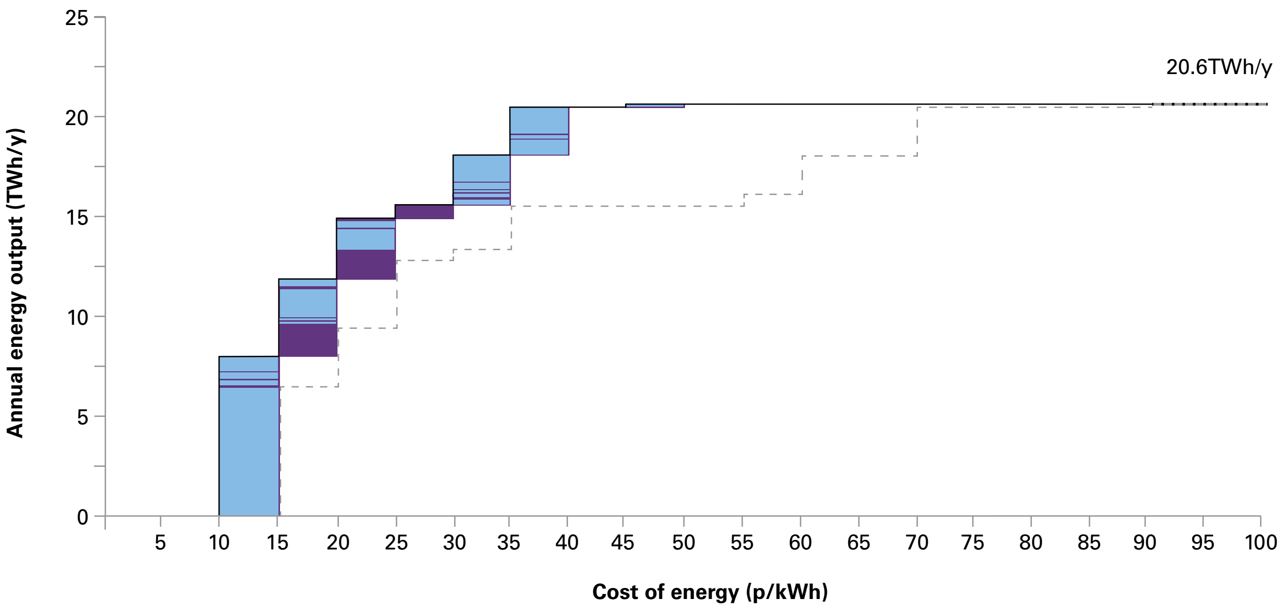
The baseline costs of energy have been calculated at reference sites, with medium resource compared to the bulk of UK sites. For both wave and tidal there are sites with more resource which would, other things being equal, provide a lower cost of energy.

The analysis in the following pages uses the baseline assumptions as a cost benchmark on technology costs to investigate the 30 tidal sites, and a number of further assumptions to allow for basic learning effects between sites. Wave resource is not considered on a site-by-site basis, but the learnings from MEA costs and resource studies are presented in 2.3.3.

2.3.1 Cost variations in accessing tidal resource

By taking base CoE for tidal technology and assuming that each device and array is sized appropriately for each individual location, a cost of energy can be projected for each site. The resource-cost curve in *Figure 9* shows the proportion of the total practical resource that can be extracted at or below a given cost of energy. In order to capture the impact of both scale and innovation, an experience rate of 12% has been assumed in this section, which reflects cost reductions from scale and experience effects as cumulative installed capacity increases[20]. A step change in cost of energy is also assumed after about 3.5TWh of AEP, which represents a switch from first generation devices currently under development to second generation devices[21].

Figure 9 *Practical resource cost curve. Each block represents one of the 30 key sites, with cost of energy (which is found to have a strong dependency to the energy at the site) shown on the x axis – Pentland Firth Deep is the most energetic and the largest site. The solid blocks represent costs with assumed learning; the dotted lines show where the blocks would be with no learning (ie current baseline costs). Finally, the blocks are colour coded by likely generation of technology needed to exploit them – darker blue is first generation*



[20] The experience rate reflects empirical evidence from other industries that costs reduce as installed capacity increases – see OECD/IEA (2000): Experience Curves for Energy Technology Policy for theory and international examples with energy technologies. At http://www.iea.org/textbase/nppdf/free/2000/curve2000.pdf. See Carbon Trust (2011): Tidal Current Resource and Economics, to be published separately, for explanation of why a lower experience rate has been chosen than some other technologies have experienced. Chapters 3 and 4 of this report detail the potential for gradual and step change cost of energy reductions.

[21] Second-generation tidal devices a) are able to access deep-water and difficult tidal streams such as the majority of the Pentland Firth and b) include a fundamental design improvement (such as multiple rotors on one support structure) that leads to step change cost of energy improvement. Second-generation devices will be required to access much of the UK resource (see following chapters).

Figure 10 *Possible sequential deployment of the tidal stream sites based on cost of energy for each site. Easy first generation sites are shown first (to the left)[22]. Pentland Firth Deep is both the biggest site by some margin, and the most energetic, so its modelled cost of energy is lower. At each stage, experience gained on previous projects helps reduce the cost of energy at each subsequent site*

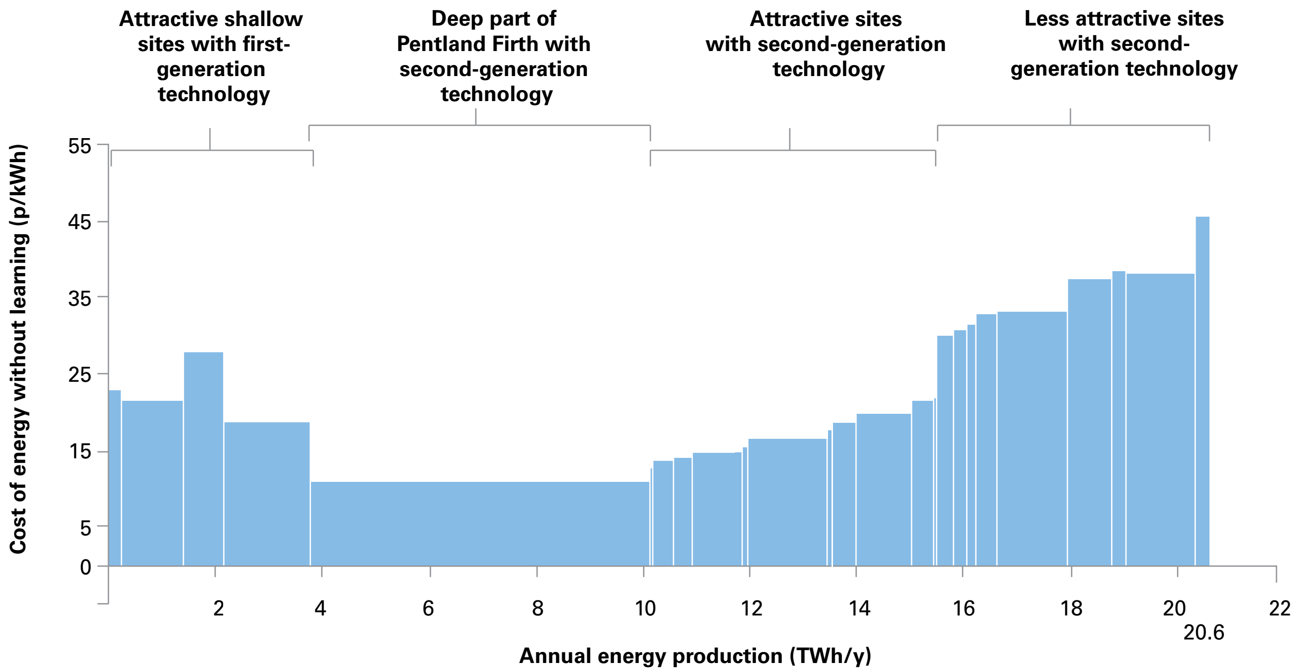


Figure 9 shows the potentially lowest cost of energy (typically the most energetic) sites to the left – Pentland Firth Deep is both the biggest site with over 6TWh/yr potential, and the most energetic. It also shows that there are some sites with high resource where cost of energy extraction will potentially be lower than our baseline cost of energy[23]. Note, though, that extracting most of the resource, including most of the high energy (cheap) resource, will require second-generation technologies able to access deep and difficult sites. These are discussed in chapter 4.

Figure 10 shows a possible order of site development. We have assumed that sheltered shallow sites that can be exploited with first generation technologies will be the first to be developed. These make up around 3.7TWh of annual energy production. Some of these sites are already being targeted by device developers for their first commercial farms.

Tackling sites in deeper waters, which tend to also have harsher conditions, will require new technologies that will be conceptually different from the first-generation tidal devices under development, in order to exploit the resource cost effectively. These devices will need to tackle increased deployment and station keeping challenges in particular. In *Figure 10* all the sites after the first 3.7TWh will be exploited by 'second-generation' devices – these sites are ordered according to cost of energy.

2.3.2 Tidal site difficulty

The variation in the cost of energy shown in *Figure 10* is a function primarily of tidal energy density (kW/m^2), but also depth and distance to shore. These factors influence multiple cost centres in a tidal energy device, including capital, installation and O&M costs, and are understood sufficiently to be built into the COE model.

[22] Note that the cost of energy for each site has been calculated using a simplified model of a generic tidal device, and in idealised hydrodynamic tide regimes. The actual CoE figures (the tops of the bars) should be taken as illustrative only.

[23] Costs not modelled here could push up the price of energy for energetic sites. These are discussed in the following section and elsewhere under the heading 'tidal site difficulty'.

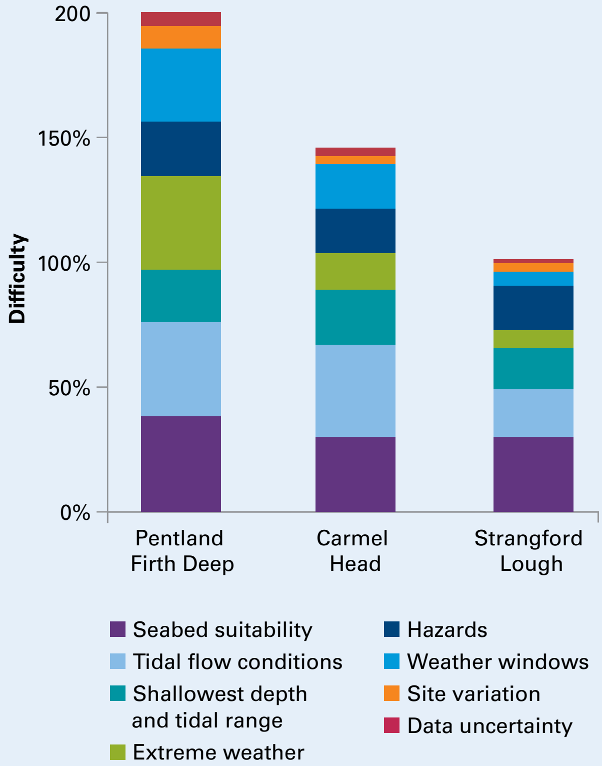
Difficulty ratings for tidal sites

The practical tidal stream resource of the UK has been estimated at 20.6 TWh. This resource is spread over a range of sites of varying sizes with varying hydrodynamic, bathymetric and weather characteristics. These factors in combination make a site either easier or more difficult to exploit than the average, as well as affecting project risk. These factors cannot easily be modelled as direct impacts on cost of energy, but they can usefully be represented as a difficulty rating. The difficulty rating is also a reflection of project risk at each site.

The Carbon Trust, working with Mojo Maritime and BMT Cordah, scored the sites by difficulties arising from the currents, water depths, weather exposure and bathymetry. Variability within the site and the extent to which sea conditions are known are also taken into account. The scores are based on expert sea-operation experience and, although subjective, are thought to prioritise the issues and sites appropriately.

This method produces a difficulty score for each site. A score of 100 has been applied to the Strangford Lough site, which is considered to be one of the most sheltered and least technically challenging ('easiest') sites to exploit.

Figure 11 *Example difficulty scores for three sites All three sites have similarly difficult seabed conditions and marine hazards, but the Pentland Firth site is much more exposed leading to shorter weather windows and more extreme weather conditions. Notably, consistency and variability of the flow is problematic in the higher resource sites (Carmel Head and Pentland Firth)*

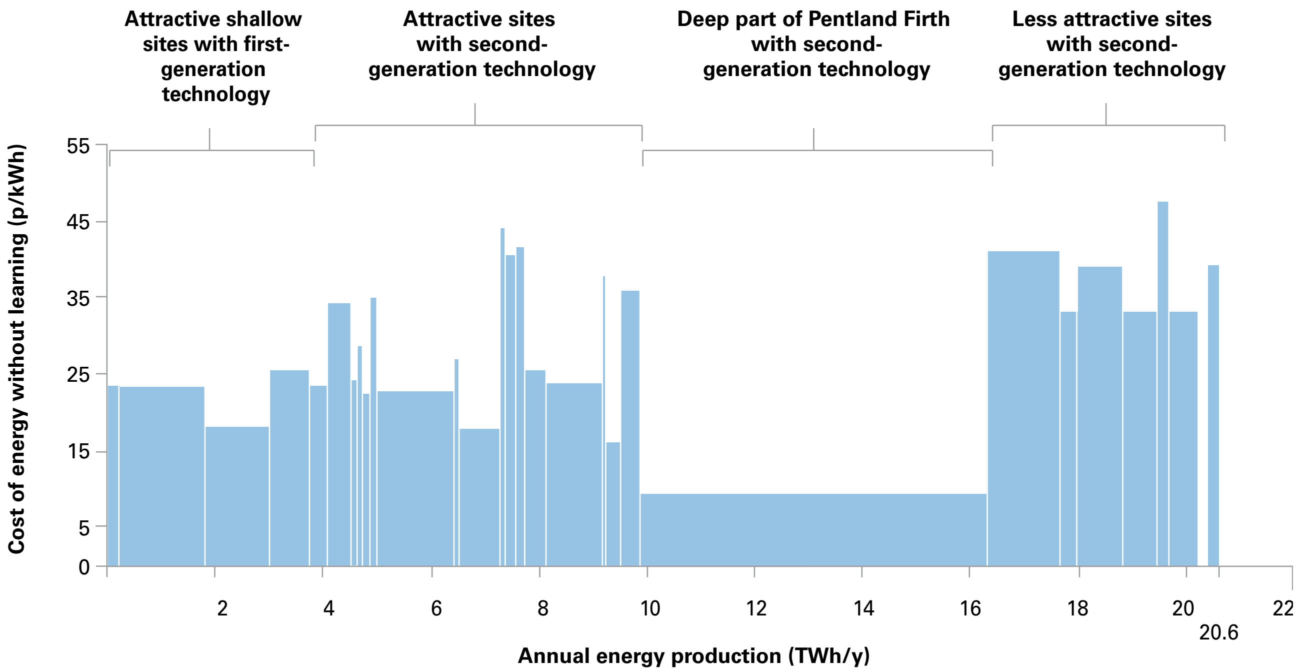


In practice, there are also a number of less tangible factors that influence site selection and the risk of deploying and operating at such sites, which in turn influence decisions on which sites to target in which order. The risk factors associated with specific sites are not sufficiently well understood to be included directly in cost of energy calculations. Instead, they have been identified by the Carbon Trust through work with experienced offshore engineers, and included as a difficulty rating for each site (see Difficulty ratings for tidal sites). The difficulty rating allows us to reconsider the likely deployment order of sites.

Figure 12 shows the same 30 sites as *Figure 10*, but the order has been changed to give equal weight to 'difficulty' and cost of energy. Although somewhat qualitative we believe this more accurately reflects the likely deployment order of the 30 sites. Pentland Firth Deep (over 6TWh of annual energy potential) is a difficult site in which to deploy tidal energy converters and has therefore moved to the right (further into the future).

Difficulty has been used here to influence site order indirectly, because we don't fully understand exactly how it will affect cost of energy through increased project risk. The relatively low cost reduction experience rate of 12% assumed for each doubling of capacity partly reflects the fact that later tidal projects are also likely to be more difficult, and that increasing difficulty could counteract some technology improvements and cost reductions.

Figure 12 *Example deployment sequence reflecting site difficulty as well as cost of energy. At each stage experience gained on previous projects helps reduce the cost of energy at subsequent sites*

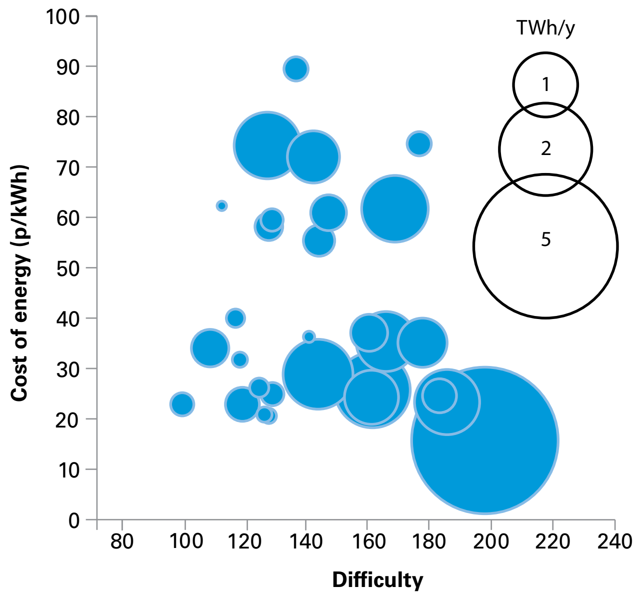


Comparing *Figures 10* and *12* shows that developing the Pentland Firth sites relatively early would reduce the average cost of energy at all sites, because of the learning achieved during more than 2GW of capacity installation. Developing technology solutions to tackle site difficulty early – bringing forward the exploitation of Pentland Firth Deep – could be a key priority for tidal device technology innovation, as discussed in chapter 4.

Figure 13 shows how the resource is distributed by site difficulty. Most of the larger energetic sites are also the most difficult to exploit. The bubble chart clearly shows that a high proportion of the sites which have the potential for an attractive cost of energy are also relatively difficult, reinforcing the need for technology and project developers to prioritise tackling site difficulty. Understanding these difficulty issues will also be key to assessing and managing risk at big tidal energy projects.

This analysis can be used to explain some of the challenges likely to be faced as more of the energetic resource is exploited. Chapter 4 revisits the concept of site difficulty, discussing device features that will be necessary to tackle the more difficult sites.

