CARBON TRUST

Making business sense
of climate change

Future Marine Energy

Results of the Marine Energy Challenge: Cost competitiveness and growth of wave and tidal stream energy

Contents

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Preface

This report presents the findings of a detailed study into the cost-competitiveness and potential growth of wave and tidal stream energy (marine renewables). It follows the completion of the Marine Energy Challenge (MEC), a £3.0m, 18-month programme of directed engineering support to accelerate the development of marine renewable energy technologies.

The study sought to answer the following key questions:

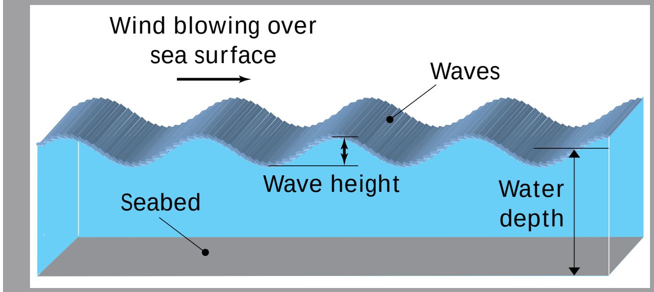
- What affects the costs and performance of marine renewables, and at what costs can electricity be generated from waves and tidal streams today?
- Can the future costs of wave and tidal stream electricity be reduced to become cost-competitive with other renewables and conventional generation in the future?
- Can wave and tidal stream farms be developed to supply large quantities of electricity to the grid and make material contributions to energy supplies? What effect would this have on carbon emissions?

In addition to answering these questions, this report also:

- Summarises the MEC approach and its outcomes;
- Indicates the size of wave and tidal stream energy resources, the potential economic prize and status of technology development; and
- Presents the Carbon Trust’s overall conclusions on the marine renewables sector, identifying barriers to development and making recommendations for future support.

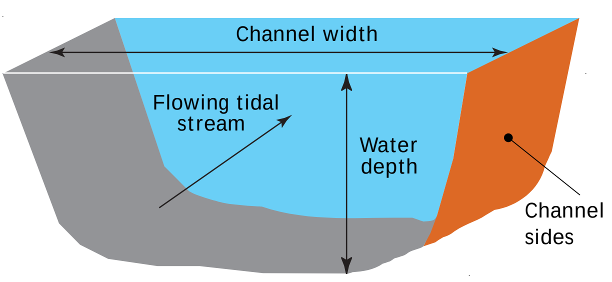
What is marine renewable energy?

There are several types of marine (or ocean) renewable energy. The Marine Energy Challenge has focused on two: wave energy and tidal stream energy.



Wave energy occurs in the movements of water near the surface of the sea. Waves are formed by winds blowing over the sea surface, and the water acts as a carrier for the energy. The amount of energy in waves depends on their height and period (the time between successive peaks). The annual average power per unit length of wave crest (e.g. 40 kW/m) is a first indicator of how energetic a particular site is.

Systems to convert wave energy to electricity are often categorised by their location in the sea, particularly the depth of water, because this has a bearing on the wave height and therefore the amount of energy. Offshore wave energy converters are designed for sites that are tens of metres deep while near-shore and shoreline systems are intended for shallower water. The latter are actually built-in to the coastline.



Tidal streams are caused by the familiar rise and fall of the tides, which occurs twice a day around the UK coast. As water flows in and out of estuaries, it carries energy. The amount of energy it is possible to extract depends on the speed of the flowing stream and the area intercepted. This is similar to wind power extraction, but because water is much denser than air, an equivalent amount of power can be extracted over smaller areas and at slower velocities. The mean spring peak velocity* is a first indicator of how energetic a tidal stream site is.

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* The greatest velocity that occurs over the tidal cycles, abbreviated as V_{msp} in this report.

Executive summary

Potential resource and industry status

Wave and tidal stream energy have the potential for bulk electricity supply in the UK and worldwide. The potential energy resources are significant, particularly offshore wave energy. Between 15% and 20% of current UK electricity demand could be met by wave and tidal stream energy, which is equivalent to carbon dioxide abatements of several tens $MtCO_2$. Estimates of market size are approximate, but the market is likely to be sufficiently large to merit considerable interest in its commercial development.

Interest in wave and tidal stream energy has picked up over the last few years, particularly in the UK. Currently, many different device concepts compete for support and investment, and while some are more advanced than others, all are at early stages compared to other renewables and conventional generation. Optimal designs have yet to be converged upon. A few large-scale prototypes have been built and tested in real sea conditions, but no commercial wave and tidal stream projects have been completed to date. European and US generation companies and project developers are taking increasing interest in the sector.

Current costs of energy

Energy from initial wave energy farms has been estimated to cost[1] between 12p/kWh and 44p/kWh, with central estimates for offshore wave farms in the sub-range 22p/kWh to 25p/kWh. Initial tidal stream farms are estimated to have costs of energy between 9p/kWh and 18p/kWh, with central estimates in the sub-range 12p/kWh to 15p/kWh.

These current costs are much higher than other forms of conventional and renewable generation. However, we consider this is unsurprising, given that wave and tidal stream energy technologies are at early stages and initial farms have limited economies of scale.

Future costs of energy

There is potential for costs to reduce considerably in future. We see four routes to cost reduction: concept design developments; detailed design optimisations; economies of scale; and learning in production, construction, installation, operation and maintenance. Design improvements are likely to be significant in the short to medium term.

We have formed views on the likely extent of cost reduction by a combination of engineering analysis and inference from other industries. In the case of offshore wave energy, cost reduction through concept design improvements is likely and could lead to a step change reduction in costs. Long-term learning rates[2] could be in the range of 10% to 15%. For tidal stream energy, we made a detailed survey of generic designs and developed a computer optimisation model for UK resource conditions. This included economies of scale and learning rates in the range of 5% to 10%.

Our conclusions are that:

- Marine renewable energy has the potential to become competitive with other generation forms in future. In present market conditions, it is likely to be more expensive than other renewables and conventional generation until at least hundreds of megawatts capacity are installed. By way of comparison, this capacity is equivalent to several offshore wind farms at the scale currently being constructed;
- Fast learning or a step change cost reduction is needed to make offshore wave energy converters cost competitive for reasonable amounts of investment; and
- Tidal stream energy could become competitive with current base costs of electricity within the economic installed capacity estimated for the UK, 2.8 GW.

Future growth

In addition to cost of energy, future growth of wave and tidal stream energy will be affected by a range of factors. These include:

- Strategic and security of supply considerations;

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[1] All current cost estimates are based on technologies at their present stages of development deployed in small farms, with a 15% project rate of return. See the main report for other details of costing basis.

[2] Learning rate: Fraction of cost reduction per doubling of cumulative production. For example, if it costs £1 to produce the first unit, the second unit would cost 90p at a learning rate of 10%.

- The availability of finance for technology and project development (including public support);
- Technology and risks, particularly the readiness of technologies to be commercially exploited, and the approach to managing risks in the development process;
- Electricity networks, including the availability of grid connections, network capacity, the electrical engineering design of devices and variability/intermittency of power generation; and
- Environmental and regulatory factors, including local environmental impact, consents and permits processes and regulatory change.

The number of factors and relationships between them make growth complex to model. We took a 'what you need to believe approach' based on detailed assumptions in order to form a view on how growth could occur. The assumptions made for an optimistic but achievable view of the future.

Results from the model indicate that across Europe, up to several gigawatts installed capacity of each of wave and tidal stream energy could be installed by 2020. This is comparable to the worldwide growth of wind energy during the 1980s. It will require investment and support of up to several £billion, and lead to annual carbon dioxide abatements of 2.0 to 7.0 $MtCO_2$/y.

It is possible that a large share of the European deployment by 2020 could occur in the UK. Up to one sixth of the UK Government aspiration of 20% renewable energy by 2020 (i.e. 3% of total UK electricity supply) could be met by marine renewables, and this could be a significant share of the contribution by UK renewables overall. Beyond 2020, the industry could develop considerably further.

Next steps

We believe that UK public and private sector organisations should continue to encourage the creation of a wave and tidal stream industry, given:

- The potential for low carbon electricity generation in this country and others, which could be highly material amongst efforts to combat climate change and increase security of energy supplies; and
- The potential significant economic returns to the UK from sales of generation device, project development and revenue from electricity generation.

The UK is well placed to leverage its skills and experience in offshore oil and gas, ship-building and power generation to accelerate progress in the marine renewables sector and capture the economic value for the UK. While technologies are at early stages, support and investment in technology development can be seen as maintaining the marine renewables option for future years, looking ahead to the time when the technologies are cost-competitive.

In particular, we see that:

- There is a strong case for industry to accelerate the overall pace of marine renewables development beyond current levels. This translates into a requirement for both significant further public support and private investment in development activities;
- Considerable emphasis needs to be placed on cost reduction to ensure commercial viability for wave and tidal stream technologies; and
- Key to the availability of private equity is clarity of the route to market, particularly in recognition of the cost gap between marine renewables and other generation. Public support for costs of energy above those of conventional power and other renewables will be necessary in the medium term.

Given this study's findings about cost-competitiveness and growth, we see a need for a parallel two-pronged approach to public support and private investment, which:

- Accelerates the progress of technology development, through ongoing RD&D into concept and detailed engineering design to bring about substantial reductions in cost; and
- Encourages early development of wave and tidal stream farms to accelerate learning effects.

Public sector funders should consider:

- Giving increased support over time for marine renewables technology development, with greater support for RD&D and cross-cutting technology issues to help deliver cost reductions;
- Supporting marine renewables project development from now into the medium term, contingent on technologies proving technically viable in the first instance, and later, evidence of reducing costs; and
- Developing a clear long-term policy framework of support to the sector to give greater investment certainty.

Based on the success of the Marine Energy Challenge, the Carbon Trust intends to continue playing an active role in supporting marine renewables. We are already forming ideas of what to do next in discussion with industry players, and we will develop these further over the coming months.

1. About the Marine Energy Challenge

In 2002 the Carbon Trust published the Low Carbon Technology Assessment. This gave an overview of a range of technology groups which have substantial potential for carbon emissions reduction, and indicated where Carbon Trust investments could be material in helping progress these towards commercialisation. Of wave and tidal stream energy in particular, the study identified that the UK could play a leading role in developing generation technologies. However it also noted that a better understanding of: energy conversion performance, capital and operating costs; approaches to construction; and survivability in marine conditions were necessary before the technologies could be considered viable.

The Carbon Trust report Building Options for UK Renewable Energy was published in 2003. This developed findings of the Low Carbon Technology Assessment for renewable power generation, focusing particularly on the UK's global competitiveness. The study noted that to maximise economic returns, UK public support for technology development should be targeted where the country has competitive strengths, and in this context identified that the UK has substantial wave and tidal stream energy resources and a high concentration of technology developers. Acknowledging the UK's expertise in offshore oil and gas production, ship-building and power generation, the report commented that "UK plc has the opportunity and potential to create competitive positions in all areas of design, manufacture, installation and operation" of marine renewables, but it also noted the difficulty of assessing the ultimate costs of wave and tidal stream energy at scale.

On the basis of these findings and other studies[3], the Carbon Trust designed the Marine Energy Challenge (MEC)[4]. This was a £3.0m, 18-month programme of targeted engineering support, intended to improve understanding of wave and tidal stream generation technologies by helping technology developers advance their designs. The programme had a particular focus on cost of energy, and sought both to clarify current costs and identify potential for future cost reductions. Technology developers bid into an open tender[5] and eight were selected to work with engineering consultants specialist in offshore engineering and power generation. The consultants worked directly with the developers to improve the chosen concepts, which were all offshore wave energy converters. In addition, detailed studies were made into other technologies where developers did not participate directly, including shoreline and near-shore Oscillating Water Column (OWC) wave energy converters and tidal stream energy generators. To address concerns about survivability and reliability, guidelines were prepared on the application of offshore engineering standards to the design and operation of wave energy converters, and research was supported into the variability of marine renewables generation to clarify implications for grid integration. Figure 1 overleaf shows the parties that were involved in the MEC.

The MEC was completed in summer 2005. Subsequently, the Carbon Trust has conducted a detailed study to assess the future cost-competitiveness and potential growth of marine renewables. This report presents the findings of this analysis, together with conclusions on specific aspects of marine renewables technology development. Given the early stage of wave and tidal stream energy technologies and the study's forward-looking nature, all forecasts and data should be considered to be rough estimates and any decisions based on this work should be taken accordingly.

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[3] Several studies have been conducted into wave and tidal stream energy in recent years, including the 1999 Office of Science and Technology's Marine Foresight Panel report Energies from the Sea – Towards 2020, and the Select Committee on Science and Technology's 7th report of session 2000-2001 on Wave and Tidal Stream Energy.

[4] As well as the MEC, the Carbon Trust is supporting development of marine renewables technology through its Open Call R&D support programme, incubator support and venture capital activities, and also helping fund the European Marine Energy Centre at Orkney.

[5] Not restricted to the UK, and advertised in the Official Journal of the European Union.

Figure 1 *Marine Energy Challenge participants*

Technology developers	Engineering consultants	Management team and overall consultants	Other organisations
AquaEnergy Development UK Clearpower Technology Ecofys Embley Energy Lancaster University Ocean Power Delivery Seavolt Technologies Wave Dragon	Abbott Risk Consulting Arup Energy Atkins Process Black & Veatch Det Norske Veritas E On Power Technology Frazer-Nash Consulting Halcrow Group Peter Brotherhood	The Carbon Trust Chaucer Consulting Entec UK Future Energy Solutions	Paul Arwas Associates University of Cambridge, Faculty of Economics University of Oxford, Environmental Change Institute David Milborrow

Note: The assistance of other organisations and individuals, notably in providing inputs to the tidal stream and Shoreline/Near-shore OWC studies, contributing to the peer review processes and helping steer the cost competitiveness and growth analyses, is gratefully acknowledged.

