Ocean Energy: Cost of Energy and Cost Reduction Opportunities

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SI OCEAN

strategic initiative for ocean energy

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1 Introduction

The Strategic Initiative for Ocean Energy (SI OCEAN) aims to provide a co-ordinated voice for the ocean energy industry in Europe and to deliver practical recommendations to remove barriers to market penetration. The project will create a common strategy for wave and tidal stream energy deployment, paving the way for market growth. This report on cost of energy is the second task undertaken as part of the technology assessment component of SI Ocean. It builds on the technology status report *Ocean Energy: State of the Art*[i] and provides underpinning analysis for a future deliverable from the project, the Strategic Technology Agenda.

Wave and tidal stream energy technologies have made significant progress in recent years. A number of full scale prototypes are now in operation and generating to the electricity grid and the plans for first arrays are well advanced. It is important for policy makers and those who might invest in ocean energy generation to have a picture of the current costs for ocean energy generation and how these are likely to reduce over time.

This report investigates the cost of energy from early arrays, and predicts how this is likely to reduce over time. It has been informed by a series of in-depth interviews with technology developers and builds on the experience of the SI Ocean partners. In Section 3 early array costs based on data from developers with mature technologies and experience of prototypes are presented, predicting costs for a 10MW array at the point when 10MW of the technology has already been installed. Section 4 examines opportunities for cost reduction in the different cost centres that contribute to Levelised Cost of Energy (LCOE). Building on the technology challenges identified in the SI Ocean *Ocean Energy: State of the Art*[i] report, specific opportunities to reduce capital and operating cost and increase yield are identified and themes such as the role of the supply chain examined.

Future costs are projected in Section 5 using learning rate assumptions. This top-down approach is cross checked by a bottom-up approach looking at the potential impact of specific cost reduction opportunities, to demonstrate that the top-down predictions can be correlated with engineering expectations.

Future work by the SI Ocean project will build on this analysis to develop a co-ordinated industry strategy to capture cost reduction opportunities and build up experience and confidence.

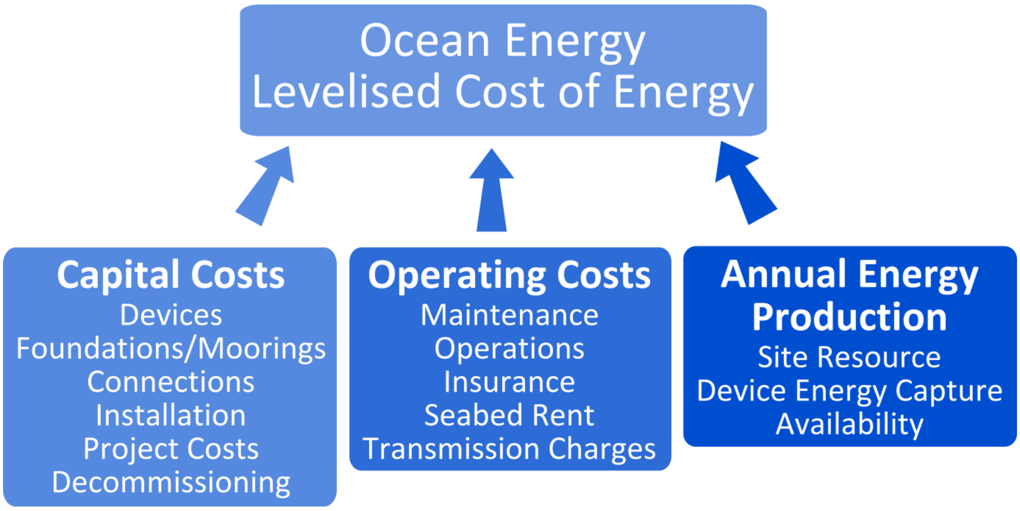
2 Factors considered in cost calculation

This section explains the method used to calculate Levelised Cost of Energy (LCOE) and identifies the important variables which influence this.

2.1 Lifetime levelised cost of energy calculation

In order to calculate the lifetime cost of energy from an array of ocean energy devices, the lifetime costs (both capital and operating), and the cumulative energy yield for the array must be considered. A discount rate is also used to account for the time value of money by calculating the present value of future costs.

Figure 1 Factors affecting LCOE



Capital costs of equipment, including installation and project management, are incurred mostly at the beginning of a project while **operating costs** such as maintenance, rent and insurance are spread over the lifetime of the array. Decommissioning costs are also considered.

The cost per kWh will depend on the amount of electricity generated by the array and so the yield of the devices at that particular location is a key input to calculate the cost of energy. This will depend on the **resource** available, the characteristics of the devices in converting the resource into electrical energy and the **availability** of the device - the proportion of time for which it is operational. **Load factor (LF)** can be derived from the **Annual Energy Production (AEP)** in kWh from a device rated at R MW using the following formula.

$$LF = \frac{AEP}{87.6 \times R}$$

A **discount rate**, must be used to translate future costs and revenue back to present values for the calculation of cost per unit of energy produced. The discount rate – a measure of the 'cost of money' - is an important variable in the LCOE calculation and will be chosen to reflect the perceived risk of a project as well as money market rates and the kind of financing (debt or equity) available

Income will be earned over the **operating lifetime** of the plant. In this report we use a discount rate of 12% and assume a lifetime of 20 years unless stated otherwise.

The **Levelised Cost of Electricity** is the sum of capital and lifetime O&M costs (discounted), divided by lifetime electricity generation to grid (discounted).

Assuming that the O&M cost and power generated is constant each year, this is represented by the following formula:

$$LCOE = \frac{SCI + SLD}{87.6 \cdot LF} \cdot \frac{r \cdot (1+r)^n}{(1+r)^n - 1} + \frac{OM}{87.6 \cdot LF}$$

LCOE: Levelised cost of electricity [c€/kWh]
SCI: Capital cost of the power plant [€/kW]
SLD: Specific levelised decommissioning cost [€/kW]
LF: Load factor of the facility
r: Discount rate
n: Facility lifetime [year]
OM: Annualized O&M costs [€/kW]

The specific levelised decommissioning cost can be calculated with the following formula:

$$SLD = \frac{SDC}{(1+r)^n}$$

SDC: Specific decommissioning costs at end of lifetime [€/kW]
r: Discount rate
n: Facility lifetime [year]

2.2 Risk factors and the impact on project costs

Perception of risk is an important factor influencing the financing of ocean energy projects. The actual rate of return used in project calculations will depend on the view of those financing the project on the overall risks involved. Projects perceived as having a high risk of overspend or of lower than predicted revenue will require a higher rate of return to make the project attractive. The **hurdle rate** is the minimum rate of return that the investor will accept on the project.

Elements of risk that affect the hurdle rate for an ocean energy project can be characterised as:

- Project risk – all projects have risks of unforeseen events and cost overruns. The marine environment, which by its nature has extreme metocean conditions which can lead to delays in installation and damage to vessels and equipment, has many associated risks.
- Technical risk – this is the additional risk associated with the particular technology. The perception of technical risk will depend on how confident the investors are that the technology will perform reliably and produce the expected output. The first ocean energy arrays inevitably have risk associated as there is a lack of experience in design, installation and operation.
- Other risks – these will include risks around lack of certainty about subsidy regimes and political support for the technology.

Along with reducing costs, certainty of cost estimation is key to the approval of commercial projects. Significant progress is being made with prototype demonstrations and plans for the first ocean energy arrays, but because no full arrays have yet been built there are uncertainties about the actual costs and performance.

The key factors for reducing the perception of technology risk are:

- Predictability of energy output from devices at the project site
- Confidence in reliability and availability assumptions
- Confidence in capex and opex estimates

2.3 The role of project developers

Significant ocean energy generation capacity will not be installed without project developers committing substantial resources to develop arrays. In practice it is likely that the main investors in projects will be energy companies (for example, currently 90% of investment in UK offshore wind projects is from utilities and independent power producers) so a crucial question for the future of ocean energy in Europe is, how do ocean energy projects become viable investments for energy companies?

Energy companies have many different generation portfolio options (including both fossil fuel and alternative forms of renewable energy) that they could choose to invest in. They are ultimately driven by shareholder returns and will only invest in ocean energy projects if they think the profitability is acceptable. When assessing projects a utility will carry out detailed cash flow modelling, looking at optimistic and pessimistic assumptions and assessing the impact on rates of return. Risk is the major influence on setting the acceptable hurdle rate. Utilities recognise the future potential of the wave and tidal industry and are prepared to accept higher risks for early arrays but will be making commercial decisions about further large scale deployment.

The ideal long term situation for utilities would be to source wave or tidal devices as they do other generating equipment i.e. to have a choice of a range of well understood 'off the shelf' products, with warranties and backup engineering support from a well-resourced organisation. A key challenge for ocean energy device developers is how to become 'the type of supplier utilities would like to have'.