Figure 13 *UK tidal stream sites classified by site difficulty. The bubble size represents the practical energy resource at each site. The cost of energy is calculated at a 15% discount rate and assumes no learning between sites. Pentland Firth has low cost of energy but is the most difficult of all UK sites*



2.3.3 Costs of wave resource

The baseline costs of first farm wave energy reported in Section 2.2 were calculated using the known wave resource at EMEC (considered a 'medium resource' site) and off the coast of South Uist (a 'high resource' site, but not the highest possible in UK waters).

The amount of energy that can be extracted from waves by a farm depends on the technology deployed. Most wave energy devices will be arranged in rows, with each row taking only a proportion of the power out of the wave front[24]. Several rows are placed one behind the other to capture the remaining energy, meaning that there are diminishing energy and economic returns from each additional row added. The final cost of energy from a wave array will therefore depend on both the energy and other characteristics of the site, as well as the trade-off between total generation and farm cost of energy. More wave energy resource would be available from UK waters if higher costs of energy prove to be feasible.

2.3.4 Technology issues for capturing wave resource

To access the majority of wave resources, a wave energy device needs to be able to extract energy from a range of wave heights and frequencies. This requires the device designer to achieve optimum resonance with the most common wave height/length, while still achieving reasonably efficient energy capture from less common waves.

The energy capture performance of a particular wave energy device can be improved in many different ways, a number of which are discussed in the following chapter. However, the MEA experience has highlighted that there are also some features that are clearly desirable in all wave devices.

Survivability

The MEA work on costs of wave energy has shown that to compete with other renewable energy technologies, in the medium term wave energy developers will need to exploit high energy sites. These sites generally also have larger extreme waves, so developers must make sure that their devices are designed with survivability built in.

Operations and maintenance

MEA analysis has also shown that operations and maintenance (O&M) costs make up around a quarter of wave levelised cost of energy. This means that the development of efficient O&M strategies must be a priority. Examples in the following chapter show clearly that innovative O&M strategies or technologies can significantly reduce lifetime costs at the device level, primarily by increasing the range of sea conditions in which O&M can be undertaken, and by reducing the time required for operations. At the array level there are also opportunities for reducing O&M costs by developing efficient deployment and recovery strategies for multiple devices, and by exploiting economies of scale for planned maintenance. The simplest way to achieve low O&M costs is to build extremely reliable devices that need very little maintenance.

Connection cost, and depth

The high baseline cost of wave energy also suggests that wave project developers will need to go relatively far offshore to energetic waters to generate competitively priced electricity. This will require particular focus on reducing the cost of cabling and connection to the national grid, perhaps by simplifying procedures or by using lighter weight moorings or foundations; and ensuring that devices can be installed in deep water. If transit times to port are high, or if developers need to go far offshore to access good resources, the focus on reducing planned and unplanned maintenance interventions will be even more important.

[24] This does not apply to onshore wave devices that can be built into the shoreline or into artificial structures in shallow water.

3. Potential for cost of energy reduction

The current baseline costs of energy from marine devices are higher than conventional fossil fuel generation and more developed renewable energy technologies such as onshore and offshore wind. There is therefore a clear need to explore the potential for cost reduction, and to understand how this can be accelerated to make wave and tidal a cost-effective option for low carbon energy generation. This has been the major focus of the MEA.

Energy from wave and tidal energy converters will become more affordable as the number of devices manufactured increases – so-called 'learning by doing'. For energy devices this equates to cost of energy (in p/kWh) dropping by a fixed rate for each doubling of cumulative annual output (in kWh/yr)[25]. This can be plotted on an experience curve or as a 'learning rate'. Technology innovation can increase the rate of cost reduction – steepening the learning curve – or start the curve at a lower level. In this chapter we discuss various innovations that have been demonstrated in the MEA, along with the effect on projected future costs of marine energy. Section 3.1 introduces the focus areas to reduce the cost of energy from marine energy devices; section 3.2 describes sample projects where cost of energy reductions have been achieved or proven. Finally section 3.3 looks at the scope for accelerated cost reduction in the future as the installed capacity of marine energy devices increases.

3.1 Focusing innovation for cost of energy reductions

The cost of energy in marine generating devices can be reduced through two distinct, but often overlapping, effects:

- from reductions in the six centres identified as the constituent parts of the cost of energy outlined in Chapter 2 (*Figures 7a* and *7b*), which reduces capital or O&M spend per kWh of output; and
- from improvements in device performance, which increase the number of kWh per unit of capital and operating spend. Efficiency improvements increase the output of the device while operating, while reliability improvements increase the time spent generating electricity.

This section uses analysis from the MEA to discuss where there is most scope for cost of energy reductions in tidal and wave technologies.

[25] For marine devices it is usually valid to replace cumulative annual output with cumulative installed capacity on the x axis while still using CoE as the metric on the y axis. See OECD/IEA (2000): Experience Curves for Energy Technology Policy for theory and international examples with energy technologies (www.iea.org/textbase/nppdf/free/2000/curve2000.pdf)

3.1.1 Driving cost reductions for tidal

Breaking down the cost of tidal energy into component cost centres gives an indication of where innovation can have an impact. But to really understand the scope for future cost reductions – and therefore be able to pinpoint where innovation is best focused – it is necessary to predict the likely progress rate for each of these centres based on likely future innovations.

Figure 14 shows projected progress rates for each cost centre based on analysis of a number of leading tidal energy concepts. In the graphic the steepness of the lines indicates the overall potential for cost savings. A steeper line – such as that seen for the installation cost centre – represents a greater potential for cost savings because:

- the cost centre makes up a high proportion of levelised cost of energy and
- the cost centre has more potential for rapid cost reductions (a high progress rate)[26].

It is clear that installation is a core focus area for tidal devices, since it accounts for 33% of the cost of energy and has a high potential for cost reductions. This potential arises because there has so far been limited experience of designing and installing tidal energy devices offshore – installation is near the beginning of the learning curve, where the curve is steepest. O&M, station keeping and structure are also compelling targets for future innovation-led cost improvements. By contrast, reductions in electrical connection costs will come from scale effects, but there is less potential for innovation in an area where thousands of installations have already been made by the offshore wind industry.

To give some context, a 2020 "check point" has been presented in the table based on a conservative deployment scenario. This scenario sees 70MW of tidal capacity in the UK and 30MW elsewhere in the world[27]. An overall cost reduction of around 39% equates to a cost of energy for the leading tidal devices in 2020 of around 18–20 p/kWh.

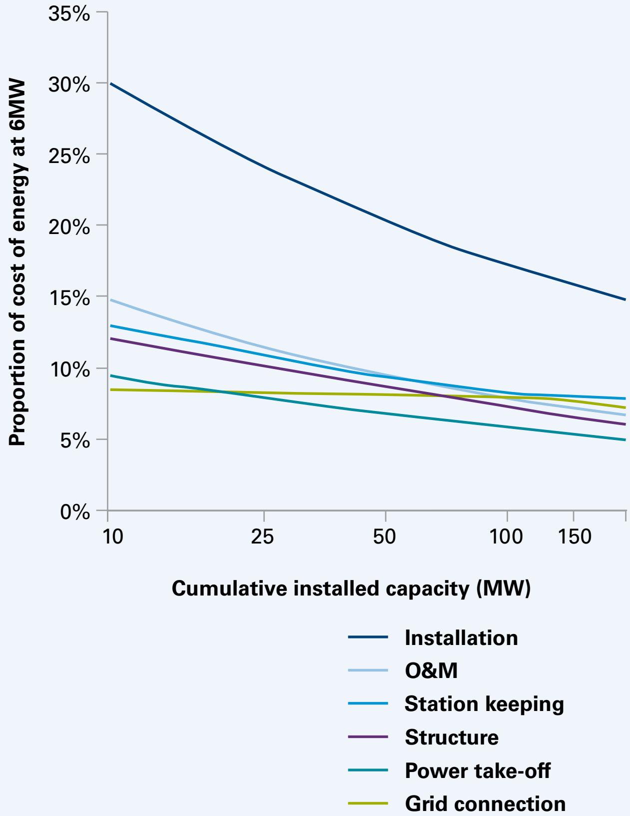
[26] The 'progress rate' for each cost centre is shown in brackets. This represents the cost reduction achievable with each doubling of capacity – a progress rate of 85% means that for each doubling of capacity there is a 15% reduction in cost. The progress rate for each cost centre has been calculated following an engineering analysis of cost reduction potential in leading devices between first farm and commercial farm installations.

[27] The roll-out scenarios have been developed from Carbon Trust analysis of the IEA Global Blue Map scenario and ESME and CCC model runs.

Tidal stream

Figure 14 *Cost reduction potential for tidal devices by cost centre*

Tidal stream: Modelled cost centre cost reductions between first and later commercial farms of currently leading tidal devices. The y-axis shows the proportion of first farm levelised CoE accounted for by each cost centre. The change between 10MW and 200MW cumulative installed capacity takes into account both experience and volume effects (the farm at 200MW is assumed to have 50MW capacity, while the 10MW farm is 10MW capacity).



Performance improvements

The modelling which provided the first farm and commercial farm costs in the graphic above suggested relatively little scope for cost of energy improvements from increased efficiency of tidal turbines, particularly when compared to wave devices. This is as expected, because the behaviour of tidal turbines in a water stream is much better understood than the behaviour of wave devices.

Nevertheless, it is fundamentally important to improve the reliability of tidal devices, and as a result increase their availability. The next section looks at a number of ways to increase reliability, as well as techniques for increasing availability by expanding O&M weather windows and reducing O&M times.

Component	*Cost centre progress rate*	*Tidal stream*
Structure and prime mover	88%	• As tidal stream structures converge towards a single design concept, cost reductions are likely as supply chain companies invest in production capacity. • Better blade design and manufacture. • Cost reductions due to improvements in station-keeping are likely to drive further cost reductions on structure, ie movement to monopile foundation designs.
Power take-off	87%	• Current generator technologies are generally considered efficient, especially in rotary applications. Nevertheless, cost and reliability innovations are required for marine applications. • Innovation is expected in second generation technologies (direct drive and permanent magnet generator concepts) which will reduce the cost and complexity of designs.
Station-keeping	88%	• Costs of station keeping are likely to fall, although more significant cost reductions will come from improved installation techniques.
Connection	98%	• Cost reductions are likely to result from increasing use of bespoke wet mate connectors (connectors that allow connections and installation in marine conditions) as the market develops. • More general electrical connection cost reductions through cable laying efficiencies, DC connections, and array scale effects.
Installation	85%	• Cost reductions are expected as gravity bases are increasingly replaced by drilled structures. In particular, drilling techniques are expected to be developed allowing submarine interventions, reducing the need for expensive and difficult jack up interventions. • Future devices are also expected to have greater energy capture (more or bigger rotors) per foundation and therefore per installation operation.
O&M	82%	• Cost of energy improvements will stem from improved reliability in design – leading to much higher availability. Once technology is proven and early failures have been engineered out, costs are expected to fall significantly. • Costs are also expected to drop as new intervention techniques are developed, particularly involving retrieval rather than on-site intervention, or the ability to work quickly and in heavy seas. • Better provision of ports and infrastructure will lead to lower servicing and transport costs. Similarly, bespoke O&M vessels will become feasible at scale leading to reduced costs and less exposure to cost fluctuations.

3.1.2 Driving cost reductions for wave

Figure 15 shows the projected progress rates for the different cost centres that make up the cost of wave energy, based on analysis of leading wave energy concepts. The table suggests likely innovation steps which will achieve these cost reductions.

The conclusion for wave energy is that reductions in structure, operations and maintenance costs, and improvements to energy yield, are all likely to make significant contributions to reducing the overall cost of energy. These areas are therefore ranked as priorities for future research and development. By contrast, the cost of the electrical connection has limited scope for reduction as it is a more established technology, although there is a unique challenge of floating connectors for most wave devices. The devices used for this analysis were floating technologies, and it should be noted that installation is a bigger proportion of levelised cost of energy if a seabed-mounted structure is considered.

Performance improvements

There is considerable scope for improving the fundamental energy performance of wave devices as experience is gained of how the devices function in real-sea conditions. Improvements are possible through changes to the design of the device itself, specifically better coupling with the sea, and also from changes to the layout of devices in arrays.

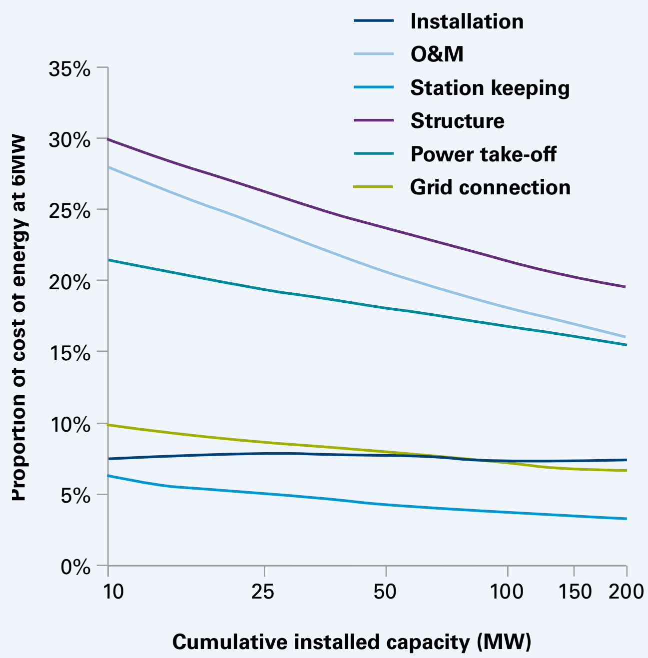
The figures in *Figure 15* include cost centre reductions only and do not include cost of energy reductions from increased yield. However, the modelling has suggested that a 2% improvement is possible for each doubling of capacity at the early stages of the industry. This is significantly higher than the equivalent number for tidal (near zero). Because wave energy capture is currently less well understood than tidal current energy capture, there is greater scope for efficiency improvements in wave.

Improving the availability of wave devices will also, as for tidal, improve the energy output per unit cost. This will become a focus area for most wave device developers once basic energy capture is proven in real seas.

Wave

Figure 15 *Cost reduction potential for wave devices, by cost centre*

Wave Energy. Cost centre cost reductions between first and later commercial farms of currently leading wave devices. The y-axis shows the proportion of first farm levelised cost of energy, accounted for by each cost centre. So a steep curve indicates both a significant cost centre, and good potential for cost reductions. The change between 10MW and 200MW cumulative installed capacity takes into account both experience and volume effects (an individual farm at 200MW is assumed to have 50MW capacity, while the 10MW farm is 10MW capacity).



Component	Cost centre progress rate	Wave
Structure and prime mover	91%	• Improved understanding of real-sea performance is expected to lead to design optimisation and especially reduction in safety factor of main structures. • Innovations in manufacturing processes such as 'batch production' of multiple units are likely to reduce manufacturing costs and improve design through learning. • Use of alternative structural materials such GRP (glass-reinforced plastics), concrete and rubbers.
Power take-off	93%	• Generators and hydraulic systems are generally considered efficient. Nevertheless, cost and reliability innovations are required for marine applications. • Innovation is expected in second generation technologies (eg linear generators).
Station-keeping	88%	• The greatest cost reduction opportunities identified are for seabed-mounted applications. • Floating wave devices use conventional mooring systems with little direct cost reduction potential. Cost savings are nevertheless expected to stem from improved deployment techniques.
Connection	99%	• Cost reductions are likely to come from increasing use of bespoke wet mate connectors as the market develops. • More general electrical connection cost reductions can be achieved though cable laying efficiencies and DC connections where distances are appropriate (greater than 60km).
Installation	92%	• Cost reductions are expected to come from the development of alternative intervention solutions which allow faster deployment using lighter weight (cheaper) vessels.
O&M	88%	• Cost improvements will stem from improved reliability in design. Once technology is proven and early failures have been engineered out, costs are expected to reduce significantly. • Costs are also expected to reduce as new intervention techniques are developed, particularly involving retrieval rather than on site-intervention, or purpose built offshore servicing platforms. • Better provision of ports and infrastructure will lead to lower servicing and transport costs.

3.2 Cost of energy reduction through innovation

The MEA has undertaken a number of research studies to explore the potential for cost reduction in each of the cost centres, focusing on key areas of high cost including power take-off (PTOs), moorings, blades, O&M and installation. Case studies from these projects, which reduce the cost of energy from existing devices, are found in this section.

Other MEA studies undertaken have investigated the prospect of lowering the entry point on the cost curve through 'step change device concepts' that are conceptually different to devices currently nearer to deployment. Some of these potential future devices are considered in the following chapter.

3.2.1 Case studies from the MEA

The MEA work to reduce the cost of energy from existing device concepts focused on two areas, as introduced in section 1.2:

- Research into lowering the costs of components in existing devices, by working with supply chain companies involved in component manufacture, including major components such as generators (Strand B). Strand B projects involved R&D targeted at key cost areas, part funded directly by the Carbon Trust.
- Developing strategies for installation, operations and maintenance with particular technology developers (Strand C). Strand C aimed to draw offshore engineers and other relevant experts, as well as potential suppliers, into the R&D process alongside device developers, and involved Carbon Trust funding of work by engineering consultants on areas suggested by device developers .

Competitions were announced for projects in each of these strands, and experts were recruited from relevant established industries such as offshore engineering and oil and gas who worked alongside academic experts on the screening of each application. Highlights from these projects are presented in the following pages.

Cost and performance improvements are possible in all six of the cost centres introduced in Section 3: structure, station keeping, PTO, installation, electrical connection, and O&M. So too are gradual improvements to increase efficiency and/or reliability, or to overcome particular locational or technical difficulties. In many cases, gradual improvements in one cost centre also create, or unlock, improvements in other centres or in efficiency/reliability.

The boxes in the following pages detail cost of energy reductions that have been achieved, or will be achieved, as a result of the Strand B and C projects from the MEA. There are examples of cost of energy reductions from most cost centres, as well as details of many innovations that bring improved performance. The step diagrams show the effect that different elements of the project have on overall cost of energy compared to estimated future costs before the project. In some cases an innovation may increase costs in one centre, but lead to more significant reductions in others to give an overall reduction.

