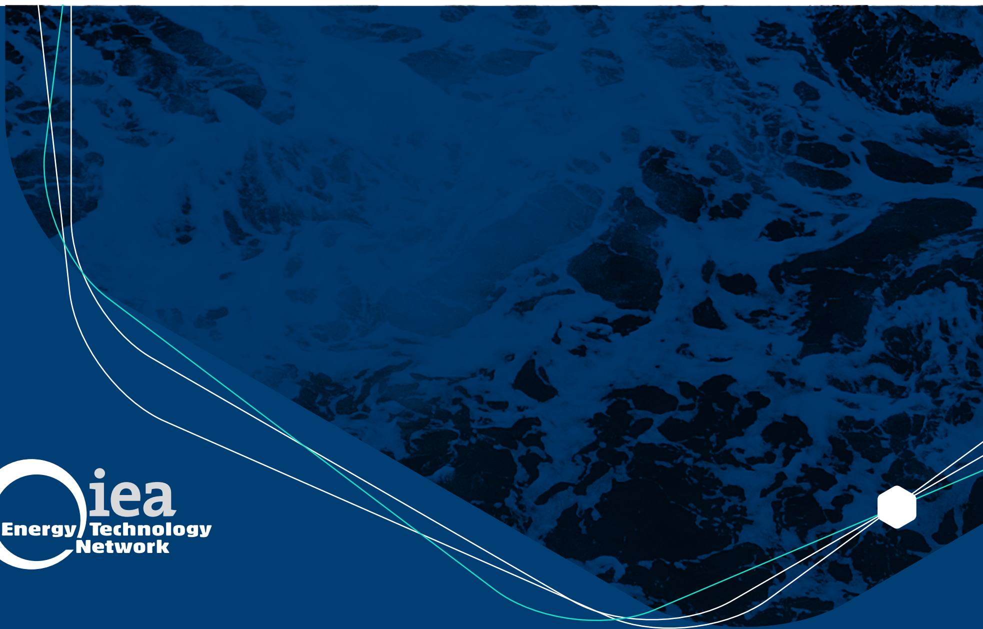
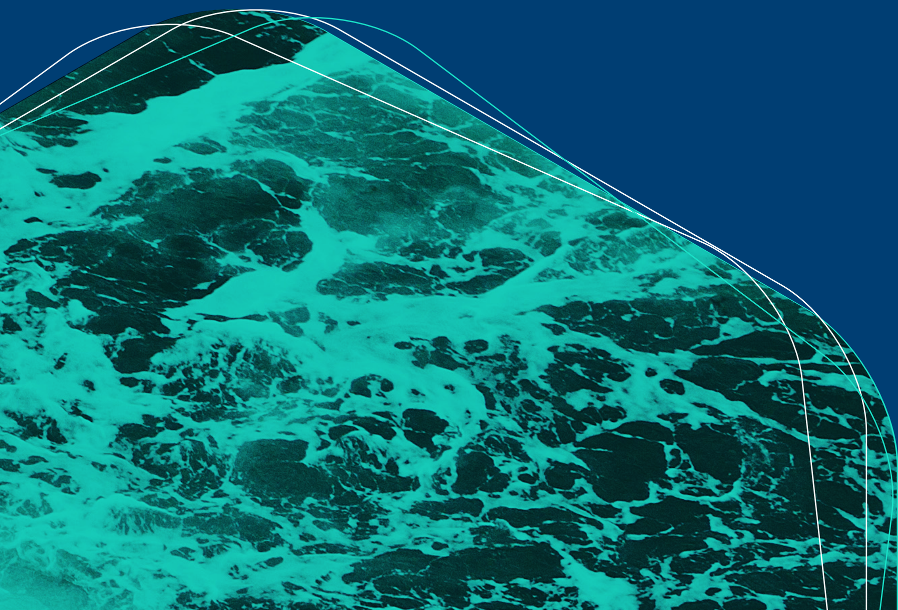


INTERNATIONAL LEVELISED COST OF ENERGY FOR OCEAN ENERGY TECHNOLOGIES

An analysis of the development pathway and Levelised Cost Of Energy trajectories of wave, tidal and OTEC technologies



May 2015

A report prepared on behalf of the IEA Technology Collaboration Programme for Ocean Energy Systems (OES)

Contents

List of Abbreviations

AEP	Annual Energy Production
CAPEX	Capital Expenditure
CBS	Cost Breakdown Structures
€	Euro
EMEC	European Marine Energy Centre
EPRI	Electric Power Research Institute
ETP	Energy Technology Perspectives
GIS	Geographical Information System
IEA	International Energy Agency
kW	Kilowatt
kWh	Kilowatt-hour
LCOE	Levelised Cost of Energy
MGD	Million Gallons per Day
MW	Megawatt
MWh	Megawatt-hour
OES	Ocean Energy Systems
OPEX	Operating Expenditure
OTEC	Ocean Thermal Energy Conversion
O&M	Operation and Maintenance
PTO	Power Take-off
TIMES	The Integrated MARKAL-EFOM System
TRL	Technology Readiness Level
USD	US Dollar
$	US Dollar

Executive Summary

Wave, Tidal Stream and Ocean Thermal Energy Conversion (OTEC) technologies have been the subject of much research both nationally and internationally. While much development has taken place, the technologies have not yet realised commercial array scale deployment. Energy system modelling to incorporate future technological advances is based around a series of assumptions which attempt to present potential pathways for new energy technologies to emerge and become established as a part of the wider energy mix. In order to enhance existing energy system modelling, a thorough investigation of the Levelised Cost of Energy (LCOE) for wave, tidal and OTEC technologies has been undertaken. This assessment draws upon industry's state of the art knowledge around the costs to deploy and operate each technology in its current state, and the cost reductions that are foreseen on the route to product commercialisation.

Each technology under consideration within this report is at a different stage of development, and presents its own unique challenges. In addition, the likely scale of technology varies between wave, tidal and OTEC, with the latter more likely to be deployed as a large-scale multi-MW power plant (similar to conventional thermal power generation) in comparison to the modular design of wave and tidal stream technologies. Wave and tidal technologies are modular in design, and therefore large power plant capacities will be achieved by the utilisation of multiple modular energy converters.

Engagement with relevant stakeholders in a number of OES Member countries has allowed an international context to be provided for each technology. As a result, mean values across a range of parameters have been obtained as a representative of the average across the industry as a whole.

The core outputs from the stakeholder engagement and subsequent analysis are presented in Table 1, which provides a summary overview of the key data across each technology type. Each technology has considered the costs and operational parameters of projects at three development phases:

i) The first project (first pre-commercial array in wave/tidal, first plant in OTEC);
ii) The second project (second pre-commercial array in wave/tidal, second plant in OTEC); and
iii) The commercial-scale target.

The commercial target is taken to be the first project that is constructed with a view to generate commercial return without the need for capital or public sector support outside of an authorised Feed-in-Tariff, and does not represent the long term future cost reduction potential – the costs could reduce further in line with learning by doing, economies of scale, and process efficiency improvements as each industry progresses.

This study has used the standard method for LCOE assessment proposed by the IEA (International Energy Agency, 2010). The project identified a need for homogenising the data and assumptions to assess CAPEX, OPEX, capacity factors and availability across a range of different developers and countries. An in-depth world-wide analysis involving relevant technology developers, supply chain companies, research institutions and experts has helped in achieving this, advancing state-of-the-art in knowledge.

Table 1: Summary data averaged for each stage of deployment, and each technology type

Deployment Stage	Variable	Wave		Tidal		OTEC	
		Min	Max[1]	Min	Max	Min	Max
First array / First Project[2]	Project Capacity (MW)	1	3 [3]	0.3	10	0.1	5
	CAPEX ($/kW)	4000	18100	5100	14600	25000	45000
	OPEX ($/kW per year)	140	1500	160	1160	800	1440
Second array/ Second Project	Project Capacity (MW)	1	10	0.5	28	10	20
	CAPEX ($/kW)	3600	15300	4300	8700	15000	30000
	OPEX ($/kW per year)	100	500	150	530	480	950
	Availability (%)	85%	98%	85%	98%	95%	95%
	Capacity Factor (%)	30%	35%	35%	42%	97%	97%
	LCOE ($/MWh)	210	670	210	470	350	650
First Commercial-scale Project	Project Capacity (MW)	2	75	3	90	100	100
	CAPEX ($/kW)	2700	9100	3300	5600	7000	13000
	OPEX ($/kW per year)	70	380	90	400	340	620
	Availability (%)	95%	98%	92%	98%	95%	95%
	Capacity Factor (%)	35%	40%	35%	40%	97%	97%
	LCOE ($/MWh)	120	470	130	280	150	280

It should be noted that the above table does not represent the maximum and minimum LCOE scenarios, but the maximum and minimum value of each parameter within the range of responses provided by each developer. The following sections of this report cover in detail the individual technologies of wave, tidal and OTEC. While parameter ranges have been summarised above, the data encapsulates a number of possibilities, which will be explored in greater detail within each relevant technology sub-section. Although current costs are high, there is a clear trajectory towards a more affordable LCOE in future projects. These costs can be seen to represent targets for each of the ocean energy technologies, which must be met if each sector is to realise its goal of becoming an economically sustainable, commercial industry. It is important to mention that the costs presented for the first commercial projects in Table 1, expected to be installed between 2020 and 2030, are not the long-term cost reduction target. Costs in the long-term are expected to decrease from the first commercial project level as experience is gained with deployment.

[1] For wave, the maximum value in the table is either that from the responses of consulted developers or from any of the reference studies analysed, this is particularly relevant for OPEX, where developers are now presenting costs that are significantly more optimistic than past studies have suggested.

[2] Availability for first arrays is anticipated to be significantly lower than the desired target for commercial projects. As such, the LCOE is not expected to be competitive for these early arrays. Subsequent cost reduction for following array deployments will enable competitive LCOE to be reached.

[3] One respondent provided significantly larger arrays than the rest, but it not has been included in this table; instead, the second largest array has been included.

1 Introduction and background

The International Energy Agency (IEA) is an autonomous organisation that works to ensure reliable, affordable and clean energy for its 28 member countries and beyond. The IEA's four main areas of focus are: energy security, economic development, environmental awareness and engagement worldwide. Through extensive modelling work, the IEA is at the forefront of providing input to international ocean energy deployment targets, and delivering practical recommendations to remove barriers to market penetration. Wave, Tidal Stream and Ocean Thermal Energy Conversion (OTEC) technologies have made significant progress in recent years. A number of full scale prototypes are now in operation and generating electricity. It is important for policy makers and investors in ocean energy technologies to have a picture of the current costs for ocean energy generation and how these are likely to reduce over time.

The assessment of the Levelised Cost of Energy (LCOE) for ocean energy devices represents a critical element of understanding in the development of ocean energy projects. While the cost of existing prototype devices is high, there is scope for significant reductions of the cost of energy.

LCOE projections are a cornerstone of the deployment strategy for all device and project developers. The final goal for all wave, tidal and OTEC technology developers is to generate power at a cost that is competitive with alternative forms of generation. Cost competitive marine energy devices could then foster ocean energy technologies as realistic alternatives of conventional electricity generation, and as complementary technology to other sources of renewable energy.

Currently, there is not an international and standardised approach to draw LCOE estimates, and the lack of rules and guidance regarding the boundaries and assumptions often makes LCOE results incomparable and non-transparent. By defining sets of parameters such as capital expenditures (CAPEX), operational and maintenance expenditures (OPEX) and input resource data, the project has delivered a clear and unbiased model to calculate the LCOE of different ocean technologies.

Furthermore, the work aims to provide an authoritative view on what cost reductions are feasible at a global level, taking into account the experience from other technologies. By undertaking a bottom-up assessment of the cost components of leading wave, tidal and OTEC systems, this work investigates the development and fabrication of leading devices or systems, and their integration into commercial arrays and large-scale power plants. The assessment includes project development, operation and maintenance costs. The work is informed by a series of in-depth interviews with technology developers, and is built upon work carried out by different international projects (e.g. SI Ocean, DTOcean, Equimar, the Danish LCOE Calculation Tool, Carbon Trust, and US Department of Energy).

An additional benefit of this project is the generation of data that will be suitable for use in the IEA's Energy Technology Perspectives (ETP) modelling. For each technology, CAPEX, OPEX and capacity factor have been ascertained, allowing improved ocean energy input data for future modelling runs. However, as described in the report, there is still a large range of variability in the data provided, due to diversity of concepts, the different assumptions on the data to calculate costs and annual energy production, which are inputs to the model. An international in-depth analysis has been carried out to narrow down these ranges and to provide a clearer vision of the real potential.

2 Methodology

2.1 Review of existing analyses and proposed approach

The aim of this study is to evaluate the current best practice in assessing Levelised Cost of Energy (LCOE) for wave, tidal and OTEC technologies. Hence, a review of existing cost assessment models was carried out. The projects reviewed for existing LCOE calculation methodologies included Equimar (Ingram, Smith, Bittencourt-Ferreira, & Smith, 2011), the Carbon Trust model (Carbon Trust, 2006), SI Ocean (SI Ocean, 2013), the Danish COE Calculation Tool (Fernandez-Chozas, Kofoed, & Jensen, 2014) (Energinet.dk, 2013), WavEC Techno-Economic model (WavEC, 2015) and the US Department of Energy Reference Model (reVision, 2015). Through this review, significant knowledge of available models regarding LCOE assessment for ocean energy technologies was built.

Firstly, a comparative table was built, which compared the models based on the parameters considered by each reference model. Cost Breakdown Structures (CBS) within most of the models were found to be too detailed and too technology specific for the purposes of this study. In addition, due to the large variety of technologies (even within wave, tidal or OTEC considered separately) and diversity of sites the study would encompass, it was agreed that a more generic and transparent modelling approach would better suit the project. It was also agreed that the model should be built only on the main parameters affecting the LCOE that are included within the IEA modelling approaches.

As a result, a standard cost model was built for the purpose of this work, which was aligned with the TIMES regional model (the Integrated MARKAL-EFOM System) utilised by the International Energy Agency (IEA) in their Energy Technology Perspectives (ETP) analysis. As such, the inputs required for TIMES model would be provided as output from this work.

Also, the project-specific cost assessment model that was developed would ensure suitability for the three technologies considered in the study. For each technology (wave, tidal and OTEC) three characteristic deployment stages were considered.

2.2 Model and parameters selection for LCOE

The Levelised Cost of Energy (LCOE) is a useful parameter to assess the economic feasibility of a technology. It is defined as the sum of all capital costs and lifetime operation and maintenance costs (discounted to present value) divided by the electricity generation to grid accumulated throughout the technology's lifetime (also discounted to present value). The methodology used in this report assumes that capital expenditure occurs in year zero, and plant operation starts in year one. It is represented by the following equation:

$$LCOE = \frac{CAPEX + \sum_{t=1}^{n} \frac{OPEX_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{Annual\ Energy\ Production_t}{(1+r)^t}}$$

$LCOE$ = Levelised Cost of Energy

$CAPEX$ = Capital expenditures

$OPEX_t$ = Operational expenditures (at year t)

AEP_t = Annual electricity production (at year t)

r = Discount rate

n = Lifetime of the system

t = Year from start of project

The parameters identified in Table 2 represent the main variables influencing the LCOE calculation. Data points were collected for each of the identified parameters at each of the three proposed deployment stages (first pre-commercial array or first project, second pre-commercial array or second project, and first-commercial project) for each technology type through discussion with individual technology developers.

By using the collected parameters, it was possible to evaluate the Annual Energy Production (AEP) in MWh produced by each project. The AEP is an estimate of total energy production of a marine energy converter system during a one-year period. It is obtained by applying the power performance characteristics of the marine energy converter to a specific marine resource, and assuming a specific capacity factor and level of availability, all of which were to be collected as part of the stakeholder engagement process.

Once the model and the parameters were defined, a suitable reference questionnaire was created to capture the relevant parameters. This questionnaire was circulated among selected international technology developers of wave, tidal and OTEC technologies, with the aim of gathering relevant values, experienced information and inputs from which to draw LCOE estimates. The selection criteria for wave and tidal developers included only companies that have tested technologies in the sea at full or part-scale (TRL≥5), and included only companies that were active in the sector at the time of writing. In the case of OTEC, data was gathered from reference reports and studies due to the limited number of developers available and at a different stage of development.