2.4 Project development and consenting costs

A series of activities are necessary to assess the suitability of a site before manufacture and installation of an ocean energy array can proceed: preparation of engineering designs, carrying out costing and obtaining necessary permissions. Project developers must carry out a set of investigations, and initial design work, and be granted approval by relevant bodies. All these activities have costs associated with them and an estimate for typical sites has been included in the 'other capex' cost centre. The barriers to site development will be further examined in the SI Ocean Market Deployment Strategy, one of the final SI Ocean project deliverables.

Site appraisal activities will include:

- Design and feasibility assessments
- Seabed surveys
- Environmental surveys, environmental impact assessment
- Resource characterisation

Consultation with local residents, fishing industry and other stakeholders is an on-going process during development stages and is an important step in gaining project approval from statutory bodies in the form of relevant leases and planning consents.

Obtaining an electricity grid connection agreement is an essential step in project development. There may be a long lead time before the grid connection is available.

2.5 Grid connection and transmission charges

Two components of cost with significant variability (between different sites and between countries) are grid connection cost and transmission charges. Connection costs will vary depending on the distance to the main grid system and the work required to make suitable connections to the transmission network. Transmission charges may also reflect requirements for grid strengthening to connect power from remote locations. For example there is likely to be a large difference in costs between connecting an array off the Outer Hebrides, which will require connection via an island to a remote part of the Scottish mainland, and an array near the Normandy coast close to high voltage lines in the French grid. This issue is currently highlighted by recent discussion of transmission charges for projects off Scottish islands. The situation in other Atlantic Arc countries will vary – grid connections for the French, Spanish and Portuguese costs are more likely to be near centres of population while connection in the west of Ireland may face similar issues to Scotland. The calculations presented in this report only include the cost of taking power as far as the nearest shore. Upgrades to the distribution and transmission system that might be needed to take power to demand centres will be an important factor in the eventual geographical spread of wave and tidal arrays.

In some countries the additional costs are the responsibility of the transmission operator while in others (for example the UK) costs fall directly on the generator. The highest additional costs are likely to be seen for remote island locations in Scotland which incur transmission costs up to £100/year /kW capacity. This equates to up to 5c/kWh additional cost – i.e. the LCOE for wave energy is increased from a base cost of 48.3c/kWh to a cost including transmission charge of 53.3c/kWh. In the UK additional transmission charges are expected to affect wave energy more significantly than tidal because of the relative distances of suitable locations to existing grid infrastructure.

3 Early array costs

In order to analyse a consistent set of costs which do not include 'first of a kind' costs we asked device developers for the cost of a 10MW array, after they have already installed 10MW.

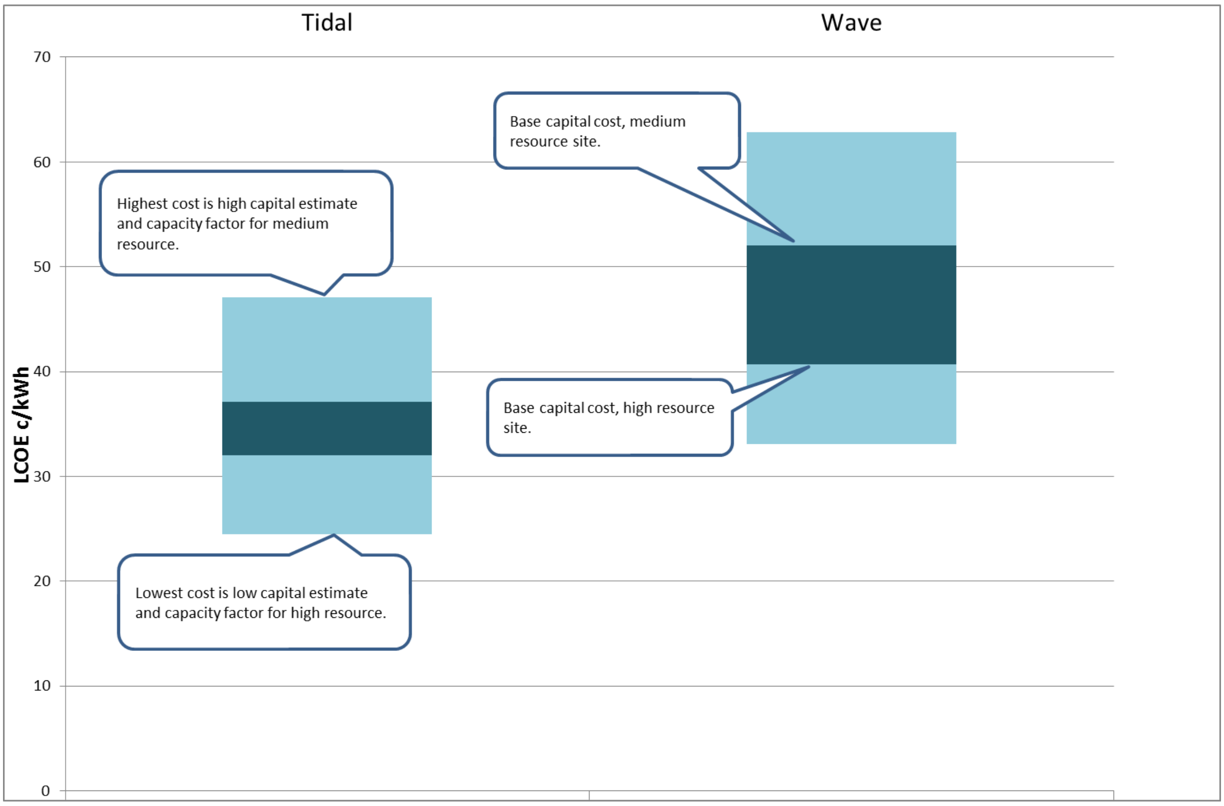
The starting point for cost estimates for these early arrays is the Carbon Trust analysis for the 2011 *Accelerating Marine Energy* report[ii] which combined extensive data collection from developers with engineering judgements about the cost savings likely to be seen between first and subsequent arrays. These figures were then updated based on a series of interviews with device developers carried out for the SI Ocean project with technology developers in both wave and tidal stream technologies. Interviews covered technologies at various stages of development in a number of countries across the EU. The cost analysis was also informed by the work published by Renewable UK in February 2013, based on the consultation on costs for the UK's Electricity Market Reform process. This consultation involved all developers with advanced plans for array development in UK waters.

The costing information available for UK installations reflect the advanced state of plans for arrays (by manufacturers from across Europe) in UK waters taking advantage of support programmes such as MEAD and NER300. A number of the interviewees are considering installations outside UK waters and do not anticipate that there will be a significant difference in specific capital costs between countries in the Atlantic Arc. Capital costs for equipment are expected to be similar while installation costs will vary with many factors, particularly with distance from port, both within and between countries.

The charts below show estimates for lifetime levelised cost of energy for early wave and tidal arrays. The costs are based on a lifetime of 20 years and a discount rate of 12%. A range is given to reflect two major variables:

- The load factor will not be the same at every site, devices with the same costs will generate different amounts of energy depending on the characteristics of the resource at the site.
- Differences in cost estimates between developers, and the inevitable uncertainty in predicting future costs. Based on expert judgement, base, high and low costs are used in the calculation of mid-point, highest and lowest LCOE.

Figure 2 Early Array Costs



The discount rate chosen has a significant impact on the LCOE. For example for a tidal energy installation producing energy at 32.0c/kWh with a 12% discount rate the calculated LCOE reduces to 23.1c/kWh at 6% discount rate. As discussed in Section 3.2, perceptions of risk have a major impact on the discount rates used by project developers in assessing a project.

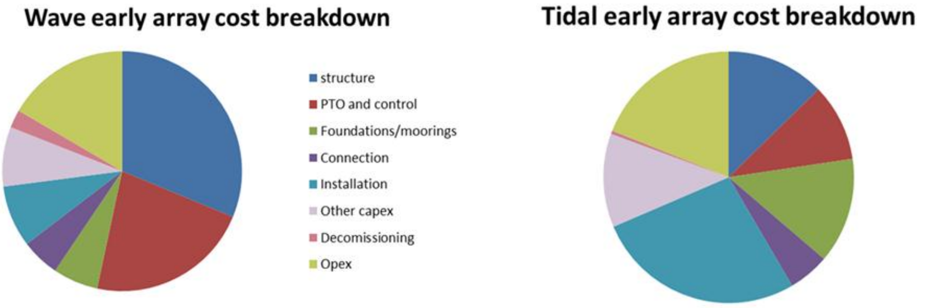
3.1 Early array cost breakdown

The cost data collected was analysed to show the contribution of different cost centres to the overall LCOE. The charts below show the typical cost breakdown by cost centre for early wave and tidal arrays. A discount rate of 12% and lifetime of 20 years are assumed in both cases.