Structure

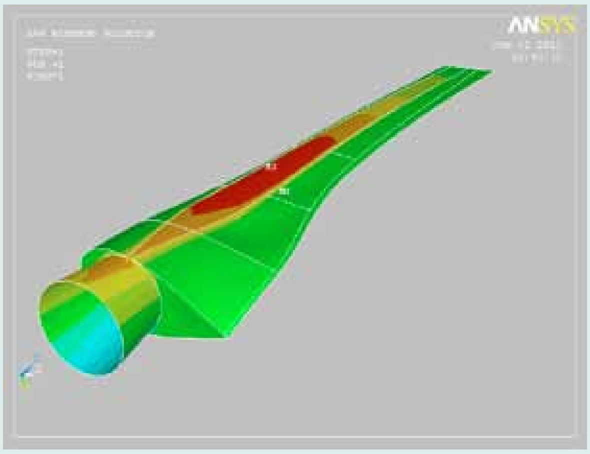
The ability of tidal turbines to capture energy is well understood, but the actual performance of turbine blade materials in tidal currents has never been proven for long durations. A project by Aviation Enterprises Ltd (AEL), a company aiming to supply carbon fibre blades to a number of tidal developers, undertook extensive materials analysis with a view to providing a much better understanding of blade performance in tidal stream environments.

Better understanding of the blade properties and service requirements will lead to, amongst other things, a thinner blade, which leads to fewer cavitation restrictions during operation.

The learning from AEL's project is already being fed to device developers. It is also being used to analyse and understand the reasons for blade failures being experienced by tidal stream prototype devices currently undergoing testing in the UK. Understanding these issues now should prevent costly failures at later stages, so information has also been shared with other potential suppliers of tidal blades, who are now focusing on better blade root design. The learning is also feeding into efforts to establish a certification process for tidal stream devices. Certification is vital to secure investment in marine energy arrays.

MEA project case study

Figure 16 *Carbon fibre tidal turbine blade project, by Aviation Enterprises Ltd. AEL makes blades for several tidal stream developers*

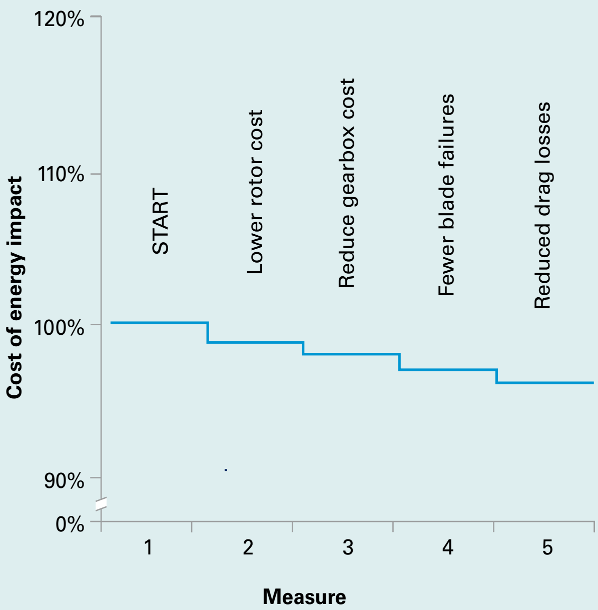


Tidal turbine blades – sequential testing and certification

No tidal stream turbine blades are yet proven in the marine environment. To certify that blades will last for the full life of the machine, sequential qualification is needed. This starts with verifying the fundamental properties of the material, its manufacture and its application and then the detailed design of the final assemblies. Without an understanding of the detailed behaviour of the material in real sea conditions, the blades are likely to be overdesigned and less efficient than they could be.

The AEL project has focused particularly on engineering of materials and joints, and on reducing manufacturing time to reduce costs.

AEL are now supplying carbon fibre blades for Marine Current Turbines and Tidal Generation Ltd (Rolls-Royce) and are in discussion with other leading tidal technology developers.



Impacts on the cost of energy

Reducing the overdesign of components reduces the quantity of material required, saving money. Reducing over-engineering can also make blades slimmer and so improve the performance, as well as reducing drag losses and the potential for cavitation.

Slimmer blades can be run faster, allowing a smaller, less expensive gearbox to be used.

A better understanding of the material, its behaviour, and likely failure modes can lead to better design and monitoring and ultimately higher reliability and fewer expensive blade failures.

In addition, if these issues are understood early on, there will be fewer blade failures that might otherwise harm the fragile development of the industry.

Station keeping

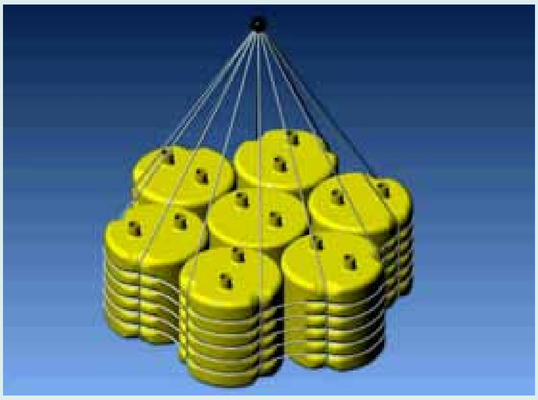
Station keeping is a particular challenge, which typically requires a device specific solution. A number of MEA projects included the assessment or development of innovative mooring structures and foundations for tidal devices, including drilled foundations and innovative support structures. But the project with broadest potential applicability involved moorings for floating devices. Station keeping is a relatively small cost centre for floating devices (typically less than 10% of all capital costs) but the example shows how technology innovation could bring a simple cost and performance improvement to many devices at an early stage in their development.

Figure 16 describes a project to test the performance and clarify the costs of nylon mooring ropes in floating marine energy converters. The research has suggested an overall cost reduction for relevant technologies – floating wave, and potentially tidal devices – of between 5% and 10% compared to the steel cables currently envisaged by most developers. Note that the overall cost of energy reduction is achieved despite an increase in capital cost.

The new plastic ropes would directly replace a current mooring solution that does function but has some significant drawbacks – steel moorings. Leading wave energy developers are already using nylon ropes in parts of their mooring systems for early full-scale devices.

MEA project case study

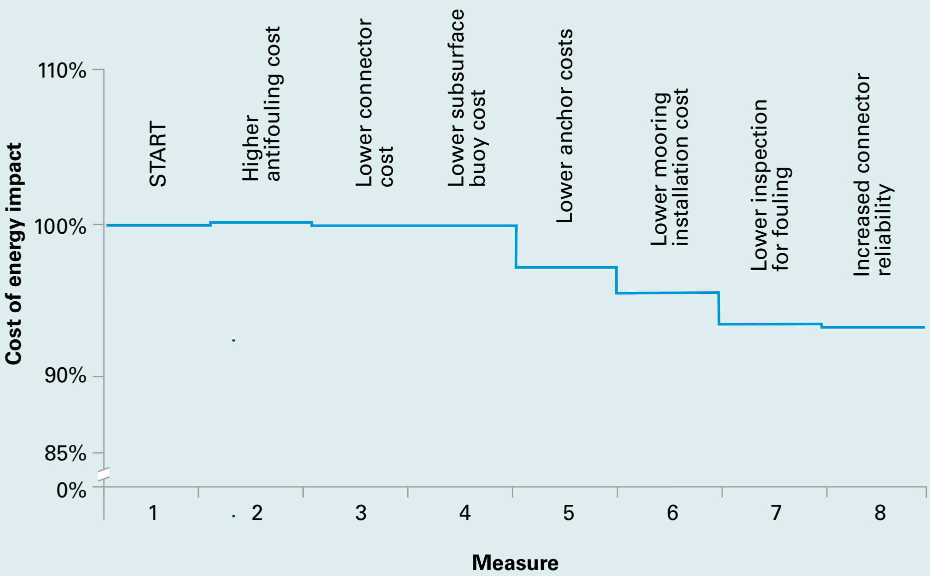
Figure 17 *Nylon mooring rope study by Tension Technology International. Nylon mooring ropes (and associated anchors) could be applicable to all floating wave or tidal devices*



Compliant lightweight fibre mooring system for floating devices

Most mooring systems consist of heavy metal cables with expensive anchors. TTI with partners Promoor have developed a new lightweight mooring system based on nylon ropes and gravity bag anchors. Nylon is more compliant than steel and can lead to lower loads on the moored device. Nylon is not yet in widespread use and so research into its fatigue performance was needed. As part of the research TTI also investigated using fabric bags filled with aggregate to replace more expensive drag-embedment anchors or the more awkward to handle gravity anchors. The research also identified ways to prevent the highly compliant mooring system from bio-fouling by using a flexible protective coating.

Impacts on the cost of energy



Swapping to nylon from steel cable can lead to better mooring compliance and lower overall loads on the moored structure. Nylon has also been shown to have good fatigue resistance, meaning it is likely to last longer and need fewer inspections. The rope system is also cheaper than the steel equivalent.

The anti-fouling coating adds expense, but as it protects the rope, fewer costly inspections are needed and the rope is likely to be more reliable and last longer.

Fibre ropes are lighter and easier to handle during installation than steel equivalents. This leads to lower installation costs. Similarly, bag anchors are significantly less expensive and easier to handle during installation than drag anchors or equivalent gravity anchors.

This work is currently progressing with further support from The Carbon Trust under the Entrepreneurs Fast Track scheme.

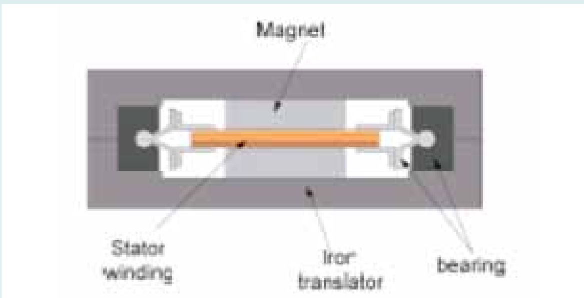
Power take-off

Nearly all wave energy devices currently use a hydraulic system to convert linear motion in the structure to electricity via a conventional rotating generator. This system has been proven in theory and practice, and is expected to form the basis of designs for the first commercial farms. Hydraulic systems require regular maintenance, however, and have many moving parts. Edinburgh University has developed a novel linear generator which could be used to replace all the hydraulic parts in many wave devices, leading to a device that converts linear motion directly to electricity.

The linear generator being developed has been demonstrated in controlled conditions onshore but has not been proven in full marine conditions, and is some way from commercialisation. In light of the significant complexities of integrating a completely new PTO system into a device, developers are continuing to design for

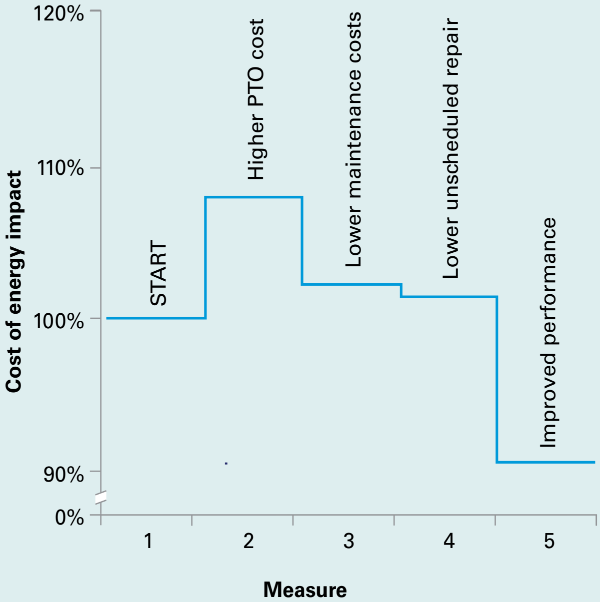
MEA project case study

Figure 18 *Linear generator for wave devices (Edinburgh University)*



Linear generator

Linear generators could be applied in many wave energy devices that currently use oil hydraulics. The University of Edinburgh has developed a novel linear generator system. This generator is simpler to construct and less costly than existing linear machines. This makes it a lower-risk alternative to hydraulics and brings forward the time when direct electrical connection can be used in wave devices.



Impacts on the cost of energy

The overall cost of a linear direct electrical machine is significantly higher than a hydraulic equivalent.

However, this new design has far fewer moving parts, which makes it more reliable.

There are far fewer parts to service, translation bearings being almost the only example, and no filters, seals, pumps or accumulators.

At part and variable load it is expected that this novel linear generator will be more efficient than a hydraulic equivalent.

At least three wave device developers are now looking at incorporating Edinburgh University's C-Gen linear motor into future generations of their devices.

hydraulic systems in the short and medium term. This research, however, allows wave energy technology developers to plan for incorporation of the linear generator in future device iterations, once the rest of the device has been thoroughly proven using the well-understood hydraulic systems.

Electrical connection

Electrical connections in marine environments are not considered a particular problem for wave and tidal devices although there will be unique challenges for first arrays. While the MEA did consider aspects of electrical connection, such as the PWP tether latch assembly (*Figure 21*), the Carbon Trust envisages that much of the innovation relating to offshore electrical connections is likely to be driven by more developed technologies such as offshore wind, although high tidal velocities and scoured sea beds will create particular challenges.

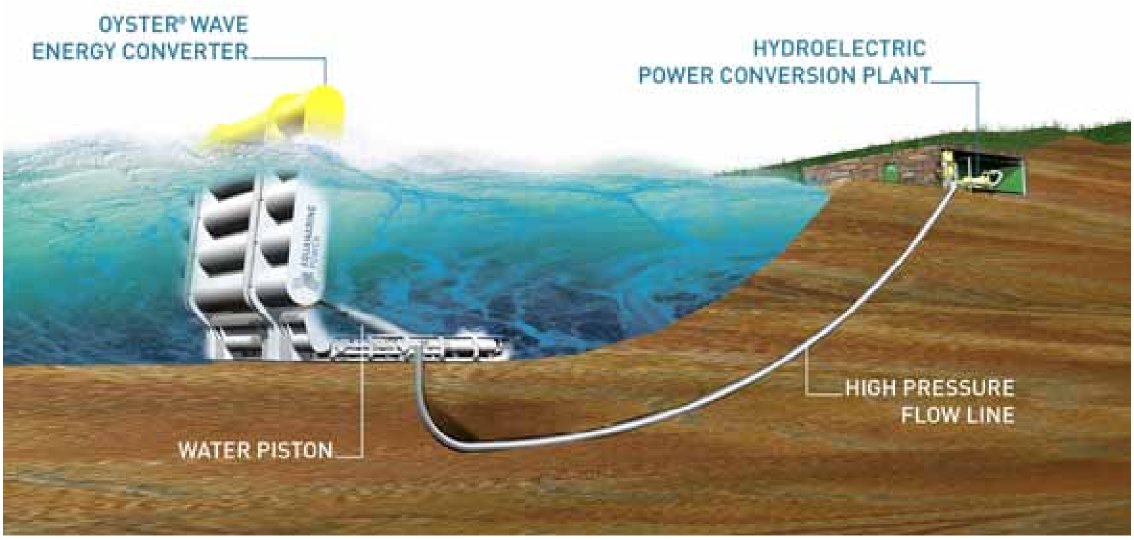
The MEA has, however, worked with developers such as Aquamarine, who are pursuing alternatives to the conventional electrical connection using sea water as a power-transfer medium, and potential hydraulic system suppliers (see *Figure 19*). This alternative power take-off system could offer cost reduction advantages over full electric systems for devices sited near the shoreline. MEA learning has shown that the distance to shore and hydraulic pipeline pressures will dictate the eventual configuration of commercial arrays.

Installation, and operations and maintenance

Installation and O&M strategies and technologies tend to be highly device-specific, although there are some important similarities. Installation makes up a very significant proportion of the cost of energy, particularly for tidal where it can amount to more than half of all capital costs. Equally, O&M makes up over a quarter of wave energy levelised cost of energy. Strand C of the MEA, in which the Carbon Trust worked directly with consultant engineers and device developers, therefore targeted development of improved installation and/or O&M techniques for particular marine devices.

The initial work with Ocean Power Technologies (OPT) on their PowerBuoy device clarified a number of operational issues, providing a much better understanding of operational costs. This led in turn to a significant redesign of the PowerBuoy concept. The conceptual innovation involved – a detachable PTO which can be slotted in and out of the device for maintenance or repairs – may not be used by OPT in the short-term but is now being considered by other marine developers, including those developing the Anaconda wave attenuator (*Figure 35* in Section 4.1.3). Similar cross-cutting learnings have emerged from a number of other MEA projects, which were initially targeted at specific companies, but have resulted in innovations that are potentially applicable to several devices.

Figure 19 *The Oyster system from Aquamarine Power uses a buoyant hinged flap to capture wave energy and pump water through a directionally-drilled pipe to an onshore-generator. Several flaps could be used to pump water to one generator*



Picture from Aquamarine Power

MEA project case study

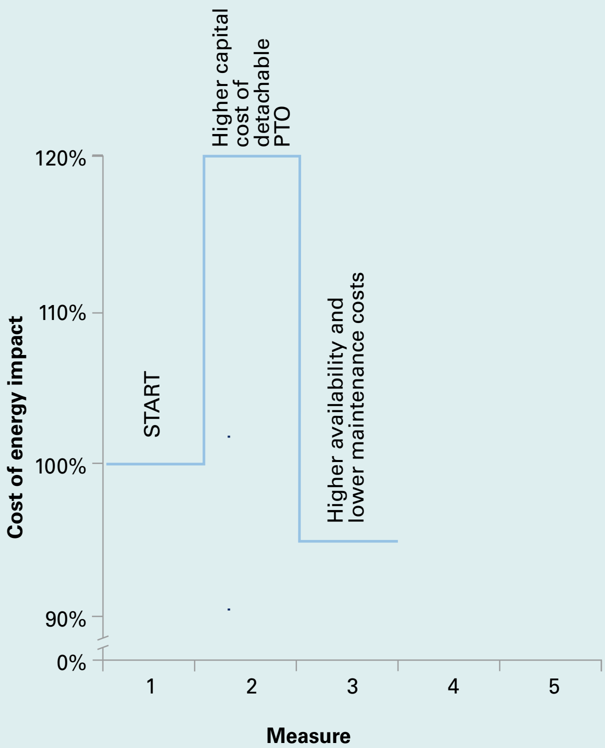
***Figure 20** Device installation and O&M studies for the PowerBuoy point-absorber wave device*

OPT installation studies

A series of studies were carried out to investigate the potential for cost reduction from installation and O&M for the OPT Powerbuoy PB150.

A detailed cost model was developed to reflect the total installation and transportation cost. This was used in a transportation study to confirm the transport method and identify suitable vessel types and handling facilities.