Table 2: LCOE Model Parameters

LCOE Model Input Parameters are highlighted in bold font. Additional parameters were used for calculation and validation	
Number of devices installed per project (at the given deployment stage)	The number of devices installed within an array during either first project, second project, or commercial project. Applicable to wave/tidal only.
Unit Rated Capacity (MW)	Generator Nameplate (or rated capacity) of the unit deployed within each project.
Project installed capacity at each deployment stage (MW)	Sum of the nameplate (or rated capacity) of all generators deployed at each stage, calculated as the number of devices multiplied by the rated capacity of the devices.
Cumulative Deployment prior to the given deployment stage (MW)	Sum of the nameplate (or rated capacities) of all devices installed and tested in a marine environment before reaching this stage (including demonstration and prototype units).
Date of Deployment	The expected installation date of the array.
Project life expectancy (years)	The target lifetime for the deployed project. It was assumed to be 20 years in all cases for consistency, although it is expected that there may be differences from project to project and at different stages of development.
Discount Rate (%)	A discount rate is used to account for the time value of money by calculating the present value of future costs. It was assumed 10% in all cases for consistency, although it is expected that there may be differences from project to project and at different stages of development.
Overall CAPEX ($/kW)	Sum of all capital expenditures. CAPEX are incurred mostly at the beginning of a project.
Project development ($/kW)	Project costs, such as environmental impact assessment and site surveys, before manufacture and installation takes place.
Grid connection ($/kW)	Cost of all electrical connections needed to connect the wave/tidal/OTEC technology to land. At present, typical distance to shore is anticipated to be less than 5 km, although this may increase in future projects long term.
Device ($/kW)	Includes cost of materials and fabrication of the structure and prime mover[4] and cost of all the items that convert the movement of the device or the surrounding water to electrical energy – i.e. the Power Take Off[5] (PTO).
Moorings and Foundations ($/kW)	Cost of all the components required to hold the device in place.
Installation ($/kW)	Cost of pre-assembly, transporting, mooring, installing foundations and attaching the device to the appropriate fixings.
Platform and moorings (OTEC specific)	Includes all the structural and mooring related components of the platform and housing for the power conversion equipment.
Cold water pipe (OTEC specific)	The riser which delivers cold water from depth to the platform. Due to the length of this pipe, it has been established as a separate CAPEX item.
Power conversion (OTEC specific)	All items involved in the conversion of mechanical energy into electrical energy, including turbines and generators.
Overall OPEX ($/kW per year)	Sum of all Operational Expenditures. They are spread over the lifetime of the project and may be broken down into sub headings such as annual O&M costs, insurance and sea bed lease rates.
Annual O&M costs ($/kW per year)	Cost of all planned maintenance and repair requirements associated with the upkeep of the device.
Insurance ($/kW per year)	Cost of insuring the technology against all risks during its deployment and operational life.
Sea bed lease rates ($/kW per year)	Cost of renting the seabed at the chosen site of deployment.
Mean Resource Level (Wave - kW/m; Tidal - v_{msp}; OTEC – Temperature differential in °C)	- Wave: "Long-term average of the directionally unresolved wave energy flux per unit width, calculated as an arithmetic mean over all sea stated occurring at a given location" (IEC/TS, 2012)

[4] *Prime mover* is defined as the "Physical component that acts as the interface between the marine resource and the energy converter from which energy is captured" (IEC/TS, 2012).
[5] *Power Take-off* (PTO) is defined as the "Mechanism that converts the motion of the prime mover into a useful form of energy such as electricity" (IEC/TS, 2012).

	- Tidal: The mean maximum velocity of the "Flow of water induced by the gravitational forces of celestial bodies" (IEC/TS, 2012), achieved during spring tides throughout the lunar cycle. - OTEC: The temperature gradient between the warm surface water heated by the sun, and the cooler water located at depth. The larger the gradient, the greater the potential for energy extraction.
Capacity factor (%)	The capacity factor is a measurement of the average production of a plant over a period of time. It is calculated by comparing the amount of actual energy production during a given period to its theoretical output if it were possible for the plant to operate at full rate power over this same time period.
Availability (%)	"Availability of a marine energy conversion system to be in a state to perform a necessary function under given conditions at a given instant of time or over a given duration, assuming that the necessary external resources are provided" (IEC/TS, 2012)

2.3 Considerations and Limitations of the study

2.3.1 Annual Energy Production

The Annual Energy Production (AEP) for a given project is calculated using the following equation:

$$AEP = Project\ Capacity * CF * Av * 8760$$

AEP = Annual Energy Production

CF = Device Capacity Factor

Av = Device Availability Factor

2.3.2 Currency and Exchange Rates

The currency used within this report is the US Dollar ($). Where applicable, prices have been converted from Euros (€) at an exchange rate of 1.33 US Dollars to the Euro. This is reflective of the average annual exchange rate over the year 2014, during which much of the data collection for this study took place.

2.3.3 Technology Readiness Level (TRL)

The parameter Technology Readiness Level (TRL) is frequently used to quantify the development stage of an ocean energy technology.

NASA's Technology Readiness Levels (TRLs) were originally used in aviation, space and defence to manage the development of high risk, novel and complex technologies (NASA, 2013). Quite recently, this development schedule has been re-introduced by utilities, research institutes and the European

Commission to assess the development stage of ocean energy technologies (Fitzgerald et al., 2012) (West Wave, 2014).

By definition, a TRL indicates the commercial ability of a technology. There are nine TRLs. The following are the definitions provided by the European Commission (EC, 2013) on TRLs:

- TRL 1 – basic principles observed.
- TRL 2 – technology concept formulated.
- TRL 3 – experimental proof of concept.
- TRL 4 – technology validated in lab.
- TRL 5 – technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies).
- TRL 6 – technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies).
- TRL 7 – system prototype demonstration in operational environment.
- TRL 8 – system complete and qualified.
- TRL 9 – actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space).

This project considers technologies at TRLs 5 or above.

2.3.4 Cost Predictions and Uncertainties at Different Technology Maturity Levels

The trend of increasing cost predictions observed over the last decade in marine energy is very common in the development of new technologies and new industry sectors. It is typical that during the early phases of product development designers are both optimistic about device performance and have a limited understanding of all the factors that will eventually contribute to lifecycle cost and performance. As a design matures, a more complete understanding of all aspects of the technology emerges, and cost predictions tend to increase, as shown in Figure 1. With the deployment of a prototype machine, the various components of a system's economic viability become fully quantified and understood.

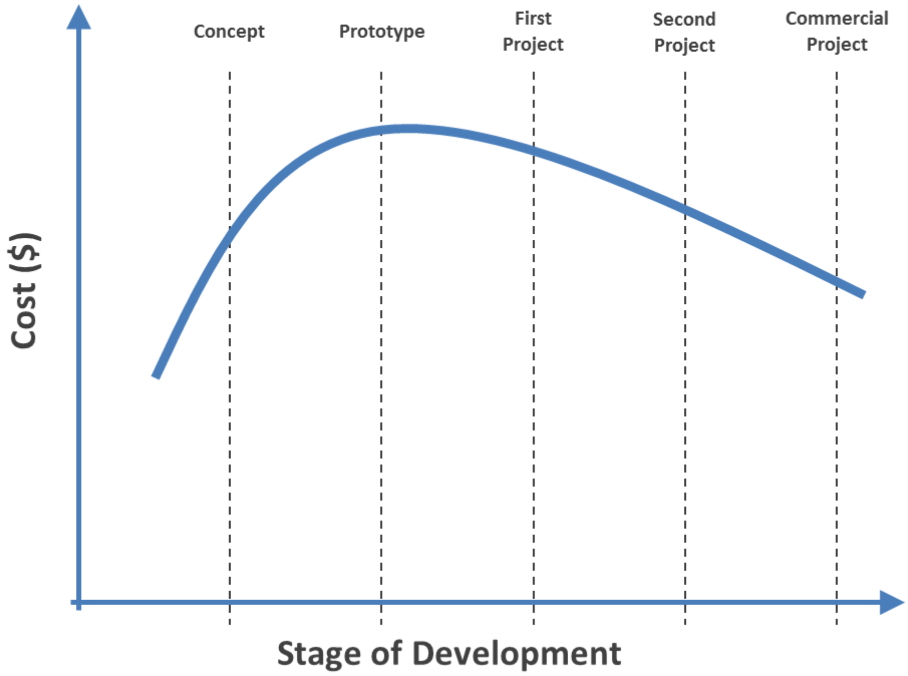


Figure 1: Project cost as a function of development stage

The key challenge in predicting commercial opening costs in the wave, tidal and OTEC sectors is acquiring meaningful data. Very few data points are available from actual deployments, and all existing data points come from pilot and demonstration projects, not larger-scale farms.

It is important to understand that most cost assessments carried out to date have been based on projected costs and were not derived from direct project experience. The reliance on projected costs leads to uncertainties in the cost assessment process, which can be substantial depending on the stage of development of the technology, and the level of detail in the assessment. Table 3, which was developed by the Electric Power Research Institute (EPRI), shows the percent uncertainty in cost estimates as a function of the amount of effort going into the cost assessment (e.g. actual, detailed, preliminary, simplified or goal) and the development status of the technology (e.g. mature, commercial, demonstration, pilot or conceptual).

Table 3: EPRI cost estimate rating table showing cost uncertainty as a percentage (Source: (Mirko Previsic, 2009))

Cost Estimate Rating	A Mature	B Commercial	C Demonstration	D Pilot	E Conceptual (Idea or Lab)
A. Actual	0	-	-	-	-
B. Detailed	-5 to +5	-10 to +10	-15 to +20	-	-
C. Preliminary	-10 to +10	-15 to +15	-20 to +20	-25 to +30	-30 to +50
D. Simplified	-15 to +15	-20 to +20	-25 to +30	-30 to +30	-30 to +80
E. Goal	-	-30 to +70	-30 to +80	-30 to +100	-30 to +200

The best cost and economic assessment datasets within this project come from demonstration or pilot plants and hence significant uncertainties remain, even if costs are predicted with great care. As shown in Table 3, the range of cost uncertainty for a preliminary or simplified cost assessment for a demonstration project is in the order of -20% to +30%, while the cost for a pilot project has a -30% to +30% uncertainty range. For the purposes of this study an uncertainty range of -30% to +30% (as per the simplified cost estimates for pilot plants) has been used for each technology under consideration.

While predicted commercial costs for larger-scale farms are well below present pilot and demonstration cost levels, significant cost reductions will need to be achieved by the industry if the technology is to be deployed commercially in competitive utility-industry marketplaces.

Learning curves are typically used when predicting longer-term cost reductions for an industry. For each doubling of the deployed capacity, a certain percentage cost reduction is attained. Similar renewable energy technologies have historically attained learning rates in the order of 10%-30%. Wind technology, for example, which is the most closely related, has demonstrated learning rates in the order of 15%. It is important to understand that these cumulative cost reductions are tied to a wide range of factors that can drive cost down, including manufacturing scale, operational efficiencies, improved reliability and availability, and fundamental design changes (Figure 2).

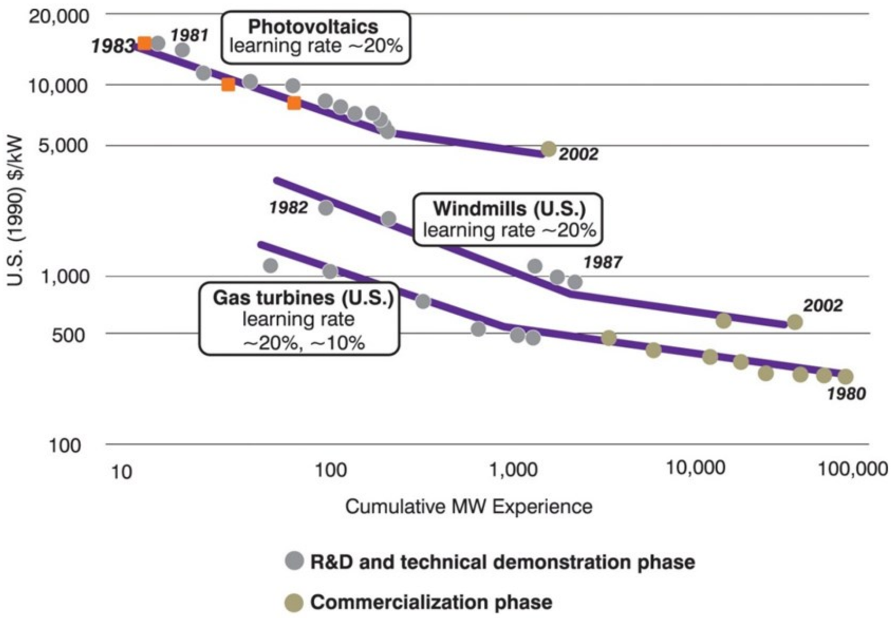


Figure 2: Historical learning curves (Project Finance, 2008).

2.3.5 Limitations of the study

Overall, this study intends to allow an oversight of the economic analysis procedure and ensure that a consistent methodology is applied wherever possible. The aim of this economic assessment is to produce an estimate of future costs of wave, tidal and OTEC technologies and to validate the ocean energy sector's learning curves.

In some cases, input parameters are generic and may be similar for the majority of devices and deployment scenarios; but in other cases, input parameters are very device and technology specific. Also, there are many sources of uncertainty associated with the economic assessment of ocean technologies. Greater levels of experience in both deploying and operating these technologies will allow enhanced estimates of the LCOE to be made.

It is a good practice when making any costs estimates to estimate also the associated uncertainty of the estimate. Therefore, the proposed calculation approach takes into account the uncertainties of various factors. However, the inherent uncertainty in the input values provided by developers is complicated further by economic variability in the exchange rates when considering multiple currencies.

Data for the tidal and wave energy sector came from a number of leading sources and technology developers, however it is recognised that this list is not exhaustive. The data collection process has succeeded in delivering a representative selection of candidate technologies for this study. In the case of OTEC, there are only a very limited number of developers. Due to these limitations, and given the large variations from between concepts and developers at different stages of development, data from previous reference international studies was included in all three cases.

3 Tidal Technology LCOE Assessment

Tidal energy technology development has seen the successful installation of numerous pre-commercial demonstration prototypes across Europe, North America, and Asia. However, the majority of the existing grid-connected capacity is located in the UK at the European Marine Energy Centre (EMEC) in Orkney. Existing test and demonstration technology is recognised to be high in cost, and in order to attain commercial competitiveness significant cost reduction must be achieved.

The first array project to reach financial close was phase 1 of the Meygen project, located in the Inner Sound of the Pentland Firth, UK. This project will consist of four 1.5 MW tidal energy converters, and represents an international industry first for the progression from single MW-scale device testing to array deployment. Further array developments are making significant progress in France.

Across the globe, increasing level of attention is being given to community scale technologies and projects with capacities in the region of tens or hundreds of kilowatts. While still of a higher cost than incumbent sources of electricity generation, these projects can be installed at a lower overall CAPEX in order to appropriately mitigate risk, and therefore represent a development pathway that could be considered attractive for phased-risk technological development and iteration prior to the emergence of a commercial product.

The developers contributing to this work on International Cost of Energy represent technology developers with real-world deployment experience, and who are actively seeking to progress on to multiple unit deployments in the near future. The scale of technology under consideration ranges extensively, with technology development at the kW scale and at the MW scale feeding into the analysis for this project.

In order to ensure anonymity, the information provided by individual technology developers has been averaged across the sector. Data has been normalised to provide a breakdown of costs “per MW”. The data has been provided by technology developers across three continents: Europe, Asia, and North America. The data within this report represents the industry average provided through consultation.

This work has reviewed reference reports on the status and costs of tidal energy technology, as well as historical cost data and models (IRENA, 2014) (Carbon Trust, 2011) (SI Ocean, 2013) (Vincent S. Neary, 2014) (DECC, 2011).

Some particular considerations for tidal energy technology are described below:

- Data included a number of technology developers with activity in Europe, Asia, and North America. Twenty questionnaires were sent and responses from eight active developers that have tested full or part-scale prototypes at sea were obtained.
- Data has been averaged across the sector to ensure anonymity.
- Only data considered as being reliable and at high TRL (≥6) has been used, and included only companies that were active in the sector at the time of writing.
- LCOE projections considered in three distinct phases: first pre-commercial array/project, second pre-commercial array/project and first large commercial-scale array/project.

- An uncertainty of ±30% has been added to the average values associated with CAPEX, OPEX and LCOE (dark mid-range in graphs), while extremes are taken from the maximum and minimum responses from the industry engagement process (dotted lines).
- Historical data from previous projects, reports and models have been added for reference.