The cost centres are those described in section 3.1 of the SI Ocean report *Ocean Energy: State of the Art*[i]. Foundation and mooring costs are considered separately from the structure of the device, and these are a higher proportion of cost for tidal than for wave reflecting the significant difficulty of fixing turbines to the seabed in high flow environments. The tidal cost breakdown is for a representative bottom mounted device and the wave cost for a representative floating device. Shoreline/ bottom mounted wave devices have a similar total cost to floating wave devices but have a profile more like tidal while floating tidal devices will have a cost profile more like the floating wave device presented here.

Other costs include project management costs and the site development costs mentioned in section 2.4.

Figure 3 Cost breakdown



Just over half of the cost for wave arrays is associated with the devices and their power take off components. Tidal structure and PTO costs are lower, with installation of tidal devices forming a very significant proportion of cost.

It can be seen from the diagram that he cost of the devices makes up only part of the total cost of array projects. Balance of plant items such as cabling, connectors and switchgear as well as installation, operation and maintenance make up a significant proportion of total lifetime costs.

3.2 Developer comments on early array costs

During interviews, device developers were asked about the most significant uncertainties in estimation of LCOE. The responses provide insights into actions required to improve certainty and reduce risk in the costing of ocean energy array projects.

A recurring theme from the interviews is that the operating costs are uncertain because of the early stage of technology development. Some device developers can now point to data of prototype operation for significant periods but for others lack of experience of long term operation means that there is uncertainty about the frequency and cost of maintenance interventions. In addition, standard rates have not yet been established for insurance which is a significant component of operating costs.

All the tidal device developers identified proving reliable operation as a crucial step to allow serious investment into tidal projects. Several interviewees mentioned the balance required between proving the current model of the device, ensuring necessary learning is gained and moving on to a new lower cost design which will in turn need a proving phase.

Uncertainty around foundation costs was highlighted as a challenge. Different seabed conditions cam affect the suitability of a given foundation type, and will affect the overall cost significantly. There will be variation in costs between sites as developers select the optimum foundation solution for the local seabed conditions.

Several developers mentioned lack of detailed information about the resource at a location as being a significant risk factor when calculating project costs. Wave resource can vary from year to year with long term trends and ocean currents, while tidal resource is very specific to the detailed bathymetric profile of a location.

Two different approaches to standardising device specifications were evident: some manufacturers prefer to deploy common components in multiple sites to build up confidence and experience, while others focus on optimising the configuration of a basic model to maximise efficiency based on the particular site characteristics at each location, leading to a number of variations on a standard model.

Additional comments from interviews with developers have informed section 4 below.

4 Later arrays: how cost can reduce over time

This section of the report looks at mechanisms for cost reduction and how these might apply to ocean energy. Cost of energy for any energy technology, including marine, can reduce with **Scale and volume**, with **experience**, and through **innovation**. After introducing the different drivers, the cost reduction opportunities for each cost centre are described and the role of the supply chain in cost reduction is discussed.

4.1 Scale/volume

Scale and volume production offer significant opportunities for cost reduction. Increasing scale can bring down costs in several different ways:

- **Upscaling of device.** As a general rule, larger scale devices have a lower cost/kW capacity as manufacture and installation costs do not increase linearly with energy output. The upscaling opportunities are constrained by the requirements to interact with the sea, for example tidal blade length may be constrained by depth of water at the site and wave device size by the optimum scale for responding to the waves at the location, but there is certainly potential to increase scale from current prototype size. Materials become more expensive when extra strength is required for larger devices, so a compromise may be necessary in order to reach the highest cost-benefit.
- **Number of devices.** Installation of a number of devices in array(s) reduces installation and balance of plant costs per MW installed. As the array scale increases savings are seen in installation vessels - larger and more specialised vessels can be afforded, and with better utilisation rates installing multiple units in each mobilisation, in cable connection costs, project development, site mobilisation and other project costs. The sharing of mooring points or mounting multiple devices on a single foundation improves the economics of installation by sharing expensive foundation and installation costs.
- **Scale of production.** Production of a number of similar devices at scale reduces costs – components produced through serial production will result in a lower overall individual component cost when compared to the cost of a one-off design through factors including:
  - Better use and higher utilisation of equipment
  - Discounts for buying larger batches of components
  - Standardisation of processes
  - Efficient use of labour
- **Scale of engineering support.** Large OEMs investing in device manufacturers bring resources and experience into ocean energy. Recent investments, for example by DCNS , Siemens and Alstom bring knowledge transfer from other sectors into the industry and are likely to lead to reduction in production costs.

4.2 Experience (learning by doing)

As the number of units produced and the level of accumulated running hours (for a particular device, and for the overall industry) increase, know-how is built up on optimum routes for production, deployment, and operation and maintenance techniques. The know-how, and improved efficiency it brings, is the mechanism by which learning by doing can offer cost reduction.

The track record of marine energy devices (successful and reliable operation of the technology itself, the installation methodology, installation contractors etc.) will have an important influence on the perception of risk and therefore on project cost assessment, as described in section 2.4.

Learning through Research & Development also contributes to the overall increase in sector experience. Device modelling (at device and array level), experimentation, tank testing, and open sea testing will provide holistic experience that will allow optimal development of future projects through use of an extensive knowledge bank.

4.3 Innovation

The third mechanism for cost reduction is innovation. Innovative cost reduction involves radical changes in design or process to remove costs. Innovation can take place at both whole device and subsystem level. It can include everything from fundamental new energy capture concepts through to innovative deployment and operation processes. This focus on experimentation and new ways of doing things is distinct from experience which improves current practice. In practice the boundaries between innovation and learning by doing will be blurred.

In the early stages of development innovation is likely to take place in a Research and Development environment, with initial development and testing of promising new concepts. At a later stage when a technology is approaching commercial operation innovation is likely to occur in the context of practical industrial projects working on short to medium term challenges, for example development of innovative installation methods as part of full scale deployment trials.

4.4 Opportunities for cost reduction

This section discusses specific opportunities for cost reduction within the different cost centres of an ocean energy array. The same cost centres are used as described in Section 3.1 of the SI Ocean Report *Ocean Energy: State of the Art*[i].

4.4.1 Cost reduction potential – structure and prime mover

Based on the assumptions for early array costs in section 3, the structure and prime mover makes up on average 31% of lifetime costs for a wave array and 13% of lifetime costs for a tidal array.

All improvements in device design are aimed at reducing capital cost, improving yield or improving reliability. **Survivability** of devices is a key requirement. The most energetic sites (i.e. those with the best potential for low cost of energy) lead to some additional requirements for robustness and reliability and manufacturers are looking to gain initial operating experience in sites with less extreme conditions before developing more challenging sites.

As operating experience is gathered and designers gain better understanding and more certainty about at-sea performance, it is likely that **design margins** will decrease so that less material and cheaper components are used in the device and that this will be reflected in standards and design codes.

Alternative **materials** for devices offer significant cost reduction potential, allowing changes in shape and optimisation of weight. For example building major components of a wave device from concrete rather than steel could reduce material and construction costs. The Anaconda device concept (described in section 5.4 of the SI Ocean Report *Ocean Energy: State of the Art*[i]) is constructed from rubber which is potentially lower cost than steel and combines the properties of the structure and the power take off.

Economies of scale in production (see section 3.1 above) will reduce specific capital costs. As production runs move from bespoke one-off prototypes to small batches for first arrays and then to continuous production in the long term, cost per unit will reduce substantially.

Wave devices

Wave developers are investigating different structural configurations which could lead to improved yield through better coupling between resource and reaction mass. Wave devices will have a higher yield at more energetic sites which tend to be further from shore. These sites lead to additional requirements for robustness and reliability and manufacturers are looking to gain initial operating experience in sites with less extreme conditions before developing sites further offshore.

Wave devices are often tuned to respond to certain wave frequencies, and in this case the structure geometry and mass will be designed around the resonant frequencies that need to be achieved to maximise energy extraction at a given location. This design philosophy will take precedence over the continued size (and energy capture) increase that has been prevalent in the wind energy sector, but many concepts can be increased in size compared to current prototypes.

There is considerable scope for increasing the power output from devices by optimisation of the device and control system.

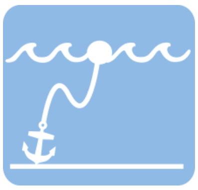
Tidal devices

For tidal turbines, the mechanisms for energy capture are well understood but there are further steps that can be made to optimise sub-component design, for instance of turbine blades to withstand turbulent conditions. Some of the most energetic tidal sites (for example the deep section of the Pentland Firth) are very challenging environments which will require heavily engineered structures or new structural concepts such as tethered internally buoyant turbines.

Avoiding fatigue failure is an important design consideration for tidal turbine blades, as is prediction of loading from waves at the site. Blades are commonly constructed from composite materials made of a polymer reinforced by carbon or glass fibres . There is scope for improvement in design to increase reliability and improve performance by improvements in blade design and innovative use of materials.