Maintenance scheduling was also studied, comparing options for repair by tow to shore with use of a DP Anchor Handler fitted with a crane to remove and replace the PTO offshore.



Impacts on the cost of energy

This research allowed OPT to investigate many of these options in depth for the first time. The studies gave much better clarity on the overall cost of energy and (like many other Strand C studies) actually increased their cost estimates – but enabled the company to direct suitable resource at maintenance strategies.

A fundamental piece of learning that arose from the installation studies has led to the design of an encapsulated PTO unit that can be detached from the primary structure and taken to shore for maintenance. It is estimated that it is simpler and cheaper to take the 25m long, 50 tonne PTO to shore for maintenance or repair than to tow the whole device to port.

The studies suggested that the new PTO (and associated structural redesign) would increase capital costs by 20%. But because the device downtime is greatly reduced, lifetime levelised costs are reduced by 4.8%. The new system is therefore seen as a potential future cost reduction option for OPT.

Pelamis Wave Power conducted a research programme to improve the operation of its installation and mooring system. The research was targeted at specific installation and O&M issues that Pelamis had identified as pinch points in its product development. The outcome – a winch and tether latch assembly uniquely suited to the Pelamis device – enables the device to be connected and disconnected in higher seas, and is now being used on the

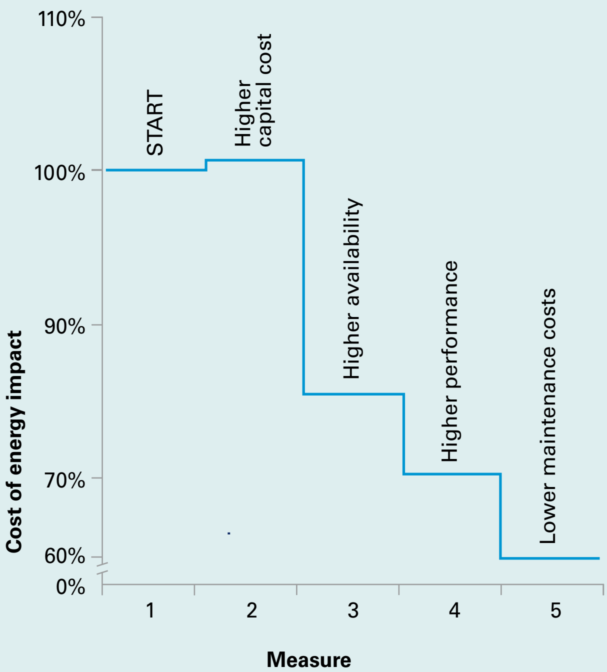
MEA project case study

Figure 21 *Installation and connection component development for the Pelamis device.*

Pelamis – enhanced installation and connection equipment

The Pelamis device is an attenuator made up of four large diameter steel cylinders connected via hydraulic rams which pump high-pressure fluid through hydraulic motors via smoothing accumulators. The current P2 commercial production machines are 180m long and 4m in diameter, have four PTOs and are rated at 750kW.

The Pelamis device is designed to be removed from its mooring and towed to a sheltered site for maintenance. Before this project, installation and maintenance of Pelamis devices required multiple specialised vessels and expertise, and was restricted to narrow sea condition windows and subject to high operational risk.



Impacts on the cost of energy

PWP undertook an extensive redesign of the offshore installation equipment, mooring connection components, and installation/disconnection procedures. This significantly widened the range of operating sea conditions in which P2 can safely be installed/disconnected,and greatly increased the proportion of the year that the P2 could be serviced while reducing the time spent waiting for suitable weather windows. As a result the predicted availability of the machines rose substantially.

PWP also considered an active 'yaw' system that enabled the device, at relatively little extra cost, to adjust its direction to suit the incoming waves. This increases the performance of the farm.

The simpler deployment and retrieval process means that fewer lower-specification vessels are needed, reducing the cost of each intervention.

When combined, these features can deliver around a 35% reduction in the cost of energy over the equivalent design used on the previous Pelamis version.

Pelamis device undergoing testing at EMEC. The simplified connection/disconnection procedure dramatically simplifies the testing programme for the full-scale device at EMEC and will significantly reduce the downtime of Pelamis devices in commercial arrays. This has proved to be one of the most successful MEA projects.

3.2.2 Timescales and dependencies

The previous section introduced a number of cost reduction innovations identified and developed by the MEA. It is important to distinguish between different timescales for cost reductions.

Some studies from the MEA result in a change that can be made immediately: for example the nylon mooring rope in *Figure 17* [TTI] is potentially a direct replacement for steel cables currently used to anchor floating devices. It could be used on the first farms of floating wave devices, delivering immediate improvements in cost of energy.

Other studies into components or installation techniques involve technologies that could be introduced today, but that only become economically feasible at scale: specialist installation vessels, for example, are only likely to become feasible when large arrays of devices are being installed – probably not until 2016 or 2017.

Longer-term innovation work will yield cost reduction benefits after extended development times. The linear motor described in *Figure 18*, for example, has the potential to replace hydraulic power take-off systems in several wave energy device concepts, but will not be introduced until several iterations of design have proved the wave device concept using well-understood hydraulic PTOs. This pushes the expected cost of energy improvement from linear generators some way into the future.

Continuous innovation – leading to continuous cost of energy reductions for marine energy – is made up of a combination of all these sorts of interventions plus the ongoing development which leads to increased energy yeilds. Several studies in the MEA have demonstrated levelised cost of energy reductions of 10% or more – and one of more than 30%. The Carbon Trust believes that there is considerable scope for continued cost of energy reductions from innovation in marine devices as the roll-out of commercial farms begins, which will combine with cost reductions from increased scale of arrays and basic learning by doing. The following section looks at possible pathways under high innovation and low-innovation scenarios, and suggests priority areas for innovation focus in light of what has been learned from the MEA projects.

3.3 Assessing the impact of innovation

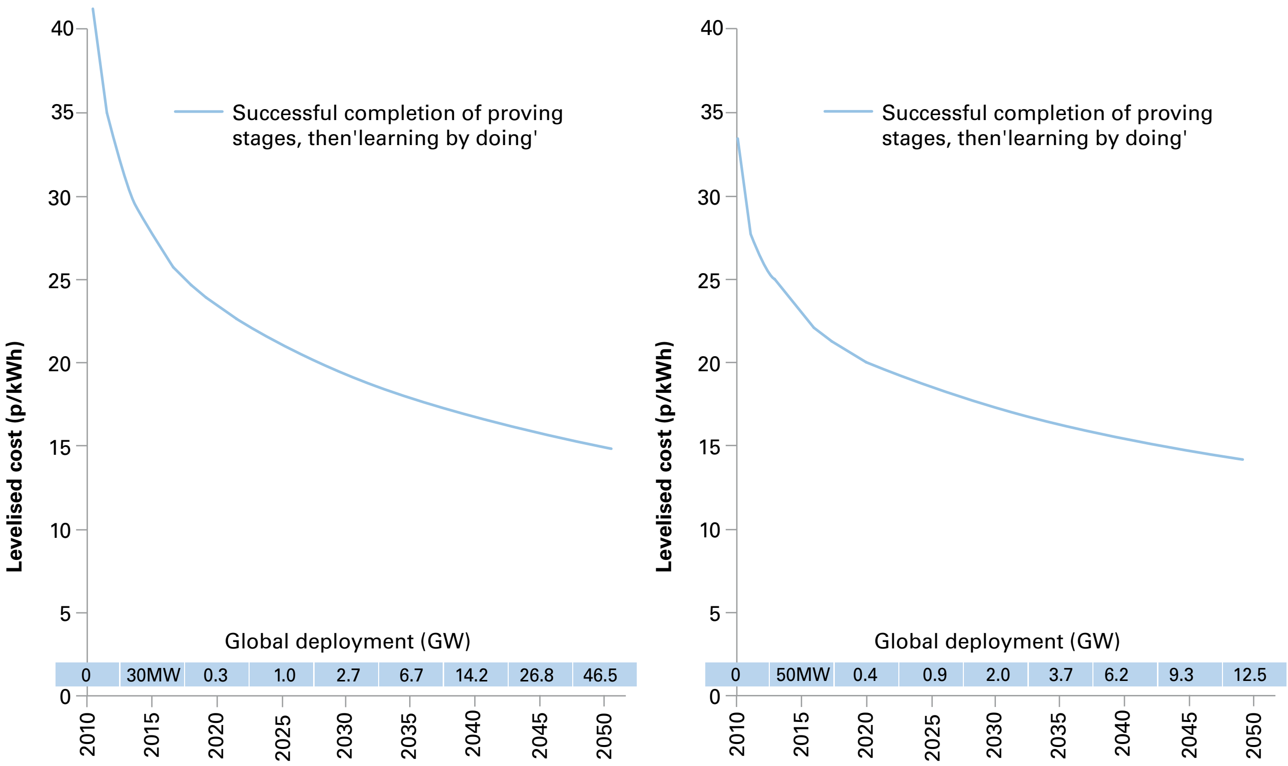
The cost of energy from marine devices is expected to fall, for a number of reasons that have been observed in other technologies. These include learning by doing as the cumulative installed capacity increases; scale effects as the size of arrays (and, probably, devices) increases enabling economies of scale; and innovation. This section begins by considering the cost reductions likely from learning by doing and scale effects, and then discusses the potential for accelerated innovation to bring cost of energy down more rapidly.

3.3.1 Baseline learning

The effect of learning by doing and scale effects have been assessed by looking at comparable industries. We looked at the efficiencies which can be achieved while manufacturing 2,000 similarly fabricated machines and concluded that learning rates of 5%-6% can be realised in the early stages of a product's life simply through smarter manufacturing and procurement. If this is applied to marine devices with roughly 1MW of installed capacity per device the following cost reduction can be modelled.

Figure 22a and 22b show that simply moving to a scaled-up manufacturing process is not going to reduce costs sufficiently for marine energy to be competitive, unless many MW of capacity are installed at costs of energy above 20p/kWh. Installing hundreds of MW at these high costs is simply not feasible, so focus is required on continued technology innovation to significantly steepen the learning curve at the early stages.

__Figure 22a and 22b__ Baseline cost of energy reductions from wave and tidal devices, based on learning by doing only. Note that the roll-out rates for wave and tidal are different[30]



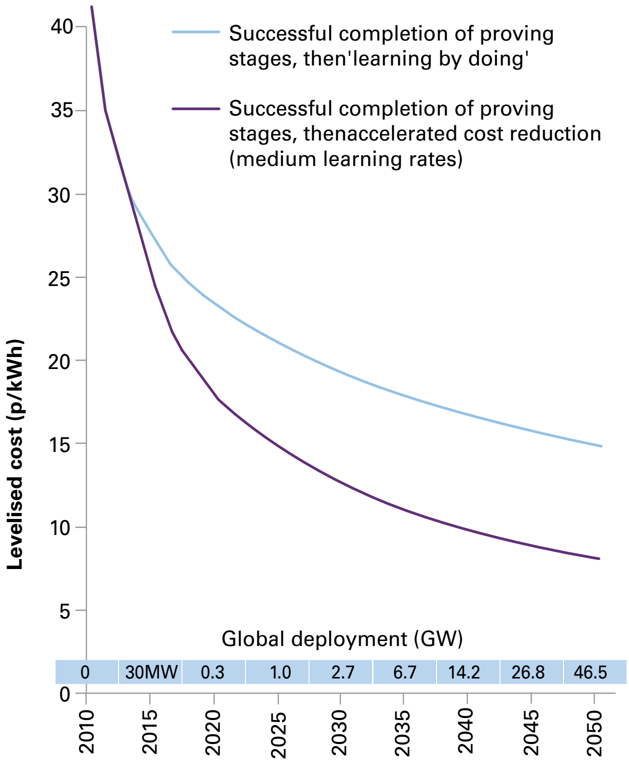
3.3.2 Accelerated innovation

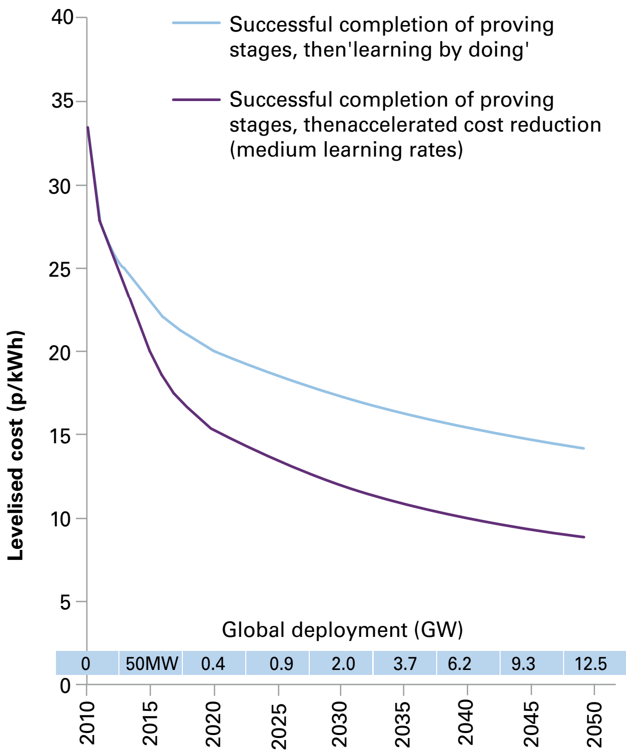
Having quantified the impact of innovation on the cost of wave and tidal energy, this can be overlaid on the learning by doing assessment to understand the full potential for cost reduction. In *Figures 23a* and *23b* an innovation-led scenario is presented in which targeted cost-reduction programmes are initiated after the first farm stage. Our experience and analysis suggests that this scenario suggests costs of energy coming down to between 15p/kWh and 20p/kWh for both technologies by 2020, when 0.4GW of tidal and 0.3GW of wave capacity will have been installed. As elsewhere in the report, costs here are modelled at a discount rate of 15%, which is considered appropriate to the relatively high-risk nature of the early wave and tidal industry.

As can be seen from *Figures 23a* and *23b*, adding innovation to the learning by doing curve significantly accelerates cost reduction relative to the baseline case. At 2020, costs for wave have reached 18p/kWh under the medium scenario, and 16p/kWh for tidal. By 2025 we see that the cost reduction has reached the level of today's offshore wind (~15p/kWh) for both technologies.

[30] The rollout rates are indicative only and are based on a Carbon Trust assessment of the potential for deployment given the state of the technologies today and government energy plans.

__Figures 23a and 23b__ Possible cost reduction pathways for wave (left) and tidal stream energy under a 'business as usual' and innovation scenario





Note: Two proving stages exist, one at full-scale prototype, and one at first array stage.

Chapter 5 describes in more detail what is required to achieve this roll-out rate in terms of market conditions and innovation support. If we take today's level of revenue support in Scotland (three ROCs for tidal and five for wave) we believe that tidal energy could become commercial by 2020 and wave by 2016. Our analysis of the industry and resource indicates that, once proven, wave energy technology will develop at a slightly faster rate than tidal, leading to parity on costs between wave and tidal by around 2035, and ultimately slightly lower costs. We believe the costs of wave technology can be reduced slightly faster, primarily because the resource is considerably more homogenous than the tidal current resource and that on a global scale we are likely to see greater levels of wave deployment, which will drive technology progress rates.

3.3.3 Different paths for wave and tidal

It is clear that the different nature of wave resource and tidal resource will have an important effect on the way devices are developed:

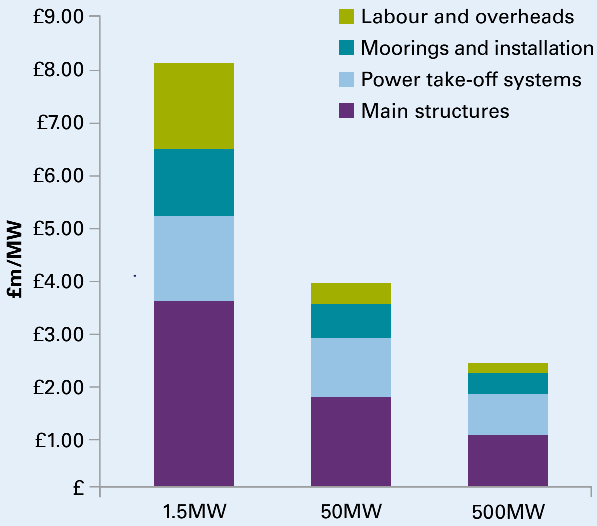
- Wave sites across UK waters are broadly similar in their characteristics – they are expanses of open sea. Wave device developers can therefore persist with a single design of converter over large areas of wave farms with only relatively minor modifications on a standard basic design. Tuning of devices for different prevailing wave conditions – for example between waves off the south-west coast of England and those off the north-west coast of Scotland – is likely to be needed to optimise energy extraction, but the underlying concept can remain unchanged .
- Tidal resource, by contrast, is concentrated in discrete locations, with specific characteristics at each site. Current device concepts can access a little under 4TWh/y of resource – equivalent to about 1.4GW

Putting it all together – Pelamis example

Figure 24 shows one example of how cost reduction might be achieved as capacity increases. The capital costs are halved compared to the cost of the Pelamis devices currently being installed at EMEC. For the Pelamis device, cost savings in the structure and PTO arise from volume and learning effects – reductions in machining costs for the main structure – which have already begun as the company moves to manufacture of its first farm. They also see scope for cost reductions through innovation as new materials could be used in the structure, and as performance improvements mean a nominal 1MW device can get smaller over time. Savings from mooring/installation are expected mainly as a result of scale efficiencies, but also from innovation in floating grid connections and advanced installation techniques including those introduced in *Figure 21*. Labour and overheads are a significant proportion of device costs at early stages, but after 50MW of installed capacity, R&D and company overheads will be a much smaller proportion of the levelised CoE for each new device.

These reductions are fairly typical of what we expect from wave devices: significant savings from bulk manufacture of complex structures and from increased sea-experience, along with innovation in materials and increased capacity per unit weight.

***Figure 24:** Cost Reduction Profile for Pelamis wave device, from Pelamis Technology Improvement Plans (2011). 1.5MW costs represent actual capital costs for individual full-scale device; 50MW and 500MW costs assume farm size of 10MW and 500MW respectively, so take into account volume savings and learning by doing (the modeling also assumes a small increase in the rating of each Pelamis device)*



capacity – but it is expected that new concepts will be needed to access deep water sites (over 30m), and each site is likely to require new solutions to difficulty issues, particularly regarding installation. Low-energy sites will also almost certainly need new device concepts to allow cost-effective energy capture.