Rationale behind the MEC

At present, most wave and tidal stream energy technology developers are small teams based in start-up companies, specialist equipment manufacturers, university engineering departments or a combination of the three. The engineering challenges of developing marine renewables are considerable and require specialist knowledge, skills and experience in several areas. Not all developers have these capacities, and by partnering them with engineering consultants who do, we expected that development could be accelerated. We also thought that independent validation of designs would add credibility to claimed cost and performance estimates and help developers to identify areas which need further development effort.

There is a wide range of technology options for both wave and tidal stream energy generation. Several hundred wave energy converter concepts have been proposed to date[6] along with tens of designs of tidal stream energy generator. This poses a problem for anyone trying to invest in the sector: Which technology should one choose? Our approach was to engage developers of several different technologies in parallel – a range of concepts at different states of development – and, where we felt other information would aid the assessment, conducting directed studies. We intended to develop a view of the sector that was both broad and deep, and seek trends towards the best prospects in order to target future support where it will be most beneficial.

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[6] By measure of patent activities.

Outcomes of the MEC

The MEC has significantly accelerated the development of wave energy converters and produced improved engineering designs. Some developers consider it has moved their concepts forward very considerably, to the effect of several years' development effort, and the estimated costs of energy of several concepts have been reduced by more than 20%. At the end of the programme, each developer received a report explaining how the MEC approach was applied to its concept and giving an independent view of the costs and performance. As these reports refer specifically to developers' commercial intellectual property, they are confidential and will not be published by the Carbon Trust.

Throughout the MEC, the Carbon Trust gathered technical data on different marine renewables technologies to allow costs of energy to be estimated. Again, because these estimates reflect commercial intellectual property, they will not be published in detail, but this report gives indications for the wave and tidal stream energy sectors as a whole. The whole sector estimates formed the starting point for the cost-competitiveness analysis discussed in this report.

The MEC has already produced several publications. These include the results of the shoreline/near-shore OWCs study, new findings on the UK tidal stream resource and technology prospects, guidelines on the design and operation of wave energy converters and preliminary conclusions on the variability of marine renewable generation. In addition, a series of electronic newsletters has been published which give an introduction to marine renewables technology and a glossary of technical terms. The reports and newsletters are available on the Carbon Trust website: www.thecarbontrust.co.uk/ctmarine

2. Potential resource and industry status

2.1 Energy resource and carbon abatement potential

The amount of energy carried by wave and tidal streams which is convertible to electricity has been estimated in several previous studies. Building Options for UK Renewable Energy indicated a practical[7] worldwide wave energy resource of between 2000 and 4000 TWh/year, while the UK practical offshore wave energy resource has been estimated at 50 TWh/year[8], (about one seventh of current UK electricity consumption[9]). New findings during the MEC suggest that the technical UK tidal stream resource is 18 TWh/year[10], which is about 10-15% of the known worldwide tidal stream resource. The UK practical near-shore and shoreline wave energy resources have been re-estimated at 7.8 TWh/year and 0.2 TWh/year[11], respectively.

Given these estimates we consider that:

- Wave energy and tidal stream energy have the potential for bulk electricity supply. In total, they could supply between 15% and 20% of current UK electricity consumption; and
- Offshore wave energy has the most potential for the UK. Tidal stream energy could also make a reasonably large contribution, but the potential for near-shore and shoreline wave energy is niche.

Electricity can be generated from waves and tidal streams without carbon emissions. In a generation mix that includes fossil fuel plants, wave energy converters and tidal stream energy generators could avoid carbon emissions associated with electricity production.

The amounts of carbon avoided depend on the quantities of generation, but as a first indication the resource estimates suggest they could be tens of millions of tonnes carbon dioxide per year for the UK, and hundreds of millions of tonnes worldwide. Consequently, wave and tidal stream energy can be considered on the world stage of high potential low carbon technologies.

The economic prize of marine renewables

Due to uncertainties about future costs, estimates of the long-term economic potential of wave and tidal stream energy tend to be approximate. However, the resource estimates suggest there could be both major domestic and export markets for wave and tidal stream energy generation equipment, as well as site development, construction, installation and operation services.

As indications of market size:

- Our consultants estimated that the value of worldwide electricity revenues from wave and tidal stream projects could ultimately be between £60b/year and £190b/year[12]; and
- A previous study[13] estimated that investments of over £500b would be necessary for wave energy to contribute 2000 TWh/year worldwide.

Overall, the market for marine renewables, particularly offshore wave energy, is likely to be sufficiently large to merit considerable interest in its commercial development.

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[7] The practical resource allows for practical and economic factors that combine to make developments commercially attractive. The technical resource describes the amount of energy technically available before such constraints are applied.

[8] Source: ETSU (1985), The Department of Energy's R&D Programme 1974-1983, ETSU Report R-26. Given developments in both wave energy technology and the availability of resource data since this assessment, we believe this figure could be higher.

[9] About 350 TWh/year. Source: DTI

[10] Source: Black & Veatch (2005), Phase II UK Tidal Stream Energy Resource Assessment.

[11] Source: Arup Energy (2005), Oscillating Water Column Wave Energy Converter Evaluation Report.

[12] Source: Entec (2005)

[13] ETSU (1999), A Brief Review of Wave Energy.

Life cycle carbon emissions and energy payback period

This report refers mainly to the carbon dioxide emissions avoided by operating wave energy converters and tidal stream energy generators instead of fossil fuel power stations. Figures for abated carbon dioxide emissions were calculated on the assumption that for every kWh of power generated from waves and tidal streams, 430 grams of CO_2 emissions would be avoided.

In addition, one needs to consider the complete life cycle (also known as the embedded) emissions of wave energy converters and tidal stream energy generators. This is because while zero emissions will be produced during operation, finite emissions will occur due to manufacturing, fabrication, transportation, installation, maintenance and decommissioning. A related concept to life cycle emissions is the energy payback period, which is the time it takes for a device to generate the energy that was used in these activities.

Assessments made during the MEC indicate that life cycle emissions and energy payback periods vary between wave and tidal stream device concepts, but are generally low. For example, one particular wave energy converter that employs 665 tonnes of steel[14] and has an Annual Average Energy Production[15] of 2.3 GWh/year has estimated life cycle emissions of between 25 and 50 g/kWh and an energy payback period of about 20 months[16].

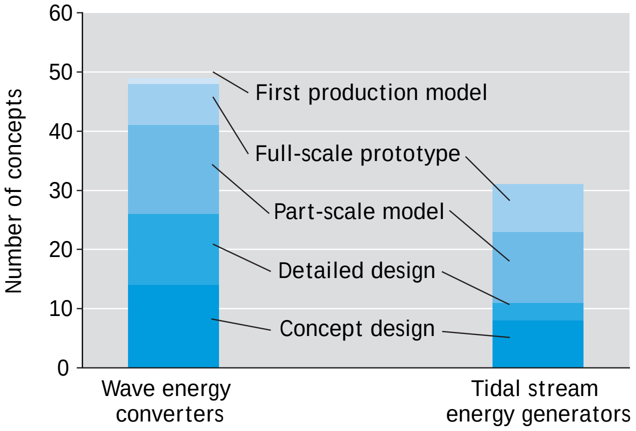
2.2 Development to date

Wave energy technology has been developed since the mid 1970s, but with sporadic progress. This is due partly to government policy and R&D support being intermittently favourable, partly in response to variations in fossil fuel prices, which sent positive signals to private investors at some times and negative signals at others. Tidal stream energy technologies began to be developed during the 1990s after UK R&D programmes into tidal barrage schemes were discontinued. To date, worldwide government R&D support for wave and tidal stream energy has been much less than other electricity generation and low carbon technologies, including other renewables[17].

Interest in marine renewables has picked up over the last few years, particularly in the UK. New concepts have been brought forward and old ones re-evaluated in the current political and economic context of increasing support for renewable energy to combat the threat of climate change, increase security of supply and create economic growth. Figure 3 (overleaf) shows notable recent UK events.

Currently, many different concepts of wave energy converter and tidal stream energy generator compete for support and investment in technology development. Some concepts are more advanced than others, both in the sophistication of the technology and development progress to date. Overall, devices are at early stages compared to other renewables and conventional plant, and crucially, optimal designs have yet to be converged upon. A few large-scale prototypes have been built and tested in real sea conditions, but no commercial wave and tidal stream projects have yet been completed. Figure 2 indicates the development status of concepts that the Carbon Trust is aware of.

***Figure 2** Development status of wave and tidal stream technologies*



Note: These numbers reflect the concepts the Carbon Trust is currently aware of, based on technology developers' claims of progress and corroborating evidence where available. This is solely a tally of different concepts being pursued, not an indication of designs which may come to fruition, prove technically viable or cost-competitive.
Source: Entec

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[14] It has previously been found that carbon dioxide emissions are broadly proportional to energy use, and given this, the most important life cycle stages are manufacturing of structural materials. Consequently, a preliminary estimate of life cycle emissions of a marine renewables device can be made by comparing the emissions due to structural materials with total energy production over the device's service life. See ETSU (1999), A Brief Review of Wave Energy.

[15] See definition in Section 3

[16] Source: Black & Veatch.

[17] Source: International Energy Agency/Organisation for Economic Co-operation and Development (2004), Renewable Energy: Market and policy trends in IEA Countries.

Figure 3 *Recent UK activities in marine renewables*

1999	Scottish Renewables Order 3 included wave energy DTI re-started wave energy part of New and Renewable Energy Programme
2000	Wavegen's LIMPET was first UK wave energy converter to generate to grid
2001	DTI started tidal stream part of New and Renewable Energy Programme
2002	The New and Renewable Energy Centre launched The Carbon Trust published Low Carbon Technology Assessment
2003	Marine Current Turbines' Seaflow tidal stream turbine installed The Carbon Trust published Building Options for UK Renewable Energy Supergen Marine R&D programme launched Regen Southwest Wavehub concept launched
2004	The Carbon Trust Marine Energy Challenge launched DTI announced £50M Marine Deployment fund European Marine Energy Centre officially opened Ocean Power Delivery's Pelamis was first offshore wave energy converter to generate to grid
2005	DTI ran workshops on consenting pre-commercial wave and tidal stream farms The Carbon Trust completed Marine Energy Challenge

Current landscape of public support and private investment

Technology development

Since 2000, total public support for technology development has been around £20m. Most of this has been in the UK, in grants for research and technology development plus support for test centre and infrastructure projects mainly from the DTI, the Carbon Trust, Scottish Executive, Engineering and Physical Sciences Research Council, Scottish Enterprise and Regional Development Agencies.

Private investment has also been forthcoming during the last five years. Several technology developers have obtained venture capital investments[18] in the range of several hundred thousand pounds per investor, totalling a few £m per investment round. In addition, one technology developer is listed on the Alternative Investment Market (AIM) of the London Stock Exchange.

Such funding and investment is considerably greater than seen previously, which is encouraging, but on the grand scale of energy and other technology development, it remains fairly low.

Project development

Some European and US generation companies and project developers are taking increasing interest in the wave and tidal stream sector. Several have formed agreements with technology developers to pursue initial farms, and the pipeline of projects is several tens of megawatts. To date, however, investments in project development have been limited.

[18] Including one by the Carbon Trust to date.

3. Current costs of energy

What affects the costs of marine renewables, and at what costs can electricity be generated from waves and tidal streams today?

These questions were the starting point for our assessment of cost-competitiveness. This section summarises the findings based on data gathered during the MEC.

3.1 Key factors affecting cost of energy

The costs of energy of marine renewables technologies depend on several factors. Principally, these include capital costs, operating and maintenance (O&M) costs and the amount of electricity produced (performance)[19]. Like wind energy, wave and tidal stream energy are free at source so there is no fuel cost.

Essentially, capital costs and O&M costs must be weighed against performance, since this is the saleable output and represents income to the generator. A high performance device can afford to be expensive if its costs are more than met by the value of electricity sold. But if the costs are so great that they exceed the income from generation, the device will not be economically viable. The balance of costs and performance is manifested in the cost of energy, and the target for this is the cheapest alternative: another form of renewable or conventional power generation.

Capital costs

The capital cost of marine renewables technologies can broken down into: the cost of the generation device itself (materials, components and labour in manufacturing and fabrication processes); the costs associated with installing it (deployment); the costs of keeping it on station (foundations or moorings); and the costs of connecting it to the grid (electrical cables and switchgear). Some of these costs are more dominant than others, and the relative distribution of cost centres varies between different device concepts and site locations. For example, Figure 4 illustrates the cost make-ups for a specific wave farm (Figure 4a) and specific tidal stream farm (Figure 4b) that have been envisaged.

It should be noted that the capital costs of wave and tidal stream energy devices are not static and will change over time due to developments in technology, the costs of raw materials and components and experience gained in manufacturing and deployment. As might be expected, the total capital cost depends strongly on the number of devices built and installed, and also where they are deployed.

O&M costs

The O&M costs of marine renewables can also be considered in several parts, including: maintenance, both planned and unplanned; overhauls; where it is most economic to re-fit components during the service life; licences and insurance to allow the devices to be kept on station and to manage the associated risks; and ongoing monitoring of wave or tidal conditions and the performance of devices.

Figure 4c gives a breakdown of O&M costs for a specific wave farm envisaged. Like capital costs, O&M costs also depend on the size of the installations and the location, and are also likely to vary from year to year. At present, it is much more difficult to estimate O&M costs than capital costs due to the lack of experience in operating wave and tidal stream farms, although it is possible to infer costs from experience with upstream oil/gas installations and offshore wind farms.

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[19] There will also be costs of decommissioning. Current estimates indicate these will be small compared to initial capital costs, and because they fall at the end of a project, the present value in a discounted cash flow analysis is low and has only a marginal effect on cost of energy.