While up-scaling of tidal turbines offers potential for cost reduction, it may be that the increase in scale will not follow the same route as wind power where power ratings have increased steadily over time. Installed devices (particularly the early arrays) will be in water depths where the sea bed and the free surface constrain the maximum rotor geometry. Also the up-scaling potential will be limited by the strength of the material in the blades. There will be a point at which additional material thickness will become difficult to manufacture using current techniques.

4.4.2 Cost reduction potential – foundations and moorings



The foundation or moorings make up 6% of typical lifetime costs for an offshore wave array and 14% of lifetime costs for a bottom mounted tidal array. Costs for floating or neutrally buoyant tidal devices could be lower.

Prototype tidal devices have used both piled and gravity based foundations, with notable successes in using remotely operated drilling rigs for piles. Installation of gravity based foundations involves lifting heavy foundation weights into position which is a costly process and only suitable for certain sites. ‘Pin’ piles, using multiple smaller pins instead of single bulky piles or gravity bases, may enable cost reduction in future and allows process innovations such as subsea drilling. It is likely that as particular foundation types are shown to be effective for particular types of site (with similar water depth and seabed conditions) these will be taken up across the industry . New techniques for pin-piling from remote-operated submarine vehicles are already reducing costs as developers move from prototypes to first arrays.

Similar factors apply for nearshore wave device foundations. Moorings for floating wave devices have less potential for cost reduction, although new (flexible) fibre materials could reduce weight and handling costs, and decrease maintenance intervals. There is a requirement to develop anchoring solutions for a variety of seabed conditions and for deep water. There are also potential improvements in deployability available (see section 4.4.6 below).

New solutions will be required for tidal device foundations taking advantage of energetic flows in deeper water which cannot be accessed cheaply using bottom mounted devices. Floating devices and platforms that are moored to the seabed also offer the prospect of lower installation and maintenance costs, with multiple rotors attached to one structure. These new solutions enable new higher resource sites to be exploited, and also have the potential for step-change cost of energy reductions due to decreased foundation costs per unit of swept area.

Foundations or moorings shared between more than one device are one of the economies of scale available for multiple device arrays, both tidal and wave. Because foundation costs are a high proportion of lifetime tidal costs the potential for cost reduction for bottom mounted tidal devices is particularly significant. Some tidal devices developers already plan to use several rotors on the same supports to increase the rating per device and dilute some fixed costs.

As the number of devices deployed is increased, development of standardised foundation designs with standard components will reduce costs for the industry.

4.4.3 Cost reduction potential – power take off

The power take off makes up 22% of lifetime costs for a wave array and 10% of lifetime costs for a tidal array.

Most advanced tidal devices use conventional generators but other concepts are being considered by developers, for example permanent magnet generators for tidal devices that eliminate the need for gearboxes and reduce losses. It is likely that future developments in power electronics will contribute to cost reduction for PTOs, and some of these developments could also increase yield by enabling reactive control mechanisms or eliminating gear-box losses.

There is significant potential to optimise the configuration of PTO and structure of wave devices to increase yield, particularly in combination with control system improvements (see section 4.4.4 below). Hydraulic power take off systems are commonly used but linear generators are also under investigation for use in wave devices. Other types of PTO also offer opportunities for improvement, for instance the turbines in OWC devices are increasing in efficiency, improving the yield in recent devices compared to their predecessors.

4.4.4 Cost reduction potential – control

Continued development of control systems and software are expected to drive yield improvements by improving the way the device interacts with the sea. Wave devices, for example, can be tuned to resonate better with a wider range of sea states, and tidal turbines could adjust their rotation speed or pitch in response to fluctuations in current. These changes should lead to improved yield.

For tidal turbines improved blade control systems will increase energy capture. In the future it is expected that control improvements will lower the lifetime cost of energy, as has been the case with pitch control of wind turbines. Pitch control not only increases yield but it is also a safety mechanism that reduces structural loads (and cost) on both the blades and the braking system.

For wave energy the crucial issue is developing a control system that can respond to the changing wave characteristics and adjust the device to maximise the energy output in each condition. Wave developers that have focused attention on optimising control systems have demonstrated increases in power output without any structural alterations to the device itself. Sophisticated systems which integrate forecasting of the characteristics of waves that are about to reach the device, making the device 'tunable' to each wave climate, are under development.

Device developers have to balance the extra cost of more sophisticated control systems and the additional complexity incurred which could be a cause of unreliability with the increased yield that can be achieved. Some developers are deliberately retaining simple control systems for early installations in order to avoid the introduction of extra potential failure mechanisms at this stage. Nevertheless, improved control systems offers a great opportunity for significant increases in yield with minimal capital cost increase (software, and minimal sensor hardware).

4.4.5 Cost reduction potential –connection

Electrical connection to the grid makes up around 5% of lifetime costs for both wave and tidal arrays (this cost is highly variable between sites). There is less potential for dramatic cost reduction in this area because much of the development has already been carried out by the offshore wind industry, but there is a requirement to develop suitable configurations for connecting arrays. Subsea hubs that allow underwater electrical connection of a number of devices will make an important contribution to economies of scale for arrays.

One area for cost reduction is wet mate connectors for electrical connection of devices at sea. These are available but currently very expensive; one driver of this is the high specification requirements of the traditional customer, the oil and gas industry.

Currently there are no industry common practices or standards for the electrical elements of array schemes, for example substation sizing varies between different schemes. In the long term standard specifications for all elements of the electrical system will bring down costs.

Development of subsea high voltage cables (both AC and DC) will also bring down costs. The expansion of offshore wind is already providing a stimulus to develop solutions for offshore cabling and much of the learning from this industry will be transferrable to ocean energy. (High voltage subsea cables are likely to be more necessary for wave arrays, which may in time move tens of kilometres offshore while tidal arrays will remain closer to shore.)

Facilities with grid connection provided, such as BIMEP in Spain and Wave Hub and EMEC in the UK, are an important enabler for connection of large scale prototypes.

4.4.6 Cost reduction potential – installation

Installation makes up 18% of lifetime costs for a wave array and 27% of lifetime costs for a tidal array. The higher proportion of the cost for tidal devices reflects the significant challenges of first installing foundations and then attaching a tidal device in high speed tidal currents. The foundation will be installed once in the lifetime of the array, but the turbine may need to be removed and reinstalled several times.

Much of the cost for both wave and tidal devices is currently absorbed by the rental of suitable vessels for the installation work. If a change in design or in installation method allows lower cost vessel to be used, this will clearly have an impact on overall costs. Several tidal developers believe high current installation costs can be significantly reduced by a variety of different approaches including specialist subsea drilling techniques (as an alternative to expensive jack-up vessels) and developing installation procedures which allow use of cheaper vessels.

Once sufficient installation work is underway to justify the investment, it is likely that dedicated specialist installation vessels will be available for wave and tidal arrays. The option mentioned in section 4.4.2 of using one foundation structure for several turbines shares the costs of installation over a higher generation capacity.

Another key element in minimising the installation costs is maximising the weather window during which installation is possible. Extra mobilisation costs and project delays are likely if the installation can only be carried out in very favourable conditions. In practice there will be a balance between using a higher cost vessel that can operate in a wider range of conditions and a lower cost but more limited option. There is scope, however, for low cost options that can cope with adverse weather conditions, such as drilling rigs or cable layers mounted on a Remotely Operated Vehicle (ROV). Subsea ROVs are not currently designed to operate in high tidal flows and therefore have restricted operating hours at tidal sites.

Installation of floating tidal devices has different requirements to those with foundations. Replacing a foundation with a set of moorings raises a number of design challenges but allows deeper water, higher resource areas to be accessed. Installation of floating tidal devices or platforms should be significantly cheaper than installation of bottom mounted devices. Equally, installation of floating wave devices is significantly cheaper than installation of bottom-mounted devices.

4.4.7 Cost reduction potential – O&M

Operating and maintenance costs make up 17% of lifetime costs for a wave array and 19% of lifetime costs for a tidal array.

Reliability is a very important factor, as off-shore maintenance is very costly by nature. A significant proportion of the total cost for maintenance is the cost to access the devices, so any decreases in planned or unplanned maintenance can achieve material cost reductions (as well as improving yield through increased availability). Just as installation in energetic waters is challenging, so is reaching a device in a boat to overhaul or repair it. A variety of approaches to access for maintenance is taken by device developers, indeed ease-of-maintenance is emphasised by some manufacturers as a 'unique selling point'. Other device developers aim to minimise lifetime O&M costs by being very robust and reliable, thus needing little maintenance.

One option is to design the device so it is simple to recover it and take it to a sheltered location to be maintained, for example a coupling for a floating wave device that allows a unit to be detached from its mooring quickly and towed to a sheltered location using a small boat. Similarly some tidal devices have a buoyant nacelle which can be easily detached and floated to the surface, and dock, for maintenance. Improvements in deployability will have benefits in reduction of both installation and O&M costs.

Some tidal device developers are investigating frames which allow submerged devices to be lifted above the surface when maintenance is required. Floating tidal devices and those mounted on platforms have the advantage that they are easier to reach than submerged bottom mounted devices.