These factors will undoubtedly impact on the build-out rates and, as a result, cost reductions from wave and tidal energy over the coming years. Wave energy might, all other things being equal, be expected to benefit from continuous gradual cost of energy reductions, while tidal device development will have to undergo a number of design-led step changes. The following section looks at the priorities for technical advances of the device concepts already under development. It also looks at the possibilities of step change device concepts emerging that are able to extract energy at significantly lower cost, or from currently inaccessible resource. These sorts of game changing, new device concepts are considered more likely in the wave sector, where developers are still learning about maximising energy capture and there is as yet little convergence around a single design concept.

4. Accelerating the marine energy industry

This chapter looks at the prioritisation of effort for cost reductions. It also considers other drivers for technology development, such as risk reduction and adaptation to specific site conditions. This builds on analysis and observations from MEA economics and resource studies, as well as learning from the projects in the three strands.

The chapter discusses two key drivers for continued innovation as the first farms of marine devices are built:

- overcoming site-specific technical difficulties, allowing the full marine resource to be accessed (particularly for tidal stream)
- continued focus on cost of energy reduction.

The discussion looks ahead to how players in the marine energy industry should be directing resource to achieve and accelerate cost reduction. It also provides a basis for future Carbon Trust thinking on targeted innovation in marine energy.

4.1 Tidal stream research priorities

A number of tidal stream energy converters have now been built and installed in British waters and further afield. These are full-scale devices, in some cases with undersized nacelles, intended to prove design concepts and gain information about performance, manufacture, installation and operation.

The Crown Estate has set the stage for large-scale deployment, with the first commercial licensing round in the Pentland Firth and Orkney waters. As developers move towards delivery of the 1,000MW of tidal energy sites that have been licenced the reliable operation of the first generation of tidal devices is a priority, which will be followed by focus on cost reduction. The first phase of these developments will use optimised versions of the full-scale devices currently being tested, which will be installed at the most sheltered and relatively shallow sites discussed in Section 2.3. These devices, which typically have one or two tidal turbines (or similar) per support structure, are described as **first generation tidal technologies.**

Innovation for this first generation of devices will be driven by the need for lower cost of energy, but energy from these first generation devices will remain expensive when compared to most other renewable generating technologies. Cost of energy reductions for first generation technologies will come through improved reliability, lower installation costs and lower manufacturing costs. Better installation techniques will also need to be developed to enable the large-scale deployment that is required to deliver the first series of UK licensed sites.

The resource work detailed in chapter 2 of this report shows, though, that the majority of the technical tidal resource is in waters over 30m deep (some 65% of a total 20.6TWh). A **second generation of tidal devices** will be needed to effectively extract energy from the whole water column at deep sites, many of which have additional challenges such as more extreme met-ocean events and higher wave loading. In addition, there will be a need for continued cost reduction through more innovative structures and innovation in other cost centres, to ensure that future costs of energy are no greater than those from the best first generation sites.

A key learning from the MEA is that second generation devices will be needed to enable tidal energy to become a full scale industry, taking the market size from around 4TWh/y to around 20TWh/yr.

Figure 25 *Indicative table describing characteristics of first, second and third generation tidal devices. First generation devices are being developed and built today, although not yet at first farm scale; second generation devices will encompass many cost reduction steps, and enable new areas of resource to be tapped (such as deeper or more difficult sites) but are generally iterations on first generation concepts; third generation devices are radically new concepts which will extend the available resource or harness tidal energy in fundamentally different ways*

	First generation	Second generation	Third generation
Objective	Prove the concept of tidal energy conversion at full farm scale. Generate reliably at lowest risk/best resource sites.	Implement all known cost saving technologies, including structural changes to allow cost effective development of more complex tidal sites.	Fundamentally different concepts which allow new areas of resource to be exploited (ie lower velocity) or are significantly cheaper, or both.
CoE and CoE reduction	Expensive due to high uncertainties and lack of knowhow, but cost softened by deployment at choice sites, or dedicated test sites.	Step change cheaper as these technologies achieve greater energy yield in deeper waters, and a greater swept area per unit of support structure and foundation, as well as incorporating all which has been learned from 1st gen. These technologies are required to economically access around two thirds of the identified UK tidal resource.	Radical concepts will have greater energy yield per unit of capital cost and per unit of O&M cost. Concepts will either be very simple (with few moving parts) or be significantly smaller per unit of energy capture.
Site	Shallow (easy).	Deep (and difficult) – most of the resource	Low resource site; shallow site; same sites but cheaper?
Concept	As per existing designs. Probably one or two rotors per support.	Ability to capture all energy at deep sites, and at lower cost. Probably multiple generators per structure. May be floating or neutral buoyancy	Radically new concept which harnesses new resource or existing resource in a more cost-effective manner

A **third generation of tidal devices** would bring an entirely new energy capture concept to the tidal stream industry. The MEA 'next generation concepts' strand has reviewed many devices and identified concepts which harness the low velocity or shallow tidal streaming sites that are uneconomic or inaccessible to more established concepts. One such concept is the Deep Green device by Minesto (*Figure 35*).

Based on our new understanding of the UK's resource and of the economics and performance of tidal stream technologies, the challenge for developing the technology can be summarised across the three envisaged generations as shown in *Figure 25*.

Figure 25 provides a framework for the rest of this section, which considers research priorities for first- and second-generation wave and tidal devices separately, as well as considering issues (depth, difficulty, and cost) relevant to all tidal developers. The end of each section discusses some second and third generation devices developed with support from MEA strand A.

4.1.1 Priorities for the first generation of tidal concepts (the next five years)

Device and farm efficiency

The performance of rotors in water is reasonably well understood. However, improvements can still be made to devices through optimised blade geometry, streamlined support structures, and simplified or more efficient drive trains. The research on blades funded by the Carbon Trust has shown that blade profile can have a big effect on turbulence and that the mechanical properties of blades can materially affect the efficiency of energy capture (*Figure 16*).

There are also some significant uncertainties about the performance of devices when sited in arrays. These include uncertainties around the interaction of the devices and their combined effect on the tidal range and velocity. The tidal resource work presented in Section 2 introduced the 'flux' hydrodynamic concept as a way of modelling these effects. There are a number of logical follow-on steps from this work that will require device developers to work with academics and public bodies and the various statutory environmental consultees to establish what effects on tidal velocity and/or range are acceptable.

Progress in this area is also dependent on device developers gaining operational data about the behaviour of full-scale devices in real tidal currents – initially of single devices and then of arrays. This work will enable device and project developers to better understand issues such as wake effects and turbulence, leading to arrays with optimised device siting to maximise energy yield.

Device and farm reliability

Increasing device availability – the proportion of time that a device is available to generate and transmit electricity to the grid – can be just as important as increasing yield through efficiency improvements. Reducing maintenance requirements, both scheduled and unscheduled, is therefore a clear priority for all tidal device developers. As device performance is proven, the focus for developers will move from demonstrating energy capture performance to demonstrating reliability. This will be particularly important as project developers begin to look at funding large arrays of tidal converters, rather than individual devices.

Aside from events such as debris impacts and wave loading, the operating conditions in a tidal stream – including extremes – are predictable. It should therefore be possible to design reliable tidal energy generators once local conditions have been clearly established. To this end it is important that relevant site data such as turbulence, reversals and directionality are collected and interpreted so that every component of a device and farm can be designed for reliability.

Reducing downtime by faster operations and higher sea-state operability

We only have to look at the early stages of the offshore wind industry to recognise that there will be early device failures in tidal energy extraction. The industry should anticipate these, and develop effective intervention methodologies for dealing with them. Furthermore, the first farms of devices should be designed with increased intervention rates in mind, as failures are likely.

Marine operations – for planned and unplanned maintenance – are typically limited by the sea conditions. These are initially characterised by the height of the waves, but are also influenced by factors such as wind and tide. Being able to access devices without delay is crucial to reducing downtime and achieving high availability, so engineering a device that can be accessed in higher sea states is a clear priority and one that becomes more important as less sheltered sites are targeted.

Figure 26 shows that increasing the capability for access in higher seas will increase the range of sea states in which access is possible, thereby significantly reducing downtime as well as reducing maintenance costs by lowering the standby time for crews and equipment. Similarly, increasing the speed of maintenance operations – by, for example, engineering for a modularised PTO that can be changed out with a new unit – can also decrease downtime by allowing maintenance or repairs in shorter and thus more frequent weather windows.

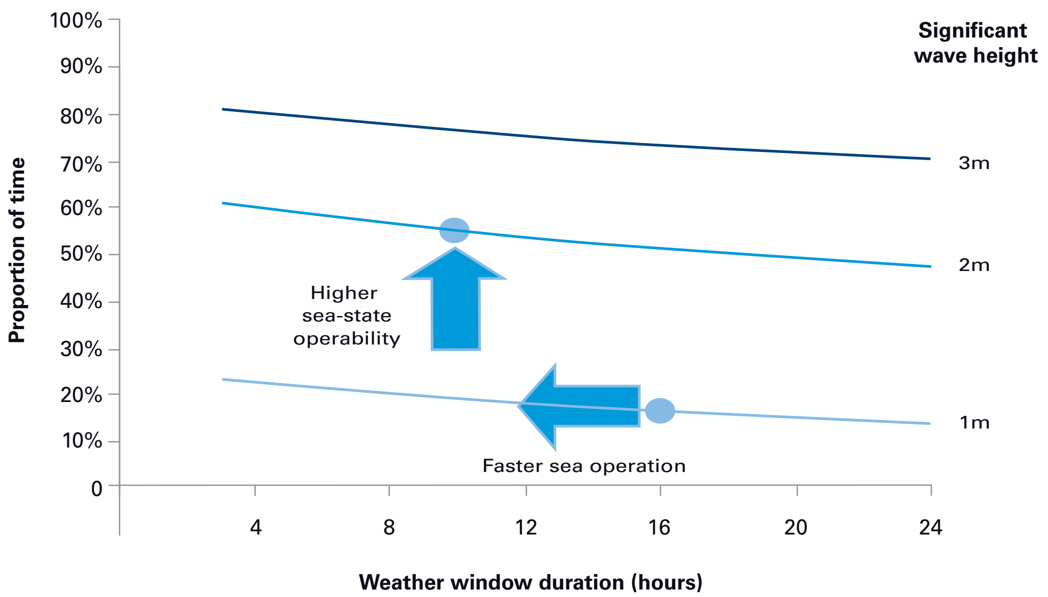
Maintenance operations for non surface-piercing tidal devices are likely to be more involved than for wave devices, so focus on recovery techniques and improved reliability is a high priority. Some device developers are using detachable nacelles which are connected and disconnected to a fixed foundation structure. There is certainly scope for innovation in this area, and the related area of wet electrical connections, which allow easier connect and disconnect. Another target for developers is the use of smaller and cheaper vessels for all at-sea operations, including installation.

Lowering installation costs

The pie charts in Chapter 3 showed that the cost of installing bottom mounted tidal stream devices makes up around one third of the levelised cost of energy. Throughout the MEA ways of decreasing installation costs have been explored. Some of these developments are design-led and can be implemented now. Others, such as more capable vessels or subsea drilling, could yield cost improvements but only become economic at a certain scale: for a subsea drilling platform that is likely to be first farm stage, while for bespoke vessels several tens of MW are likely to be needed to justify the investment. One lesson from the MEA and other Carbon Trust projects is that jack up barges for installation can be problematic in tidal streams. Dynamic positioning vessels that have much better potential for manoeuvring within an array are likely to play a key role in future tidal deployments.

Additionally, designs could be scaled up in such a way that there is more power produced for each difficult sea operation or foundation. It is expected that this will be a key design feature of second-generation tidal devices – allowing a step change in levelised cost of energy. Devices with larger rotors or multiple rotors on single supports might achieve this goal, allowing lower deployment costs per installed MW.

Figure 26 *Sea operations are typically possible below a certain wave height – in the example shown lines are drawn indicatively for 1m, 2m and 3m for a site around Orkney. Device downtime can be reduced by increasing the range of sea states in which maintenance can be undertaken and by faster sea operations*



4.1.2 Priorities for the second generation of tidal concepts – accessing the full resource

As seen in the Tidal Resource section (Chapter 2), a fundamental technological shift will be required to access the full tidal potential of the UK. Around two-thirds of the practical resource will require something beyond existing technology to extract energy at reasonable cost. This section looks at making the transition from the best of the first generation concepts towards new designs which are able to access the full UK resource. The two key areas are depth and difficulty.

Tackling deeper sites

Most existing tidal stream devices are suited to sites between 25m and 35m depth. This is either because they use structures that are surface piercing – where the cost of engineering a structure for deep water (greater than 35m) is prohibitive; or they are bottom mounted and position the turbine at a hub height of 20-25m from the sea floor. In deeper water these bottom-mounted designs are not able to exploit the energy in the whole water column.

The distribution of the tidal resource identified in Section 2.1 is shown in *Figure 28*. It is clear that to make the most of the UK resource, devices able to capture all the energy in water columns well over 25m will be needed, and to fully exploit the resource, depths over 50m will also need to be tackled.

Figure 27 shows that, while there is significant resource for first generation shallow devices, second generation devices will be needed to exploit the full resource. It should be noted that the deep part of the Pentland Firth, which has the highest velocity – and therefore potentially lowest cost of energy – has an average depth of more than 60m.

A number of potential second generation devices use more than one turbine installed on a single foundation, to increase energy capture in the water column, but also to reduce installation costs per foundation. The MCT second generation device in *Figure 33* is an example from MEA 'next generation concepts' strand. Other concepts might include devices with floating or neutral buoyancy structures, or vertical axis turbines. The increasing power of availability towards the surface of a deep water column is shown in *Figure 27*, along with some possible second generation concepts.

Figure 27 *The high energy flows in a deep water column are nearer the surface, away from the bottom. A second generation of tidal turbines will be needed to access the optimum section of a deep water column – these might involve floating or neutrally buoyant devices*

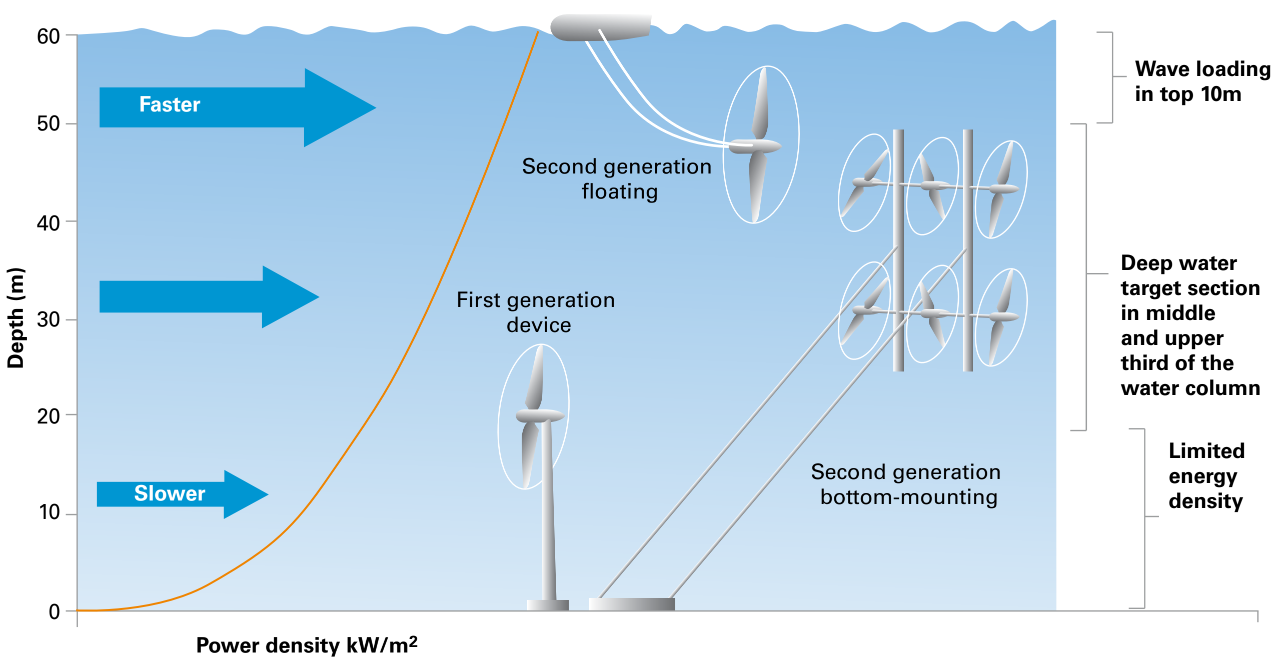


Figure 28 *Distribution of average depths at UK tidal sites. The majority of the resource is in water depths 25m and over, though around 20% is still available at shallower depths. Only a small proportion of the resource is in depths over 75m*

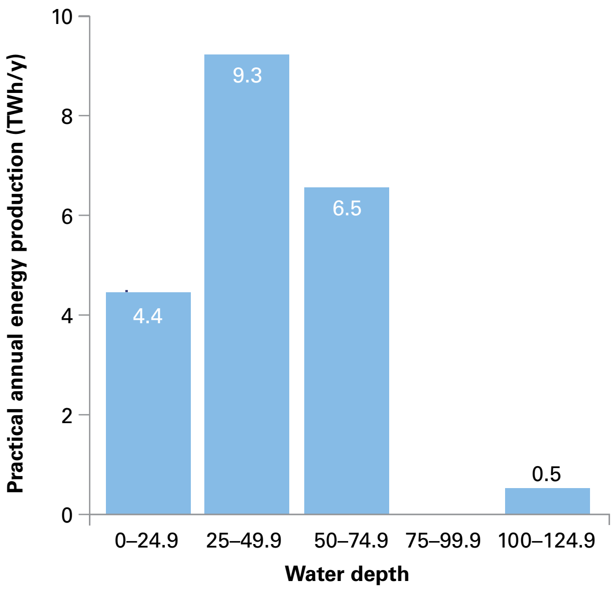
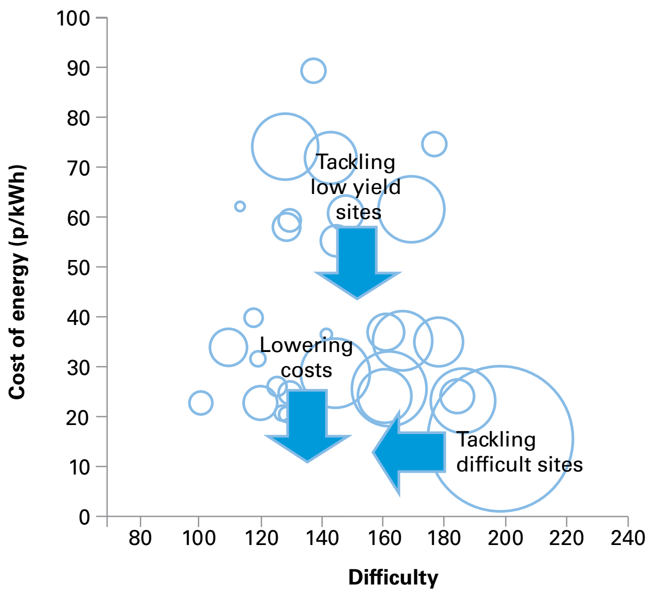


Figure 29 *UK tidal sites; bubble size relates to size of resource. Tidal stream devices need to lower costs and find ways to access the more difficult sites*



A powerful conclusion from the MEA tidal resource assessment is that device developers should concentrate on developing devices that are able to access all of the energy in a deep water column of 50 or more metres.