Figure 4 *a) Breakdown of capital costs for a wave farm*

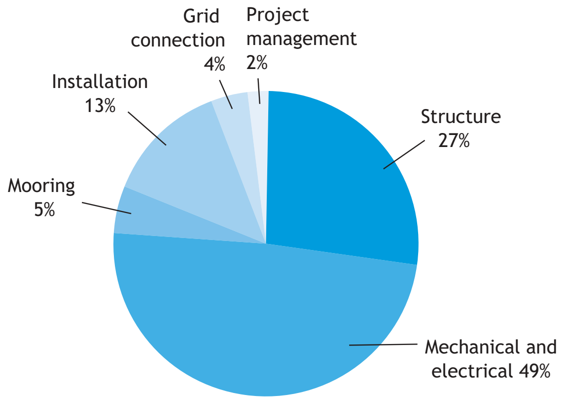


Figure 4 *b) Breakdown of capital costs for a tidal stream farm*

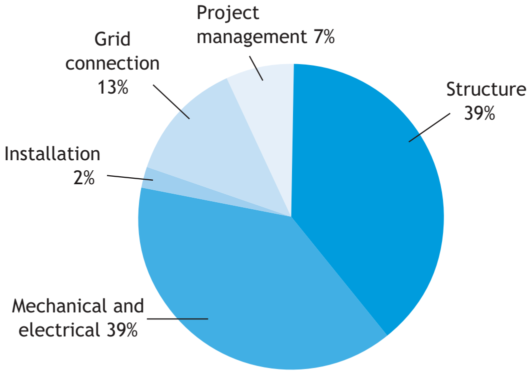
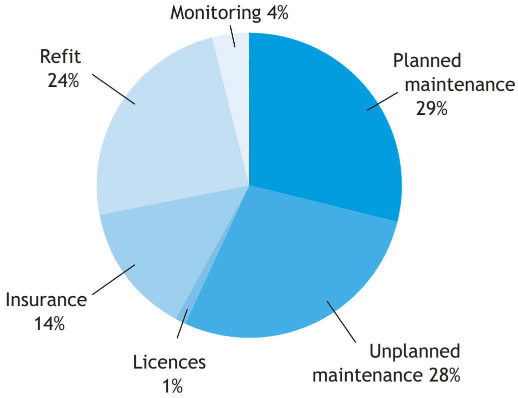


Figure 4 *c) Breakdown of operation and maintenance costs for a wave farm*



Notes: Based on data gathered during the Marine Energy Challenge.
The charts refer to specific types of wave energy converter and tidal stream energy generator, and are not representative/typical of wave energy or tidal stream technologies as a whole. There are considerable variations between different technologies, project locations and project sizes (numbers of machines installed). Also, future design improvements, performance/cost optimisations and learning effects could change the relative weighting of some cost centres. The O&M chart shows annual average costs evaluated over the entire life of a wave farm.
Source: Entec, based on data provided by Atkins and Black & Veatch

Performance

The performance of marine renewables devices depends on: the energy available in the resource; the design of the prime mover (mechanical components) that extracts energy from the resource – e.g. the rotor of a tidal stream turbine; and the power take-off system (equipment used to convert the mechanical energy into electricity).

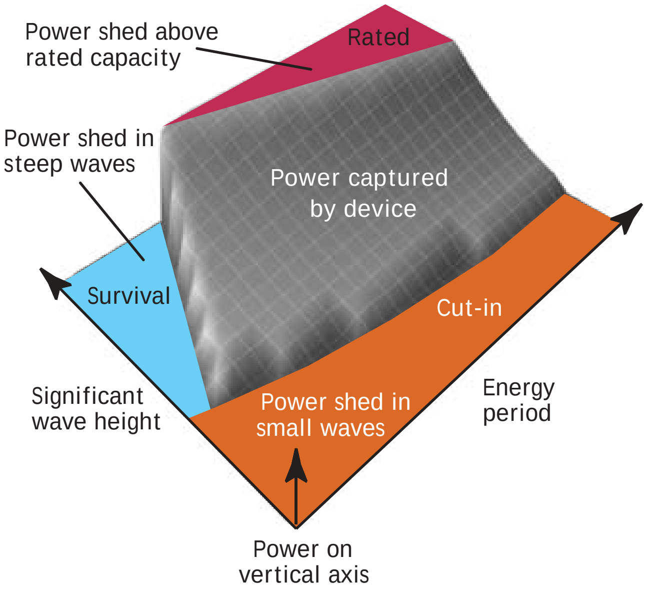
As wave energy converters and tidal stream energy generators can be configured in many different ways, their performance characteristics vary. It is necessary to study specific designs in order to understand performance characteristics in detail, but it is possible to make general observations about groups of devices and identify common requirements for high performance. These include the extent to which a device's capacity for energy extraction/conversion is matched to the available energy resource, the efficiency of the system's energy conversion ('resource-to-wire') and its availability (proportion of time the device is ready to generate, whether or not the resource conditions are suitable for generation). Figure 5 indicates what the performance characteristics of wave energy converters (Figure 5a) and tidal stream energy generators (Figure 5b) may be like, in particular how the power output depends on different physical parameters (wave height, wave period and tidal stream flow velocity).

Like other renewables and conventional generation, the generation performance of marine renewables can be described using the following terms:

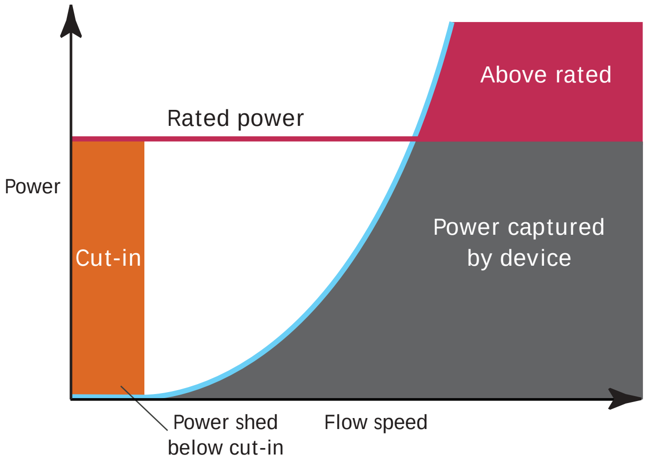
- Annual Average Energy Production. This is the total amount of electricity expected over the service life divided by the length of the service life (allowing for the fact that annual generation may vary from year to year due to changing resource conditions, device availability and/or energy conversion efficiency); and
- Long-Term Capacity Factor. This is the ratio of average annual energy production to the product of rated capacity and the number of hours in a year. Data gathered during the MEC suggests that long-term capacity factors for wave farms and tidal stream farms may be of a similar magnitude to wind farms – between 20% and 45%, depending on the technology and site.

***Figure 5** Performance characteristics of wave energy converters and tidal stream energy generators*

a) Example wave energy converter power surface



b) Example tidal stream energy generator power curve



Notes: These graphs indicate ranges of operating conditions for wave energy converters and tidal stream energy generators. They are for illustration only, and neither represents a specific device technology. In each graph, the grey area shows where power would normally be generated. The orange area highlights conditions where there is insufficient energy in the resource to generate economically, and the red areas where the available energy is at or above the rated capacity of the generator.
Source: Entec

Calculating cost of energy

Drawing all of the above together, an installation's cost of energy is determined by a discounted cash flow calculation. Given a certain discount rate and period, the cost can be estimated using the following equation, where 'PV' indicates the present value over the service life:

$$\text{Cost of energy} = \frac{\text{Capital cost} + \text{PV(O\&M costs)}}{\text{PV(Energy Production)}}$$

MEC approach to cost of energy

The capital costs, O&M costs and performance of a marine renewable device are interrelated and an improvement in one may require a trade-off with another. This means that before a device's cost of energy can be estimated, it is necessary to define a self-consistent basis of design. This is not necessarily the optimal design in the first instance, but one that could actually be built (i.e. using certain materials and known construction techniques), could be deployed (i.e. using certain vessels and moorings or foundations) and will work (i.e. survive the marine environment and produce electricity reliably).

During the MEC, the first stage of evaluation was to define a baseline design. The costs and performance were then determined and the baseline cost of energy estimated. In some cases, this indicated that the costs were too high to justify the performance, and subsequently ways were sought to either decrease the costs, improve the performance, or both. An iterative design process followed during which different design possibilities were explored and their potential benefits were quantified. This resulted in improved designs with lower costs of energy and/or greater confidence that certain cost and performance levels could be reached.

3.2 Current costs

Based on the evidence gathered during the MEC, it is possible to indicate the costs of marine renewable energy today. Although the previous section applies equally to wave and tidal stream energy, it is important to point out that the costs of each technology category are different, and henceforth they are treated separately.

Choice of metrics

Given that costs depend strongly on the numbers of machines built and installed, a practical difficulty in discussing current costs is the present industry status. With no commercial wave or tidal stream projects yet built, the firmest evidence of costs and performance comes from large-scale prototypes. However, the capital costs of these are likely to be greater than production models for commercial projects for two reasons:

- Prototypes are built as one-offs, whereas production models may be constructed in batches with associated economies of scale; and
- Design improvements resulting from prototype testing may reduce costs and/or increase performance before production models are built.

Also, the performance of prototypes is likely to be much lower than production models because the prototypes are used primarily to gather engineering data for ongoing development, rather than generate electricity for revenue. Furthermore, in practice, one can only make broad-brush distinctions between prototype O&M costs and development activities. Prototype costs of energy are therefore not a good indicator of commercial costs of energy.

An alternative is to estimate the costs and performance of first production models, but this usually requires assumptions about economies of scale, design improvements, performance levels and O&M costs. These carry large uncertainties and may not make for a self-consistent design basis, lending doubt as to the validity of the results.

Given these issues, our approach to reporting current costs is as follows:

- Describe capital costs for both first prototypes and first production models, since these can be estimated reasonably well and comparisons are instructive. However, for the time being, we allow only batch production benefits (small economies of scale) between the two stages; the significance of design improvements is discussed later. The capital cost figures therefore represent today's technologies manufactured in small volumes. Figures are given per unit installed generating capacity (£/kW) since this allows comparisons with other technologies[20] (e.g. offshore wind); and
- Give costs of energy for first production models, based on the reported capital costs and technology-specific estimates of performance levels and O&M costs. These were developed in detail by bottom-up calculations of annual average energy production and reference to O&M strategies and procedures (as far as defined). The following general assumptions apply to the figures quoted:
    - Devices are installed in farms of 10 MW total installed capacity. This is broadly indicative of the size of early stage developments; actual first projects (or first stages of projects) may be smaller.
    - The project rate of return is 15%. This is based on discussions with energy project investors about risk/return expectations. 15% is higher than some projects using conventional and renewable technologies achieve, but reflects investors' perceptions about current technology risks for marine renewables.

Uncertainty and lowest-cost groups

Our analysis indicates that in the cases of both wave energy and tidal stream energy, the variety of concepts reflects itself in wide ranges of capital costs and costs of energy. This range is exaggerated by uncertainties in the cost and performance estimates of individual devices, which are large in most cases and very large for less advanced concepts. Although statistical average or median costs of energy can be calculated, these tend to be misleading due to the influence of unpromising, high cost devices. An alternative approach is therefore necessary to contain the range and describe the most promising, low cost technologies.

Our method was to identify 'lowest-cost' groups of wave energy converters and tidal stream energy generators, which are subsets of the whole technology range. These groups were selected using engineering judgement and are therefore partly subjective, but this shortcoming is outweighed by their usefulness over other descriptions. Each lowest-cost group consists of several fundamentally different concepts, so should one prove technically unviable and/or more expensive than estimated, there is an alternative route to the same cost. This gives confidence that the lowest-cost groups are reasonable indicators of current costs.

Lowest cost groups of technologies are described below, except near-shore and shoreline OWC wave energy converters which are identified specifically on the basis of design data in the public domain[21].

Capital costs of prototypes and first production models

Figure 6 compares the capital costs of first prototypes and first production models. The total capital cost of first prototype wave energy converters could be up to £9,000/kW, but certain prototypes have already been built at costs below £4,300/kW. This should not be taken to exclude more expensive concepts, providing cost reductions are possible between prototype and first production models. Initial wave farms could be installed for between £1,700/kW and £4,300/kW.

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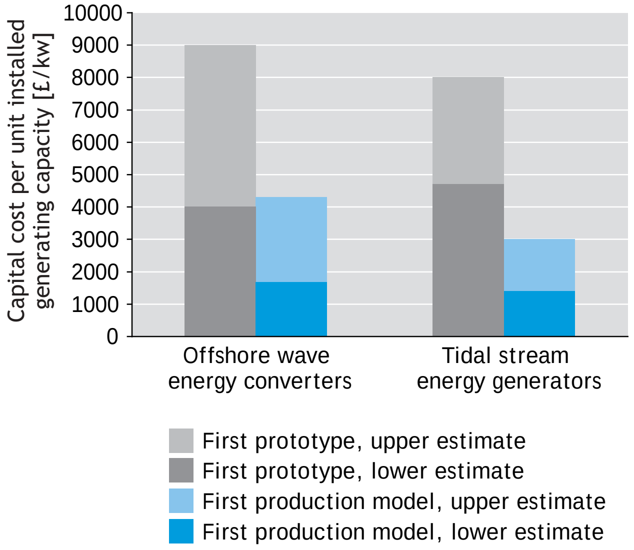
[20] In theory, a better metric is capital cost per annual average power generation, which takes into account the long-term capacity factor. However, for this to be meaningful for any single device, the certainty of the performance estimate needs to be high, and in order to compare between devices, the certainty of estimates should be similar. Our experience is that performance estimates often have wide error bands and that the certainty varies considerably between devices. This can make capital cost per annual average power generation figures misleading.

[21] Arup Energy (2005), Oscillating Water Column Wave Energy Converter Evaluation Report.

First prototype tidal stream energy generators could cost up to £8,000/kW, but certain concepts have already been built for under £4,800/kW. Again, this should not exclude concepts with greater capital costs providing future cost reductions are possible. Initial tidal stream farms could have costs between £1,400/kW and £3,000/kW.