3.1 CAPEX

The CAPEX costs could be considered as relatively well understood for first array projects, given the advanced stages of development for a number of technologies and sites; however the level of infrastructure associated with these early array deployments varied between consultation respondents, leading to a large range in initial CAPEX costs. For example, the level of inter array cabling, or number of export cables required to shore depends on the fundamental technological choices made by developers. Methods utilised in first array deployments may not be employed for future commercial projects. The anticipated cost reductions of future arrays come with a level of uncertainty; however, increasing levels of convergence on future target costs can be seen across the range of respondents within this study.

The range of CAPEX costs can be seen in the figure below:

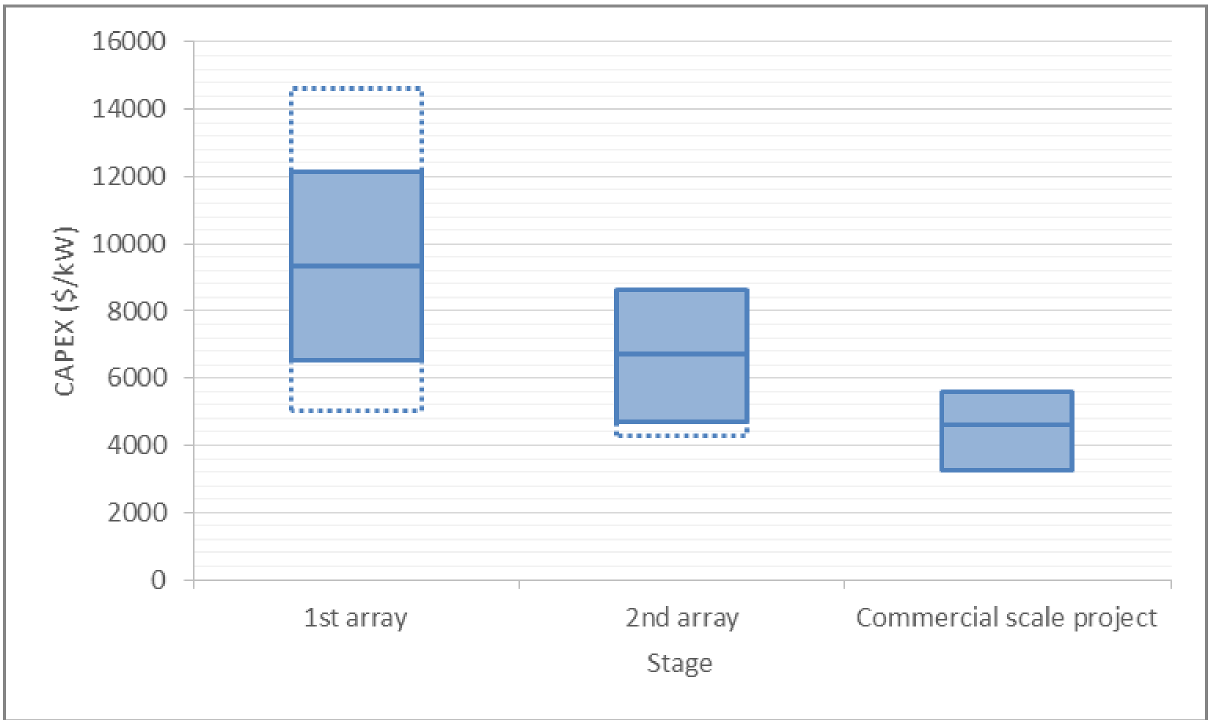


Figure 3: CAPEX Cost Ranges at Differing Stages of Deployment [Note: Where dotted lines exist, these represent the maximum/minimum cost values provided from the stakeholder engagement. The solid lines with shaded area represent the industry averaged cost with an uncertainty bound of ±30%, with the exception of when the maximum or minimum from consultation falls below the ±30% uncertainty limit].

The first array costs documented in this analysis are in line with those calculated in previous work, where ranges such as 5600-12000 $/kW (SI Ocean, 2013), 9600-16000 $/kW (Carbon Trust, 2011), and 4800-8100 $/kW (Black & Veatch, Ernst & Young, 2010) are found in the literature.

As the level of deployment increases, the overall CAPEX costs are anticipated to fall. Significant cost reduction is anticipated in the areas of installation, grid connection, and project development. This is in alignment with a move to larger arrays, and through process improvements as a result of learning by doing. In addition to the falling mean CAPEX value as deployment progresses, there was significant convergence in the range of CAPEX costs, with industry convergence resulting in a reduced spread in the level of CAPEX cost variation by the time companies deploy their first commercial project. It should be noted that the figures for "commercial scale project" above represent the early commercial arrays deployed by technology developers, and as such do not represent the long term cost reduction possibilities in the event of large scale array build out. Further cost reductions will likely be seen as the industry enters a post-commercialisation phase.

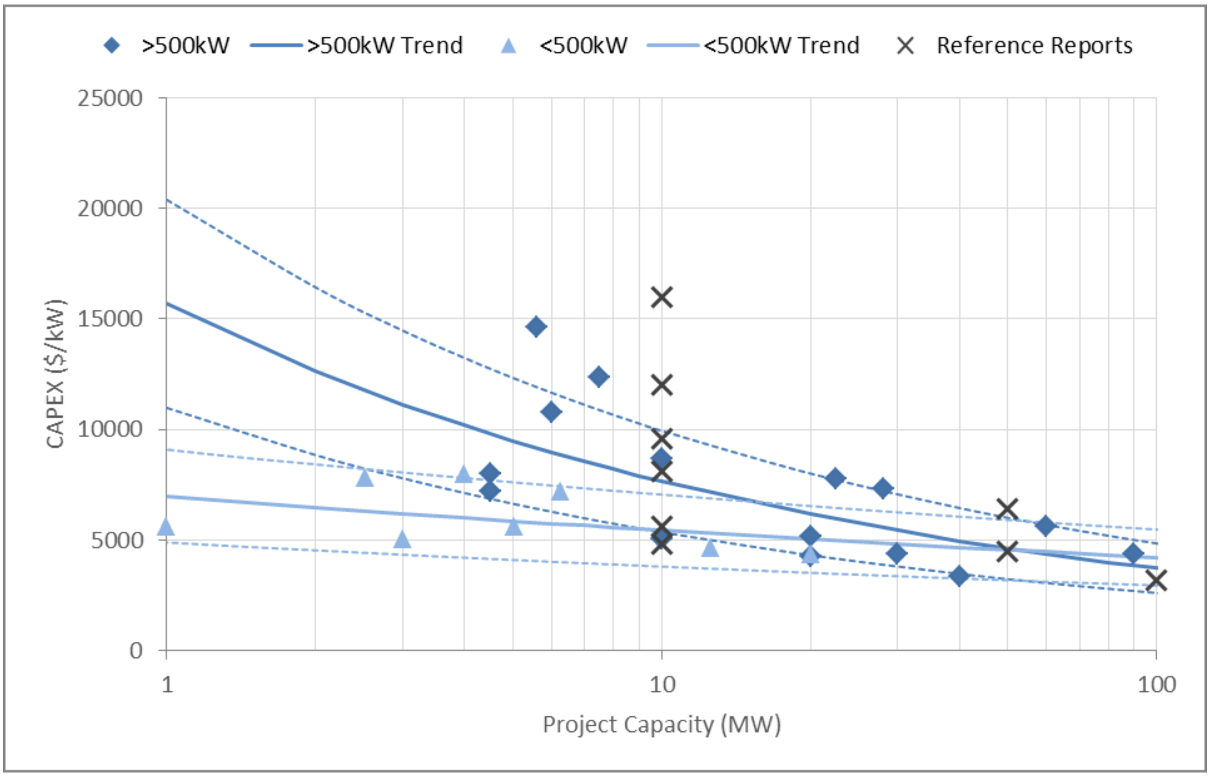


Figure 4: CAPEX cost per kW installed relative to project deployed capacity. Note: The above chart does not represent a learning curve. This represents the starting cost for arrays at a given scale. Future cost reduction effects will result in cost reduction through learning, but cannot be demonstrated on this figure.

The consultation process considered technologies at both large (≥500 kW) scale and small (<500 kW) scale, with the trend associated with each mode of scale differing slightly. The technology scales have been separated in the above plot in order to highlight the two emerging trends. While current capital costs for the first arrays have a diverse spread for the larger scale technologies – particularly in the early projects – the small scale technologies claim to offer lower capital costs per kW installed. When the average trend line is plotted with 30% uncertainty bounds, it can be seen that all of the small scale technologies fall within the ±30% uncertainty level for that technology scale. For the large scale technologies, there are two outliers that exceed the +30% uncertainty level on the average trend line, however these represent first array projects, and future projects generally fall within the ±30% uncertainty range. The future cost reduction trend for large scale technologies is significantly greater than that of the small technologies, indicative of the greater levels of cost reduction that must be achieved when progressing to larger arrays. There is convergence between large and small scale technologies towards the anticipated CAPEX cost value at the commercial scale project. It should be noted that the above figure is not representative of learning, but instead projects the starting cost that will be achieved using given deployment scales. Learning by doing will result in cost reduction, but this cannot be extrapolated from the above figure. Long term learning effects will be considered later within this report.

3.2 OPEX

Due to the uncertain nature of O&M costs, and the direct negative impact of any unscheduled maintenance routines, the OPEX cost parameters were highly variable. While certain technology developers are confident that existing deployment experience has allowed for low costs associated with maintenance needs, the OPEX costs remain largely unproven even in the most mature technologies. The cost of offshore operations is a significant driver in the levels of uncertainty as indicated by the wide range of responses from the developers consulted.

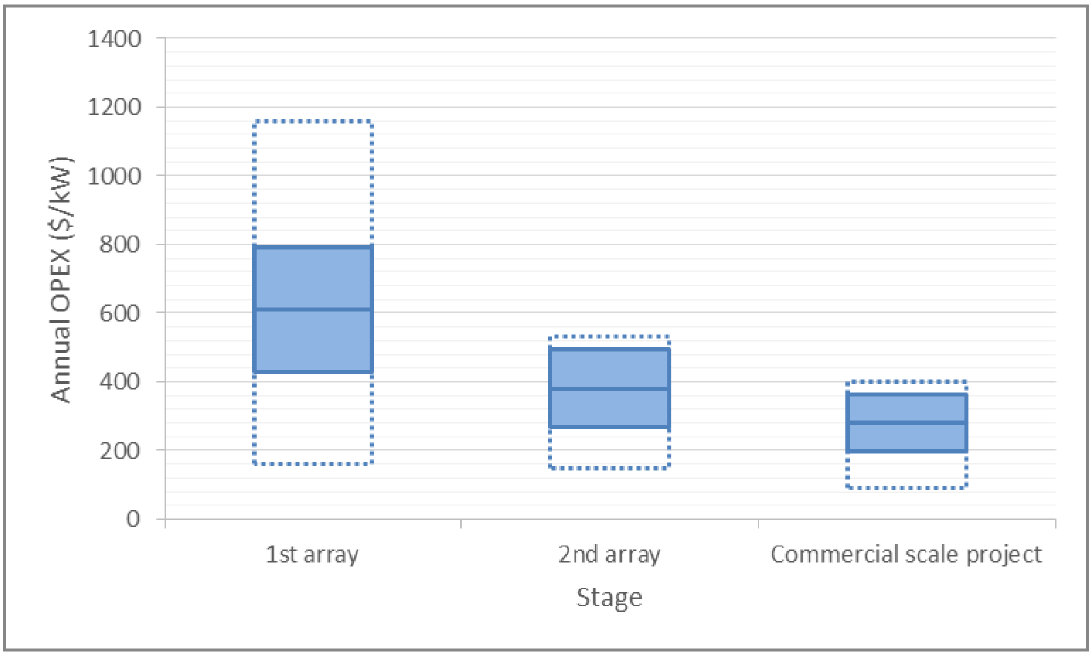


Figure 5: OPEX Cost Ranges at Differing Stages of Deployment [Note: The dotted lines represent the maximum/minimum OPEX values provided from the stakeholder engagement. The solid lines with shaded area represent the industry averaged cost with an uncertainty bound of ±30%].

As deployment levels increase, the OPEX costs must reduce in order to achieve economic performance of ocean energy technology. The cost associated with annual O&M is expected to fall dramatically across the industry. Although an increase in array size will result in significant increase in the number of units deployed, OPEX costs are expected to fall as technology matures and sufficient proof of reliability is made. However, opportunity to increase the scale of array deployment will only occur if sufficient confidence in the technology is established within key stakeholder groups.

3.3 Annual Energy Production

The annual energy produced from an array of devices is calculated based on two key factors – Capacity factor (or load factor) and availability. Increased capacity factor results in a higher Annual Energy Production (AEP) per kW installed.

Responses to the stakeholder engagement suggested that capacity factor was likely to range between 35% and 42%. Previous studies have suggested that capacity factors are likely to range between 27% and 35% (SI Ocean, 2013), but this new research reflects an upward trend in the anticipated capacity factor of the early arrays. As such, a 35%-42% range has been considered herein. The sector averaged trend shows a slight increase in capacity factor between 1st array and 2nd array deployments. However, the commercial target sees a slight reduction in anticipated capacity factor, perhaps due to use of less energetic resource locations for larger scale deployments, but also due to an inversely proportional trend between average device capacity factor and overall array size. As array scales increase, the net energy extraction and "farm shadow effect" will cause a reduction in the resource available for extraction reaching devices located behind the first row.

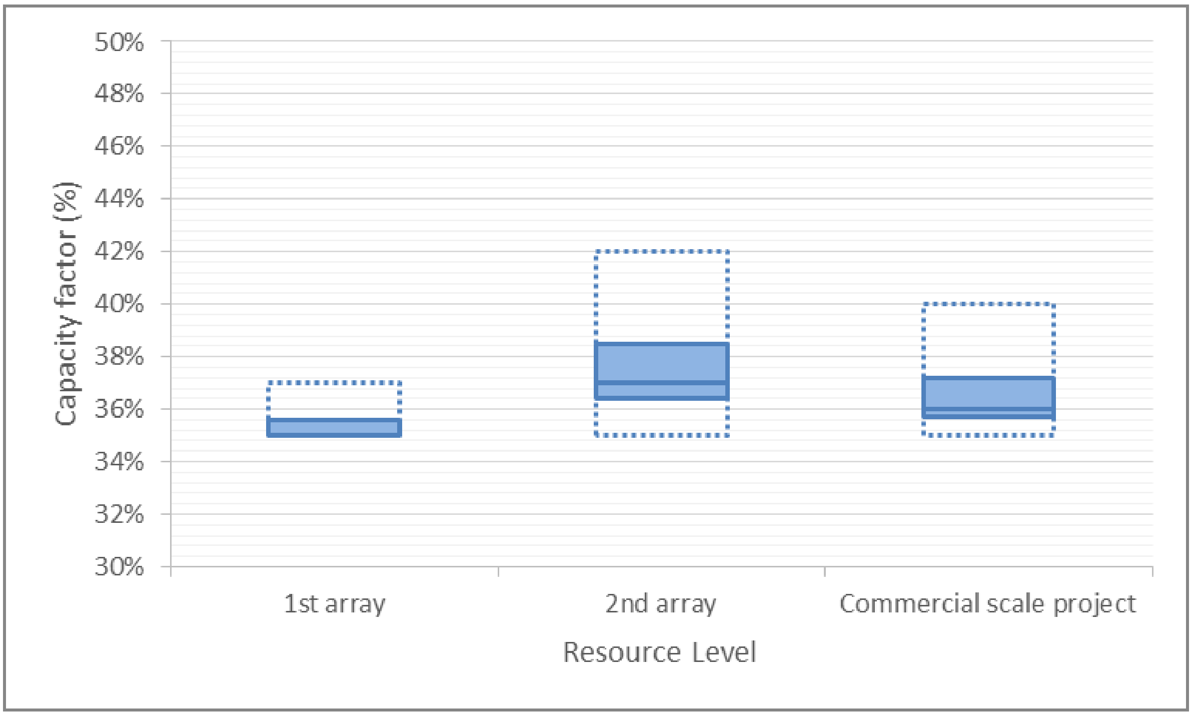


Figure 6: Industry averaged capacity factor and local maximum and minimum values (dotted lines) at each stage of deployment.

Availability was assumed to improve over time by each technology developer, with respondents suggesting ranges of between 75% and 98% for the first arrays, with an increasing trend in availability expectations as projects progress. The sector averaged availability trend shows increasing availability from a mean value of 88% for the first array to a mean value of 96% for the commercial array projects. It can be noted that certain technology developers are anticipating very high availabilities, even in the first array project. A summary of the availability ranges provided from the stakeholder engagement can be seen below.