Tackling site difficulty

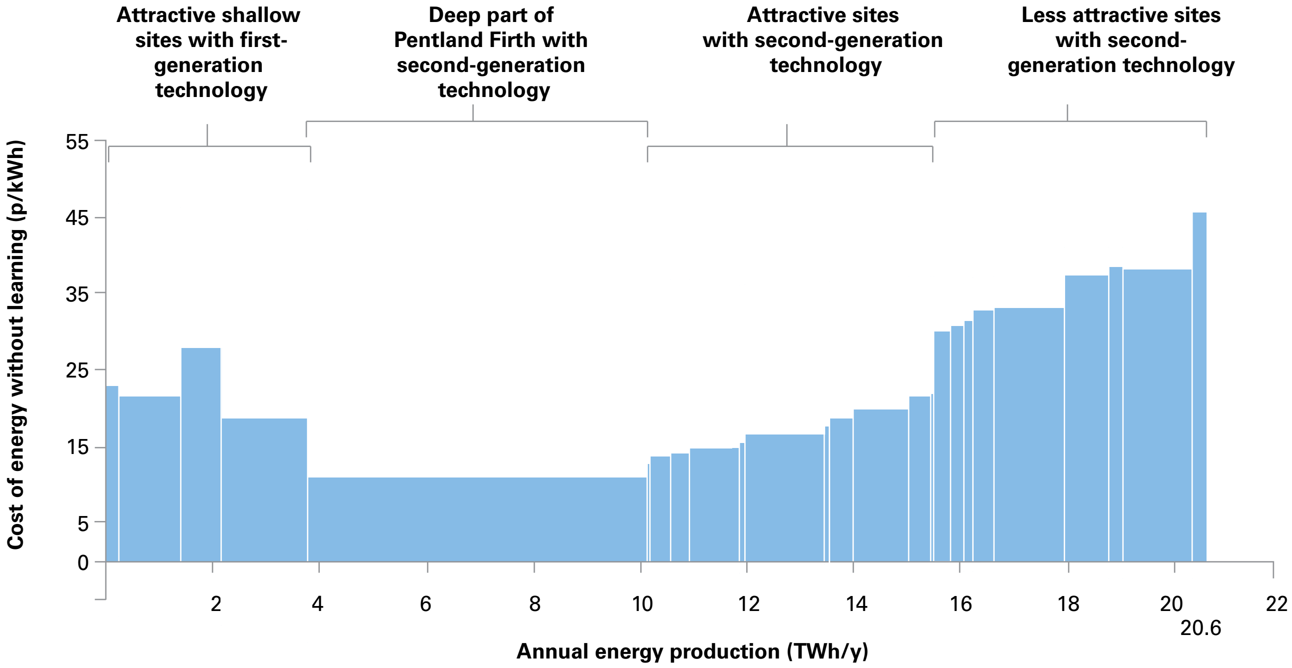
Figure 29 shows the 30 sites considered in the resource study presented according to the cost of energy (in this analysis cost of energy was strongly correlated to the resource in kWh per m^2 of cross-section at the site) and site difficulty. It shows the need for technology innovation to tackle site difficulty, to achieve reasonable costs of energy from low-yield sites, and to lower costs in general. It is clear that there are few 'easy' sites, so as well as working towards exploiting currents in deep waters, and reducing costs, second generations of tidal devices will also have to deal with complex difficulty issues. The difficulty rating is a reflection of the risk of developing a specific site, meaning that many sites with relatively good cost of energy (high tidal current speeds) will require further technology innovation to reduce risk to an acceptable level.

New technologies or techniques will be required that enable tidal arrays to be deployed in these difficult sites. Bringing forward these technologies and techniques will mean that sites with higher energy (and therefore lower cost of energy, other things being equal) can be exploited earlier. Dealing with site difficulty is also closely related to reducing the risk of projects at these sites – reducing risk will have a direct impact on energy costs.

The Pentland Firth is a case in point. *Figures 10* and *12* in Section 2.3.1 (shown again here) show the 30 tidal sites with two potential deployment orders: the first is based purely on projected site costs (difficulty is not taken into account); the second is ordered according to cost and difficulty. The Pentland Firth has potential for the lowest cost of energy of any site, but is also the most difficult; it therefore gets pushed down the deployment order when difficulty is taken into account

It is not clear exactly how difficulty and resource will interact to determine the actual deployment order for the UK tidal resource. It is clear though that if we are able to develop the required technologies early to exploit the Pentland Firth the cost of later sites would be lower due to the significant learning over 6 TWh/year worth of experience. Vitally, that learning which will bring the cost of energy down will then be done at high-energy sites, keeping the overall cost of energy within realistic bounds.

***Figures 10 and 12** Possible deployment orders of the 30 sites, showing sites ordered by cost of energy alone (left) and by cost of energy and difficulty (right). Pentland Firth and other sites with good cost of energy are hindered by difficulty*



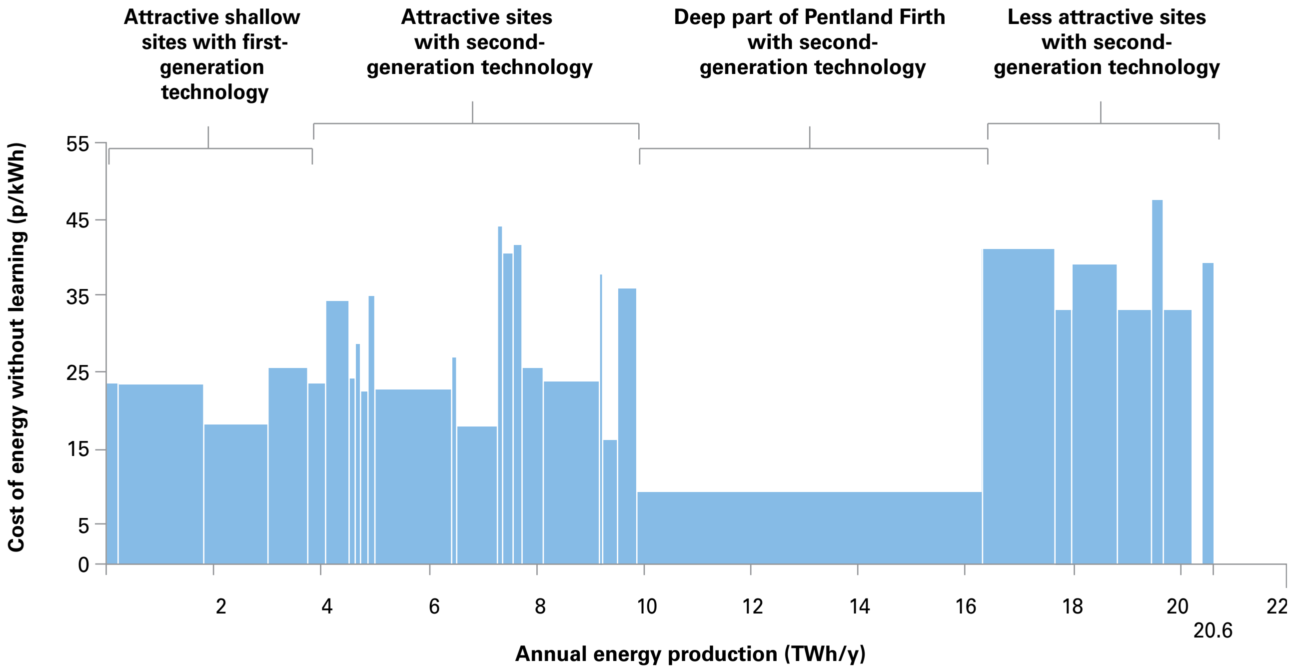
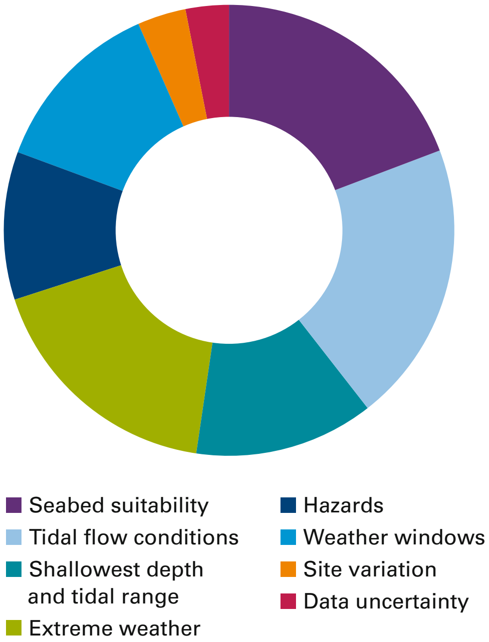


***Figure 29** Energy weighted split of difficulty scores for the practical tidal stream resource (these difficulty factors were introduced in Section 2.3.2)*

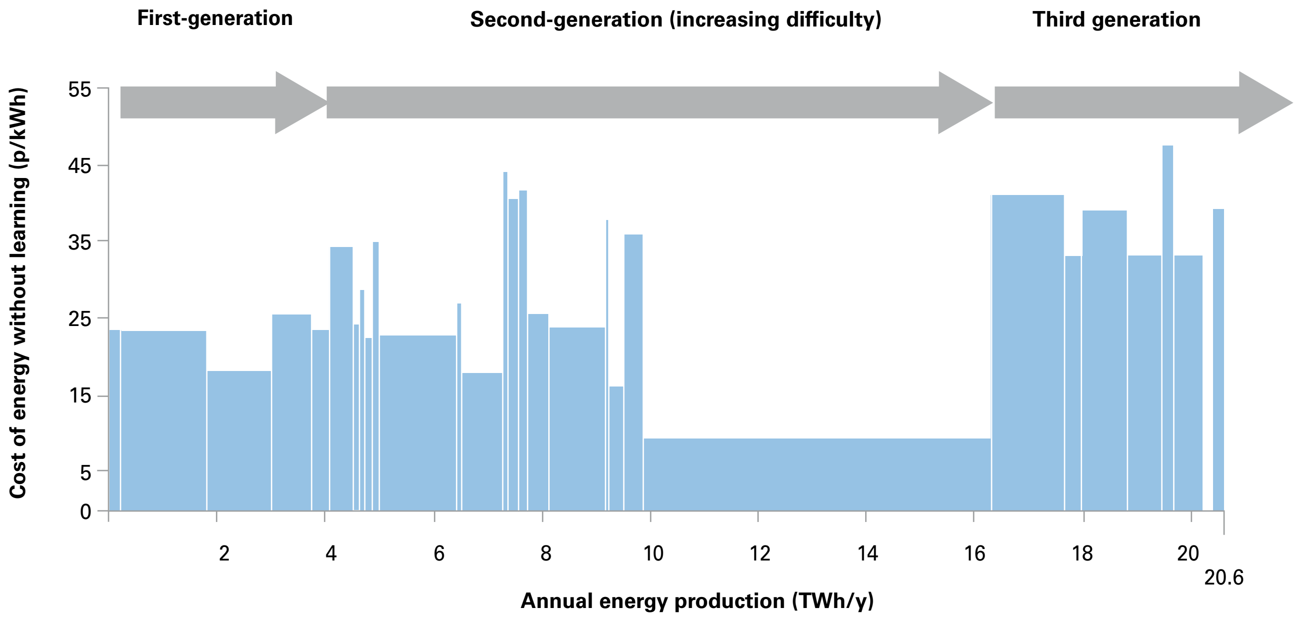


Seabed suitability	New installation procedures may need to be developed for seabeds with steep slopes or boulders.
Tidal flow conditions	High velocities can create problems for operations, and may require new advanced dynamic positioning systems. Turbulence and non-linear flows reduce energy capture and may lead to reliability problems.
Shallowest depth and tidal range	Shallow sites limit rotor size, but also make operations difficult. High range can create difficulties for operations, particularly in relatively shallow water.
Extreme weather	Survivability in extreme weather (particularly extreme waves) will need to be a focus for all device developers going to exposed areas.
Hazards	Operating techniques will need to be developed for site-specific marine hazards such as proximity to land / shallow water.
Weather windows	Weather and wave windows are shorter at difficult sites, meaning O&M and installation procedures will need to be streamlined. Devices need to be ultra-reliable at sites with short weather windows.
Site variation	Tide differences across sites mean that devices may need to be uniquely engineered.
Data uncertainty	Data uncertainty increases project risk.

The site difficulties for the total resource are summarised in Figure 29. The specific difficulty issues will be unique to each site, and one conclusion of the work was that surveying and site assessment will be required for all new sites, but some issues stand out as requiring early consideration. Seabed conditions and extreme weather/short weather windows represent the most problematic site issues for tidal developers. These will require flexible installation/foundation techniques, and rapid operations. Technologies to extend the operational range during deployment will also be needed, such as vessels that can operate in higher tidal velocities.

A range of new techniques will be required to cope with these difficulties. In practise individual sites will present unique difficulty problems, and there will be variation within sites, but with the appropriate innovation support a suite of solutions will be developed. Knowledge about the difficulty of the resource as a whole (shown in the pie chart), and of the Pentland Firth in particular, provides direction on where to focus engineering resource to reduce project risk at all sites.

Figure 31 *UK tidal sites ordered by cost of energy and difficulty (as in Figure 12). These 30 sites include all commercial-scale sites with energy density over 1.5kW/m2 and depth of more than 15m. Fundamentally different technologies may be able to capture energy from sites beyond 20.6TWh (off the right-hand side)*



4.1.3 Demonstrated step changes in second- and third-generation tidal devices

A separate strand of the MEA looked into the potential for entirely new device concepts with potential for a significantly lower cost of energy than that of today's front-running technologies. The work investigated the possibility of devices that could offer a step change in either or both of the following:

- Cost – this might include devices with significantly less structural mass per unit of energy captured; or devices that use a material that is significantly cheaper than the steel used in most existing designs.
- Performance – the MEA aimed to identify and prove the feasibility of devices that could offer 'step change' improvements in capture efficiency (rather than incremental improvements on existing designs) or could access new resource that existing designs are unable to access.

Figure 31 shows the 30 tidal sites that make up the practical resource as discussed in Section 2.3.1 – a total of a little over 20TWh/yr. These sites include all UK waters with enough energy density to generate electricity using currently conceived device concepts. The sites can be split into three distinct groups that more or less correspond to the three generations of tidal energy converter discussed in this section and presented in *Figure 25*.

The following pages present examples of second and third generation devices developed through Strand A of the MEA.

Second-generation tidal

As has already been suggested, second generation tidal devices capture energy from a wider range of sites, and at lower cost:

- They capture energy from the whole cross-section of a deep water tidal site, while also coping with difficult

Figure 32 Marine Current Turbine's first generation 'SeaGen' device installed at Strangford Lough, with turbines raised for access

conditions. This may be done by including multiple horizontal axis turbines on one support structure, but other designs such as vertical axis, floating or neutrally buoyant turbines could also increase the proportion of a deep site that can be exploited. This enables second-generation tidal devices to access the majority of UK high-energy sites, including, vitally, the deep part of the Pentland Firth.

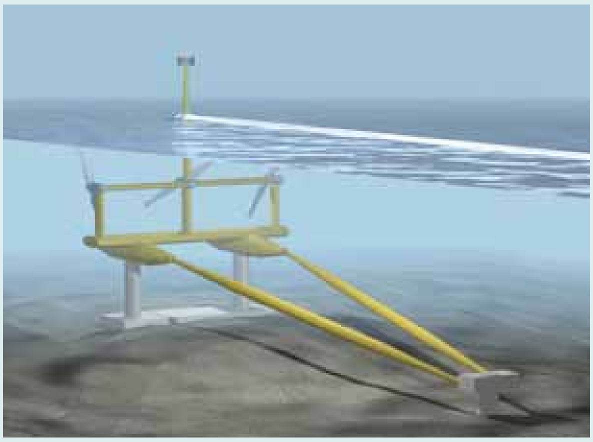
- They do this while also providing a step-change cost of energy reduction. This means that – all other things being equal – a second-generation device in a first-generation site would have a lower levelised cost of energy. (In practice, however, other characteristics of deepwater sites may keep the actual price of energy from second-generation devices relatively high.)

Marine Current Turbines (MCT) is one of the leading tidal stream developers. Its first-generation tidal device is currently being tested in Strangford Lough.

MCT's initial design (*Figure 32*) incorporates two rotors on a vertical support structure that can be raised out of the water. This allows for easy access to the turbines, which is especially useful for early stage testing and maintenance. But the design is only relevant at shallow and relatively low wave sites. A second generation of MCT turbines is expected to include multiple rotors on a single foundation and support structure – see *Figure 33*.

MEA project case study

Figure 33: *Second-generation tidal example: Marine Current Turbine's future device concept contains multiple rotors on a single support structure and single foundation.*



Marine Current Turbines second generation

MCT's second-generation SeaGen-U device is envisaged as a multi-rotor device on a common support structure. This new device enables many rotors to be deployed in a single operation and addresses regions with water depths greater than 40m or extreme tidal range. One variant of this design is fully submerged with no surface-piercing element and addresses regions with water depths greater than 40m or extreme tidal range. The whole structure can be raised or lowered for maintenance.

The early development of the second generation device received funding from the MEA. The study estimated the cost of energy from three different foundation systems and deck structures, and included:

- A high-level review by each of the principal engineering disciplines to determine whether or not the concept is technically feasible.
- An independent review of the likely costs associated with the technology.
- A review of the increased market penetration SeaGen-U could expect as a result of the better suitability to attractive deep sites.
- Identification of the key issues, risks and opportunities.