Figure 6 *Capital costs of first prototypes and first production models*



As special cases:

- First prototype near-shore Oscillating Water Columns (OWCs) are estimated to cost between £3000/kW and £9000/kW;
- First production model near-shore OWCs are estimated to cost between £1150/kW and £2800/kW;
- First prototype shoreline Oscillating Water Columns (OWCs) are estimated to cost between £5500/kW and £10000/kW; and
- First production model shoreline OWCs are estimated to cost between £1550/kW and £5500/kW.

Source: Entec

Costs of energy of initial farms

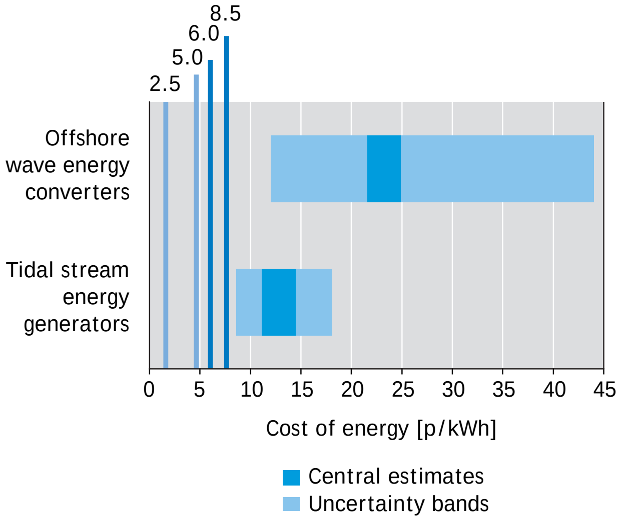
Figure 7 shows the costs of energy generated by wave energy converters deployed in initial farms. We consider the lowest-cost group offshore wave energy converters to range from 12p/kWh to 44p/kWh, with central estimates in the sub-range of 22p/kWh to 25p/kWh. The wide range of costs is due mainly to the diversity of concepts, but is also caused by large uncertainties about performance and O&M for individual designs. Central estimates for near-shore and shoreline OWCs are within the lowest-cost offshore wave energy converter range, at 15p/kWh and 28p/kWh respectively. Other wave energy converters have costs in excess of 50p/kWh, and performance no lower, nor O&M costs any higher, than competitors. This suggests that despite uncertainties in performance and O&M, capital cost per kilowatt is a good indicator of competitiveness.

Energy from initial tidal stream farms has been predicted to cost between 9p/kWh and 18p/kWh, with central estimates in the sub-range 12p/kWh to 15p/kWh[22]. The fact that this range is smaller than wave energy converters is due partly to the choice of concepts being more limited, and partly to greater certainty about performance. Although O&M costs are uncertain, performance levels between lowest-cost group concepts are similar. This again points to capital cost per kilowatt as a good competitiveness indicator.

It can readily be observed from Figure 7 that the central estimate costs of tidal stream energy are lower than those of offshore wave energy. It is important to emphasise that:

- This is solely a depiction of current costs, and gives no indication of how the costs of wave and tidal stream energy may reduce. This is discussed in Section 4; and
- The apparent advantage of tidal stream energy over wave energy needs to be taken in context of the resource estimates noted in Section 2. Notably, both the UK and worldwide offshore wave resources are estimated to be considerably greater than their tidal stream counterparts.

Figure 7 *Costs of energy today*



Notes:

- The complete bars represent lowest-cost group technologies, at today's stage of advancement, manufactured in small volumes and installed in initial fams up to 10 MW capacity, at a project rate of return of 15%.
- The central estimate bands represent the ranges of central estimate costs for different technologies.
- As special cases, near-shore Oscillating Water Columns (OWCs) are estimated to have central estimate costs of 15p/kWh, and shoreline OWCs 28p/kWh.
- See Figure 9 on page 18 for details of the four target costs of energy (vertical lines)

Source: Entec

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[22] Source: Black and Veatch

Causes of high costs in prototypes and initial farms

The capital and O&M costs of early wave and tidal stream energy generators can be expected to be higher than long-term costs due to several practical and economic factors, including the following:

- While demand for materials and parts with which to build marine renewable devices is low, these materials and parts may not be ideal; technology developers temporarily need to make do with what is available 'off-the-shelf'. Bespoke solutions to reduce costs are the subject of R&D and will take time to develop;
- There is limited experience of installing, operating and maintaining plants in some situations that are ideal for energy extraction from waves and tidal streams. Contractors' perceptions of risk are likely to be reflected in higher costs; and
- Some routes to overall cost minimisation are uneconomic while only small volumes of devices are produced and installed. These include novel manufacturing processes and the use of customised vessels for installation, operation and maintenance.

3.3 Conclusions

The current costs of both wave and tidal stream energy are considerably higher than conventional and other renewable energy generation. We consider this is unsurprising, given the early stage of technologies and the implications of the assumptions noted, particularly that projects are constrained to 10 MW total installed capacity and thus have limited economies of scale. The following section discusses how and to what extent the costs of marine renewable energy could be reduced.

4 Future costs of energy

Can the costs of wave and tidal stream electricity be reduced to become cost-competitive with other renewables and conventional generation?

This question is crucial to the future of technology development, and to date, uncertainty about the answer has been a barrier to commercialisation. This section explains our approach to assessing future cost reduction potential, indicates how the costs of wave and tidal stream energy could reduce with increasing installed capacity and notes implications for investment and support.

4.1 Routes to cost reduction

Broadly speaking, we expect economies of scale to be possible in production (manufacturing, construction, installation and O&M), and cost reductions to occur with increasing numbers of devices produced – a concept known as learning. This is based on knowledge of marine renewables technology and also empirical evidence of other generation technologies, including renewable technologies such as photovoltaic cells and wind turbines[23]. Cost reductions have been observed for these technologies as manufacturing increases in scale and installed capacities rise. Although there is some disagreement about exact learning rates[24], the general trends are widely accepted and borne out by the fact that prices are lower today than previously.

However, while conceptual and detailed designs of marine renewables devices are still evolving, it is insufficient to think about economies of scale and learning alone. More significant at the current stage of development is the ability of engineering design improvements to minimise costs of energy before large numbers of devices are manufactured and installed. Indeed, while only a few large-scale prototypes have been deployed, design improvements give the firmest evidence of cost reduction potential. It will be some years before sufficient numbers of devices have been produced that the impacts on economies of scale and learning can be measured.

Engineering design can be considered in two respects: concept design, which concerns the fundamental operating principles and general assembly of devices, and detailed design, which is how the concepts are actually realised. Concept design improvements might involve changes to a device's size, shape or general assembly, while detailed design optimisations could, for example, improve performance in particular resource conditions or minimise the time required in maintenance. Reflecting the state of technologies on entry work in the MEC focused mainly on concept design improvements, particularly identifying the remaining design avenues to be explored as part of the iterative design process. However, some technologies within and outside the MEC are now ready for detailed design optimisations to enhance performance or reduce capital and O&M costs, beyond the platforms envisaged for first large-scale prototypes.

In short, we identify four possible ways of reducing costs of energy (Figure 8)[25]:

- Concept design developments;
- Detailed design optimisations;
- Economies of scale; and
- Learning in production, construction, installation and O&M.

Although sequenced logically, cost reductions may not occur in this order because the design process is iterative and the latter two effects are linked. It is therefore impossible to uniquely identify the benefit each mechanism could have in future (indeed, such disaggregation is often difficult for previously developed technologies). However, we believe that design improvements (both concept and detailed) are likely to be significant in the short to medium term.

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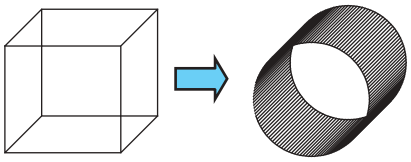
[23] See for instance IEA (2000), *Experience Curves for Energy Technology Policy*

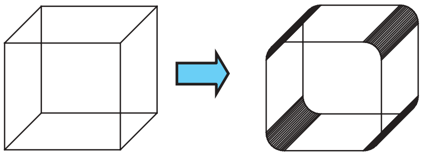
[24] Learning rate: Fraction of cost reduction per doubling of cumulative production. For example, if it costs £1 to produce the first unit, the second unit would cost 90p at a learning rate of 10%.

[25] An alternative interpretation of routes to cost reduction groups concept and detailed design into one category, 'learning by searching', and economies of scale, learning in production, construction, installation and O&M in another, 'learning by doing'. These terms are found in academic literature.

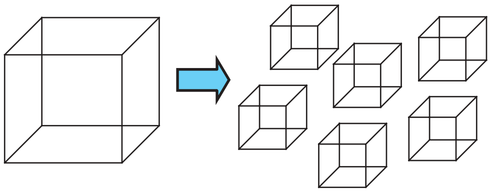
Figure 8 *Routes to cost of energy reduction for marine renewables*



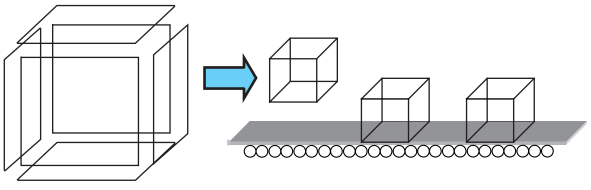
Concept design developments



Detailed design optimisations



Economies of scale



Learning in production, installation, operation and maintenance

4.2 Assessment of cost reduction potential

We have formed views on the extent of potential cost reductions by a combination of engineering analysis of marine renewable technologies and inference from other industries.

The engineering analysis approach involved breaking down designs into cost centres, sub-assemblies and components, studying the potential for improvements to each, and then re-building the devices at lower cost. This was essentially the MEC approach to cost of energy, but in order to form a medium-term view we looked beyond design platforms at the end of the MEC. A practical constraint was uncertainty about trade-offs between certain design changes and performance enhancements, which could only be resolved by further engineering analysis and testing beyond the scope of this study. Limited industry knowledge about certain novel engineering processes (e.g. volume fabrication in concrete) was also a constraint.

We looked at the experience of other industries to form a long-term view of learning rates (the combined cost reduction arising from of economies of scale and learning). In particular, ship-building, offshore oil/gas and wind power were considered because the associated technologies have similarities in design and function to marine renewables and use many of the same parts. As far as possible we studied the sectors' initial stages in order to gauge leaps made early on, but we also looked at cost reductions since the technologies have become more mature.

This formed a common basis for our analyses of all marine renewables technologies, but beyond this, different approaches were taken for wave energy and tidal stream energy.

Wave energy converters

The wide range of options for wave energy converters makes a study of the potential for concept design improvements very difficult. However, the early stages of technologies suggests that cost reduction by this route is quite likely. It could be that a present early-stage concept is cheaper than more advanced designs, or that advanced designs become cheaper through fundamental design changes. It is impossible to foresee every potential design change or quantify its benefits[26], but overall, the impact could be a step change reduction in cost of energy below the current lowest-cost group.

We have some indications of the potential for detailed design optimisations for more advanced concepts, and these suggest material reductions in capital cost and increases in performance are possible. However, for devices we are familiar with, such enhancements have not yet been combined to form a self-consistent design basis, and/or theoretical evidence has not been validated, so the net potential cost of energy reduction is unproven.

Our consultants found that economies of scale could be possible in several aspects of construction, installation, operation and maintenance. The cost reduction potential varies considerably between different concept designs, particularly due to differences in general assembly and O&M strategies. For some designs, it is difficult to tell whether long-term reductions in costs of energy will be due mostly to capital cost reductions, O&M cost reductions or performance improvements. Due to the uncertainties about O&M, our consultants took O&M costs as a fixed proportion of capital costs.

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[26] Identification of design features likely to reduce costs is one objective of current work under the EPSRC Supergen Marine research programme (Work Package 7). Conclusions had yet to be reached at the time of writing but we remain in touch with the study team.

By a combination of engineering analysis and inference, our consultants consider that the long-term learning rate in cost of energy for wave energy converters is likely to be between 10% and 15%[27].

Tidal stream energy generators

The smaller range of tidal stream energy generator concepts allowed a detailed survey to be made of different generic designs, including horizontal-axis turbines, vertical-axis turbines, reciprocating hydrofoil machines and venturi systems. Our consultants assessed the relative merits of different approaches, including fundamental design options such as foundations/moorings and shrouding, and then estimated capital costs, O&M costs and performance.

Detailed design optimisations of the generic concepts could not be considered in full, but basic optimisations for UK resource conditions were possible. This was attractive in order to understand whether tidal stream energy could become cost-competitive in the UK, given the country's estimated share of the worldwide resource (10-15% – see Section 2). A computer optimisation model was developed to estimate costs of energy under different resources conditions, including deep and shallow water. Economies of scale and learning were embodied in this model, and our consultants considered that long-term learning rates could be between 5% – 10%[28].

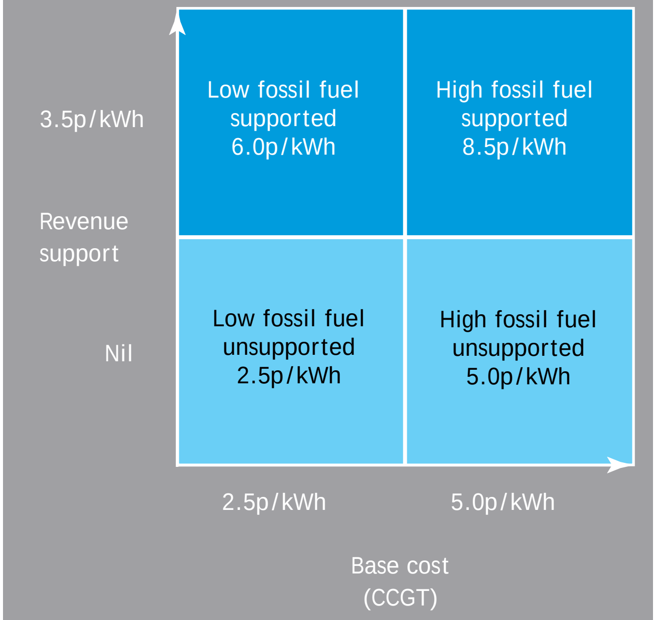
Key sensitivities in future cost of energy analyses

- Discount rate. We expect the rate of return required to finance marine renewables projects to fall as experience increases and risks reduce. This will be linked to increasing amounts of installed capacity. For both wave and tidal stream energy, a rate of 15% was applied to initial projects while 8% was taken for the long term. Since reducing the discount rate is effectively another form of learning, a distinct learning rate was applied, independent of learning on costs;
- Period. The financing period (or capital recovery term) of marine renewables projects will depend on the sources of finance and investors' risk/reward expectations. As a first approximation, we assumed the period was equal to the service lives of wave and tidal stream farms, predicted during the MEC to be between 15 and 25 years, depending on the device. For consistency, the term was normalised to 20 years.