If the device has to be taken some distance to a port with suitable facilities for maintenance, this adds to maintenance costs and the downtime required, so suitable local port infrastructure enables lower maintenance costs.

A crucial factor in the O&M costs is how frequently the device requires maintenance. Interviews with device developers revealed a wide range of expectations about required maintenance intervals. Suppliers of horizontal axis tidal turbines point to the very long maintenance intervals (up to 50 years) for traditional hydroelectric turbines and some are aiming for 5 year or longer intervals. Offshore wind experience is that electrical / electronic components are more likely to fail than mechanical components and a variety of approaches are being pursued, from designing in redundancy so that the device can tolerate a certain number of failures, to ensuring that components likely to fail are in a dry, easily accessible location such as an above-surface platform.

Predictive condition monitoring, using sensors on the device for early detection of potential faults, are likely to be developed to reduce maintenance costs. In the long term when there are many devices installed far offshore, offshore O&M bases will be established.

4.4.8 Cost reduction potential –whole system

The opportunities identified in sections 4.4.1 to 4.4.7 relate to specific cost centres but potential for improvement of the whole device assembly should also be considered. In particular there is scope for improving the yield from the device which could lead to a significant reduction in LCOE. For floating wave devices there is the possibility to move further from shore to higher energy wave climates, where the load factor of the device will be higher. Modelling suggests that the revenue from the extra energy generated will outweigh the additional costs of longer cable connections and deep water mooring until the very deep water beyond the continental shelf is reached.

The situation for tidal energy is less straightforward. Site assessment will be a balance between the sites with highest tidal flows (some of which will be exploited by early arrays) and those with other favourable features that lower total costs such as distance to shore connections. In practice there will be a range of load factors for both the early sites and future developments. It is likely that gradual improvements will be seen in the efficiency of energy conversion over time but significant increases in yield will require next generation devices that can access the high energy tidal flows in deeper water.

Interactions between devices will affect the energy generation from arrays. There is currently limited understanding of 'array effects' – the extent to which one device will shadow or otherwise affect others nearby. Detailed measurement and modelling of both wave and tidal array performance is required to ensure optimum array layout to maximise yield.

4.4.9 Cost reduction potential –project costs

The overall costs for array installation can be reduced by innovative approaches to the Engineering, Procurement and Construction (EPC) contract structure. Building on experience from offshore wind and other similar industries, appropriate contract structures can be devised with suitable incentive mechanisms and optimum sharing of risk. Projects are currently originated and developed by utility R&D teams, or by technology developers bringing experience of EPC in large offshore projects is likely to have benefits in project planning and cost reduction.

Insurance costs are a current area of uncertainty. There is a need for the industry as a whole, and individual device types, to build up a track record of operation to establish a basis for insurance cost calculations.

4.5 The role of the supply chain

Interviews with device developers confirmed that there is already an EU-wide supply chain operating and components are being sourced from many countries - for example hydraulic equipment sourced from Germany. The supply chain for ocean energy presents opportunities for suppliers from across the continent, not just the Atlantic Arc countries.

Examination of the supply chain for components and services for ocean energy installations highlights opportunities for cost reduction. Many mechanical and electrical components are used in a wide variety of applications and improvements in these applications may also benefit ocean energy. For example, subsea cables are being developed for offshore wind installations. Future developments in wider areas – for instance advances in materials science – may have applications in ocean energy.

Some device developers mentioned that supply chain companies had shown interest in adapting standard components for ocean energy applications, taking advantage of a new business area. In some cases suppliers are taking the lead in testing components under the operating conditions required. 'Marinisation' of components so that they can withstand operation at sea, is a key theme in transferring standard components to ocean energy applications. However, several interviewees noted that the overall market for components for ocean energy, even with optimistic deployment projections, is small compared to other markets, for instance for conventional power generators, and it may prove challenging to make the case for suppliers to focus on marine-specific development. In the case of companies who traditionally supply the oil and gas industry, the margins available in ocean energy may not be sufficient to attract their interest. New entrants to the market may provide competitive pressures to bring prices down.

The industry is seeing a number of specialist suppliers and contractors e.g. vessel operators developing alongside the first ocean energy installations and building up key technical and operational expertise for the future.

The motivation for OEMs interested in supplying components as part of the supply chain for devices is driven by the size of the market of a particular device or sub-component. If development of a particular component for the ocean renewable energy sector could result in a product that could then be sold into other markets (technology export), then there is an immediate knock on effect on the potential volume of production that could be achieved, and the levels of interest in investing in the development of such a product. Similarly, use of off-the-shelf components from an existing industry for application within the ocean energy sector (technology import) could provide another avenue for unlocking economies of scale.

Standardisation, in terms of standard specifications for components and equipment, is likely to be a key step in driving out cost and establishing economies of scale. The standardisation of particular sub-components within a device, whether that be across several variations of device (such as between device developers) or across a range of technologies (for example between wave, tide and offshore wind) will extend the market of a specific product or sub-component beyond the boundaries of a particular single technology.

4.6 Summary of cost reduction opportunities

The tables below show a summary of the cost reduction opportunities identified in this section. The opportunities are classified to show whether they mainly impact on reduction of capex, increase in yield or reduction in opex. It should be noted that the different cost reduction opportunities are likely to become important at different stages of development. Future SI Ocean work will consider the likely timing of developments and the implications of this for support strategies.

Summary of opportunities –wave

	Capex reduction	Yield improvement	Opex reduction
Structure & prime mover	Material optimisation Upscaling of devices Batch and serial production Reduced over-engineering Regional manufacturing	Geometry optimisation Optmisation of array layout	
Power take-off	Improved power electronics Improved hydraulic system Alternative / improved PTOs	Improved control systems and algorithms Improved hydraulic system Improvements in metocean forecasting Drive train optimisation Improved power electronics Array yield optimisation	Modular subsystems
Foundations & moorings	Improved moorings Improved foundations Improved piling techniques Cost effective anchors for all sea bed conditions.	Deep water installation techniques	
Connection	Off-shore umbilical / Wet-mate connectors Subsea hubs Array electrical system optimisation (transformers etc.) Offshore grid optimisation	Optimised subsea transmission to reduce losses	Improved connection and disconnection techniques
Installation	Specialist vessels Modularisation of subsystems Improvements in metocean forecasting Fast deployment and other economic installation methods Subsea and seabed drilling techniques Improved ROV and autonomous vehicles		
O&M		Improved availability through: Intelligent predictive maintenance Techniques to reduce weather dependency	Increased reliability Modular components. Simpler access Specialist vessels Far offshore O&M strategy Intelligent predictive maintenance Improved ROV and autonomous vehicles

Summary of opportunities –tidal

	Capex reduction	Yield improvement	Opex reduction
Structure & prime mover	Material optimisation Upscaling of devices Batch and serial production Reduced over-engineering Multiple rotor platforms Regional manufacturing	Optimisation of siting to maximise yield Micro-siting techniques Improved yaw and pitch mechanisms Hydrodynamically optimised structures Upscaling length of blades	Multiple rotor platforms
Power take-off	New drive train configurations Alternative and improved PTOs	Direct drive Improved hydraulic actuation systems Improved control systems and algorithms Array yield optimisation	Modular subsystems
Foundations & moorings	Improved subsea/seabed drilling Specialist vessels Improved piling and fixing techniques Improved mooring techniques (floating devices)	Floating or neutrally buoyant devices accessing high energy flows Hydrodynamically optimised foundations/platforms	Specialist vessels
Connection	Off-shore umbilical / Wet-mate connectors Subsea hubs Array electrical system optimisation (transformers etc.)		Improved connection and disconnection techniques
Installation	Specialist vessels Improvements in metocean forecasting Modularisation of components Improved ROV and autonomous vehicles		
O&M		Improved availability through: Intelligent predictive maintenance Techniques to reduce weather dependency	Intelligent predictive maintenance Increased reliability Modular components. Simpler access Specialist vessels Intelligent predictive maintenance Improved ROV and autonomous vehicles

4.7 Differences between cost reduction opportunities for wave and tidal devices

This section of the report has described the opportunities identified for reducing the LCOE for ocean energy. Many of these are common for both wave and tidal energy but there are also some opportunities specific to one or other technology and some differences in the status of the two types of generation.

Tidal turbines are based on a familiar technology with more than a century of history in hydroelectric power, and with many features similar to turbines for wind energy. The theoretical performance of turbines and their limits are well understood and the confidence this gives is reassuring for investors, as is the investment by a number of large OEMs in tidal developers which can be seen as a sign of maturity. However the number of suitable sites for current generation tidal generation technology is limited. This means there is less scope for learning by doing for tidal compared to wave. There is a recognition that a new generation of tidal turbines may be needed for more challenging sites (and to continue reducing costs). These are unlikely to be bottom-fixed structures.