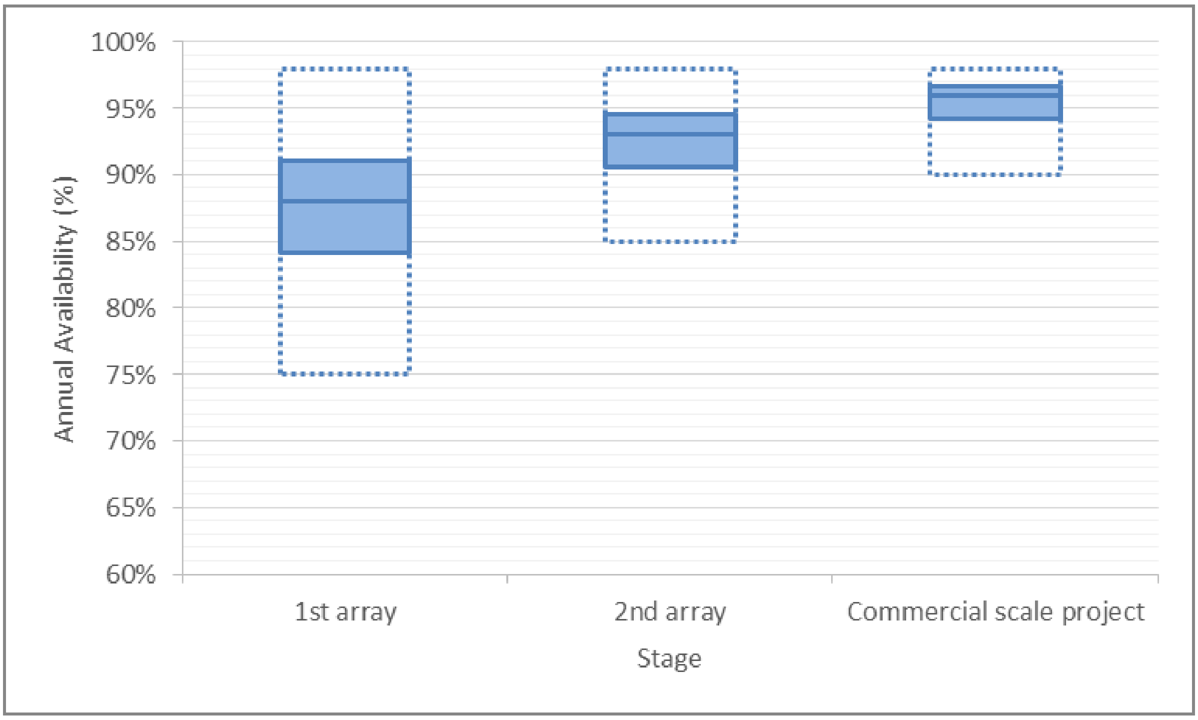


Figure 7: Industry averaged availability and local maximum and minimum values (dotted lines) at each stage of deployment.

The level of Annual Energy Production can have a significant impact on the overall LCOE, so developers are targeting high device availabilities in order to minimise the LCOE. These high reliabilities and availabilities require demonstration, with improvements on current statistics necessary in order to meet these stringent targets.

3.4 Levelised Cost of Energy

The LCOE calculation is described within Section 2 of this report. It has been suggested that the levels of uncertainty associated with estimates at this stage of technology development could be in the order of ±30%. The CAPEX and OPEX costs that have been used were acquired from analysis of industry averaged data for first array, second array, and long-term project targets have been used as the input values in the LCOE calculation, resulting in the following LCOE ranges.

The LCOE ranges are diverse within the first array deployment, but clear convergence is seen across the tidal energy sector as progression is made towards commercial scale projects. The SI Ocean project indicates a current LCOE range of 250-470 €/MWh (SI Ocean, 2013), which equates to approximately 333-625 $/MWh. This SI Ocean data range is within, but at the lower end of, the spectrum identified within the “first array project” phase of this analysis.

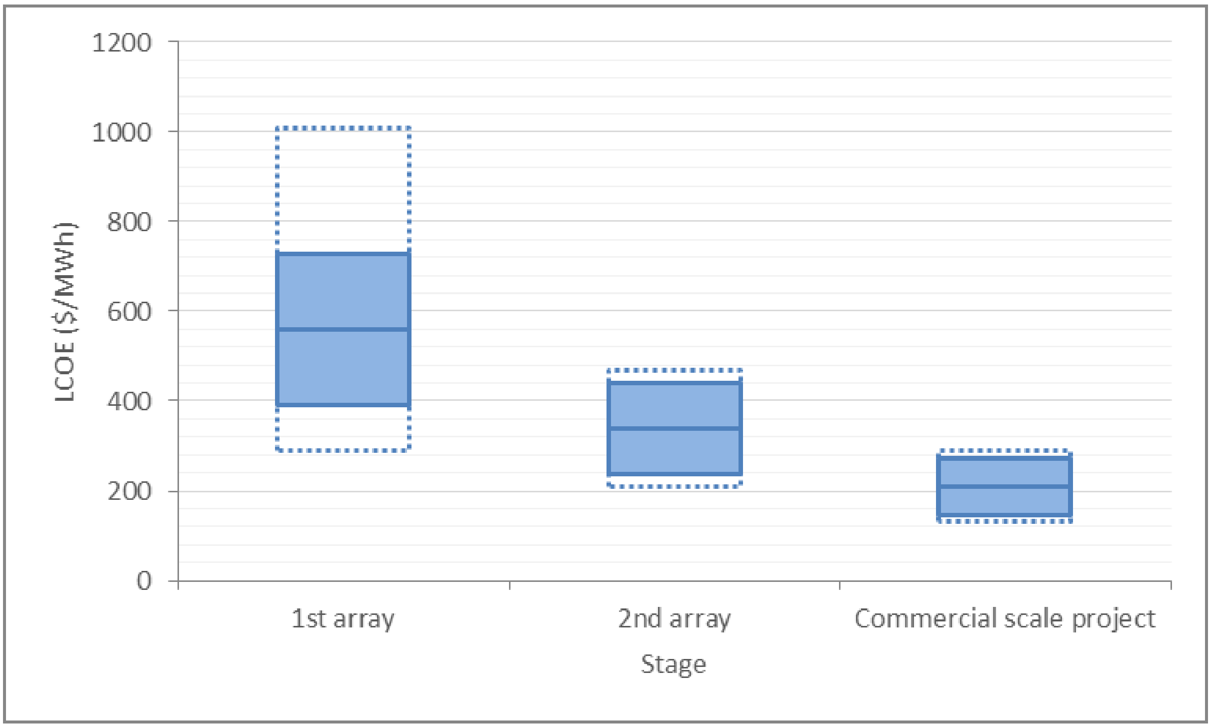


Figure 8: LCOE Ranges at Differing Stages of Deployment. [Note: The dotted lines represent the maximum/minimum OPEX values provided from the stakeholder engagement. The solid lines with shaded area represent the industry averaged cost with an uncertainty bound of ±30%].

The industry averaged LCOE value has been achieved through averaging across a range of technology developers. The percentage breakdown therefore does not represent one particular technology, rather an average across the tidal energy industry as a whole. A breakdown of CAPEX (by specific cost centre) and OPEX contributions to the LCOE is presented in Figure 9 below.

3.4.1 LCOE Breakdown

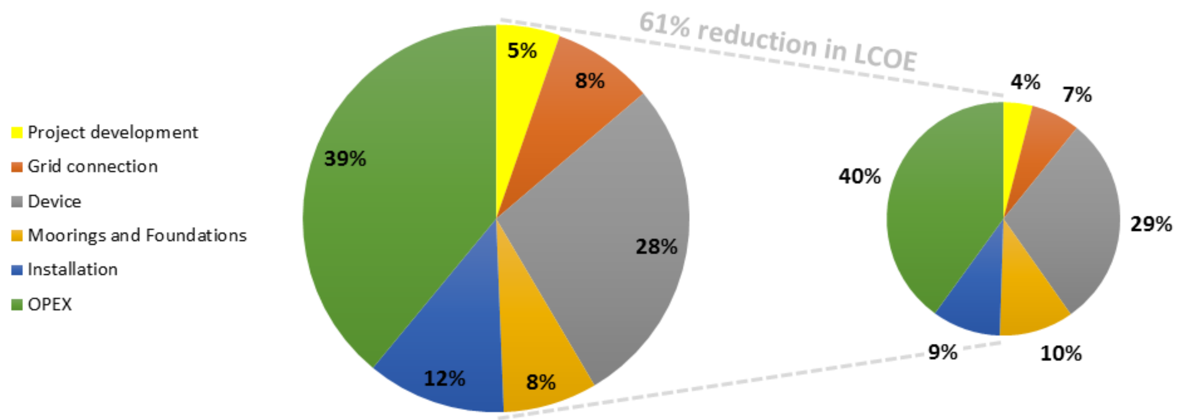


Figure 9: Tidal LCOE Percentage Breakdown by Cost Centre Values at Current Stage of Deployment (Left) and the Commerical Target (Right) [Note: the area of the chart represents the LCOE]

The size of the pie chart has been adjusted such that the area of the chart is representative of the total LCOE. Whilst the cost breakdowns may appear similar, there is a significant difference in the overall LCOE value. Although costs in real terms are expected to decrease across all the identified cost centres resulting in a lower LCOE value, the relative breakdown of CAPEX associated with the device itself is expected to increase relative to other CAPEX costs. Operational costs are expected to represent an increased proportion of the overall LCOE in commercial arrays.

3.4.2 LCOE trend by size of the project

The uncertainty levels at each deployment stage, as agreed through industry consultation, resulted in the calculation of maximum and minimum bounds of ±30%, based on the LCOE reduction trend associated with the industry consultation data. In general, the responses from industry indicated an increase in array scale with increasing maturity of the technology. The scale of array to be deployed at each of the stages under consideration varied widely, and again the LCOE chart has been presented with two technology scales: Large scale (≥500 kW) and small scale (<500 kW).

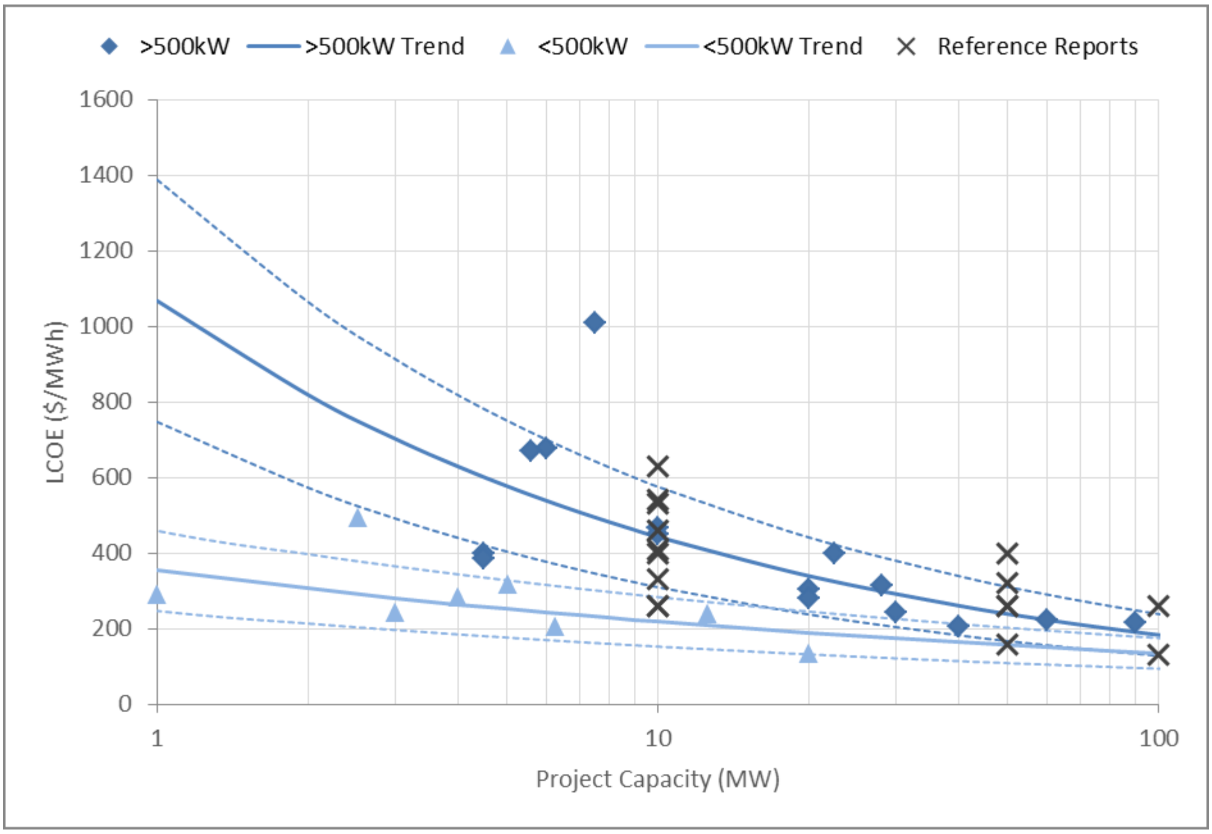


Figure 10: LCOE relative to project deployed capacity

It must be remembered that the above chart does not represent the effects of learning, merely the initial LCOE of array projects at given array scales. It would be anticipated that learning by doing would result in cost reductions over time, and this will be discussed in the following section.

3.4.3 LCOE long term projections with learning

By using the stakeholder responses obtained within this study, the projected deployments for each technology can be cumulatively plotted to form an industry-level deployment and levelised cost trajectory. It has been assumed, for the sake of this learning rate calculation, that the respondents to this study represent the complete deployment schedule for tidal stream energy, and that their deployment targets, when combined, represent the full industry-wide roll out of tidal stream energy technology. The industry trend line has been plotted (incorporating both small scale and large scale technologies).

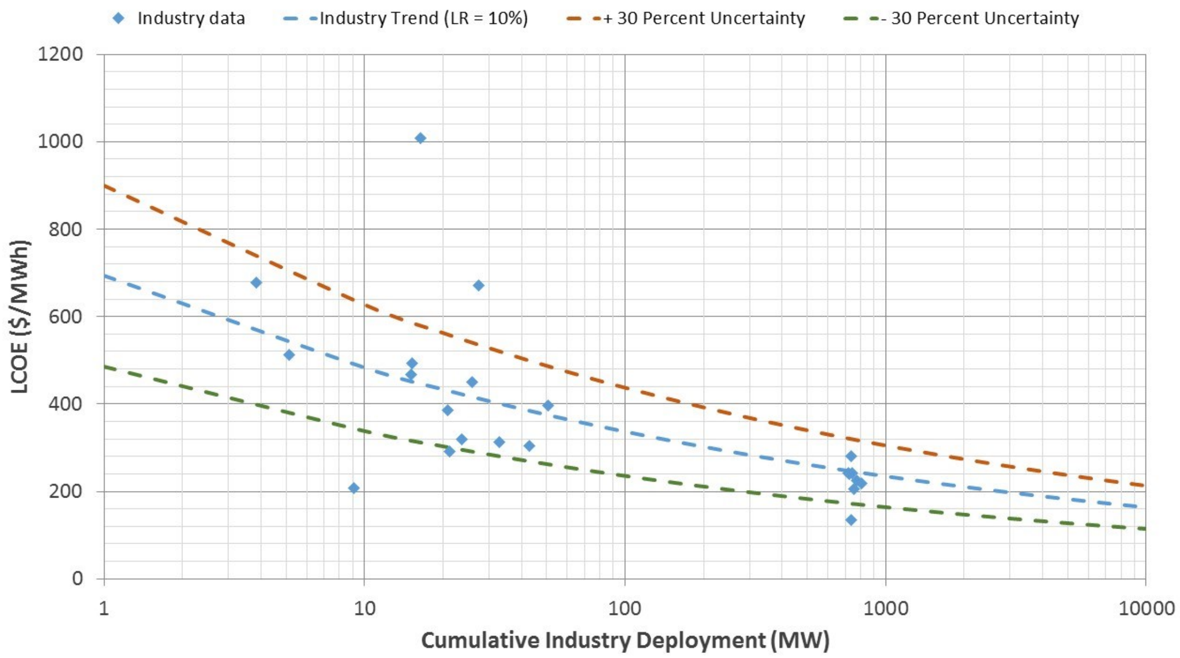


Figure 11: Possible learning rate trends for the tidal energy sector.