Target costs of energy

In the present market conditions, we consider a rational target for the base cost of energy to be the cost of CCGT, since this is cheapest form of generation. We considered two cost points: 2.5p/kWh and 5.0p/kWh. The former reflects the cost of CCGT over the past few years in the UK, and the second is a view of a future cost given a certain sustained increase in fossil fuel prices and the cost of associated carbon emissions. In order to gauge the future progress of wave and tidal stream energy against other, more mature renewables (particularly wind power), we also counted the value of UK Renewable Obligation Certificates (ROCs) and Climate Change Levy Exemption Certificates (LECs)[29]. We assumed the overall benefit of these to generators would be 3.5p/kWh. Together with the two electricity cost points, this gave four target cost levels, as shown in Figure 9.

***Figure 9** Target cost of energy levels*



	2.5p/kWh	5.0p/kWh
3.5p/kWh	Low fossil fuel supported 6.0p/kWh	High fossil fuel supported 8.5p/kWh
Nil	Low fossil fuel unsupported 2.5p/kWh	High fossil fuel unsupported 5.0p/kWh

Source: Paul Arwas Associates

In future, one might take different target costs, due to changes in both:

- The costs of energy of other conventional and renewable technologies, some of which are themselves following cost reduction trends (e.g. wind power);
- Changes in government instruments and market conditions to value carbon emissions.

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[27] Source: Entec

[28] Source: Black & Veatch

[29] In the UK, the Renewables Obligation and Climate Change Levy effectively increase the value of renewable electricity over conventional (fossil fuel and nuclear) power.

4.3 Estimates of future costs

Cost-curve scenarios for wave energy converters

Due to the difficulty of quantifying concept design improvements, the unproven nature of detailed design optimisations, and the range of possible learning rates, we approached predictions of the future costs of wave energy on a scenario basis.

Initially, we considered how the costs of offshore wave energy converters could reduce from the sub-range of central estimates mentioned earlier if learning happened continuously from now. Applying the slowest long-term learning rate expected (10%) to the upper bound of the current lowest-cost group (25p/kWh) gives a scenario for slow technology development, (Scenario A). A faster development scenario is produced by applying the fastest rate (15%) to the lower bound (22p/kWh), (Scenario B). Figures 10a and 10b show cost curves for these two scenarios.

It can be seen that in Scenario A, about 5 GW of capacity needs to be installed before the high fossil fuel supported level (8.5p/kWh) is reached, while in Scenario B the same level is met after only 250 MW. Effectively, the low fossil fuel unsupported level (2.5p/kWh) is never realised in Scenario A, whereas it takes about 40 GW to meet in Scenario B. First and foremost, these results show there is a strong sensitivity to the learning rate, and indicate the benefit of progressing at a rate closer to 15% rather than 10%. But they also suggest that:

- An increase in base electricity costs, over recent historic levels, may be necessary to make offshore wave energy cost competitive; and
- Offshore wave energy is likely to be considerably more expensive than other renewable and conventional generation until at least hundreds of megawatts of capacity is installed.

Given these findings, we considered what could happen if there was a step change to reduce the starting point to 10p/kWh after 50 MW capacity had been installed, and learning occurred at 15% thereafter. A cost curves for this additional scenario, C, is shown in Figure 10c. It must be emphasised that the 10p/kWh starting point does not relate directly to an actual estimate for any offshore wave energy converter studied by our consultants, and to be realised, scenario C would require major cost reductions before large wave farms are deployed, beyond levels our consultants can currently foresee. However, a step change to 10p/kWh could be considered a best case, and it is instructive to compare scenario C to A and B.

Figure 10a *Offshore wave energy cost reduction scenarios Scenario A: 24.9p/kWh starting point, 10% learning rate*

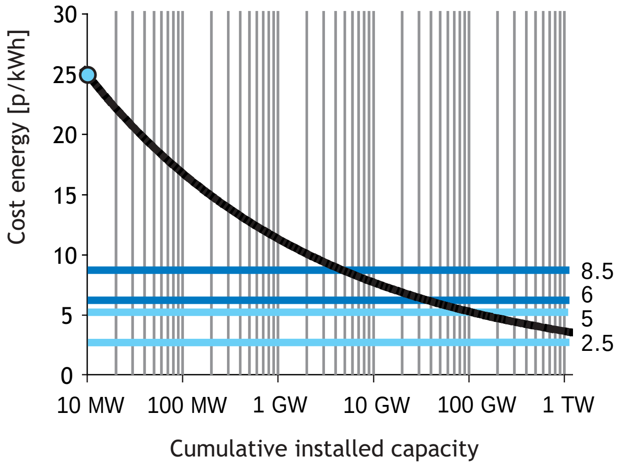
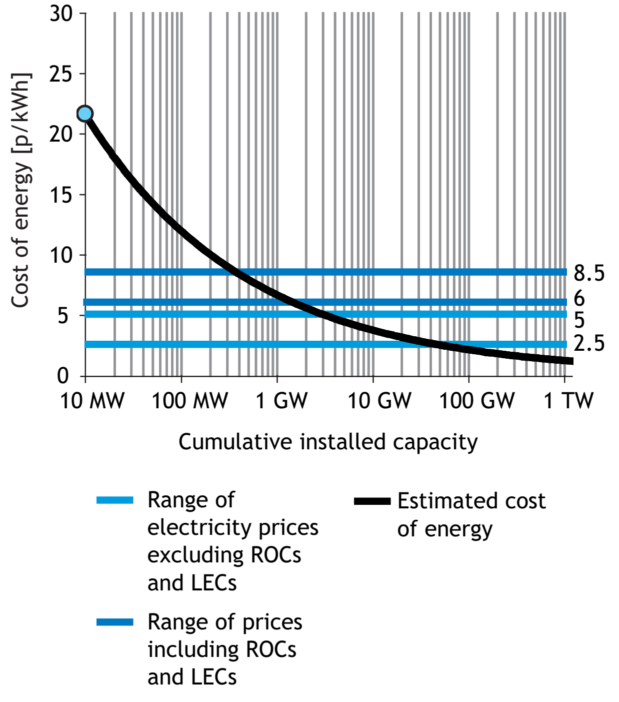
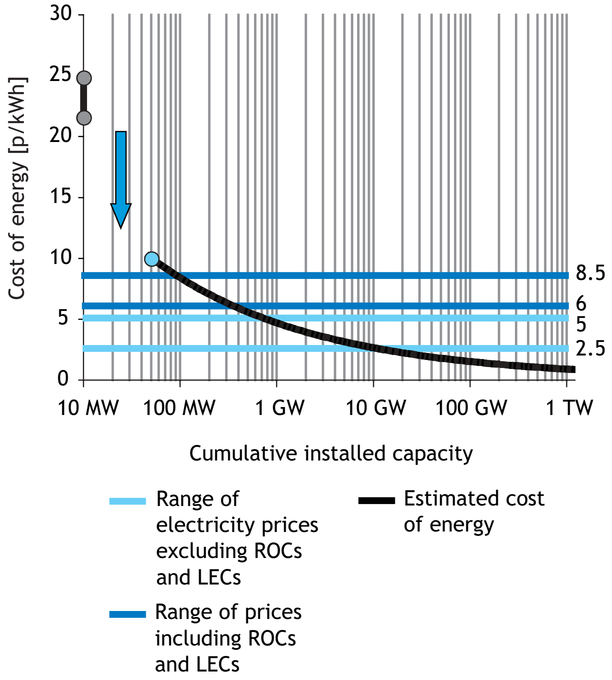


Figure 10b *Offshore wave energy cost reduction scenarios Scenario B: 21.6p/kWh starting point, 15% learning rate*



Note: Curves implicitly includes a gradually falling discount rate from 15% to 8%.
Source: Entec

Figure 10c *Offshore wave energy cost reduction scenarios Scenario C: 10.0p/kWh starting point, 10% learning rate*



Note: Curve implicitly includes a gradually falling discount rate from 15% to 8%.
Source: Entec

The obvious impact of the step change is to allow a much more rapid progression to the lowest target levels. Notably, the 6.0p/kWh hurdle is cleared below 400 MW, and although not shown, it turns out that the same level would be met below 1.0 GW had there been a step change to 10p/kWh and learning at 10%. Taking these findings with those for scenario B, it can be concluded that offshore wave energy could become competitive with CCGT generation within several gigawatts of installed capacity, provided that:

- A step change to 10p/kWh occurs and learning is anywhere in the range 10% to 15%; or
- A step change does not occur but learning is at 15%.

The total investment required to install wave and tidal stream farms and make progress towards cost reductions can be deduced from the area under each learning curve. By comparing the three scenarios, it is possible to assess the significance of the learning rate and step change to 10p/kWh on the amount of investment needed to reach different target levels.

- To reach the high fossil fuel supported level (8.5p/kWh), £18.5b is needed in Scenario A while only £770m is required for Scenario B. This massive difference points again to the sensitivity to learning rate, but also indicates that with slow learning, it would be prohibitively expensive to fund cost reduction down to even the highest target considered; and
- To reach the low fossil fuel supported level (6.0p/kWh), a total investment of £2.2b is required in Scenario B, while only £500m is needed for Scenario C. This further difference underlines the overall economic value of efforts to reduce costs of energy before large capacities of generation are deployed; particularly design improvements (the first two routes shown in Figure 8).

Based on the total investment costs, it is possible to estimate the necessary costs of support[30] above the base cost, ROC and LEC support. Assuming a constant high base electricity cost of 5.0p/kWh, this is £3.1b in Scenario A and £190m in Scenario B, but the figures are considerably higher at the lower base cost of 2.5p/kWh. In any case of base cost, the cost of additional support is much lower in Scenario C. This suggests that to make long term support above the RO and CCL likely, the base electricity cost may have to rise in combination with fast learning, or a step change reduction in the costs of offshore wave energy has to occur.

[30] Again on a Net Present Value basis, such that no distinction is necessary between capital support and revenue support mechanisms.

Near-shore and Shoreline OWCs

As a special case, we considered the cost reduction potential of near-shore OWCs. Applying a learning rate of 13%[31] to the 15p/kWh central estimate of current costs (see Figure 7) gave a cost curve similar to those discussed for offshore wave energy. This suggested that the high fossil fuel supported level could be reached after 400 MW total installed capacity, and the low fossil fuel supported level by around 1.1 GW. However, the point at which the 6.0p/kWh level is crossed is close to the total UK near-shore OWC resource, which indicates that for costs to reduce further, it would be necessary to develop overseas[32].

We did not consider shoreline OWCs for the following reasons:

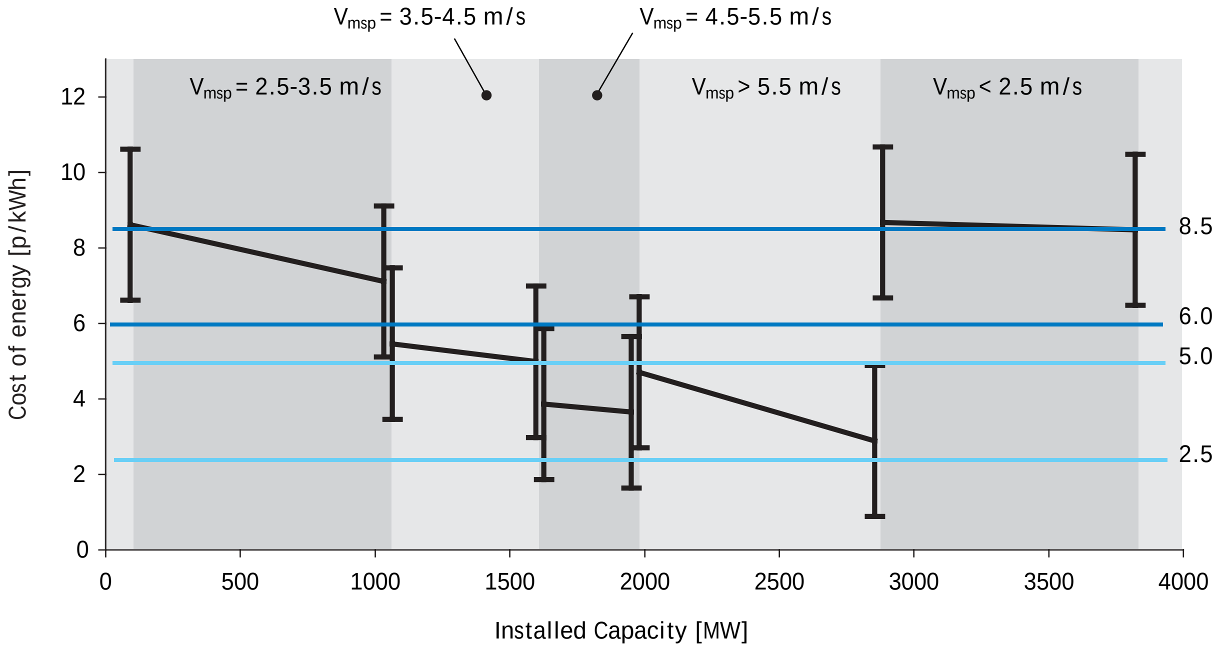
- The UK shoreline OWC resource is insignificant compared to UK electricity demand;
- Progress towards cost reductions is likely to be constrained by the small resource size (see Section 2); and
- A large part of the capital costs relate to site-specific construction work. Unless included in other large coastal structures (e.g. harbour defences), and these are to be built in any case, it is difficult to see how economies of scale could be achieved.