There has been much less convergence on a single device type for wave than tidal, with a wide range of options under development. This means learning is more fragmented and device specific than for tidal, though many common components such as connectors and moorings do benefit from industry-wide learning. Recent years have seen investments from large industrials and utilities into wave energy developers but not on as large a scale as for tidal developers.

Wave devices are currently more expensive to build and operate than tidal, however there is great scope for cost of energy reductions through scale effects because very large arrays can be built using identical devices and moorings. The wave energy resource is larger and in theory all of this can be accessed by current generation devices - it is likely that as deployment progresses wave arrays will be built further offshore in more energetic sites using the same device types and, as discussed in section 5.1 below, the improved load factor at these locations will have a significant impact in bringing down LCOE.

The differences between the development pathways and total potential energy for wave and tidal energy should be taken into account in support activities for the industry.

5 Future costs

5.1 Applying learning rates to wave and tidal energy costs

Leaning curves represent the general reduction in cost for a technology as deployment increases. Historical observations have shown that costs for a technology (or per unit of energy for generating technologies) tend to fall by a fixed percentage for each doubling of production. Cost per unit plotted against deployment levels is a straight line on a logarithmic plot for many different technologies. This decrease comes through a combination of scale, experience and innovation, as described in section 4.

Learning curves are frequently used to predict future energy costs based on historical costs for the particular energy generation technology. The technique should be applied with caution to ocean energy since wave and tidal energy are not yet commercialised and there is as yet no active market to set prices. As will be clear from section 3 of this report, there is also some uncertainty over early array costs. The early history of other technologies, for example offshore wind turbines, shows considerable fluctuations in costs in the early stage of development.

Despite these limitations, applying a learning rate to predict future costs is a useful way to project costs in the future and examine the deployment levels required to bring costs down to target levels. An industry debate about the levels of learning achievable provides useful input to a strategy to achieve the maximum cost reduction possible from experience gained in deployment. The application of learning rates in the following section has been balanced by an engineering sense-check on what is considered technically feasible.

5.1.1 Learning rate calculation

Capital cost

The principle of learning rate calculations is that there is a constant cost reduction for each doubling in deployed capacity.

The capital cost at a certain deployment level can be calculated with the following formula:

$$SCI_F = SCI_R \left(\frac{C_F}{C_R}\right)^{\frac{\ln(1-LR)}{ln2}}$$

SCI_F: Specific capital cost in the future [€/kW]
SCI_R: Specific capital cost in the reference year [€/kW]
C_F: Cumulative global installed capacity in the future [GW]
C_R: Cumulative global installed capacity in the reference year [GW]
LR: Learning rate [0]

The early array costs described in section 3 were used as the reference point, with the cost with a 'base' capital cost at a 'high resource' site (the bottom of the dark band in figure 2) being used as the starting point, at a nominal cumulative deployment of 20MW. This assumes that a consensus on common designs is reached following the installation of early arrays.

Capital costs at different points were calculated using the formula above. Opex and decommissioning costs were assumed to be a constant proportion of the capital cost.

Load factor

The model allows different load factors to be assumed at different deployments. The load factor was held constant for tidal energy on the basis that average load factor is unlikely to increase with deployment. In practice there will be a range of load factors for both the early sites and future developments and, as discussed in section 4.4.8 increases in individual device efficiency over time are likely to be balanced by reduced availability of high yield sites and the tendency for array yields to drop as farm size increases.

Section 4.4.8 explains that there is a great deal of scope for wave device yield improvements over time as floating devices are installed progressively further from shore where the wave resource available increases significantly. There is also great potential for improved forms and control systems. For these reasons a 'load factor learning rate' was included in the wave cost modelling.

The load factor at a certain deployment level can be calculated with the following formula:

$$LF_F = LF_R\left(\frac{C_R}{C_F}\right)^{\frac{\ln(1-LFLR)}{ln2}}$$

LF_F: Load factor in the future
LF_R: Load factor in the reference year
C_F: Cumulative global installed capacity in the future [GW]
C_R: Cumulative global installed capacity in the reference year [GW]
LFLR: Load factor learning rate [0]

5.1.2 Tidal LCOE projections

Figure 4 chart shows tidal energy cost plotted against deployment on a linear scale. The starting point is the high resource site early array LCOE (the lower end of the dark blue bar in figure 2)

Figure 4 Tidal costs with deployment (linear scale)

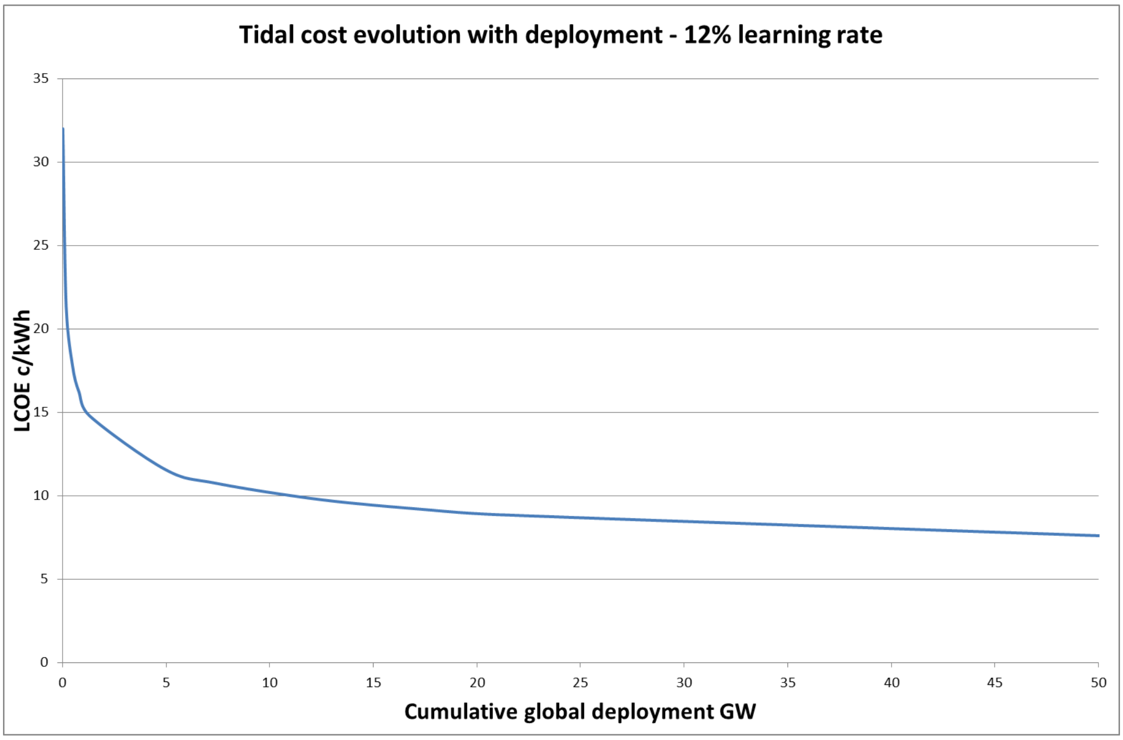
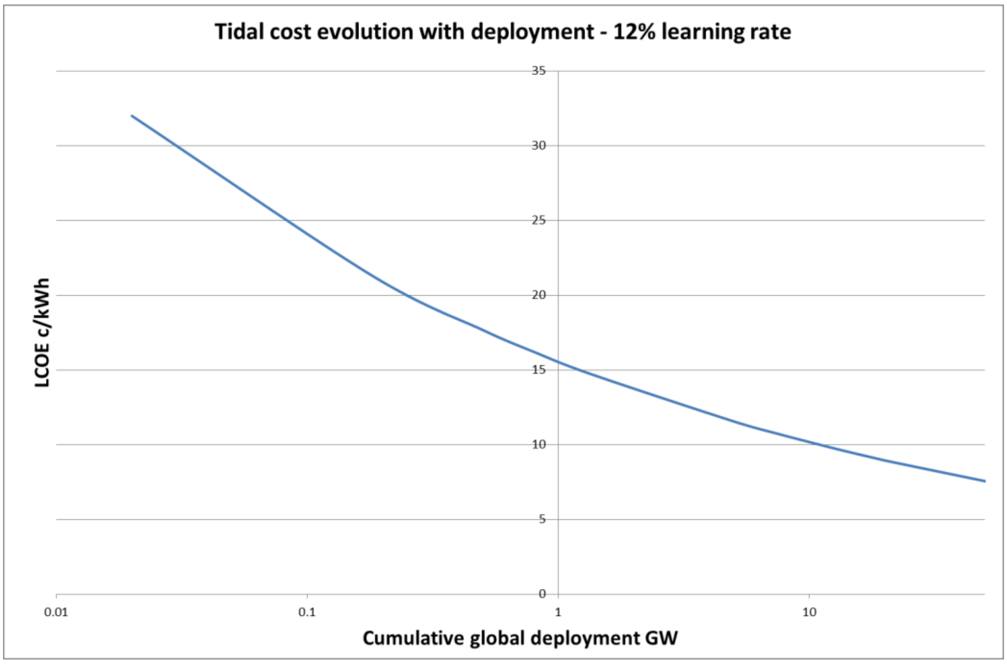