It must be stressed that this learning rate projection is based upon a plausible, yet hypothetical deployment scenario, in which the LCOE of tidal stream energy would reach cost competitiveness with the current costs of offshore wind (approximately 240 $/MWh) within 1250 MW of cumulative deployment. Further cost reduction would be expected with continued deployment

Whilst individual technologies offer different cost reduction and learning opportunities, the analysis presented here represents a less optimistic learning rate than has been associated with other European projects such as SI Ocean. In SI Ocean, data suggests that an LCOE of 100 €/MWh (approximately 133 $/MWh) could be achieved after 10 GW of cumulative deployment, using a learning rate of 12%. However, the analysis carried out within this report suggests that previous work may be optimistic, with costs only reducing to approximately 160 $/MWh within the given 10 GW deployment frame.

3.5 Tidal Stream Energy Conclusion

Although tidal stream energy converters have converged upon the horizontal axis turbine, there still exists design diversity in terms of number of rotors, rotor diameter and rated capacity of early prototype designs. Many of the early companies developing technology for the tidal stream industry focused on MW scale devices and multi-MW arrays. However, a number of companies are now present whose focus lies firmly on the smaller capacity devices.

The data suggests that small scale technology could offer a lower LCOE in the short term with the early projects, however there is convergence in terms of LCOE once MW scale technologies reach their commercialisation target and larger deployment capacities.

It is anticipated that in order to meet national level deployment targets, the use of large scale technologies will be required in the long term. However, the short term deployment programme will see significant benefit from a greater focus on the symbiotic deployment of technologies at the lower scale of the spectrum.

It is difficult to present the cumulative deployed capacity of the tidal energy industry without being subjective (the number of stakeholders engaging with this project do not cover the full spectrum of tidal stream energy deployment worldwide, but represents a reflective proportion of industry stakeholders; however this list is not exhaustive).

The commercial targets presented in this report are the CAPEX, OPEX, and LCOE values that developers anticipate to reach with their first commercial project. As such, continued cost reduction can be expected with larger scale roll-out and deployment of tidal energy technology. The commercial targets described within this report confirm that the tidal energy sector will require continued support and incentive mechanisms in the medium-term to enable the projects to be economically viable and financially attractive, albeit the level of support provided could see reduction if technologies meet their commercialisation target aspirations. The cost reduction trends outlined in this report clearly mark out the trajectory that the tidal energy sector must achieve in order to maintain continued positive public and private sector support.

4 Wave Technology LCOE Assessment

Wave energy technology has significantly advanced in the last decade, from small scale testing to full scale demonstration. The lead has come from the UK but other regions of Europe, Australia, North America and Asia are also taking wave energy development seriously.

Recently, the wave energy sector has seen a slowing-down in the rate of progress from leading technologies trying to reach TRL 7/8, due to the high investment needs combined with the challenging environmental conditions and technical risks. Additionally, an increasing number of innovative concepts are being developed at lower TRL, and this is having an impact on the consolidation of new market leaders into full-scale demonstration.

As with tidal stream technology, the technical and financial difficulties in up-scaling to hundred kW or MW-scale devices have had some serious consequences. In some cases, this has led to a scaling-back of devices: This involves looking for intermediate niche markets to commercialise wave energy technologies, accelerating learning rates and reduce risks at a more affordable scale, prior to targeting utility-scale projects (tens or hundreds of MWs).

This work has assembled data from reference reports on the status and costs of wave energy technology, as well as historical cost data and models (WavEC 2015a, 2015b; Carbon Trust, Amec 2012; Carbon Trust 2011; Ernst & Young, Black & Veatch 2010; SI Ocean Project 2013; Revision 2012; Sandia National Laboratories 2014). The data has been reviewed through a survey to leading wave energy developers with real at-sea deployment experience.

Some particular considerations for wave energy technology are described below:

- Data was obtained from prior reference reports and a number of developers (ensuring anonymity) from Europe, Asia, Oceania and North America. Thirty questionnaires were sent and responses from eleven active developers that have tested full or part-scale prototypes at sea were obtained.
- LCOE projections were also considered in three distinct phases of development (as per section 3.)
- The scale of the prototypes tested (from developers) ranged from a few to several hundred kWs. Only data considered to be reliable and at high TRL (≥6) has been used.
- Given the variety of concepts and stages of development, responses from technology developers result in very wide data ranges. The average values within many parameters were heavily influenced by over-optimistic assumptions, and it is recommended that the entire range of values is considered rather than the industry averaged value, as the average is not representative of the sector. Higher TRL responses tend to provide higher costs, and can vary significantly from concept to concept.
- Historical data from previous projects, reports and models has been included in the analysis and graphs, in order to provide a more comprehensive analysis.

4.1 CAPEX

Responses obtained from the questionnaire show a large range of CAPEX, especially for the demonstration early projects and small arrays.

There is also significant variability of CAPEX values published for the first pilot projects installed worldwide[6]. However, the trends from published data on historical costs, planned projects and reference reports were found to be relatively similar, and tend to converge for commercial scale projects.

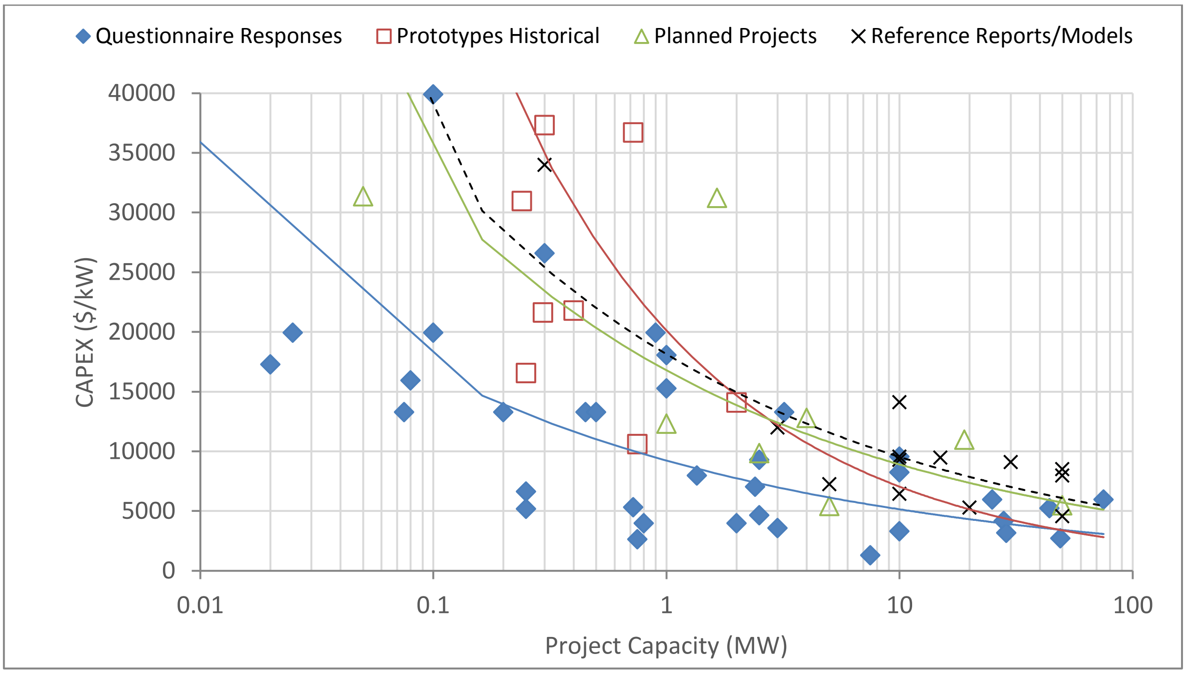


Figure 12: CAPEX cost per kW installed relative to project deployed capacity. The graph includes costs received from the questionnaires as well as published costs for demonstration projects, planned projects and reference reports. Note: The above chart does not represent a learning curve. This represents the starting cost for arrays at a given scale. Future cost reduction effects will result in cost reduction through learning, but cannot be demonstrated on this figure.

The causes of the significant difference at early stage deployment can be explained from differences among concepts (no convergence, unlike tidal stream) and among TRL levels. An increased CAPEX cost is observed for those developers at higher TRL than those at lower TRL, leading to the conclusion that early TRL technology developers tend to be optimistic due to lack of real experience at sea, underestimating costs for full-scale prototypes and arrays. There may be also different levels of transparency among developers, due to commercial reasons as well as difference between costs in different countries. It is important to mention that to quantitatively evaluate such differences there is a need to perform a broader study involving more data and economic indicators than have been covered in this study.

As previously described, this section provides ranges of costs rather than average values. Average costs should not be taken as representative of the variety of concepts, TRL levels and scale. Figure 13

[6] It is important to mention that some of the published values do not fully include the total costs of the project.

shows CAPEX cost ranges at different stages of deployment. The extreme ranges are based on the data obtained by particular developers, filtering out those below TRL 6 and any significant and obvious outliers, while additional data points are based on data from reference international reports. The existing reports are indeed aligned with planned costs for first arrays, as well as estimates for commercial scale project estimates from those developers at higher TRL (which generally represent the upper part of the range of responses).

Results from questionnaires indicate that the costs of first small pre-commercial arrays could range between 4000 and 18000 $/kW. Some recent analysis from SI Ocean Project, Sandia National Laboratories and WavEC indicate that costs of first arrays could be around 9000-14000 $/kW (SI Ocean, 2013) (WavEC, 2015) (Vincent S. Neary, 2014), while other sources indicate more optimistic forecasts of 5000-7000 $/kW (Revision 2012). Costs are expected to decrease fast with scale decreasing progressively towards 6000-9000 $/kW for first commercial arrays. Significant cost reduction is widely anticipated, resulting in costs of as low as 4000 $/kW according to an assessment for the US, or 3000 $/kW according to optimistic developers.

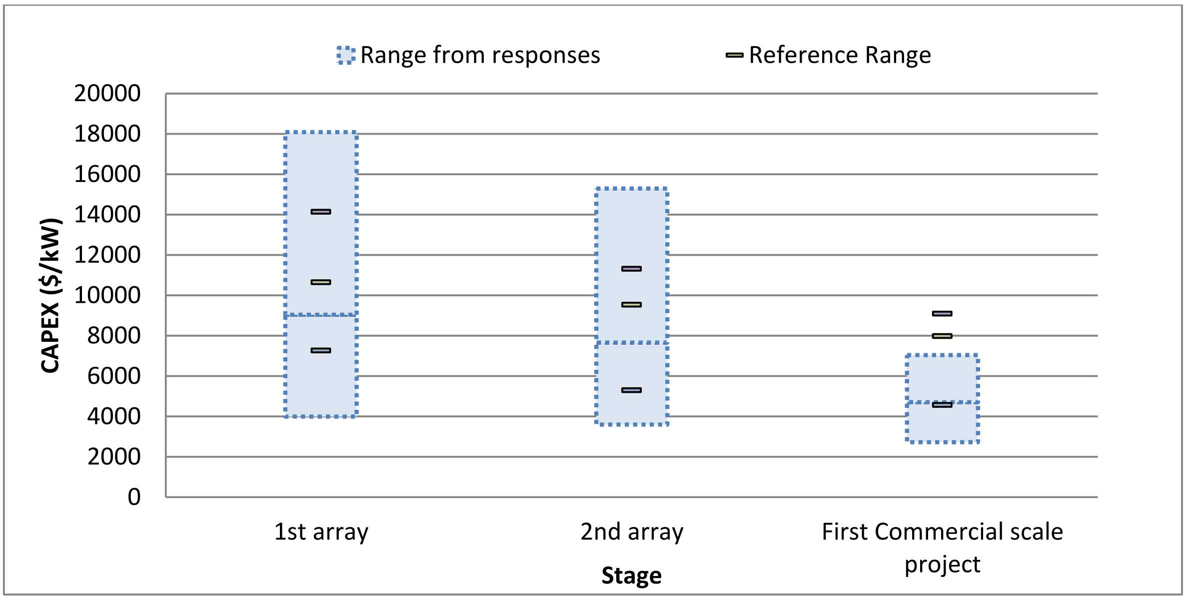


Figure 13: CAPEX Cost Ranges at Differing Stages of Deployment [Note: Where dotted lines exist, these represent the maximum/minimum cost values provided from the stakeholder engagement. The solid lines with shaded area represent the industry reference values based on estimates from reference international reports].

Although the previous ranges may show high CAPEX compared to other mature technologies, it represents only the start of the learning curve for wave energy, offering the opportunity to further reduce costs with learning. As an example, these costs would be similar to those of offshore wind today or of solar PV installations in 2008, after thousands of MW had already been installed. The solar industry has reduced CAPEX costs by approximately a factor of three. In the case of offshore wind a lot of effort is put on offshore wind cost reduction on installation, foundations and up-scaling (limited further improvement is possible on the turbines), from which wave energy may also benefit.

SI Ocean Cost of Energy report (SI Ocean Project 2013), describes in detail how costs reductions can be achieved for wave energy technologies. The report indicates that costs reductions can be achieved through scale/volume, experience (learning by doing) and innovation. New materials, scaling-up devices as well increasing the number of units per projects, serial production of devices and cost-effective manufacturing processes can lead to significant cost reduction.

There is significant cost reduction potential in the structure and power take-off systems. Although the impact on energy production will be commented later on, optimised control systems may also imply an increase of power, resulting in an increase of the device rating and a reduction of the CAPEX per kW installed (note that all graphs show CAPEX per kW, not CAPEX, thus very dependent on the rating strategy of each developer). Also, innovative components and strategies for the balance of plant, sharing components such as mooring systems, cable connection or installation costs could help in reducing the total project CAPEX.

4.2 OPEX

Offshore maintenance is very costly by nature and reliability is crucial for ocean energy technologies, especially for smaller scales. Given the limited operational experience from most developers, the uncertainty in O&M costs for first arrays is very high.

Responses from developers range from 150 $/kW/year to around 1300 $/kW/year. Three international studies converge in 430-470 $/kW per year as the expected costs for the first array, reducing the costs to 250-260 $/kW per year for the second array. The most pessimistic case is published by Sandia National Laboratories[7], expecting around 1500 $/kW per year for the first small array of only 3 MW (10 devices of 300 kW each) and reducing to 500 $/kW per year for a 15 MW array.

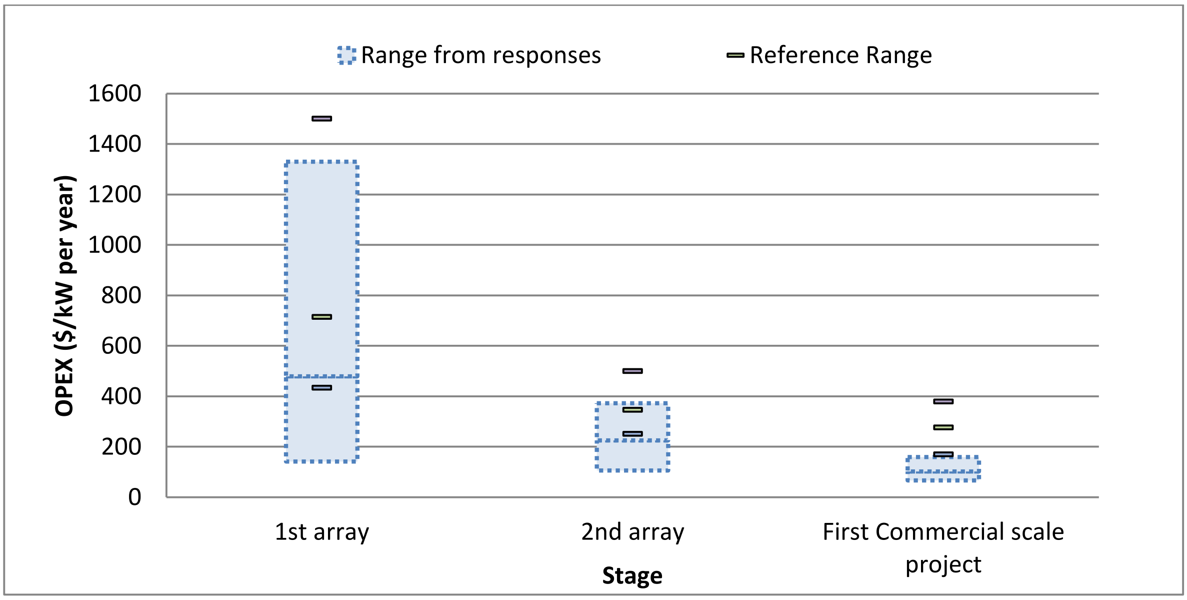


Figure 14: OPEX Cost Ranges at Differing Stages of Deployment [Note: The dotted lines represent the maximum/minimum OPEX values provided from the stakeholder engagement. The shaded area is based on international reference reports and analysis].

[7] It is important to mention that the Sandia study was focused on one particular type of technology.