Cost-resource curves for tidal stream energy

The computer optimisation model developed to estimate costs of energy under different resource conditions was used to generate the cost-resource curves presented in Figure 11. These differ from the cost-curves generated for the wave energy converters in that the cost-resource curves recognise the available resource at tidal stream sites around the UK. Figure 11a is based on a view of the likely order of site exploitation with regard to water depths and mean spring peak velocities. Developments are assumed to happen in a particular sequence, which may not actually occur in practice, but is necessary to assume in order to estimate the cost of energy when most of the UK resource has been exploited. Figure 11b illustrates how the cost of energy may reduce in a more likely progression of developments, where different sites are developed at the same time rather than sequentially. 2.8 GW is an estimate of the maximum economic UK installed capacity, and represents the limit of this UK-only analysis.

Figure 11b shows that the cost of energy may have fallen to 7p/kWh by the time 1.0 GW of capacity has been installed, and after 1.5 GW could drop below 5p/kWh. The indication is that tidal stream energy could reach the lowest supported level some time before the entire UK resource is exploited. At the highest velocity UK sites, the ultimate lowest cost of energy is estimated to be 3p/kWh.

***Figure 11a** UK tidal stream cost-resource curves a) Step wise cost-resource curve*



Note: Assumes deployments in a logical sequence depending on mean spring peak velocity V_{msp}
Sources: Black & Veatch, Entec

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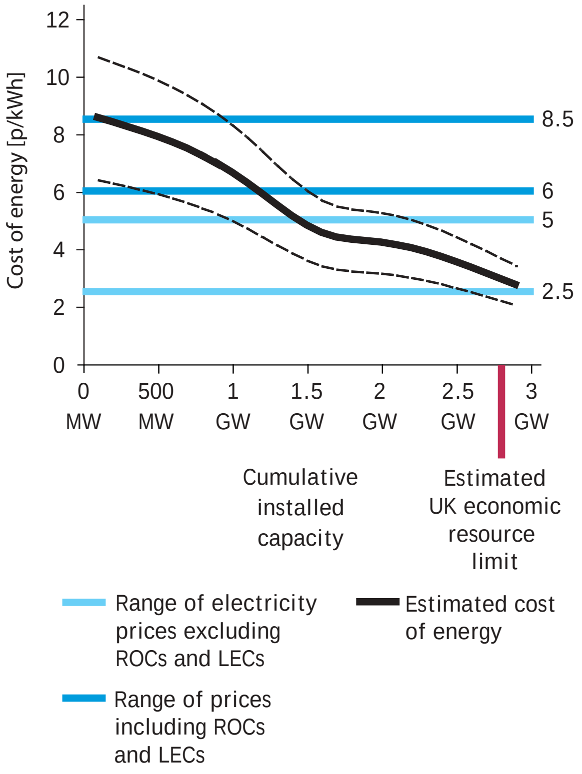
[31] Source: Arup Energy.

[32] Overseas developments could happen before the UK resource limit is reached, of course, but this is nevertheless a useful marker.

Similar to the wave energy cost curves, the total investment can be deduced from the area under the curve in Figure 11b. This would be £4.3b to achieve the 2.8 GW capacity. Depending on the base cost of electricity, the cost of support above the base cost, ROC and LEC support could be between only a few tens of million pounds to up to £500m.

***Figure 11b** UK tidal stream cost-resource curves*
b) Smooth cost-resource curve



Note: Solid line indicates central estimates while the dashed lines show error bands.

4.4 Conclusions

Based on the above, we conclude that:

- There is potential for marine renewable energy to become competitive with other generation forms in future;
- In the present market conditions, wave and tidal stream energy is likely to be more expensive than other renewables and CCGT until at least hundreds of megawatts capacity are installed. By way of comparison, this capacity is equivalent to several offshore wind farms at the scale currently being constructed;
- Fast learning or a step change cost reduction is needed to make offshore wave energy converters cost competitive for reasonable amounts of investment; and
- Tidal stream energy could become competitive with current base costs of electricity within the economic total installed capacity estimated for the UK, 2.8 GW.

5. Future growth

Can wave and tidal stream farms be developed to supply large quantities of electricity to the grid and make material contributions to energy supplies? What effect would this have on carbon emissions?

In this section we develop the findings about costs of energy to consider the growth of marine renewables over time. Key factors affecting future growth are introduced and a set of assumptions necessary to take a future view are stated. We then indicate what progress could be made up to 2020, including estimates of total installed capacity, investment and support.

5.1 Key factors affecting growth

Apart from cost of energy, a range of factors will affect the future growth of marine renewables. These can be considered in five categories:

- Strategic and security of supply;
- Financial;
- Technology and risks;
- Electricity networks; and
- Environmental and regulatory.

Strategic and security of supply

As apparent in Section 4, sustained high fossil fuel prices leading to a high base cost of electricity would bring forward the time when wave and tidal stream energy become cost-competitive and reduce the necessary costs of support. In addition, a rising oil price and/or shifts in domestic and imported fossil fuel supplies in the UK could raise interest in both the indigenous nature and lack of fuel price volatility of marine renewables. This could mean they are considered strategic within the energy mix and important for security of energy supply. The potential for carbon emissions reduction and economic development, as indicated in Section 2, should also be seen in a strategic context.

Financial

Fundamentally, growth of marine renewables depends on a willingness to finance both technology development and project development. Different parties will need to provide funds at different stages, and it is important to recognise the entry criteria, risk/reward expectations and exit points of each investor. Figure 12 indicates the parties who may be involved and the investment stages between technology development and initial project development.

Given the early stages of technologies, financial support is needed particularly for technology development at present. This includes academic and industrial R&D, engineering design and prototype testing. Academic R&D support is likely to come mainly from governments, although this may be supplemented by a flow of private equity via technology development companies and/or university commercialisation initiatives. A combination of RD&D grants, venture capital and possibly strategic investments is probable to support technology development companies in engineering design and prototype testing.

A few developers of more advanced concepts are now seeking to develop initial farms. Support to meet current costs of energy (see Section 3) will be necessary to make such projects economic, and notably, this is currently offered in two countries: the UK and Portugal[33]. While the support in each country is structured differently, a common feature is that it is effectively limited to tens of megawatts of installed capacity. Depending on fossil fuel prices and the extent of cost reductions within the scope of the schemes (see Section 4), there may still be a cost gap after the capacity limits are reached, and it is uncertain what will happen then; specifically, whether/how the cost gap will be bridged.

In the UK, the Renewables Obligation ends in 2027. So for projects to benefit from ROCs over the 20 year period envisaged in Section 4, they need to be installed by 2007. It is likely that only a small number of wave and tidal stream farms will achieve this. Without changes to legislation, developments commissioned later than 2007 will benefit for only part of their project lives.

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[33] The UK DTI Wave and Tidal Stream Energy Demonstration Scheme was launched in 2005. This offers a capital grant of up to £5m for any single project plus revenue support at 10p/kWh for 7 years post-commissioning. A total of £42m is available. In Portugal, revenue support is available at 23 Eurocents/kWh for projects over 12 years post-commissioning. 50 MW total installed capacity is supported. Details about support in other countries are given in the Forum for Renewable Energy Development in Scotland (FREDS) 2004 report Harnessing Scotland's Marine Energy Potential.

Figure 12 *Investment stages in technology development and project development*

	Initial technology development	Large-scale prototype	Initial small farms	Larger farms
Purpose of investment	Concept and detailed engineering design, tank model testing, sub-assembly and component testing	Manufacturing, fabrication, installation and testing/monitoring sea-going prototype. See note 1	Consents and permits, resource assessment, bathymetric and geotechnical surveys, site civil/electrical engineering design, transformers, subsea cables and switchgear, device installation and monitoring. See note 2	As initial farms but at larger scale
Destination of investment	Universities and technology development companies	Technology development companies	Technology development companies, project developers or stand-alone project vehicles	Project developers or stand-alone project vehicles
Risk-return expectation	Very high	Very high	High	Medium
Capital required	Up to several £100k per concept	Several £m per prototype. See note 1	£5m to £10m per project. See note 2	Tens of £m per project

Notes:
1. This assumes testing at a dedicated facility, development of which has already occurred and been financed by a third party(ies), and which offers readily available electrical connections. This is the model of the European Marine Energy Centre.
2. Some site development activities may not be necessary, and therefore associated costs not incurred, if third-party test 'hubs' are used. This is the model of the proposed Regen Southwest Wavehub.
Source: Entec

Technology and risks

After the availability of finance, the second fundamental requirement for growth is the readiness of technologies to be commercially exploited. Finance and technology readiness are closely linked, and one without the other will not allow growth to occur.

At any point in time, technology readiness depends on the rate and continuity of development in preceding years. Judging by the experience of other technologies, fast, continuous development is likely to be necessary to maximise learning and bring about cost reductions in the shortest possible time.

Important to the rate of development is the size and number of individual actors, and relationships between them. Many small, non-collaborating technology developers are likely to make progress slower than either many small collaborating actors or a few large non-collaborating ones, principally due to their ability to attract investment and deploy resources. However, the extent of collaboration will be limited by the need to protect commercial intellectual property (IP) to attract private investment.

Given the wide range of technology options, a key measure of progress in technology development will be the extent of convergence on optimal designs. This could be brought about by collaboration between developers and consolidation of IP. In parallel, developers of less promising concepts are likely to fail to attract investment, thereby further reducing the choice of technology options. Knowledge on the part of investors to enable the selection of promising technologies will have an important bearing on the convergence process.

The success of technology development is also likely to depend on the approach to managing risks. There is a commercial pressure to develop rapidly in order to maximise the value of investments in technology development, and a related argument that to delay developments is to delay learning and progress towards cost reduction. However, because the engineering challenges of design, manufacturing, fabrication and installation are significant, a counter argument is that a slower, more progressive approach is better to manage risks.

Managing technical risks in development

Survivability and reliability represent key challenges for marine renewables, due to the economic consequences of catastrophic failures and/or long periods of unavailability. For the technologies to succeed, much attention needs to be paid to technical risks in design, construction, installation and operation.

From an engineering perspective, this can be tackled in two ways. One is by importing knowledge and experience from other industry sectors, such as offshore oil and gas, including risk assessment procedures (e.g. Failure Modes and Effects Analysis[34]) and engineering standards. In recognition of this, we commissioned guidelines on the application of existing engineering standards to wave energy converters during the MEC (see Figure 13). The other approach is rigorous and extensive testing, including single components, sub-assemblies and complete functional prototypes. This will require dedicated test facilities such as those established at EMEC[35] and NaREC[36], and also the involvement of supply-chain manufacturers.

A combination of the two approaches is likely to lead to the fastest development with lowest risks. Judging by past experience, it could take several years to develop technical evidence to levels comparable with other generation technologies (e.g. wind turbines) and to the satisfaction of investors and insurers.

In practice, the balance between progress and risks is likely to mean developers take a cautious approach to deployment, particularly for first prototypes and small initial farms consisting of a few devices. Larger developments of increasing numbers of devices and installed capacities could then follow, perhaps expanding the same sites as initial farms. This represents a step-wise approach, and both evidence of achieving certain cost and performance targets and an assessment of marginal risks are likely to be necessary between each step.

Electricity networks

The growth of marine renewables projects is highly dependant on the ability to connect to the grid. Network connection has already been demonstrated to be technically possible[37], but the number of sites where both a suitable wave or tidal stream energy resource exists and it is possible to grid-connect is limited. Information on this constraint is scarce and the UK situation is currently being investigated by an industry study[38] (not complete at the time of writing).

Where connections are possible around the UK, they will most likely be to distribution networks close to the coast which serve small populations. The capacity of these networks is likely to be limited without modifications and reinforcements, and given the high costs and risks of initial wave and tidal stream farms in their own right, upgrade costs are unlikely to be palatable to developers. This may restrict the capacity of initial farms and/or the number of initial individual developments, but the economics of later, larger projects could possibly support upgrades to overcome capacity constraints.

Wave and tidal stream farm development also has implications for transmission networks. Figure 14 shows that the UK's most energetic wave energy resources are off northwest Scotland, but unfortunately grid capacity here is very limited. Interconnectors to the Scottish islands are already insufficient to accommodate proposed wind farms, and without upgrades, wave and tidal stream farms may be precluded. If marine renewables were developed in Scotland, north-south power flows could be increased above levels already foreseen for wind farm developments, and this has a bearing on the Scottish interconnector.

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[34] Source: Atkins

[35] The European Marine Energy Centre, Orkney, Scotland

[36] The New and Renewable Energy Centre, North East England

[37] In the UK, both EMEC and the Wavegen LIMPET shoreline OWC (Islay) are grid-connected.

[38] The British Wind Energy Association npower juice Path to Power project. This is also considering regulatory, environmental and financing issues.

Figure 13 *Guidelines on design and operation of wave energy converters*

By design, wave energy converters are subject to challenging environmental conditions of large waves and strong winds, and need to survive large structural forces. Access to offshore wave energy converters is also difficult, which makes reliable operation with minimal manual intervention important.

Early in the MEC, we identified a need for guidance on the application of existing standards to wave energy converters. This was in consultation with technology developers and offshore engineering experts, some of whom had already begun applying standards to their designs. We subsequently commissioned Det Norske Veritas to produce a set of guidelines that give signposts to particularly relevant standards and an interpretation of where and why these are helpful. The guidelines are intended mainly as a design aid for wave energy technology developers but should also interest investors and insurers.