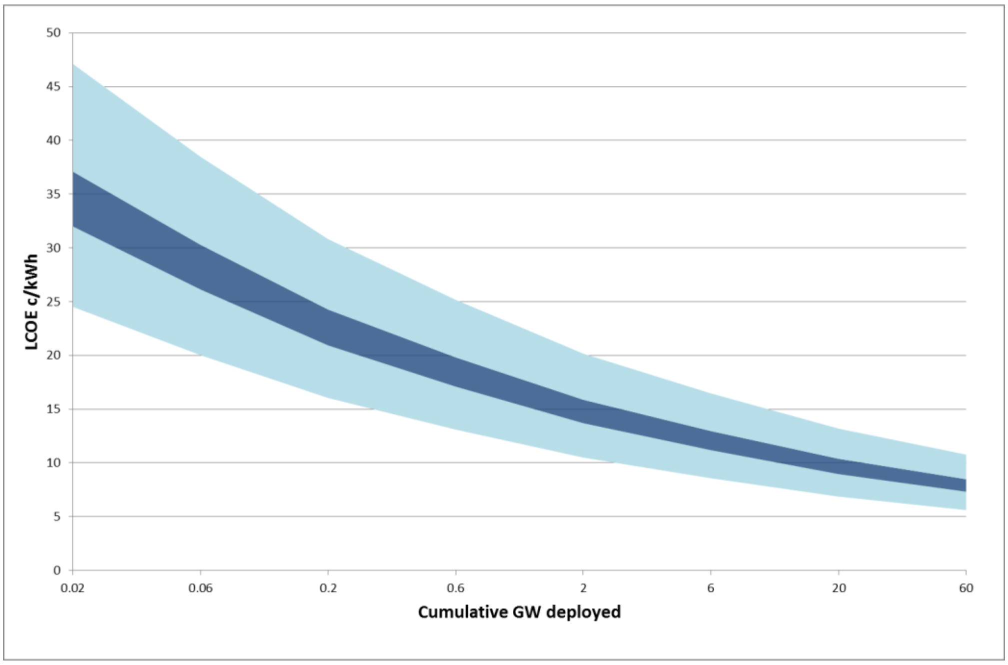
Figure 5 which plots the same curve but with deployment on a logarithmic scale, allows a closer view of the crucial period where deployment increases from 0.1 to 10 GW, which is likely to correspond roughly with the decade from 2020 to 2030. (Deployment projections will be the subject of future work in the SI Ocean project).

Figure 5 Tidal costs (deployment on logarithmic scale)



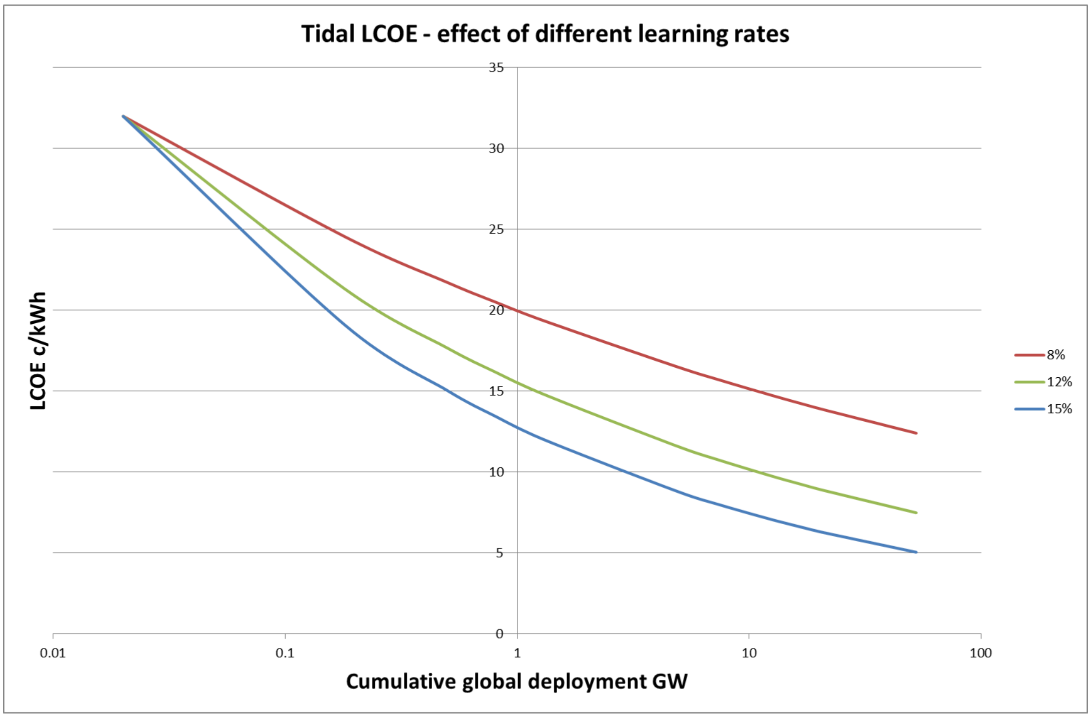
In practice, there will be a range of capital costs and load factors at each stage of deployment. Figure 6 below shows learning curves plotted using the varying resource and cost assumptions shown in figure 2 as starting points.

Figure 6 Tidal LCOE ranges (deployment on a logarithmic scale)



In the graphs above a learning rate of 12 % is assumed as this matches modelling based up on bottom up engineering modelling (see section 5.2 below). Figure 7 shows the sensitivity to different assumptions about learning rate, based on the same starting point as figure 5. The learning rate can be increased through a number of interventions but particularly by increased investment in innovation and R&D.

Figure 7 Tidal costs with deployment –effect of different learning rate



5.1.3 Wave LCOE projections

Figure 8 below shows wave costs on a logarithmic scale. The starting point is the high resource site early array LCOE (the lower end of the dark blue bar in figure 2). As for tidal, a capex reduction of 12% for each doubling was used for modelling as this matches well with bottom up estimates (see section 5.2 below). For wave a 3% learning rate for improvement in load factor was included in the modelling. As explained in section 5.1.1 it is likely that load factor for wave devices to increase over time and the 3% learning factor gives future load factor projections which match well with expert opinion.

Figure 8 Wave costs (deployment on logarithmic scale)

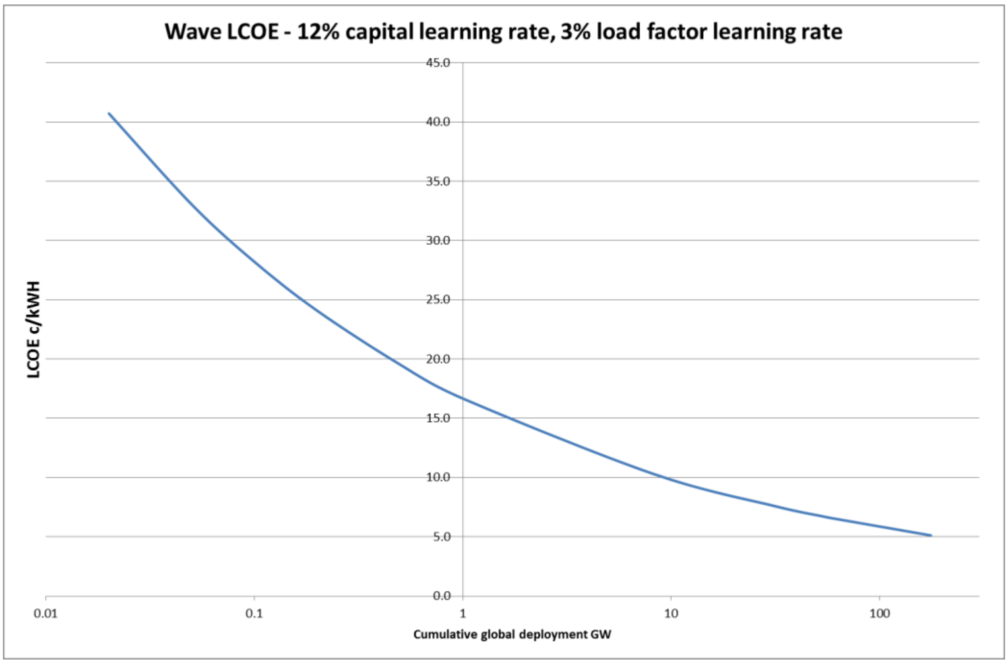
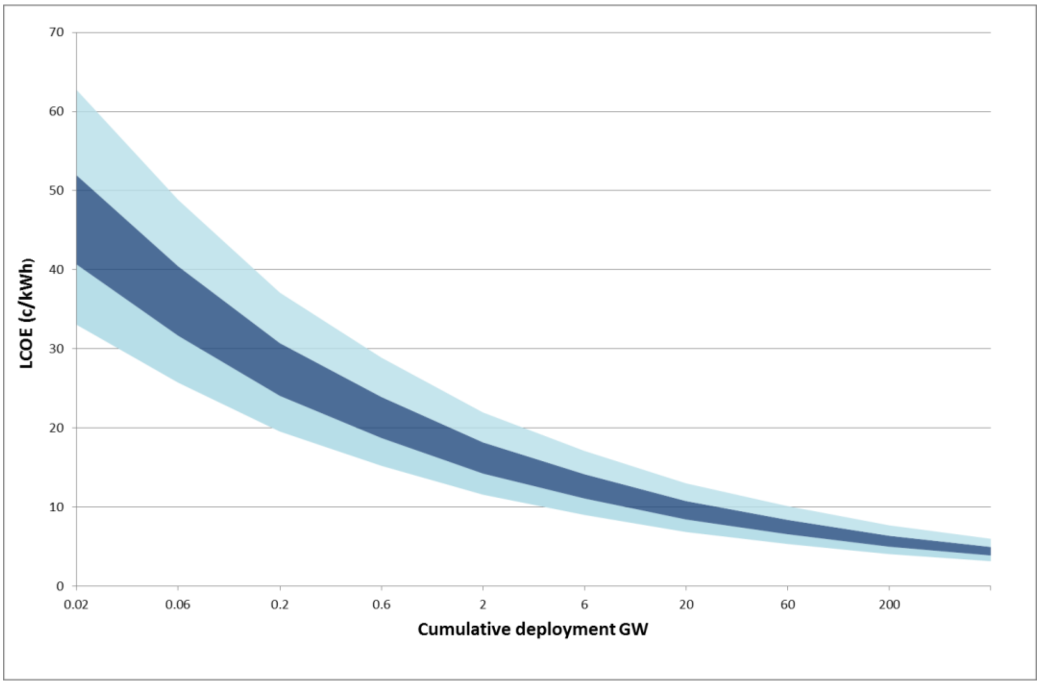