In the future, the expected costs for first commercial arrays published reference studies estimate OPEX around 260-300 $/kW per year, with a maximum range of 170-380 $/kW per year. Developers are much more optimistic estimating values between 70 and 170 $/kW per year, which are similar to those of offshore wind today.

There is significant activity in optimizing O&M strategies to minimize OPEX and maximize availability even at an early stage of the design. Both developers and the supply chain are working on several aspects including reliable technologies and components (some manufacturers have a 'unique selling point' utilising some components with long maintenance intervals), using sensors for predictive condition monitoring to detect faults, optimize weather windows to maximize availability of the farm as well as using smaller (and therefore cheaper) vessels and equipment, amongst other aspects.

4.3 Annual Energy production

The energy production will vary from technology to technology, depending on the geometry, PTO and control strategies. There will also be variation from site to site depending mainly on the resource levels and on the distance to shore and port (with an impact on electrical losses and farm availability). Developers were asked to provide separately the expected capacity and availability factors for different resource levels and stages of development.

There is a wide range of results but, for sites with an average wave flux above 25 kW/m (which is expected for a number of future commercial projects), there is some convergence. Trends from responses for high TRL developers and reference reports show capacity factors around 25-35% for medium/high resource sites and 30-40% for high resource sites, with some studies indicating even 50% capacity factors.

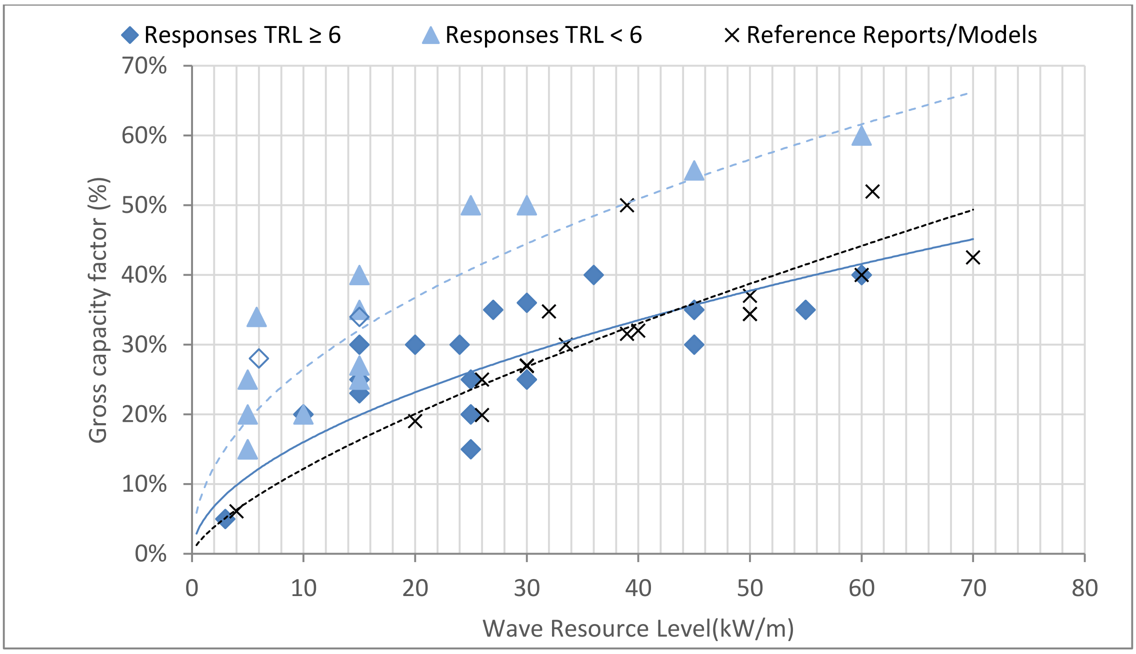


Figure 15: Gross capacity factor at sites with different resource levels based on developer responses (at different TRL levels) and from reference international analysis [Note: Gross capacity factor is excluding availability].

The graph shows an increasing capacity factor with the level of resource. This is mainly because developers and reports assume the same device or model for different sites in their calculations. However, in the future, developers will probably have different models or series of devices according to the resource level, adjusting their capacity factor to optimise its LCOE (the optimum is not necessarily the higher, as there is a trade-off between the energy harvested and the extra costs of the device due to higher loads and larger equipment for higher power output). As in other similar technologies, the optimum is typically said to be somewhere between 25-40%.

From Figure 15 it is also possible to see how lower TRL[8] developers also tend to show higher capacity factors (as well as lower costs as indicated in the previous sections). For the LCOE analysis only developers above TRL 6 have been included.

Responses from developers also indicate that the capacity factor is expected to increase with the development stage of the technology, mainly due to the fact that as the technology matures it will be placed in more energetic sites. Capacity factor improvements will also result from improvements in the performance of devices and sub components to optimise energy extraction (note that availability also increases but is analysed separately). It can be observed that developers are slightly more conservative than reference studies for the first arrays and more optimistic at commercial stage. This is due to the fact that most of this studies assume approximately the same capacity factor for each phase (assuming the same resource levels).

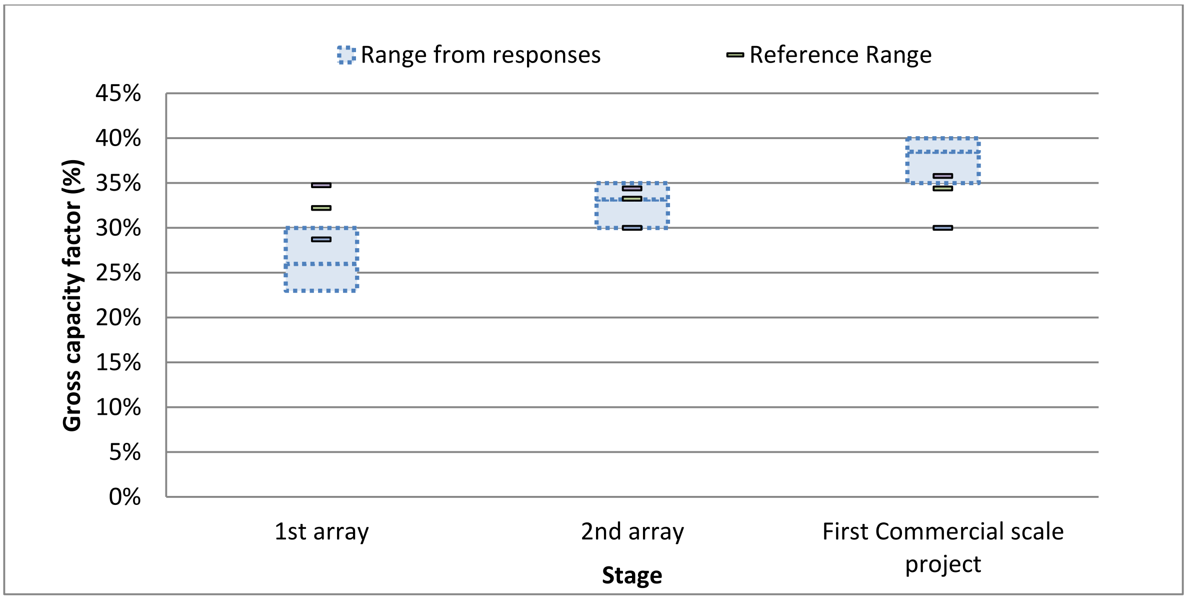


Figure 16: Gross capacity factor at different development stages based on developer responses and reference international analysis [Note: Gross capacity factor includes losses but excludes availability].

[8] As indicated at the start of the section, for both the LCOE analysis and the main results, only developers above TRL 6 have been included.

This study has also looked at availability separately. In the first projects, failures are expected to occur impacting availability and energy production (but not the designed capacity factor). Similarly, as with the capacity factor, developers have provided more realistic data with lower availability of around 80% for first arrays (ranging between 65-95%), and expectations for this to increase to around 90% due to improved reliability and better O&M strategies. For commercial projects, availability is anticipated to reach above 95%. Reference studies however, assume constant availability of around 95% in their LCOE studies, which seems to be very optimistic for early arrays.

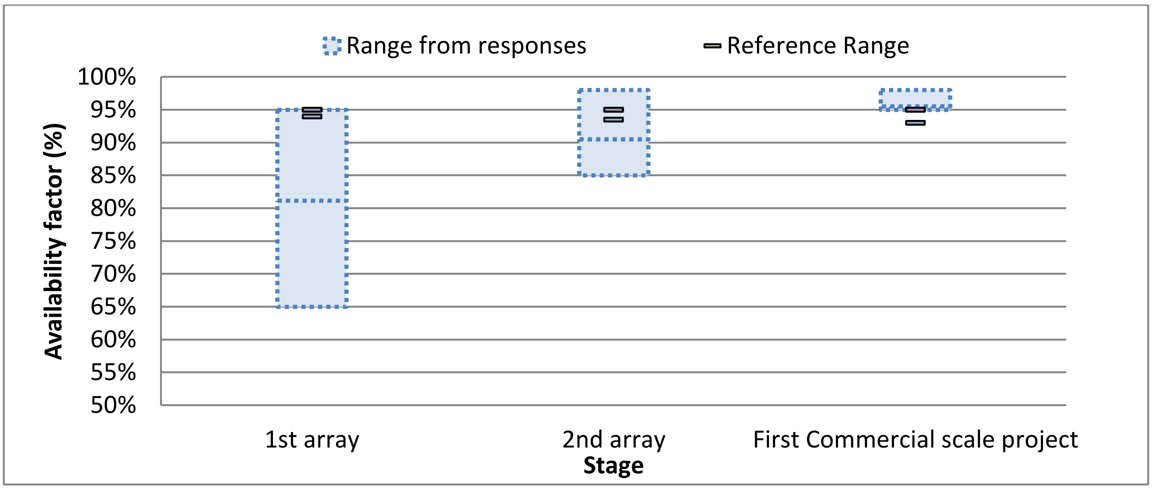


Figure 17: Availability factor at different stages based on developer responses and reference international analyses.

The final AEP of these projects can be obtained by multiplying the gross capacity factor by the availability described above, and then by the project capacity and the number of hours per year (8760).

$$AEP = Device\ Capacity * Gross\ Capacity\ Factor * Availability * 8760$$

4.4 Levelised Cost of Energy

Developer responses provided a very high range for the first pre-commercial array but converge for the second pre-commercial array (200 $/MWh to 700 $/MWh) with good alignment with data from reference studies (with a narrower range between 350 $/MWh to 670 $/MWh). The large ranges are due to differences in cost estimates explained in the previous sections, but also largely on the assumed availability factors for early projects, which have a huge impact on LCOE.

In fact, LCOE should be compared against other energy technologies only once wave energy technology is mature, reliable and commercial; this is from the first commercial scale project onwards (stage 3 in the graphs). The results show some narrower bands for both developer responses (120-280 $/MWh) and results from reference studies (280-480 $/MWh), which are significantly more conservative. The differences are a combination of lower costs (CAPEX and OPEX) and slightly larger energy production expected from developers. Note that production will depend not only on the technology, but on the resource at the project site. Therefore it is expected that wave energy projects will have significant different LCOEs depending on their location.

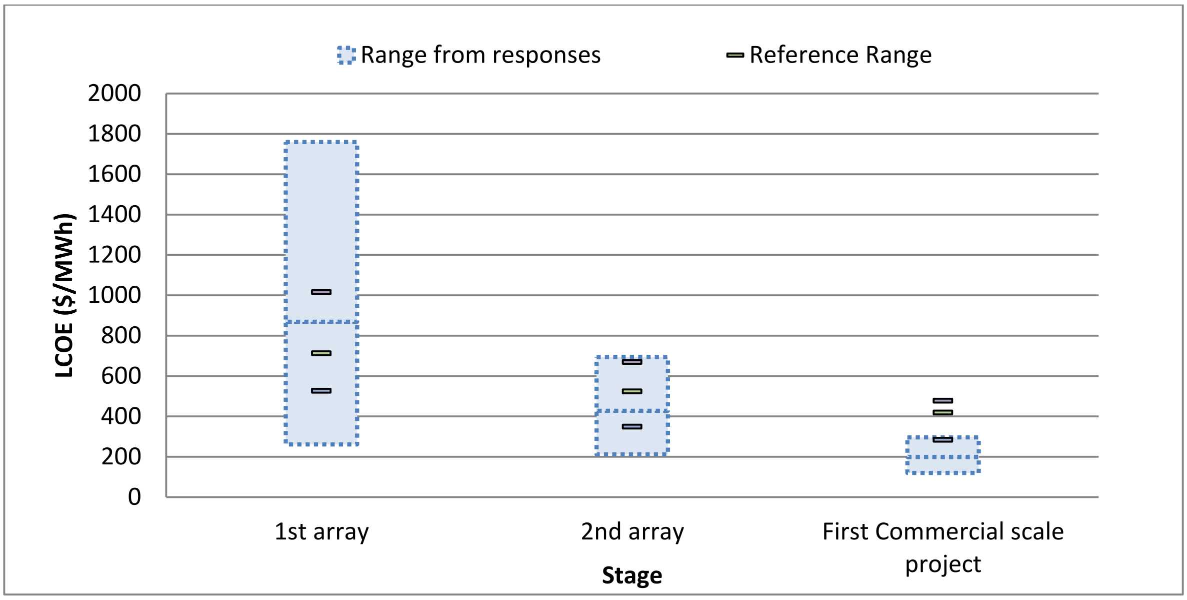


Figure 18: LCOE evolution at the three stages based on developer responses and reference international analysis.

It is also important to mention that the highest LCOE values for the first commercial scale farms are based on Sandia and WavEC Techno-Economic models, which accounted for scale effects (30-50 MW) and for the learning gained in the previous projects, which could decrease significantly the LCOE (e.g. 30% setting the maximum to around 330 $/MWh, assuming a 15% discount rate).

As described in the long term projection section, the costs of the first commercial scale projects represent only the start of the learning curve and will continue to decrease the deployment of farms in the next decades.

4.4.1 LCOE Breakdown

Figure 19 shows the average cost breakdown from developers' responses. It can be observed that the costs of first wave energy arrays are going to be driven by the device costs (both structural and PTO) as well as by the high O&M costs. However, the average may not be representative of some technology types, and significant differences in the breakdown will appear for different devices (e.g. floating vs. near shore bottom mounted devices: bottom mounted devices have significantly higher foundation and installation costs, but may offer lower connection costs and O&M costs).

In the case of wave energy, where most developers have developed floating solutions, mooring systems represent a smaller share of the LCOE compared to tidal.

For grid connection, most responses indicated costs as 10% of CAPEX (around 6-8% of LCOE, similar as in tidal), but a few developers included very low costs 1-4%[9] decreasing the average.

[9] Probably assuming that the grid connection was partially or totally provided to the projects (e.g. test sites)

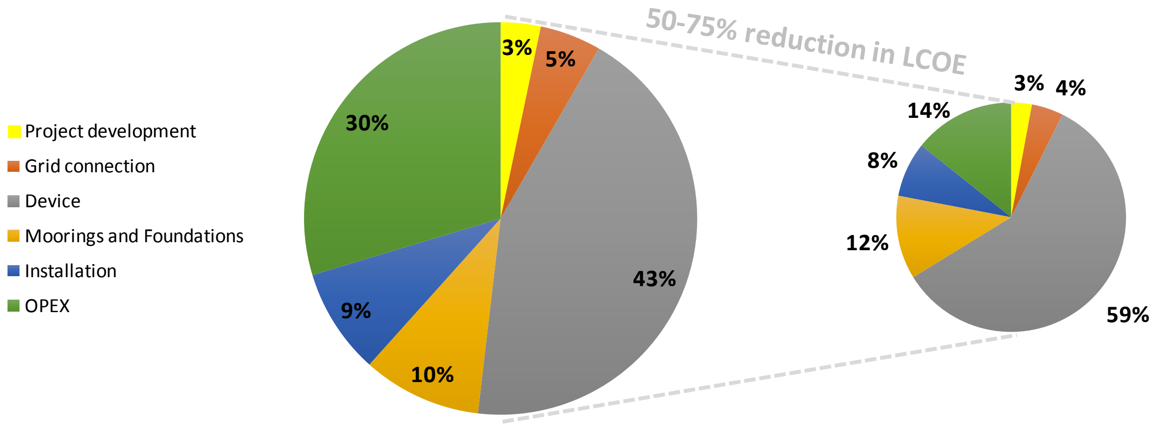


Figure 19: Wave LCOE Percentage Breakdown by Cost Centre Values at Current Stage of Deployment (Left) and the Commerical Target (Right) [Note: the area of the chart represents the LCOE].