The purpose of the guidelines is not to enforce existing standards onto wave energy converters necessarily. This would be misguided, since wave energy converters differ from other offshore equipment in several key respects (such as that they are unmanned and do not carry large quantities of hydrocarbons). Rather, it is intended that the guidelines will help developers identify where standards may be helpful, and by applying them in these cases, gain a head-start in designing technical risks out of their concepts.

The guidelines do not represent new technical standards but rather interpret what is known already for the specific application of wave energy conversion. We see them as a ‘stop-gap’ while dedicated standards for wave energy converters do not exist. Other parties such as EMEC have also begun work on standards for wave and tidal stream energy, and these activities are important to the sector.

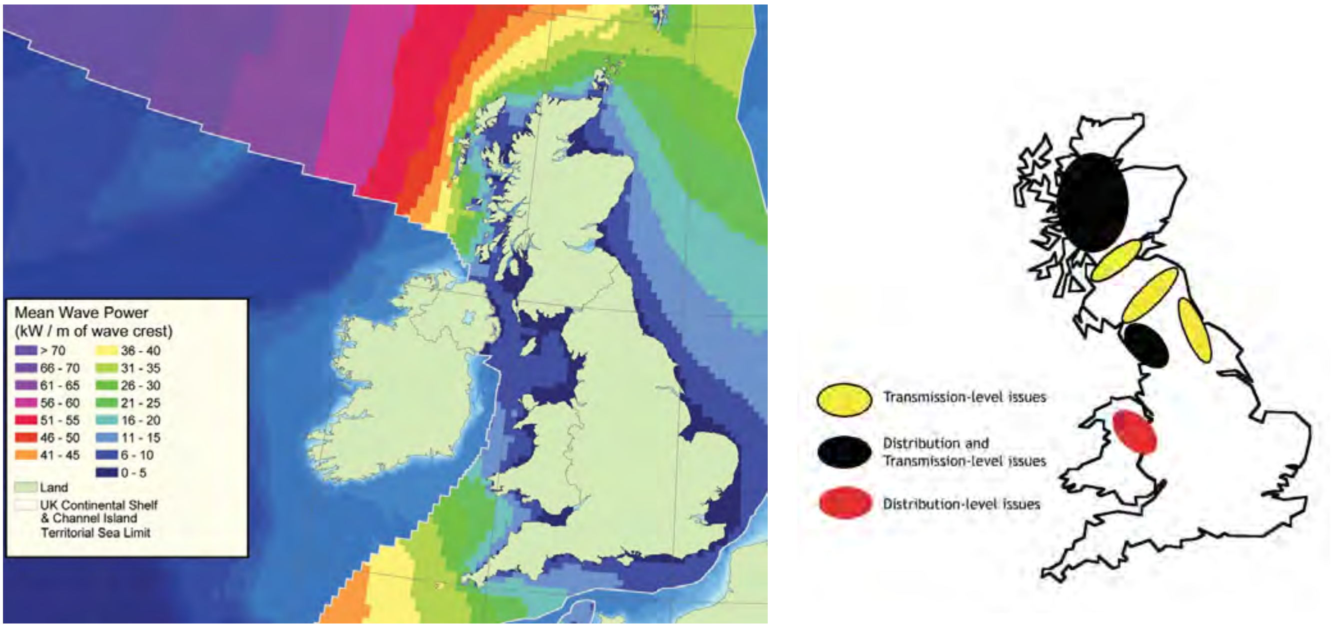
The Guidelines are available free on the Carbon Trust website.

For initial wave farms, transmission capacity may be a secondary issue to the availability of distribution network connections, due to the ability to locate in many possible areas, some albeit with a compromise in energy resource, (which due to subsequently lower performance could cause costs of energy to be higher). However, if not accommodated in current upgrade plans, transmission capacity could be a major constraint to large wave farms of tens of megawatts capacity. Tidal stream developments of all sizes may be more affected by distribution and transmission network constraints than wave farms due to the more limited number of possible sites.

The electrical engineering design of marine renewables devices impacts on their ability to be grid-connected. In particular, the choice of electrical machine and/or use of an inverter may influence the capacity that can be installed, due to low fault levels close to the coast. The response of generators under fault conditions may be important as installed capacities increase, as has been the case with wind turbines. However, these concerns are secondary to network capacity in the short term.

Like the wind, waves and tidal streams are variable renewable energy sources. Their intermittent generation has implications for large scale grid integration, but at small scales is likely to have only a marginal impact on network management, similar to the effect of wind farms in the UK today. Variability is therefore not an immediate concern. In future, there could be some benefits of combining wave and tidal stream energy with wind energy (see box overleaf).

Figure 14 *UK areas of high wave energy and grid capacity constraints*



a) Areas of high wave energy

b) Key system capacity constraints

Sources: Carbon Trust & DTI (2004), Renewables Network Impacts Study; DTI (2004), Atlas of UK Marine Renewable Energy Resources

Variability of wave and tidal stream power

The amount of energy in waves and tidal streams naturally varies over time. Consequently, the power output of wave energy converters and tidal stream energy generators will also vary. It is important to understand the variability of the resource in order to predict amounts of generation, and also assess implications for grid integration, particularly balancing supply and demand. Key issues are the degree of variation over different timescales, relationships between power supply variability and demand variability, and the predictability of variations.

As part of the MEC, we commissioned the Environmental Change Institute at the University of Oxford to look into the variability of marine energy resources. Key findings of the study are as follows:

- On average, wave power could deliver significantly more energy during high demand periods than at other times;
- Adding wave power to the grid may result in lower overall variability than adding just wind power;
- The capacity credit of a mixed system including wave, tidal stream and wind power could be higher than just wind power, and the balancing costs could be lower;
- Existing wave forecasting models are valuable for predicting wave power up to five days ahead; and
- Due to the correlation characteristics between wind, wave and tidal stream energy, it could be that electricity network capacity can be better utilised (allow greater net energy transfer) by a combination of these renewables, rather than any one singly.

More details of the study are available on the Carbon Trust website.

Environmental and regulatory

Environmental concerns and government regulation may affect the rate of growth of marine renewables. The installation and operation of devices is likely to have some impacts on the local natural environment. Studies to date suggest that local environmental disbenefits are likely to be minor, but further research is required into device-environment interactions[39] amongst other topics. The DTI has allocated £2M of the £50M Marine Renewables Deployment Fund to environmental studies, and some Cowrie[40] work is relevant to wave and tidal stream energy.

In the UK, processes to consent and permit initial wave and tidal stream farms have recently been clarified by a DTI guidance note[41], which followed workshops in Spring 2005 to identify the concerns of developers, government departments and agencies (including the Crown Estate) and environmental stakeholders. Environmental impact assessments will be required, and the required consents relate to the Electricity Act, Food and Environmental Protection Act and Coastal Protection Act, similar to offshore wind developments. Consenting arrangements for larger, later wave and tidal stream farms are not yet clear, but Crown Estate competitions for seabed leases could possibly be held[42] like the two rounds to date for offshore wind.

Key aspects of future UK regulatory frameworks are likely to be Strategic Environmental Assessment (SEA) and marine spatial planning. The Scottish Executive has begun a SEA with a view to future wave and tidal stream developments, and DEFRA is carrying out a marine spatial planning pilot study. A Marine Bill has been proposed to manage sustainable development of the UK marine and coastal environment, and spatial planning is a central concept of this. The government intends to produce a draft bill in Autumn 2006, and the bill could be enacted by the end of 2007 at the earliest. The Marine Bill's implications for wave and tidal stream projects are unclear, although a stated intention is to facilitate consents for offshore renewables projects. It is possible that a new Marine Agency could be created with responsibility for spatial planning.

Development of wave and tidal stream farms may also impact upon other sea users and commercial activities, including shipping, fishing and aggregate extraction. However, due to limitations of available data, it was not possible to address these during this study.

5.2 Assessment of growth potential

The number of factors affecting growth and the relationships between them make growth complex to model. The limited evidence of some key factors such as grid capacity compounds this. However, it is possible to take a 'what you need to believe' approach to form a view on how growth could occur, based on a number of detailed assumptions.

The following table shows a set of assumptions we have developed in order to take a view of future growth. We consider that overall, the assumptions make for an optimistic but achievable view of the future. Given the present stage of technologies, it is impossible to characterise growth beyond 2020 with any certainty, and for this reason the scope of assumptions is limited to the next 15 years. All assumptions are made on a Europe-wide basis.

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[39] Such as the impact of tidal stream energy generators on flow momentum.

[40] A UK, industry-funded environmental research organisation for the offshore wind industry.

[41] DTI (2005), Guidance on consenting arrangements in England and Wales for a pre-commercial demonstration phase for wave and tidal stream energy devices (marine renewables).

[42] As envisaged in the DTI consultation paper Future Offshore (2002).

Growth Factors	Assumptions: 2005-2010	Assumptions: 2010-2020
Strategic and security of supply	Fossil fuel prices are at sustained high levels, leading the base cost of electricity to rise gradually to 5.0p/kWh by 2020.	
Financial	£80m capital investment is made to support academic R&D, engineering design and prototype testing. This comprises government grants and venture capital investments. Between £120m and £200m capital investment is made into project development of initial wave farms. This comprises private equity investments in projects and government capital grants.	There is still a cost gap after capacity limits associated with current support schemes are reached. But the success of demonstrating prototypes (see below) motivates further government support and private investment in both technology development and project development.
Technology and risks	Technology development is continuous and occurs at a rate proportionate to the amount of finance available. Academic R&D efforts accelerate beyond current levels and focus on key barriers to cost-competitiveness. Detailed design optimisation of better developed technologies progresses in parallel with work to prove/disprove alternative concepts. Large-scale prototypes of several types of wave energy converter and tidal stream energy generator are successfully demonstrated. In proportion to the capital available for project development, development of initial wave and tidal stream farms proceeds to a total installed capacity of between 60 MW and 100 MW. Progress with proving large-scale prototypes and initial farms dictates overall progress. Survivability, performance and reliability become clearer due to the results of large-scale prototypes, but uncertainty remains about large-scale farms. Progress with technology development is not fast enough for a market pull to occur.	Technologies converge on five or fewer optimal concepts (both wave and tidal stream). Subsequent efforts are focused on developing these. The convergence of technologies reduces the number of isolated actors and allows technology development to accelerate. Industrial R&D picks up in parallel with continuing academic R&D. Larger farms up to several tens of megawatts are developed, and their performance and reliability is demonstrated. A market pull occurs and causes deployment rates to accelerate rapidly.

Growth Factors	Assumptions: 2005-2010	Assumptions: 2010-2020
	Risks are managed in progressive, step-wise technology and project development programmes. Technical risks in design, construction, installation and operation are well managed by the application of appropriate standards and testing.	
Electricity networks	Developers of initial wave and tidal stream farms seek connection points where no upgrade is required. Network capacity does not increase due to demand from marine renewables projects. Overall, there are sufficient grid-connectable wave energy sites that distribution network capacity is not a constraint. However, the capacity of most sites is limited to 10 MW, and the choice of larger sites is restricted.	Project developers seek connections for projects of tens of megawatts installed capacity, some of which require upgrades.
Environmental and regulatory	The environmental impacts of large-scale prototype wave energy converters and tidal stream energy generators are monitored. Developments in some coastal areas are prohibited or restricted by ecological concerns, but this does not restrict overall growth. Regulatory arrangements to consent and permit wave and tidal stream farms are developed. They include strategic environmental assessment and spatial planning, both of which facilitate rather than hinder developments. Projects take between 12 and 24 months to consent from the time a proposal is raised with the relevant authorities.	

5.3 Estimates of future growth

Deployment by 2020

Based on the 'what you need to believe' model, we predict that up to a few gigawatts of wave and tidal stream energy could be installed across Europe by 2020. Specifically, our analysis indicates that between 1.0 GW and 2.5 GW of each of wave energy and tidal stream energy could be installed.

The investment necessary to reach these levels of deployment, costs of support above the rising base price and level of carbon dioxide abatements are shown in Figure 15 below. To put the table in context:

- The overall deployment is greater than the current installed capacity of UK wind farms, and equivalent to several large offshore wind farms[43]; and
- The progress in increasing installed capacity is similar to wind energy worldwide between 1980 and 1990. For comparison, the box overleaf gives further details of the historic progress of wind energy, including amounts of public support.

It is possible that a large share of the deployment envisaged across Europe could occur in the UK. If this happened, up to one sixth of the UK government aspiration of 20% renewable energy by 2020 could be met by marine renewables (i.e. about 3% of total UK electricity demand).

Figure 15 *Conclusions from growth model to 2020 across Europe*

	Wave energy	Tidal stream energy
Total installed capacity (MW)	1,000 to 2,500	1,000 to 2,500
Total capital deployed (£m)	1,000 to 2,500	1,000 to 2,500
NPV cost of support above base electricity cost (£m)	700 to 2,200	500 to 2,000
Annual carbon dioxide abatement ($MtCO_2$/y)	1.0 to 3.3	1.0 to 3.7

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[43] For instance, the London Array is proposed to have a total installed capacity of 1.0 GW. Source: London Array Ltd.

Although the contribution to reducing carbon emissions would be relatively small in the context of total UK emissions, it could still be a significant share of the contribution by UK renewables overall.

Further benefits of the UK taking a leadership role in market development relate to the potential for economic returns, as indicated in Section 2 and discussed further in Section 6.