Figure 9 shows the cost variation expected using the costs from figure 2 as the starting point.

Figure 9 Wave LCOE ranges (deployment on logarithmic scale)



5.2 'Bottom up' modelling

In order to cross check costs from the learning rate approach an alternative approach was used to model cost reduction over time based on engineering judgment of the potential rate of cost reduction for different cost centres. Based on knowledge of the technologies involved and progress in other sectors, a progress rate is applied to each cost centre. The model allows the annual energy production to be adjusted to reflect improvements in yield expected at different roll out points.

The progress rates used were based on a detailed engineering analysis of a set of devices carried out for the Carbon Trust, including an estimate of costs after 10MW and 200MW capacity has been installed.

The charts below show a comparison of the bottom up modelling with the results based on application of an overall learning from figures 5 and 8 above, showing a good match with the learning rate calculations.

Figure 10 Tidal learning rate cost projections compared with bottom up model

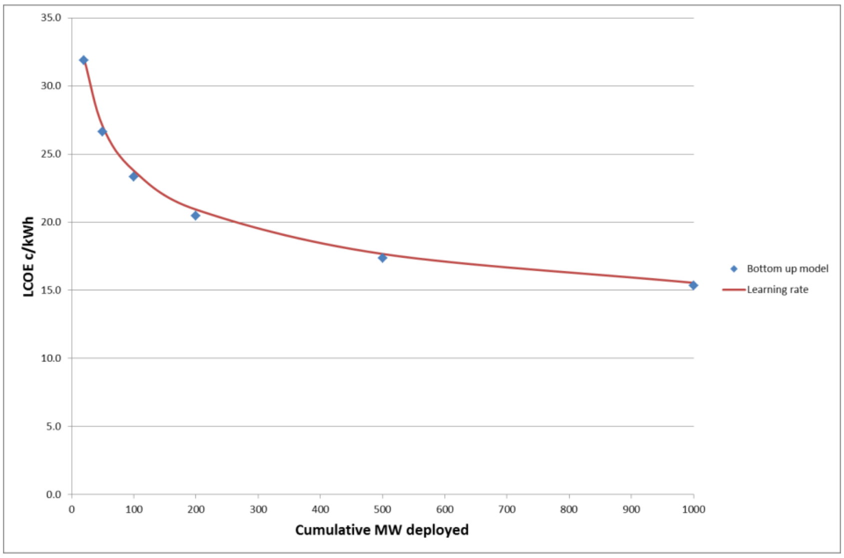
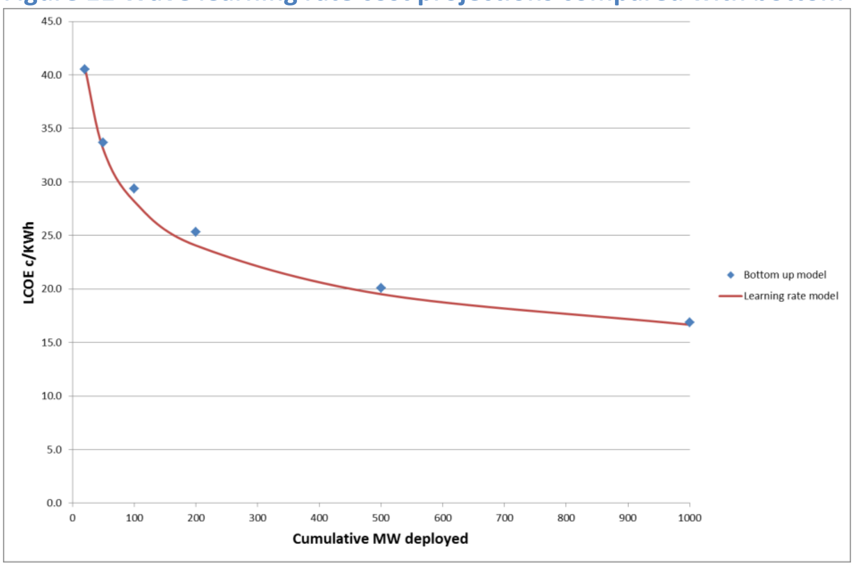


Figure 11 Wave learning rate cost projections compared with bottom up model



6 Conclusions

The development of wave and tidal technology has made significant progress in recent years. A number of companies are moving from prototype development to the installation of first demonstration arrays, a significant step forward towards commercial deployment.

Predicted cost of energy from first arrays is relatively high compared to other renewables at a more advanced stage of development (such as offshore wind) but rapid reduction in costs from prototypes is already evident and there is reason to expect significant reduction in cost of energy will continue as deployment increases. Credible paths to reduce capital and operating costs and to increase yield have been identified. Early array costs for wave energy are higher than for tidal but in the long term wave energy has larger overall resource potential and so could deliver at similar LCOE to the long term tidal estimates.

Risk, and perception of risk, has a significant impact on cost estimates for the sector. Wave and tidal energy is currently seen as high risk because of a lack of operational experience and this has an impact in terms of higher hurdle rate requirements. There is a need to build up reliability and operation experience to increase certainty in LCOE estimates and reduce risk for investors. Support for early deployment will be crucial as the most rapid cost reductions are expected it is in the first 10s of MW deployed.

Knowledge sharing across the industry will be required to ensure that the full benefit is gained form early experience. There are also opportunities for building on experience from other industries and for working with the supply chain for components and services across Europe to reduce costs.

The opportunities for cost reduction identified in this report are at a various levels of commercial readiness. Some will require innovation support activities while others will follow naturally from experience gained as deployment levels are increased. The strategy to achieve sustained cost reductions will be analysed in greater detail within the next stage of work for SI Ocean, the development of a Strategic Technology Agenda.

Glossary

AEP	Annual Energy Production.
Array	A set of multiple devices connected to a common electrical grid connection.
Availability	The proportion of the time the device is available to generate electricity.
Balance of plant	The components of an array apart from the devices
Discount rate	The percentage rate used to calculate the present value of a future cash flow.
Hurdle rate	The minimum rate of return (discount rate) a developer will accept on a project.
Load factor	The ratio of the actual output of a power plant over a period of time compared to its theoretical power output if the plant were to operate consistently at full load over the same period.
Levelised Cost of Energy (LCOE)	Sum of discounted lifetime costs divided by sum of discounted lifetime electricity output. Lifetime costs include capital, operating and decommissioning costs. It is an expression of cost, not revenue or price.
MEAD	Marine Energy Array Demonstrator programme of the UK's Department of Energy and Climate Change.
PTO	Power Take Off system which converts mechanical energy to hydraulic/electrical energy
O&M	Operations and Maintenance.
OEM	Original Equipment Manufacturer.
OWC	Oscillating Water Column (wave energy converter)
ROV	Remotely Operated Vehicle.
Yield	Percentage of available energy converted.

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[ii] *Accelerating Marine Energy, the potential for cost reduction – insights from the Carbon Trust Marine Energy Accelerator* July 2011 http://www.carbontrust.com/media/5675/ctc797.pdf