As explained in the previous section, the LCOE is expected to be drastically reduced from the first array to the first full commercial project (around 75% based on developers and 50% based on reference studies). This is a combination of reduction in CAPEX and OPEX, but also an increase in production. The main difference from the first project is a drastic reduction of O&M costs (average reduction of around 80%), as seen in section 4.2. However, it seems difficult that wave technology will reach O&M costs similar to offshore wind so rapidly, only after a few tens of units are deployed. It is therefore likely that O&M will still represent around 20-25% of the LCOE, as shown in other reports (Carbon Trust 2011).

4.4.2 LCOE long term projections with learning

While wave energy costs are expected to be high for the first arrays (as was the case with certain other technologies at the same early stage in development), developers and reference international analysis believe there is a high cost reduction potential given the high novelty of the technology (it is intrinsically new, not sharing the technical principles with other sectors as for example tidal energy with wind and hydro). Also there is a large market potential estimated to be above 200 GW worldwide which could lead to significant learning with experience (Cruz, 2008) (IEA-OES, 2011) (SI Ocean, 2014).

Based on developers' responses, a logarithmic trend line has been plotted, on the assumption that their projects would be the cumulative industry deployment during the pre-commercial stage (see tidal section for further explanation). Although it is likely that other developers will install their first early arrays in between (increasing the global installed capacity), not all developers who responded are likely to succeed and deploy their desired projects, which could compensate the first assumption. A check of these assumptions with reference reports was carried out: the second array from these developers would start at a cumulative installed capacity of 40 MW, while other reference sources

(AMEC/Carbon Trust, 2012) (SI Ocean, 2013) assumed 20MW (which is more optimistic, as the initial capacity for applying the learning curves is lower).

On the other hand, the obtained trend lines were more optimistic to that published in earlier reports (Carbon Trust and SI Ocean assumed 15% for wave), but still within typical learning rates for energy technologies (10-30% as described in section 2.3.4). The trendline including data from all developers at TRL ≥ 6 for their planned projects show an average learning rate of 17%. If the smaller projects (below 1 MW) are removed, the learning curve becomes steeper reaching 30%, which would mean a very drastic cost reduction.

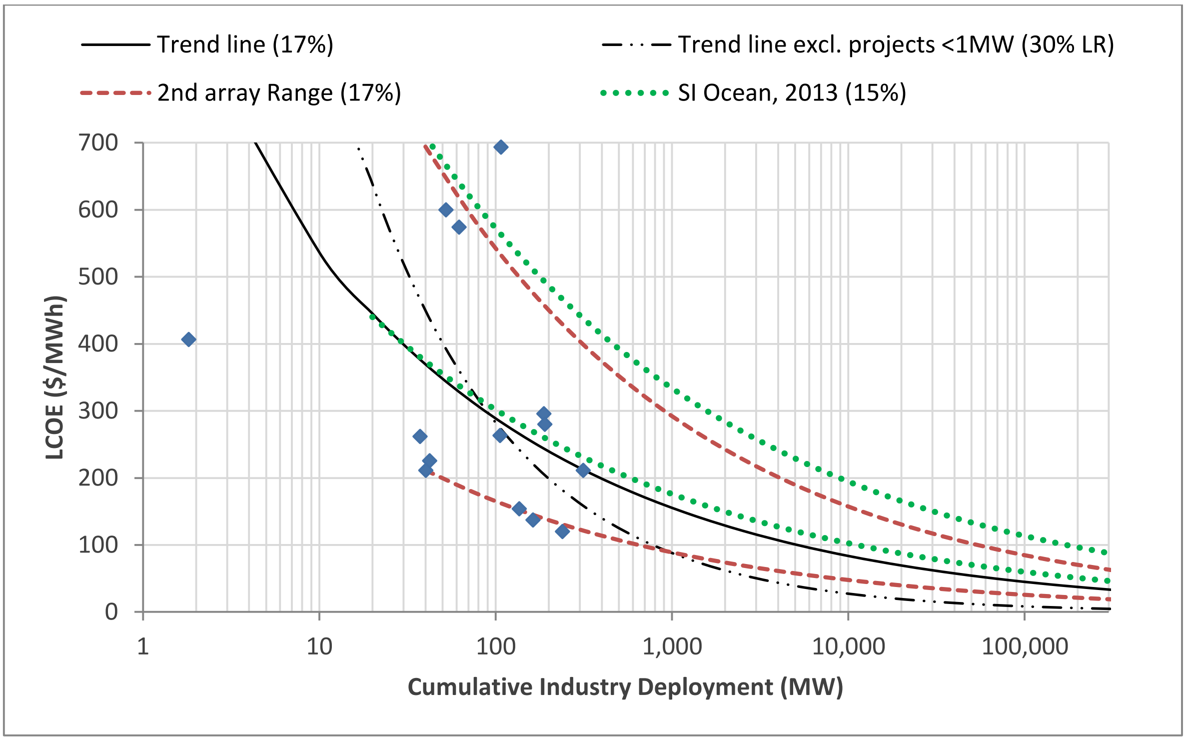


Figure 20: Possible learning curve trends for the wave energy sector obtained from responses. Learning curves from SI Ocean report are also plotted. Blue diamonds represent developer data points.

In the previous graph also two ranges have been included. The red dotted lines assume the 17% learning rate applied to the LCOE range of costs for the second arrays from developers, and assuming a starting point of 40 MW. The SI Ocean learning curves have been added in green, assuming 15% learning rate and a starting point at a global capacity of 20 MW. The range of responses show a more optimistic cost reduction lower band, although those of more mature technologies are within the SI Ocean range (closer to the lower band).

Overall, there is a good convergence between both studies showing a fast cost reduction potential for wave energy. LCOE levels could reach similar costs to the 2014 costs of offshore wind after a few hundred MWs have been deployed globally (or a few tens of units for the most optimistic developers). The curves show that in the long term, after more than 10 GW of capacity are deployed, wave energy could reach 100-150 $/MWh, or even lower in the more optimistic estimates.

4.5 Wave Energy Conclusion

Wave energy technology has not yet reached convergence. Developers are developing very different concepts and at different technology readiness levels, showing a wide range of cost and performance data. This analysis has shown that developers at an early stage tend to be more optimistic than those at a more mature level, particularly on CAPEX.

There are large variability and uncertainty on the existing data, some of which is simulated or estimated without experience at full-scale or detailed engineering analyses. Although data from eleven developers was included in the analysis, representing a broad spectrum of technology options, given the design variety mentioned and the different TRL levels, the list of developers to consider has not been exhausted. This section has also looked into reference reports, mainly in Europe and North America to compare the results in order to provide the widest range of the spectrum.

Results show significant differences among developers in terms of CAPEX and OPEX (up to +100% / -50% at early stages compared to the average). Estimates for OPEX are particularly optimistic compared to those of reference studies. Estimates on energy production, based on capacity factors and availability tend to be more conservative than previously published data (due to the latter value).

There is wide range of LCOE estimates for early arrays, but the central values are in alignment with reference studies, due to a combination of more optimistic costs and more pessimistic availability for first arrays. Estimates for LCOE for small second arrays are in the range of 200-700 $/MWh (the first is expected to have low availability), showing positive prospects even at the higher end compared to early stage energy technologies.

At commercial scale, developers expect a rapid decrease in LCOE through learning, innovation and scale leading to around 100-300 $/MWh. In the future, wave energy could continue to reduce costs at high rate with the increase of installed capacity, reaching competitive levels of LCOE after one or a few GWs of capacity have been installed (note that wave energy could achieve more than a hundred GW of cumulative installed capacity if the technology becomes competitive).

However, as previously stated, it is difficult to provide a single or a narrow band of LCOE estimates for the sector given the diversity of technologies and uncertainties involved. An in-depth collaborative effort could help the sector to move forward, sharing non-commercially sensitive information to build knowledge, help to reduce uncertainties and costs, and improve reliability, availability and performance, which could ultimately understand what the real cost drivers are and advance through the cost reduction path.

5 OTEC Technology LCOE Assessment

Ocean Thermal Energy Conversion (OTEC) produces power using the temperature differential between the ocean surface and deep water. An OTEC plant pumps cold ocean water from about 1000m water depth to the surface, where a thermodynamic power cycle is used to generate electricity. Most recent OTEC efforts have focused on a closed-loop Rankine cycle to produce power, using a working fluid with a low-temperature evaporation point, such as ammonia. This is considered to be a relatively low-risk approach because most components and subsystems can be sourced using readily available commercial technology.

The first electricity-producing OTEC plant was built in 1930 in Cuba and produced 22 kW of electricity. Since then, almost a dozen power-producing OTEC demonstration facilities have been constructed and tested around the world, leading to a refined understanding of the technologies required to make OTEC a viable, commercial-scale renewable energy technology. However, MW-scale OTEC power plants have yet to be demonstrated. Consequently, most of the data contained in this report is based on techno-economic design studies.

A literature review was performed to establish a credible baseline for cost and performance data from OTEC systems. A summary of relevant recent literature is provided below.

Luis Vega at the University of Hawaii has published several papers on the economics of OTEC since the 1980s. In 2010 he published an updated study that brings all historical estimates to present value, adjusting for inflation (Vega., 2010). He also published the cost data for a first-generation 50 MW OTEC plant design in 2010 (L. A. Vega, 2010).

Lockheed Martin developed several design studies for the US Navy including a mini-spar design with a power generation capacity of 2.5 MW (Lockheed Martin, 2011), a spar design with a capacity of 5-10 MW (Lockheed Martin, 2010), and a detailed design study for a novel manufacturing process to construct the 1000 m cold water intake pipe (Lockheed Martin, 2011) (A. Miller, 2012). These design studies, some of which are over 1000 pages long, provide detailed information on the different subsystems and their costs. Lockheed Martin was also tasked by the US Department of Energy to develop a cost and economic assessment of OTEC, which was published in 2012. The study provides detailed cost breakdowns on OTEC power plants at capacities up to 400 MW and establishes US and global supply curves that provide an indication of the resource potential (Lockheed Martin, 2012).

A global resource assessment was carried out by a US Department of Energy funded effort in 2012 to estimate the extractable potential from OTEC and visualize the results using an online Geographical Information System (GIS) portal (Lockheed Martin, 2012). While only indirectly relating to OTEC's economic viability, the study credibly establishes the vast global technical potential for OTEC.

Finally, The Asian Development Bank published a study in 2014 for its member countries, which included resource potential, cost, and economic assessments for OTEC (Asian Development Bank, 2014).

Additional relevant data sources include PhD dissertations, technical papers on power cycle efficiencies, and project data that were reviewed to consider potentially disruptive techno-economic drivers. Finally, inputs from a wide range of OTEC experts and IEA members were solicited to validate the viability of the cost and economic assessment carried out.

The cost data used for this report largely relies on techno-economic assessments of closed-cycle OTEC power plant designs that are deployed on a floating spar platform. These designs are thought to present the lowest amount of technical risks, and large-scale engineering, design, cost, and economic assessments have been conducted to benchmark their techno-economic viability.

Some particular considerations for OTEC technology are described below:

- Cost and economic data was reviewed by IEA stakeholders in Europe, Asia, and North America.
- Data has been averaged across the sector to ensure anonymity.
- A good amount of design convergence seems to exist. Most of the publicly available cost and economic analysis has been performed in the United States.
- LCOE projections considered at three distinct plant scales. Only the impact of plant scalability is considered.
- An uncertainty of ±30% has been added to the average values associated with CAPEX, OPEX and LCOE.

5.1 CAPEX

The literature review and surveys indicate generally a good agreement on CAPEX and OPEX data, but the data demonstrates a strong dependence on plant scale. This is largely due to the fact that the fixed cost in constructing an offshore platform and connecting a deep-water OTEC plant back to shore is a significant contributor to total cost. While shore-based OTEC plants have long been considered a stepping stone toward these deep-water platforms, the economics of bringing deep-ocean cold water to shore is in most cases cost-prohibitive.

As shown in Figure 21, CAPEX data indicate an uncertainty band of about +/- 30%, which is consistent with the limited project experience. Individual data points are shown in orange, while the fitted trendline is shown in blue. The grey dotted lines indicate the +/- 30% uncertainty bound.

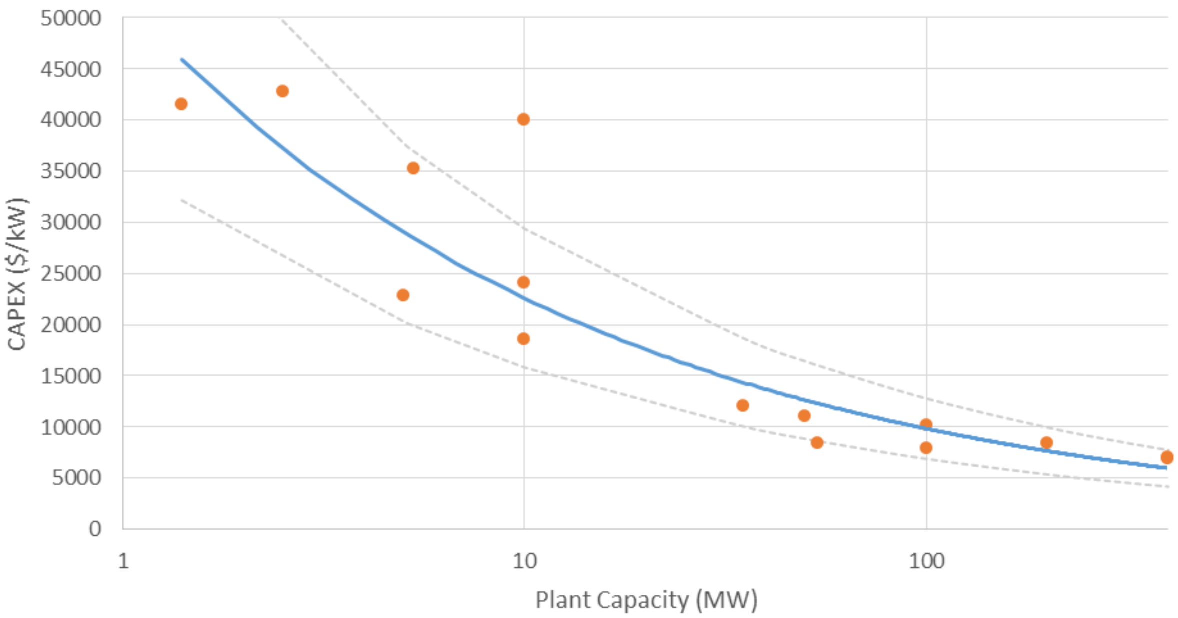


Figure 21: CAPEX as a function of plant capacity (Log Scale)

Representative cost breakdowns at 5 MW and 100 MW scale are shown in Figure 22. The principal cost categories align with the cost categories for the wave and tidal sections in this report. The only additional cost element is the cold water pipe.

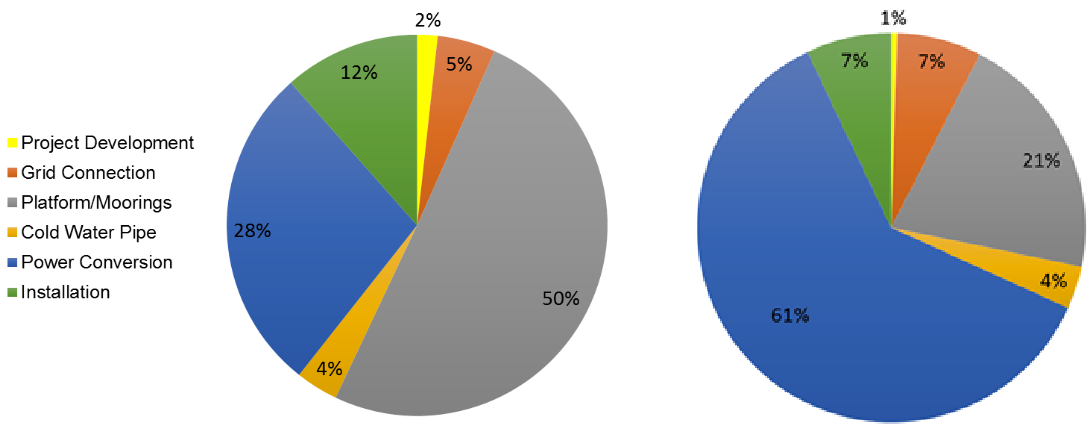


Figure 22: CAPEX cost breakdown at 5 MW deployment scale (left) and 100 MW deployment scale (right)

5.2 OPEX

Similar trends in uncertainties are observed for O&M costs, albeit fewer reliable data points were available to benchmark the cost data. Figure 23 demonstrates that OPEX is a relatively constant function of CAPEX at different deployment scales. However, it should be noted that because all of the data is based on engineering cost estimates, the uncertainties in the assessment are likely greater than the collected data may indicate.