Impacts on the cost of energy and future research

The second generation structural costs were found to be 58% lower than for an equivalent size farm using SeaGen on a quadrapod and 26% lower than those using SeaGen on a monopile.

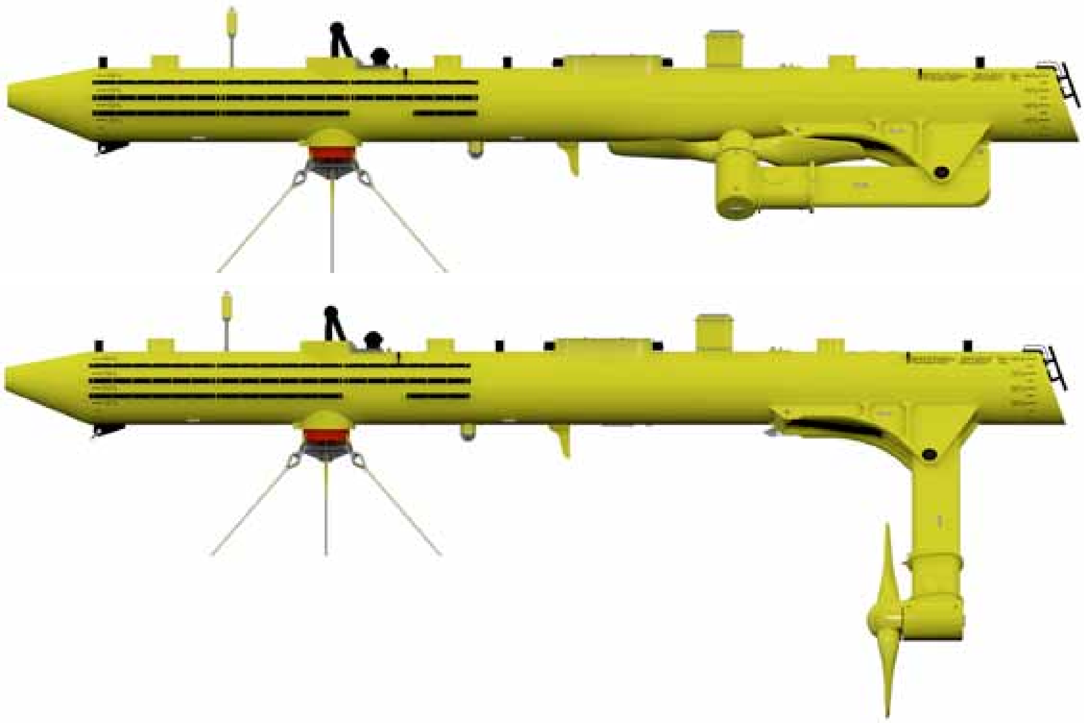
Overall, the total capital cost for the second generation technology is estimated to be around 20% lower than the deployment of a SeaGen system per megawatt installed.

Indicative results from the stability assessment confirmed that the second generation platform would remain stable in both damaged and intact conditions.

O&M strategy is one of the most critical aspects to the success of the device and remains one of the less well developed areas. Further research into appropriate O&M strategies for particular sites will be necessary during detailed project development.

Otherwise, ongoing cost reduction is likely to focus on increased capacity power train and rotors plus alternative structural materials of marine turbine technology. Much of this can be learnt from the first generation SeaGen device.

Figure 34 *ScotRenewables' floating tidal device – shown in transportation/survival mode and generating mode – would be able to access high-energy resource near the surface of deep tidal streams, and should benefit from lower installation costs than fixed tidal turbines*



Other devices under development use floating or neutrally buoyant turbines to access the deep water resource with cheaper anchoring systems. ScotRenewables, based in Orkney, were supported by the Carbon Trust's Applied Research scheme at the tank testing stage, and also for the engineering design and cost of energy analysis of the full scale design. ScotRenewables is installing a 250kW grid-connected prototype at EMEC in March 2011, with funding from the Scottish Government's WATES programme.

The main prize for second generation tidal devices is over 6TWh of annual energy potential in the deep sections of the Pentland Firth (about 2GW of capacity). The tidal velocities in the Pentland Firth are high, and over large surface areas, so there is good potential for large farms of devices producing low-cost electricity, if depth and difficulty issues are overcome.

Third-generation tidal

Our tidal resource work shows that around 4TWh/yr of resource is probably uneconomic using envisaged first or second generation devices. But a third generation of tidal devices – probably including dynamic features or some other innovation to extract energy more effectively from low-energy sites – could be economically able to exploit this resource. These dynamic devices could also generate electricity from sites with velocities too low to have been included in the main resource study.

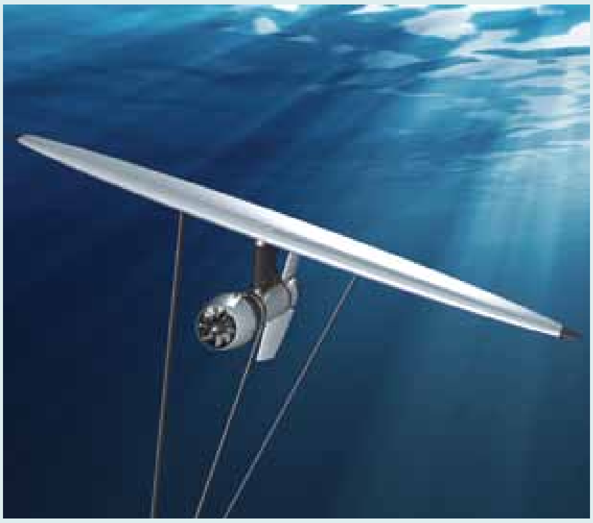
These sites have relatively low energy density, and therefore significantly higher cost of energy if exploited with currently conceived first or second generation concepts. Devices are under development, however, that have the potential to capture energy much more efficiently than simple rotors on static structures. One of these, the 'Deep Green' technology detailed in *Figure 34*, uses a dynamic tethered structure which moves in the tidal stream. This increases the water velocity across the device, meaning that a much smaller turbine and PTO can be used to extract the same amount of energy.

MEA project case study

***Figure 35** Minesto's 'Tidal Kite' Technology moves through a tidal stream to significantly increase the speed of water through the rotor. The MEA undertook concept feasibility and development studies for this device concept*

Minesto's Deep Green dynamic tidal concept

Deep Green is a tidal stream device designed to increase velocity through its rotor by moving across a tidal flow. The device has a wing that is tethered to the sea bed which is flown, much like a kite, in loops through the water. A turbine underneath the wing then extracts the power from the relative motion of the wing and the water.



This system allows a relatively small wing to sweep a very large area, and to travel at much faster speeds than the passing water. This means that a much smaller rotor can be used for the same capacity. A 1m diameter is planned for a 500 kW device, in a flow where a fixed turbine would require 30m or more of diameter. As long as there is space the device can therefore generate power from relatively low velocity tidal streams. Minesto could therefore make use of tidal stream areas that other devices developers avoid because the energy available is too diffuse.

This system brings many new challenges. A study was conducted to deliver:

- a high-level assessment of the concept's technical feasibility
- an independent assessment of the likely achievable cost of energy
- an understanding of key issues, risks and opportunities
- recommendations for further work ,many of which have been taken forward by Minesto and by the Carbon Trust's Applied Research scheme.

Impacts on the cost of energy, and other learning

The study clarified numerous cost components, leading to a significant cost of energy increase compared to the developer's early estimates. Nevertheless, the device does have the potential to achieve a step change cost of energy reduction compared to fixed turbines if a number of the assumptions made prove justified. It also has potential to open up the exploitation of several TWh/yr of potential energy production from low energy sites.

Significant further innovation and testing will be required, due to the technical complexity of the project compared to a fixed turbine.

Future research directions

- The performance of the device is very sensitive to the drag on the tether and wing as it moves through the water. This is an important technical issue that needs further investigation.
- There remain challenges in managing fatigue and reliable control of such a permanently moving device.
- There are many technical issues to overcome, but the device is sufficiently different from competing designs to potentially offer either a significantly lower cost of energy, or the ability to exploit entirely new resource.

Figure 36: *Pulse Tidal's oscillating device sweeps a rectangular, rather than circular, area using oscillating foils. This means that a bigger cross-sectional area can be presented to the tide, so the device may be able to exploit shallower sites than axial flow turbines.*

Source: Pulse Tidal

Initial studies undertaken by the MEA into the Deep Green tethered glider concept suggested it offered genuine potential for step change cost of energy reductions from lower-energy sites, although numerous aspects of the design needed further investigation including control system, drag and wing size optimisation. Follow-up work in the MEA investigated specific design aspects – particularly regarding drag on the mooring line, and the control system – as well as clarifying potential for low cost of energy in the future.

Third-generation devices have the potential to open up new areas of low-velocity tidal seas that were not included in the tidal resource study because of diffuse resource. This could extend the technical UK resource by several TWh per year. Finally, devices are also under development that could access those relatively high-energy sites that are currently ruled out by depths shallower than 15m.

4.2 Wave research priorities

We have already seen that the baseline costs of wave energy today are higher than those for tidal energy, and significantly higher than other renewables. There is therefore a significant cost reduction challenge.

Aside from a more energetic environment itself, there are no specific difficulties created by the high-energy sites – the challenge of dealing with bigger waves is accompanied directly by scope for lower cost electricity generation. This implies that, once performance and costs are proven, the eventual build out of wave technologies will be quite straightforward. There is no specific requirement for second-generation technologies to overcome barriers; instead, second-generation wave devices will compete directly on cost of energy and are likely only to be adopted if they show significant cost reductions over first-generation devices.

Energy production is currently the most significant uncertainty in the economics of wave energy and the short-term focus of the industry must be to build an evidence base to prove that devices generate as expected. Building on this, the Carbon Trust believes that the ability to capture more energy for a given capital and operations expenditure is key to demonstrating potential for commercial wave energy at an early stage.

The scale-up challenge goes hand-in-hand with generating more energy per unit of CAPEX. This may be through smarter array configuration and shared sub-systems (lowering CAPEX per MW installed), or through sizing up and tuning devices to increase energy capture. Simply increasing the volume of production of wave devices can also account for significant savings. It is estimated that this 'learning by doing' can account for as much as 50% of the anticipated cost reductions in the very early stages, when there is a big cost difference between manufacturing units individually or in tens or hundreds.

The core focus for cost reduction innovation has been suggested in Section 3.2. The structure, PTO system and operations and maintenance have been identified as the cost centres with the greatest potential for cost reduction. Enabling technologies such as retrieval systems (for floating) or simple intervention techniques (for seabed-fixed devices) are also identified. In the short-term there is scope for increased energy capture, with little extra cost, via improved controls or tuning designs for specific resource characteristics. Further down the line step-change innovations such as novel PTO systems are highlighted as future disruptive technologies which will have a significant effect on the cost of energy from wave arrays.

We are yet to see significant design convergence in the wave energy industry, and while the number of wave concepts being progressed has declined in recent years, this has been due to a lack of funding rather than clear conclusions around future prospects for particular technologies. The UK has managed to capture much of the best technology in its current marine innovation programmes, such as the MRPF, WATES and WATERs and TSB's initiatives, but there is scope for further research on device type, and in particular researching new concepts which demonstrate better coupling with the sea and are therefore able to extract more energy per unit of material. One example of a device which shows early promise from an entirely new design concept is given in Section 4.2.3.

4.2.1 Proving energy capture

The costs of wave energy remain uncertain, both compared to tidal stream energy and in absolute terms. This is because the performance of devices is in many cases not fully proven and in all cases not well understood, and because there is little empirical evidence from devices deployed at full scale.

The baseline wave cost of energy presented in chapter 2 reflects this. It is both high and has large error bars. At sea testing of wave devices is particularly important to prove device concepts, and to give much greater certainty to cost of energy forecasts. Confidence relating to device performance will also strengthen the industry in the eyes of key players such as financial investors and project developers.

The testing of full-scale devices being undertaken in the MRPF involves monitoring the devices in known sea conditions to validate the mathematical models used to predict their performance. With these validated models the yield from future farms can be assessed much more accurately, and the next iterations of devices can be optimised more effectively.

4.2.2 Improving energy capture

Maximising the energy extraction from a given size of device is a key area of focus for wave developers, many of whom see great potential for increasing capacity factor by operating much closer to their 'boiler plate' generating capacity. We call this 'technology headroom', and it is likely to be realised as a result of learning from at-sea operations. For example, with little or no additional cost Pelamis Wave Power (see *Figure 21* in Section 3.2.1) should be able to increase energy extraction from their devices by developing a better control system, but they need at-sea experience of how their device behaves before they can do this.

Analysis from the MEA suggests that energy capture is expected to improve significantly between first farms and first commercial farms, equating to a cost reduction experience rate of 96%. We believe more significant energy capture improvements are possible, but even small changes can lead to a very significant reduction in cost of energy while adding little or no extra capital cost.

Energy capture improvements can come from both component level and system level engineering – wave device developers are to a large extent doing new things, which means there is great scope for improving the design of individual components and the way different system components interact. Improvements can also come from experience gained through at-sea testing of devices. Some wave energy devices have the potential to improve their energy capture with little or no changes to their structural form, for example by changing control systems or by better optimisation of farm layouts.

The total size of the accessible UK wave resource is currently less well understood than the tidal resource, but it is clear that it is more evenly distributed across large areas of sea. Basic sea conditions are likely to be broadly similar at each site – or at least across a large number of sites – so the potential for large arrays of mass-produced devices is high.

Clearly scale-up is only commercially feasible once the design has been fully proven, so there will be an extended proving period during which wave electricity is relatively expensive. The scope for cost of energy reductions, though, remains considerable from wave energy converters as both scale of farms (and devices) and volume of production increases. Understanding of device performance in arrays will need to improve, and innovation in array configuration and design (electrical connection, shared operations etc) will also be needed to achieve this.

4.2.3 Demonstrated step changes in wave – continuous cost reduction, and targeting high-resource sites

As mentioned above, wave energy sites are much more similar to each other than are tidal sites. There is therefore no absolute technical requirement for second-generation wave devices. It is expected that first-generation devices can evolve to be more efficient and more robust, and better able to cope with the highest resource sites where the best economics can be secured. There is of course room for new entrants to the market where new devices have the potential to fundamentally change the baseline economics of energy generation.

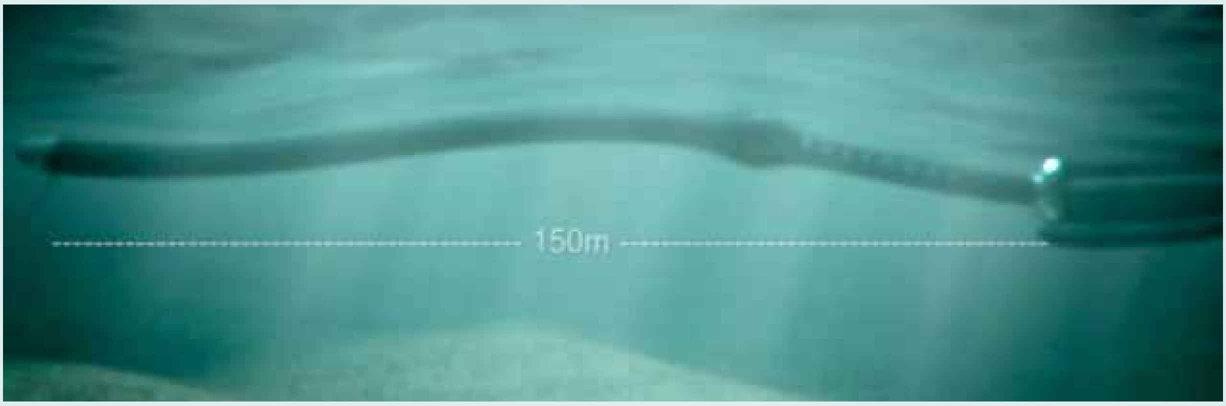
Our understanding of the cost make-up of wave devices allows us to identify the areas where the next generation of wave concepts are likely to demonstrate benefits. As seen in Chapter 3, reductions might be a result of significantly cheaper materials or lower build cost, simpler O&M procedures, or new modes of operation which result in significantly greater energy capture.

Figure 36 shows just one example from the MEA new devices strand, in which a device with an inherently new design and different material (rubber, as opposed to steel or concrete in nearly all other wave devices) was shown to have the potential for step change cost of energy reduction.

As mentioned before, there is not yet a clearly established lead technology concept for energy capture from waves, unlike in tidal, where axial flow turbines are dominant. There is always, therefore, good potential for unproven designs to emerge that may look very different to existing devices and that could revolutionise energy capture.

MEA project case study

***Figure 36** Anaconda rubber attenuator. Distensible Tube Wave Energy Converter. The Anaconda device is made primarily from rubber rather than steel. In the long-term there is great potential for significant cost reductions, as rubber is both comparatively cheap and comparatively easy to fabricate. But these cost advantages are not guaranteed and would only be achieved after a move to volume manufacturing. The MEA engagement with Anaconda developers Checkmate Sea Energy therefore concentrated on cost clarification and a manufacturability and durability assessment*



The Anaconda is a 'Distensible Tube Wave Energy Converter'. It comprises a rubber tube of around 5m diameter and up to 200m in length, filled with water and anchored just below the sea surface perpendicular to the waves. As waves pass along the outside of the tube a bulge wave forms inside the tube. This bulge increases in size as the wave passes along the length of the device. Once the bulge reaches the end of the tube it flows through a turbine via an accumulator to extract its power.

The research project reviewed the developer's performance and cost of energy calculations and provided expert comment on the likelihood of step change cost of energy reduction. This included:

- Studies on the manufacturing options and associated costs for production of very large rubber structures (potentially many times larger than any rubber structures currently manufactured).
- Fatigue and lifetime assessment for rubber materials in the marine environment.
- Investigation into materials that could be used instead of or in combination with natural rubber.
- Uncertainty analysis, and R&D roadmap development.

Impacts on the cost of energy and future research

- Estimated costs show uncertainties. One main uncertainty is in the fatigue life of rubber, which has a huge impact on cost of energy.
- Potentially low maintenance costs due to simplified design.
- Potential for optimistic cost of energy to be better than or as good as front-runner devices.
- Rubber manufacture at this scale may require quay-side factory for rubber components.
- Proof is needed on the fatigue performance of rubber, or an alternative material with similar properties. Further studies funded by Checkmate Sea Energy are suggesting that fatigue life is as good or better than initial projections.
- The device is sufficiently different from all others to offer a potential step change in performance and cost of energy.
- The potential for the power take-off to be separated from the rest the tube is being investigated. This will help minimise the need to bring the rubber structure back to shore for maintenance.