Comparisons with wind power

Technology

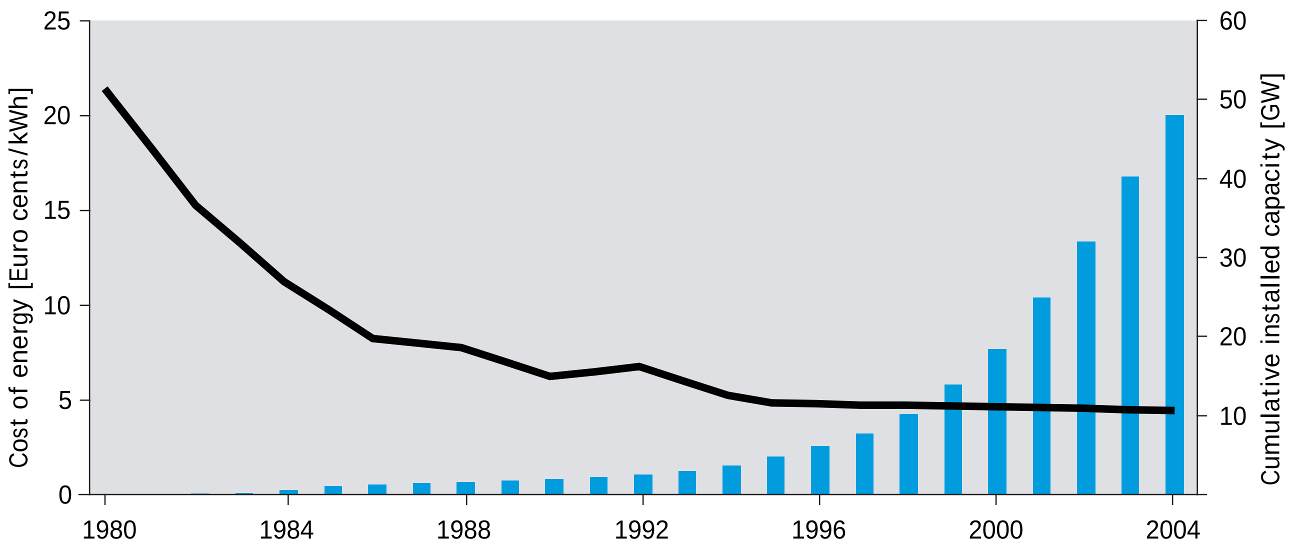
Wave energy converters and tidal stream energy generators have similarities to wind turbines, such as in their use of structural materials (steel, concrete) and components and unit generation capacities. Construction and operation of wave and tidal stream farms are also likely to be similar to offshore wind farms.

Overall, wave and tidal stream technology is at a similar stage to wind technology in the 1970s and early 1980s, when a range of wind turbine concepts were being investigated, and it was uncertain which, if any, concept would become cost-competitive. Wind turbine manufacturers converged on the 3-bladed upwind horizontal-axis design, and competitiveness with conventional generation has now been demonstrated for high wind speed sites.

Growth

Largely since technology convergence, the growth of wind power has been rapid. Global installed capacity grew from around 10 MW in 1980 to 2.0 GW in 1990 (see Figure 16), and exceeded 50 GW during 2005. Average growth has been 15.8% over the past five years[44].

Figure 16 *Growth of wind energy worldwide*



Note: The bars show worldwide cumulative installed capacity and the line indicates costs of energy.

Sources:
- Growth figures: BTM Consult (2005);
- Cost of energy data 1980-1994 for Denmark: Chapman and Gross (2003), The technical and economic potential of renewable energy generating technologies: Potentials and cost reductions to 2020; and
- Cost of energy data 1995-2005 for Denmark and USA: Milborrow (2006), Windpower Monthly vol 22., No.1.

Cost reduction and subsidy support

Figure 16 indicates how the cost of wind energy has reduced with growth in installed capacity. Evidence of the cost reduction trend was seen in the UK during the 1990s, with NFFO[45] contract prices falling from 10.0p/kWh to below 3.0p/kWh[46]. Learning rates appear to have differed over time (meaning they depend on the time interval chosen for analysis) and between countries, but an overall rate of 18% has been identified[47].

Growth in installed capacity would not have occurred without subsidy support, and the cost of wind power is unlikely to have reduced to the extent it has without growth. By extension, therefore, the cost of wind power has been reduced by subsidies. Total subsidy support by European countries and the USA totals the equivalent of several £b[48], including £714 million support under successive NFFO rounds in the UK[49].

Deployment beyond 2020

Although it is difficult to characterise growth after 2020, estimates of the total resource size (see Section 2) suggest that the industry could develop much further beyond this date, both in the UK and worldwide.

5.4 Conclusions

Although dependant on a complex array of factors, there is considerable potential for marine renewables to grow. By 2020, several gigawatts of generating capacity could be installed, and potentially meet a small but significant share of the 2020 UK renewables aspiration. Beyond 2020, the industry could grow much further.

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[44] Source: BTM Consult (2005).

[45] Non-Fossil Fuel Obligation (England and Wales), Scottish Renewables Order and Northern Ireland Non-Fossil Fuel Obligation.

[46] Source: DTI (2001), A summary of the experience of wind energy support through the NFFO. Note that between the early NFFO rounds, the price reduction was partly due to a change in contract length.

[47] Sources: Junginger et al (2005), Global experience curves for wind farms; IEA (2000), Experience Curves for Energy Technology Policy.

[48] Information on subsidy levels in different countries is fragmented, but the following are useful indications: The US spent $1.2 billion (1999 dollars) between 1947 and 1999 on wind energy subsidies (Source; Goldberg (2000), Federal energy subsidies: Not all technologies are created equal). Denmark spent DKr 3.8 billion (about €0.75 billion) on subsidies for wind between 1993 and 1998, including tax expenditures and prices subsidies (Source: O'Brien et al (2001), Encouraging Environmentally Sustainable Growth In Denmark, Economics Department Working Papers No. 277, OECD; in money of the day). Germany is estimated to have spent a total €1.4 billion on R&D support, price subsidies and feed-in tariffs up to 2000, (source: Neij et al (2003), Experience curves- a tool for energy policy programme assessment). A different source indicates Germany spent around €1 billion on wind support in 2001 alone (Source: Eurelectric (2004), A Quantitative Assessment of Direct Support Schemes for Renewables). Data collated by Paul Arwas Associates.

[49] Between 1990 and 2001. Source: Frontier Economics (2001), Evaluation of DTI Support for New and Renewable Energy under NFFO and the Supporting Programme

6. Next steps

The preceding sections indicate the potential for future cost reduction of wave and tidal stream energy generation, and how growth could occur over the next fifteen years. Based on this evidence and our experience of working with technology developers in the MEC, this final section draws conclusions on next steps for the development of marine renewables in the UK.

6.1 Overall perspective

At a high level, we consider that UK public and private sector organisations should continue to encourage the creation of a wave and tidal stream industry. This view is based on:

- The potential for low carbon electricity generation in this country and others, which could be highly material amongst efforts to combat climate change and increase security of energy supplies; and
- The potential significant economic returns to the UK from sales of generation devices, project development and revenue from electricity generation, as indicated in Section 2.

The UK is well placed to leverage its skills and experience in offshore oil and gas, ship-building and power generation to accelerate progress in the marine renewables sector and capture the economic value for the UK. While technologies are at early stages, support and investment in technology development can be seen as maintaining the option of marine renewables for future years, looking ahead to the time when cost reductions have occurred to an extent where the technologies are competitive with other conventional and renewable generation.

We consider there is a strong case for industry to accelerate the overall pace of development of marine renewables beyond current levels, which translates into

Figure 17 Key actions to put marine renewables on the path to growth

Technology developers	Maintain strong focus on cost reduction; and Accelerate engineering testing and prototype demonstration to develop track records of survivability, reliability and generation performance characteristics.
Public sector funders	Give increased support over time for marine renewables technology development, with greater support for RD&D and cross-cutting technology issues to help deliver cost reductions; Support marine renewables project development from now into the medium term, contingent on technologies proving technically viable in the first instance, and later, evidence of reducing costs; and Develop a clear long-term policy framework of support to the sector to give greater investment certainty.
Academic researchers and funding bodies	Place greater emphasis on cost reduction topics, particularly to overcome cost barriers that are common to many device concepts.
Ofgem and electricity network operators	Actively consider the future capacity of wave and tidal stream energy when planning grid modifications and upgrades.
Government, industry and environmental stakeholders	Take a pragmatic, prioritised approach to overcoming environmental uncertainties; and Take a proportionate approach to local environmental impacts of small developments, recognising the global environmental benefits of low carbon generation from future, larger projects.

a requirement for both significant further public support and private investment in development activities.

Given the current costs of energy found in this study, we think that considerable emphasis needs to be placed on cost reduction to ensure the commercial viability of wave and tidal stream technologies. The MEC has demonstrated that certain technologies have considerable potential for cost reduction, but further efforts in maximising performance and minimising capital and O&M costs will be needed for some years to come.

Key to the availability of private equity is clarity of the route to market, particularly in recognition of the cost gap between marine renewables and other means of generating electricity. Our cost-competitiveness analysis indicates that public support for costs of energy above those of conventional power and other renewables will be necessary in the medium term.

Figure 17 summarises our view of actions key players should consider to accelerate progress.

6.2 Strategic development objectives

With wave and tidal stream energy resources being significant in the UK and overseas (see Section 2) there is potential for both strong domestic and export markets in marine renewables. Noting the experience of countries exporting generation technologies (particularly Denmark with wind turbines[50]), considerable returns can be gained from developing both generation products and services to construct, install and operate in parallel. We consider that to maximise economic returns and make the fastest progress towards cost reduction and growth, UK plc should encourage both wave and tidal stream technology development and project development. We therefore see a need for a two-pronged approach to public support and private investment, which:

- Accelerates the progress of technology development, through ongoing RD&D into concept and detailed engineering design to bring about substantial reductions in cost; and
- Encourages early development of wave and tidal stream farms to accelerate learning effects.

Noting the key barriers identified in this report of high costs, uncertain costs and performance, and the unproven nature and diversity of technologies, we identify four key objectives for development support:

1. Maximise the extent of cost reductions by all four of the routes identified in this study (concept design improvements, detailed design optimisations, economies of scale and learning). For offshore wave energy, set an environment for fast learning and maximise the likelihood of step change cost reductions;
2. Increase certainty about costs and performance;
3. Develop track records of survivability and reliability; and
4. Encourage convergence on optimal technologies as soon as possible.

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[50] For details, see the case study in Carbon Trust (2003), Building Options for UK Renewable Energy.

Approach to technology development

Our assessment of a range of technologies in the MEC leads us to the view that there are no fundamental engineering barriers to the technical proving of wave and tidal stream energy devices. However, considerable further engineering effort will be necessary to see wave energy converters and tidal stream energy generators succeed.

To maximise the likelihood of success, we see a strong need to:

- Accelerate the development of promising technologies that are already advanced. This should not be without heed to the balance of progress and risks, but is in recognition that a considerable number of engineering challenges lie ahead;
- Continue investigating promising concepts that are less advanced but have potential to compete with current front-runners; especially those offering step change cost reductions. This is because current front-runners may not ultimately be most economic; and
- Stop developing unpromising technologies. This sounds obvious, but, in our assessment, some concepts currently being pursued, including those falling outside the lowest-cost groups described in Section 3, are unlikely ever to be cost-competitive.

Technical barriers to project development

Apart from generation technologies, there are a range of technical barriers to development of wave and tidal stream farms. These are related to financing and insurance, and can be defined on a top-down basis by considering the evidence needed to satisfy a technical due diligence exercise. Present uncertainties include a lack of:

- Proven methodologies to conduct resource assessments and energy yield predictions, which are key inputs to project financial models;
- Standards for certification of device structural integrity, reliability and moorings or foundations; and
- Evidence of long-term availability, linked to robust maintenance philosophies.

Again, from an engineering perspective, we see no reasons why these barriers cannot be overcome. Some are likely to be solved in the course of technology development, but we see a role for coordinated industry projects in parallel.

6.3 Development costs and timescales

Our experience of the MEC and observations about the progress of technology development teams indicate that:

- Evaluation of wave and tidal stream concepts to the point that costs of energy are reasonably firm can cost up to several hundred thousand pounds;
- Development of engineering designs to the point of finalisation for initial large-scale prototypes is likely to cost several million pounds; and
- Manufacturing, installation and testing a large-scale prototype is also likely to cost several million pounds.

Furthermore, the capital costs of initial wave and tidal stream farms are likely to be upwards of £5m per project, with several hundred thousand pounds of O&M costs.

Given the progress of successful technology development teams to date, we think the passage of designs from initial concepts to full-scale prototypes is likely to take at least five years. Initial projects could take between one year and three years to develop and finance, and can be expected to operate for at least 5-10 years in order to make investments worthwhile. Noting these timescales, it can be concluded that substantial public funding and private investment in technology development is likely to be needed for at least 10 years. In addition, public support for project development will be necessary for at least 15 years.

6.4 Approach to future support and investment

We consider that greater private investment in technology development is likely to be most material to accelerating progress and achieving cost reductions. At present, there is an important role for venture capital and strategic investments, and more involvement of both large industrial equipment manufacturers and smaller, more specialist manufacturers, fabricators and installers could bring great benefits.

However, public funding and policy support are also critical, and public sector organisations need to take a leadership role for two key reasons:

- While technology risks are high, the appetite of private investors in technology development will be limited. Interest is picking up but will take time to grow as uncertainty reduces and track records are developed; and

- In order for technology developers to make robust cases for private investment, they must be able to demonstrate a clear route to market which satisfies investors' entry and exit criteria. Crucially, this requires a visible long-term policy commitment to support cost reduction and growth.

6.5 Next steps for the Carbon Trust

Based on the success of the MEC, the Carbon Trust intends to continue to play an active role in supporting marine renewables. We are already forming ideas of what to do next in discussion with industry players and will develop these over the coming months. We are also developing the above conclusions within a review of the policy framework to support renewables to 2010 and 2020, which will form part of our input to the UK Energy Review and be published later in 2006.

As further specific outcomes of this work, we intend to publish two technical reports:

- A summary of the MEC methodology for cost of energy assessment. This is to help others replicate the MEC process and help bring clarity and consistency to the commercial assessment of device concepts; and
- A summary of R&D requirements for cost reduction. This is to input to the R&D Roadmap initiative being conducted by Edinburgh University under the Future Sources of Energy theme of the UK Energy Research Centre.

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The Carbon Trust works with business and the public sector to cut carbon emissions and capture the commercial potential of low carbon technologies.

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