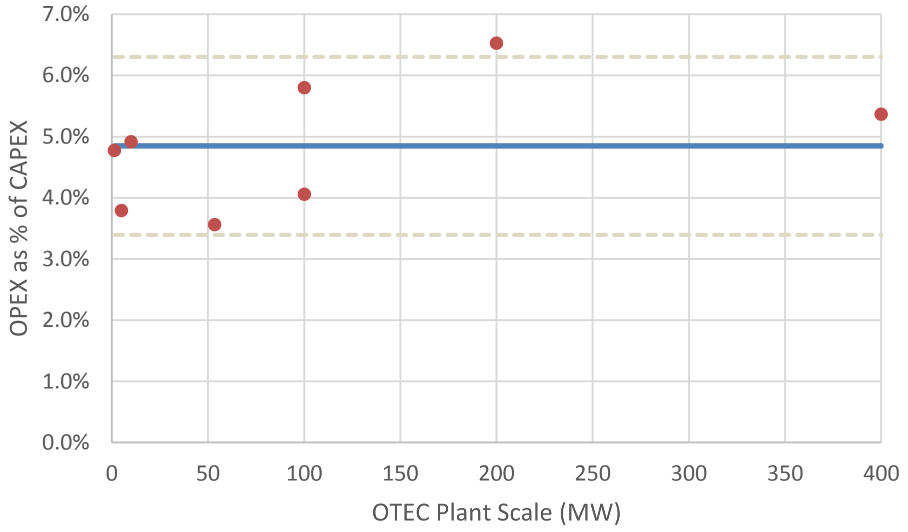


Figure 23: OPEX as a percentage of CAPEX at different deployment scales

To understand where OPEX costs are borne, Figure 24 provides a breakdown of costs at a 100 MW plant scale. A large percentage of the cost is borne by a 10-year overhaul, which requires replacement of a significant portion of the power-producing machinery, including the heat-exchangers. The “Other” category includes a provision for insurance.

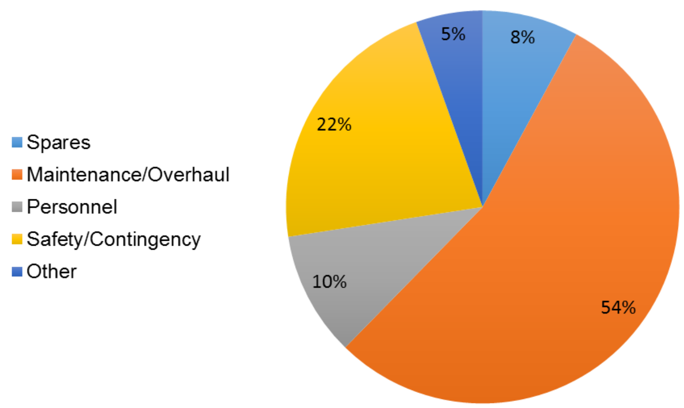


Figure 24: Representative OPEX Cost Breakdown for a 100 MW OTEC plant.

5.3 Annual Energy Production

It should be noted that OTEC provides a largely constant power output and is therefore ideally suited to provide base-load power. Most OTEC cycle designs pump cold water from about 1000 m water depth. At that water depth, temperatures are relatively constant and the temperature differential is driven by the surface temperature. Temporal variability of the power output is observed only as a function of season, reflecting seasonal changes in surface water temperatures. Capacity factor depends largely on the plant rating, but typical values on the order of 90% - 95% are provided by literature. To normalize costs, a unified assumption of a 92% capacity factor was made, consistent with various studies and expert inputs. Base load power, has typically a higher economic value than intermittent renewable energy sources that typically require stand-by generators or curtailment to match an electrical load. Such benefits are highly application specific and should be considered on a per-case basis when evaluating the viability of OTEC.

5.4 Levelised Cost of Energy

Based on the data presented, an economic trade-off study was conducted assuming a discount rate of 10%, a plant life of 20 years, and a capacity factor of 92%, which includes accommodations for availability. Consistent with the CAPEX and OPEX data, a strong dependence on plant scale can be observed in Figure 25. The 30% uncertainty is indicated with the dotted lines.

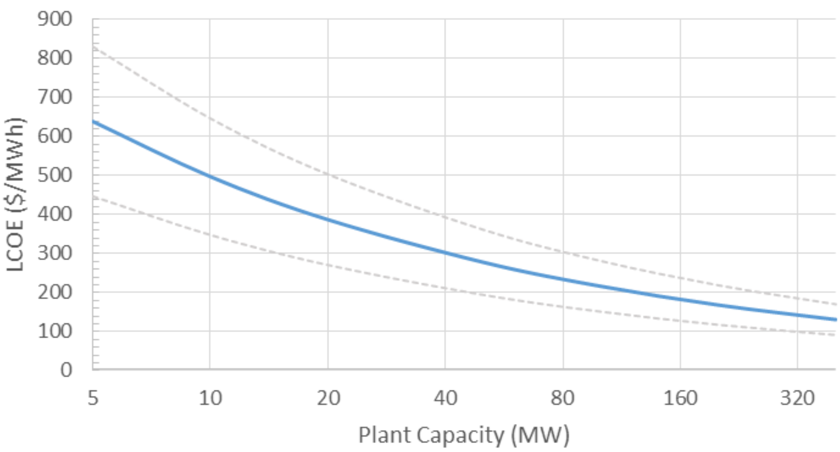


Figure 25: LCOE as a function of plant scale

Going from a 5MW to a 100MW plant scale also shifts the importance of the cost-centres. The following two graphs show the LCoE breakdown by cost centre.

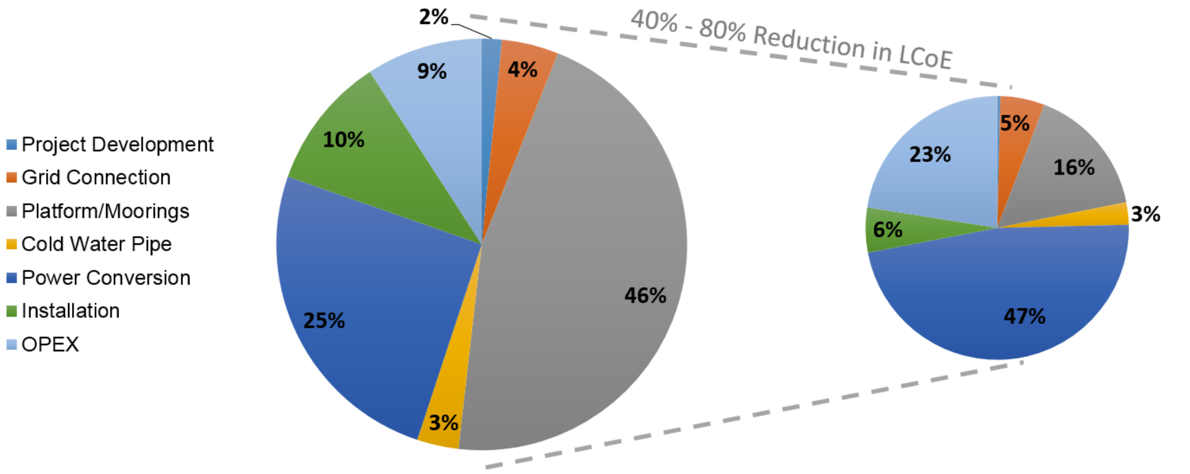


Figure 26: LCoE Cost Centers for 5MW plant (left) and 100MW plant (right).

The techno-economic driver for resource quality or power density is the temperature differential between the surface water and the deep cold-water resource. Deep-water temperatures at 1000 m can be considered largely constant at about 5 degrees Celsius. As a result, the annual average surface temperature in a deployment location provides a useful proxy for the economic viability of a plant. The trade-off graph in Figure 27 shows the LCOE at a 100 MW plant capacity as a function of surface temperature. It should be noted that the cost model assumes a 1000 meter water depth to access the cold-water resource. In some locations, such as Florida, the deep-water resource can be found in much more shallow waters.

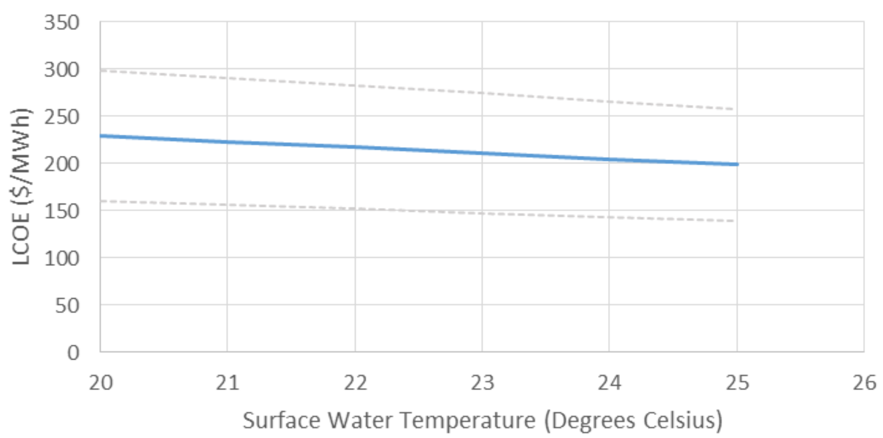


Figure 27: LCOE as a function of surface water temperature at 100 MW OTEC plant scale

The baseline assessment assumes a discount rate of 10%. However, the financing of such projects is highly dependent on a wide range of factors. The sensitivity study in Figure 28 shows LCOE as a function of the project discount rate, assuming a project life of 20 years.

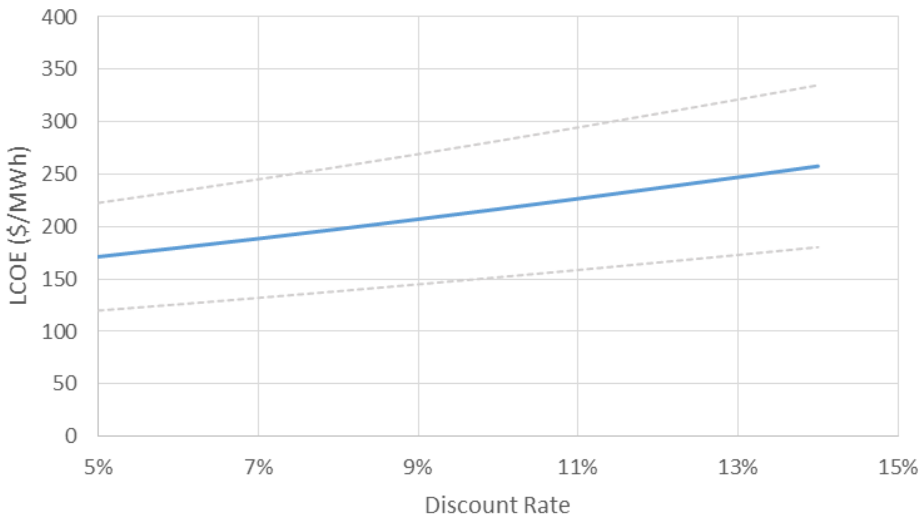


Figure 28: LCOE as a function of Discount Rate at 100 MW OTEC plant scale

OTEC has the potential to create value beyond the generation of electricity. The deep cold ocean water can be used to provide cooling to buildings, replacing energy-hungry air-conditioning systems. The deep-ocean water is also very nutrient-rich and can be used in aquaculture to raise cold-water species such as Lobster and Salmon. Finally, a key advantage of open cycle (OC) OTEC is that it can provide fresh-water from sea-water. Theoretically, an OC-OTEC plant can produce about 2,100 cubic meters of fresh water per day for each MW installed.

The value-stream generated from these by-products can potentially offset some of the electricity-generation costs. However, because the added value from these products is highly site and technology specific, no further analysis is provided in this report.

5.5 OTEC Conclusion

Although OTEC technology has existed for decades, commercial adoption has been slow. Research is continuing on different power cycles and niche market applications including desalination of seawater, cooling of buildings, and use of cold-water in aquaculture applications. Interesting research has also been conducted into utilizing hydrothermal vents to produce power; preliminary studies show a significant resource potential for this offshoot of OTEC technology.

Results show significant convergence in terms of CAPEX and broad stakeholder agreement in terms of OPEX.

There is wide range of LCOE estimates for early deployments of OTEC technology at smaller plant capacity, but the stakeholder engagement and reference studies demonstrated alignment with an uncertainty level of ±30%. Estimates of LCOE decrease with increasing plant scale, showing positive prospects for development and deployment of large OTEC power plant.

At commercial scale, developers expect a rapid decrease in LCOE through learning and plant up-scaling, leading to an LCOE of around 100-180 $/MWh. Significant cost-reduction potential exists beyond simply scaling the plant size, for which limited consideration has been given in this study.

6 Discussion and Conclusions

This project has contributed significantly to the state of the art in knowledge of LCOE and cost reduction trajectories for Wave, Tidal Stream, and OTEC on an international level. Industry consultation has allowed the development of revised cost models for all the technologies considered, producing revised expectations on the development trajectory for each technology.

Some similarities exist among the technologies considered. Current LCOE values are very high for wave, tidal and OTEC technologies in comparison to the incumbent power generation technologies, leading to significant cost-reduction requirements in order to become competitive. Although progress has been demonstrated to date, the level of progress is not on par with expectations. The rate of deployment has been significantly slower than anticipated by some investors and policymakers.

At this stage in the development of each technology, the best available data comes from pilot projects. In conjunction with a simplified cost model, as used within this approach, the uncertainty level was expected to be in the region of ±30%, consistent with studies in other technologies both within and outside of the energy sector.

There were also a number of differences between the technologies that were clear within this study. Wave energy sector development lags that of tidal stream energy, and there is an identified lack of fundamental performance and operational data to validate the early stage projections made by wave energy technology developers.

Tidal stream energy converters have largely converged on horizontal axis designs; however there is a clear split in the development trajectory. The first considers large scale technology, greater than or equal to 500 kW in capacity, which has been the mainstay of development to date. The second considers the development of small scale technology less than 500 kW in scale. The data provided for this project suggests that the smaller scale technologies could offer a lower LCOE in the short term, with greater opportunity to achieve cost reduction targets through up-scaling of technology. Larger scale technology will reach cost competitiveness with the smaller scale technologies only after considerable deployment has taken place.

The economies of scale and LCOE analysis clearly indicate that OTEC plants at a large scale are economically more attractive for the first project. In contrast, while wave and tidal stream energy technologies could achieve lower LCOE through multi-MW array deployment, the route to multi-MW arrays must first allow for development and deployment of the earlier lower-capacity arrays. LCOE reductions for wave and tidal stream energy are dependent on build out of early arrays, and not immediate progression on to large-scale multi-MW projects. Confidence in the technology must be gained at these early array stages prior to the progression and build-out of larger array capacities.

Wave and tidal stream energy technologies are modular in design, and therefore the range of perceived deployment capacities for future array projects varied widely.

There was a limitation of data which restricted the OTEC data set to values obtained through literature review. Consultation with existing OTEC developers suggested that the values from the literature review were appropriate for the imminent deployment of larger scale power plant currently under development, validating the approach used within this study.

Geographic distribution of the OTEC resource is limited to near-equatorial regions, due to the need to maximise the temperature differential between the warm surface water and the cooler deep-ocean water.

OTEC offers additional benefit of desalination in addition to electrical power production. This is particularly attractive given the suitable locations for OTEC technology deployment. This could impact the LCOE although it is an external factor. Wave and tidal stream energy offer the ability to be connected to a desalination plant, but would, in most cases, use the electrical energy produced by the ocean energy converter to provide the input power to a high pressure pump system for the reverse osmosis process (one exception is Carnegie Wave Energy's Perth Wave Energy Plant).

The challenges for each sector are clear. Demonstrable progress in reliable unit operation is required in order to verify and validate the cost projections that have been made within this report. High costs are intrinsic to the early stage development of technology, but clear evidence of progression down the cost curve is needed in order to restore confidence in the ability of each sector to deliver the targets that have been set.

The outputs of this work have resulted in the generation of all input data required for the TIMES regional modelling, carried out by the IEA within their Energy Technology Perspectives document. By making a clear distinction among wave, tidal and OTEC technologies, the relevant parameters for each technology can allow for a more robust piece of modelling work that more truly reflects the diverse nature of these very different ocean energy technologies.

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