5. The next steps

A successful marine energy industry will require involvement from a range of different organisations, both in the UK and elsewhere. These include device developers, project developers, Original Equipment Manufacturers, investors and governments. This chapter discusses the steps these organisations can take to continue accelerating the industry.

The leading companies developing wave and tidal stream energy converters are currently at the stage of 'full-scale grid-connected prototypes'. The objective at this stage of technology development is to demonstrate that the device can be built and installed, and successfully generate electricity. The next steps for the industry are to move on to building small arrays (around 5-10MW) to demonstrate that multiple devices can installed and operated in the same location, and that arrays of devices are able to generate electricity at a significantly lower cost of energy than the individual prototypes.

Following this the first farms will be developed with expectation of a commercial return, although they will at first require either capital funding or significant revenue support. As the scale of projects grows, technology developers will need to work increasingly closely with a number of new industry players, including original equipment manufacturers and marine contractors who will be heavily involved in installation and O&M. At the same time, other technology developers are working on smaller-scale prototypes and proving the concepts of entirely new devices.

Original Equipment Manufacturers are becoming increasingly involved in marine energy, through investments or via direct technology development. The involvement of players such as ABB, Alstrom, Andritz Hydro, Rolls-Royce, Siemens and Voith is one of the key developments in marine energy in the last few years. These multinational companies are big enough to give project developers (utilities) confidence and ultimately warranties for devices in early arrays.

This section details how industry players – device developers, project developers, component manufacturers, investors and government bodies – need to engage with technologies and with each other over the coming years. It considers what needs to happen in the short-term to get small arrays and commercial farms built; as well as what technology developers and others have to do to make sure that the industry stays on track for accelerated cost reductions in the medium and long-term, and progresses towards exploiting the full UK marine resource.

5.1 Device developers

Immediate focus

Proving costs and performance in real sea conditions – Several device developers are deploying full-scale devices, so the costs and performance are beginning to be quantified with greater certainty. Developers must demonstrate not only that devices will work in real sea conditions, but also that the costs and performance meet their and their investors' expectations – making feasible the progression to commercial returns from arrays of these devices. Proof of device performance and costs at the 5-10MW farm stage will increase confidence in the industry and increase the likelihood of future investments from funders such as project developers, industrial and private investors and the government, as well as bringing forward the date when projects can be part funded by external finance rather than simply from developers' balance sheets.

Technology shakedown and monitoring programmes – Real-sea experience will also help redefine the technology risks, enabling developers to identify unreliable components and systems and propose better alternatives. In addition to proving that the technologies work as intended, monitoring programmes can be devised to gather data that will help identify the true loads and stresses on the systems, such as wave loading on both wave and tidal devices. This information can help refine designs and lower costs by reducing the over engineering which is required to cope with risk and uncertainty, as well as suggesting opportunities for improving energy capture from future devices. Real-sea experience also informs improvements to operations that can often be made relatively easily. One example of learning from full-scale installations currently being funded through the MRPF is that there are numerous problems with using jack-up barges for installation of tidal devices. Future devices, particularly when installed in arrays, are likely to use boats with dynamic positioning capability.

Working with the supply chain – There is potential to improve the reliability and cost of components and sub systems in marine energy devices. This might involve refinement or replacement of complete systems as new innovations come online. Once farms, and therefore component orders, are large enough, many more companies will be able to provide competitive component supplies, expanding the supply chain, and giving more options to developers negotiating design refinements for the development of marine specific components. Technology developers should also seek to widen their supply base to ensure that they are using the most suitable components and capturing and creating enthusiasm in supply chain companies for this emerging market opportunity.

Environmental monitoring programmes – Continuing to monitor the level and nature of any environmental impacts is an important aspect to quantifying the risks of industry development – to the environment, and to project economics. As technology developers have the most experience of operating their devices in the sea, they are best placed to gather evidence on their effect. Early indications suggest a limited impact on marine mammals from devices tested thus far, but developers should continue to monitor the environmental impact of their devices and consider pooling data on expected and measured impacts, perhaps through industry or government bodies.

Maximise opportunity from full-scale prototype devices – Full-scale pre-commercial devices are being installed in a number of locations across the UK, particularly at EMEC. Technology companies will soon move their focus to installing first arrays of devices in more commercial conditions, but the industry should maximise the opportunity presented by the first full-scale devices, which are installed in locations with monitoring and testing infrastructure on site. These can be used as a test bed for longer term R&D and future component innovation.

Medium to long-term focus

Create technology improvement plans – Whatever the business plans of the developers, all would benefit from compiling a list of the new technologies or improvements they wish to implement on their device. Cost-engineering and validation of the cost centres used in this report (and the Carbon Trust Cost of Energy spreadsheets, available online) is a good starting point for technology improvement. Expressing improvements in terms of levelised cost of energy, rather than cost per MW of capacity, enables developers to prioritise interventions according to the metric that counts to their final customers. It is also important that developers are not tempted to reduce CAPEX in the short-term at the expense of increased lifetime cost of energy from their devices.

Many companies will choose to implement only a subset of these changes at a time to minimise the development costs and risk. Nevertheless, understanding the scope for technology innovation alongside commercial development of first farm devices will help explain to investors how costs can be brought down in the future to be competitive under expected support mechanisms. A clear development plan will also help other innovation investors to position innovation support programmes to maximise benefit to the industry.

Scaling-up production facilities – In time, production facilities for devices will need to be scaled up, as will equipment for installations and maintenance. Scale-up will bring manufacturing efficiencies but also additional overhead burdens for technology companies.

Plan for second generation technologies – This report demonstrates that there is a requirement for second-generation tidal technologies. Many technology development companies will currently be concentrating on proving that their first-generation concepts work, but outline plans should be developed now to explain how second-generation technologies can be developed and by when, particularly for tidal current developers.

5.2 Project developers

The ultimate customers for marine energy technologies are utilities or independent project developers. They will in due course be investing in projects in expectation of a commercial return, but it is likely that early farms will not provide this, given the technical risk involved and cost uncertainty with the current levels of subsidy. The key goal of the first farms, therefore, is to reduce the technical risk for developers in the future, and to bring the costs down to a point where revenue support is sufficient to make future farms commercially viable.

There are a number of advantages for early-moving developers who are now becoming actively engaged in the industry, in terms of relationship building and understanding of technical issues. Several utilities have also taken significant stakes in certain technologies, in addition to developing projects. These investments, which have enabled them to get close to the technology and learn from it, are currently fairly modest but are vital for unlocking capital for later stages. Industrial and utility investors are experienced in evaluating new technologies and markets and bring other benefits such as business acumen, engineering capability and project skills to the table. Investments or interest by such organisations are highly valuable in bringing confidence to the market and encouraging subsequent wider investment.

Bring experience from offshore wind farm development – Many utilities and project developers have relevant experience from offshore wind. Offshore wind farms have faced numerous challenges and many will provide lessons for the marine energy industry, particularly in O&M, installation and aspects of the supply chain.

Work together on generic problems – This report has shown that there is a very significant marine energy resource in the UK (and more again worldwide). There are many areas where developers would benefit in the short and long-term from working together, particularly in understanding environmental impacts, arranging grid connection, and making the case to government and the public for marine energy.

The Carbon Trust also believes that developers should engage in non-competitive R&D effort to move forward the industry as a whole. Many technical challenges related to array development are not device-specific, such as deployment (in increasingly deep and/or shallow waters), foundations, various aspects of electrical connection, and many operations.

5.3 Service and component supply chain

Immediate focus

Engage with device developers – As the marine industry gears up towards commercial-scale projects, it becomes increasingly worthwhile for potential component manufacturers to investigate the market and develop relationships with the leading technology companies. Technology developers, including utility and industrial backers, can play a vital role in giving confidence to the component supply chain that planned projects will happen in the next five years. A proactive approach from potential suppliers will help shorten the development time of commercial projects and ensure that their innovations are included in the technology development plans. The same applies to installation and maintenance contractors with specialised offshore equipment.

Promote the advantages of good components to device and project developers – Through sound onshore testing programmes new, lower cost components can be developed and derisked prior to at sea testing. Lower cost options are obviously better, but so too are any systems that increase the efficiency of the device or enable it to spend more time generating electricity. Chapter 3 of this report provides examples of how this can be done and demonstrates how even minor changes can have significant effects.

Plan for scaling up manufacturing sites – We estimate that the worldwide tradeable market for marine energy devices accessible to UK based business is up to £340 billion, peaking at £29 billion per year, and that UK industry could capture 22% of this, or around £76 billion to 2050[31]. Scaling up manufacturing capacity (from a base of virtually nothing) will obviously be necessary to create this market. Proactive investment from the supply chain now will position companies to deliver the most effective components and technologies for devices in the future, and set up the potential for introducing innovations earlier and more efficiently. For these investments to take place the supply chain requires confidence in the market. This confidence will be secured through government policy, utility-scale project development plans an encouraging track record from device developers.

Many other industries have tackled problems similar to those experienced by the wave and tidal industry, although perhaps none with such a combination of challenges. Industries such as North Sea oil and gas and offshore wind can provide knowledge of offshore operations. Wherever relevant, the latest innovations from these industries should be incorporated into wave and tidal device design.

Innovation focus

Bring forward components and equipment that offer advantages when used at scale – The next steps for device developers will be in scaling-up their technology into farms or arrays. Equipment or methods that help with this scaling process, such as specialist installation and maintenance vessels and electrical connection equipment will soon be in demand. Such systems might not offer a significant advantage when used at the individual device scale, but could have great value when used at array scale. This will provide early opportunities for marine contractors to offer their expertise and to benefit from the wave and tidal stream energy industries.

5.4 Investors

To date, investment in marine energy technology companies has been dominated by equity investments by venture capital and angel investors and, at a later stage, industrials (including future supply chain companies and electricity utilities). According to members of Renewable UK governments (UK and Scottish) have provided around 25% of the total funding for full scale prototypes now being tested, the remainder coming from the private sector in which industrials are increasingly important.

As technology companies move towards 5MW projects, they will be working with developers to find equity investments in projects while also looking for continued investment at the company level.

Utilities and project developers will take the biggest stakes in marine energy farms. Arrays of around 5MW capacity are likely to require investments in the region of £30m-£50m. A number of consortia have already formed, with a view to developing commercial farms sites in the Orkney Waters Strategic Area identified by The Crown Estate. These companies will have to install pre-commercial farms of around 5MW at these sites before technology is available for the 100MW+ farms they are planning.

At the same time there is an ongoing need for equity investments in companies, both those now looking to sell full-scale generators, and those starting out at the beginning of the technology development process. The industry is beginning to see industrials taking stakes in later stage technology companies, replacing venture capitalists who had previously invested in early stage marine energy companies. The investments by industrials are made for learning purposes, and with the expectation of a return in due course. For the technology developers these investors are attractive since they have a longer term view than typical venture capital investors and can bring engineering expertise and credibility to the technology development companies.

Business support – Some emerging technologies are being developed by relatively small businesses containing highly innovative and talented teams. Commercial support can help these companies to concentrate on their technology development and minimise the burdens of running a business. A 'reality check' is also usually necessary for early stage technology developers, to ensure their technology has realistic prospects for reliable generation at reasonable cost of energy. Similarly, in the experience of the Carbon Trust a sense check of development costs and timings for particular projects proposed by technology developers is very useful.

5.5 Government bodies

Set the market and regulatory framework – For marine energy to begin to reach its full potential a stable revenue support framework is needed that enables the cost effective early deployment of the technologies. The very first farms from each developer will almost certainly require capital support as well as revenue support, but a stable framework for revenue support is needed to enable developers to build out the first tens and

[31] Carbon Trust (2011): Marine Green Growth Paper

hundreds of MW of early commercial farms. Setting such a framework will send clear signals to investors that the opportunity in marine energy is real and that final customers – developers – are interested. An appropriate tariff is needed to provide a long-term market signal, and stability for the industry.

Provide legislative support for planning marine energy projects – Before large arrays of marine devices can be deployed in UK waters, a clear position on planning for marine energy is needed. In the UK this means a streamlined consenting process, and Strategic Environmental Assessments, which are completed for some regions, and forward planning on connection to the transmission system. The National Grid do have current plans for enabling grid connection around the Pentland Firth and Orkney Waters sites, but current plans only suffice for less than 200MW of capacity. Development of the UK resource to its full potential – particularly at the Pentland Firth for tidal and off the Outer Isles for wave – will require government organisations to coordinate between developers and the National Grid.

Strategic planning for renewable energy – The Crown Estate – as owner of the sea bed, with rights to UK's Renewable Energy Zone – has a crucial strategic role in the deployment of marine energy in the UK. The Crown Estate has been active in this area through leasing competitions and other engagements with the industry. It should now focus on setting out a roadmap for the wave and tidal industry, to create a long-term pathway.

Coordinate efforts to understand the environmental implications – Consenting authorities should, wherever possible, work with the industry to understand the impacts, refine assessment methodologies and gather data on possible environmental effects of marine energy extraction. One aspect of this is Strategic Environmental Assessment (SEA): under EU law, plans for major infrastructure development, such as the wide-scale deployment of marine energy, will require SEAs. An SEA has been completed for Scotland, which has allowed The Crown Estate to run a seabed leasing round in the Pentland Firth Strategic Area, but assessments will have to be completed for other UK waters before large-scale schemes can be planned there. Where possible environmental data should be gathered and held centrally, so project or technology developers can pool resources and avoid unnecessary repetitions.

Continue to focus on technology innovation – The MEA has shown that cost of energy reductions in both tidal and wave energy are necessary and possible. But to acheive the required rate of cost reduction the industry will need a continuous effort on technology innovation. Industry players are increasingly prepared and able to pay for innovation work, either individually or in consortia, but to leverage this money through bodies like the Carbon Trust or TSB some public funding is likely to be necessary.

6. Closing remarks

This report has necessarily focused on costs as well as technical performance. The costs of energy for wave and tidal are found to be higher now than when the Carbon Trust first reported on the industry in 2006, which should not be misinterpreted as poor progress. In the past five years the industry has been focusing on technology demonstration – getting full-scale prototypes in the water – and on fundraising. The MEA has enabled companies to maintain a simultaneous focus on innovations to bring costs down now and in the future.

While the industry is in its demonstration phase it's important that the cost challenge and cost reduction potential has been studied. The MEA has identified real potential for significant cost reductions over the first few hundred MW of installed capacity. We have estimated that by the time the industry is half way through developing the Pentland Firth and Orkney Waters initial licencing round cost of energy will have decreased by around 30%.

Looking forward, technology developers will benefit from having clear plans to reduce their costs of energy. Many will pragmatically choose to concentrate on a subset of these, given their available resources and appetite for risk. Innovation support can be provided to help bring forward the development of some of these systems, either by providing additional support to the teams, or by working with others in the supply chain to develop innovative systems. Such continued technology acceleration can encourage and support companies to investigate game-changing ideas and technologies and bring forward second-generation technologies where these can make real changes in opening up the market. Globally, countries should play to their strengths and share the costs of progressing the industry. The UK is well placed to deliver on many facets of wave and tidal energy, but we should also look overseas to identify strengths and draw in relevant expertise where it exists. Similarly, other countries should avoid duplication and foster expertise and technology which genuinely add value to this global industry.

While today's front-running technologies must now focus on cost reduction, a pipeline of promising 'next generation' concepts should be maintained, but with a high-quality threshold. The nature of funding to date means there has been little collaboration and some technologies have been developed without gaining from the experience of devices at later stages. Future funding should ensure that best practice is built on, particularly hard-won knowledge in areas such as installation, and that cross-industry sharing of experience is maximised. Existing expertise in high-value areas such as blades and control systems should be retained in front-running developers and their supply chains, and their expertise used in new concepts so that new device developers do not have to 'reinvent the wheel'.

The industry will need public support for some time to come. But government backing needs to sit alongside a new, focused industry. Corporate investment with an appetite for risk and longer timeframes and, in the case of industrial investors, the ability to inject the necessary new skills set into the industry, are also essential. This report identifies the key areas which the industry should now focus on to accelerate reduction in costs. It should also give investors and stakeholders increased confidence that marine energy has significant potential in the UK and further afield.

Glossary

AEL	Aviation Enterprises Ltd
AEP	Annual Energy Production (in GWh or TWh)
BERR	Department for Business, Enterprise and Regulatory Reform
CoE	Cost of Energy (typically in pence per kWh)
DECC	Department for Energy and Climate Change
EA	Environment Agency (England and Northern Ireland)
EMEC	European Marine Energy Centre
ESME	Energy Systems Modelling Environment (of the ETI)
ETI	Energy Technologies Institute
ETSU	Energy Technologies Support Unit
FORCE	Fundy Ocean Research Centre for Energy
GIS	Geographical Information System(s)
MCT	Marine Current Turbines (tidal device developer)
MaRS	Marine Resource System (of The Crown Estate)
MEA	Marine Energy Accelerator (managed by the Carbon Trust)
MRDF	Marine Renewables Deployment Fund
MRPF	Marine Renewables Proving Fund (managed by the Carbon Trust)
O&M	Operation and Maintenance
OPT	Ocean Power Technologies (wave device developer)
PTO	Power Take Off
PWP	Pelamis Wave Power (wave device developer)
ROC	Renewable Obligation Certificate
R&D	Research and Development
SEA	Strategic Environmental Assessment
SEPA	Scottish Environmental Protection Agency
TSB	Technology Strategy Board
TTI	Tension Technology International
WATES	Wave and Tidal Energy Support Scheme (Scottish Government)
WATERS	Wave and Tidal Energy: Research, Development and Demonstration Support (Scottish Government)

The Carbon Trust is a not-for-profit company with the mission to accelerate the move to a low carbon economy. We provide specialist support to business and the public sector to help cut carbon emissions, save energy and commercialise low carbon technologies. By stimulating low carbon action we contribute to key UK goals of lower carbon emissions, the development of low carbon businesses, increased energy security and associated jobs.

We help to cut carbon emissions now by:

- providing specialist advice and finance to help organisations cut carbon
- setting standards for carbon reduction.

We reduce potential future carbon emissions by:

- opening markets for low carbon technologies
- leading industry collaborations to commercialise technologies
- investing in early-stage low carbon companies.

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