Making business sense of climate change

Cost estimation methodology

The Marine Energy Challenge approach to estimating the cost of energy produced by marine energy systems

Commissioned by The Carbon Trust
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1. Introduction

1.1 Why is this report needed?

The Marine Energy Challenge studied many different marine energy concepts, each at a different stage of development. The most important comparator is the cost of energy. The process of calculating the cost of energy is relatively straightforward. However, because each device and deployment location is different and each is at a different stage of development, obtaining meaningful estimates for each can be complicated.

This document explains a simple approach to estimating the cost of energy applicable to all marine energy devices. It shows how costs and performance can be calculated in a consistent way and compared between devices. It allows for more sophisticated methods to be used, if available, by highlighting both where known quantities are used and where only estimates are available.

The Marine Energy Challenge showed that the cost of energy from most marine energy devices is currently too high, but that with further consistent development these costs can reduce. This method helps clarify both the costs and the stage of development to which the costs refer.

This method brings the following benefits—

- Demonstrates how the cost of energy can be calculated from cost and performance information
- Brings clarity to the cost estimation method
- Shows some ways that costs can be estimated in the absence of accumulated experience
- Provides a framework for collecting information on devices at different stages of development
- Provides a start point of an assessment method from which discussions on status and potential can be made between investor and technology developer.

1.2 Marine Energy Challenge approach to cost of energy

The cost of energy produced by a marine energy device is related to the incurred costs and quantity of energy generated by the device. The Marine Energy Challenge aimed to lower the devices' costs of energy; this can be done by reducing the costs of building and operating a device and by increasing the device's energy production. The Marine Energy Challenge looked at all options for reducing the cost of energy.

The costs include capital costs and operation and maintenance (O&M) costs. The performance of a device is related to the amount of electricity it produces. These are all interrelated and an improvement in one may require a trade-off with another. This means that before a device's cost of energy can be estimated, it is necessary to define a sensible basis of design. This describes the fundamental operation of the design but might not describe the optimal configuration. Nevertheless the design should be one that could actually be built (i.e. using certain materials and known construction techniques), could be deployed (i.e. using certain vessels and moorings or foundations) and will work (i.e. produce electricity reliably and survive the marine environment).

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

The cost of energy is a moving metric. As designs evolve the costs will change. Ultimately developers need to reduce the cost of energy to as low a level as possible. In the meantime this may mean trying slightly more expensive options that have greater long-term cost-reduction potential. Whatever the approach, the cost of energy should always be kept under review and any previous estimates and assumptions revised.

2. Cost of energy

2.1 The cost of energy equation

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

$$\text{Cost of energy}[\text{£/kWh}] = \frac{PV(\text{Capital cost}) + PV(\text{O \& M costs}) + PV(\text{Decommissioning costs})}{PV(\text{Energy production})}\left[\frac{\text{£}}{kWh}\right]$$

$$\approx \frac{\text{Capital cost} + PV(\text{O \& M costs})}{PV(\text{Energy production})}\left[\frac{\text{£}}{kWh}\right]$$

Equation 1

A more complex version of this equation would allow for the capital cost expenditure to be split over several years and perhaps could include a mid-life refit. It also includes the costs of decommissioning the scheme. The simplified equation above contains only the most important variables.

2.2 The present value approach

The 'present value' approach underpins many different financial investments. It is routinely used to assess and differentiate investment opportunities. There are many ways to interpret the present value of an investment, but the calculation process is roughly the same regardless. The interpretation of the present value depends on who you are, or rather what type of investor you are.

The basic principle of the present value approach is to recognise that the value of £1 today is more than £1 in the future. To account for this we 'discount' the value of money spent and income generated in the future. The level of discounting can be interpreted in several ways—

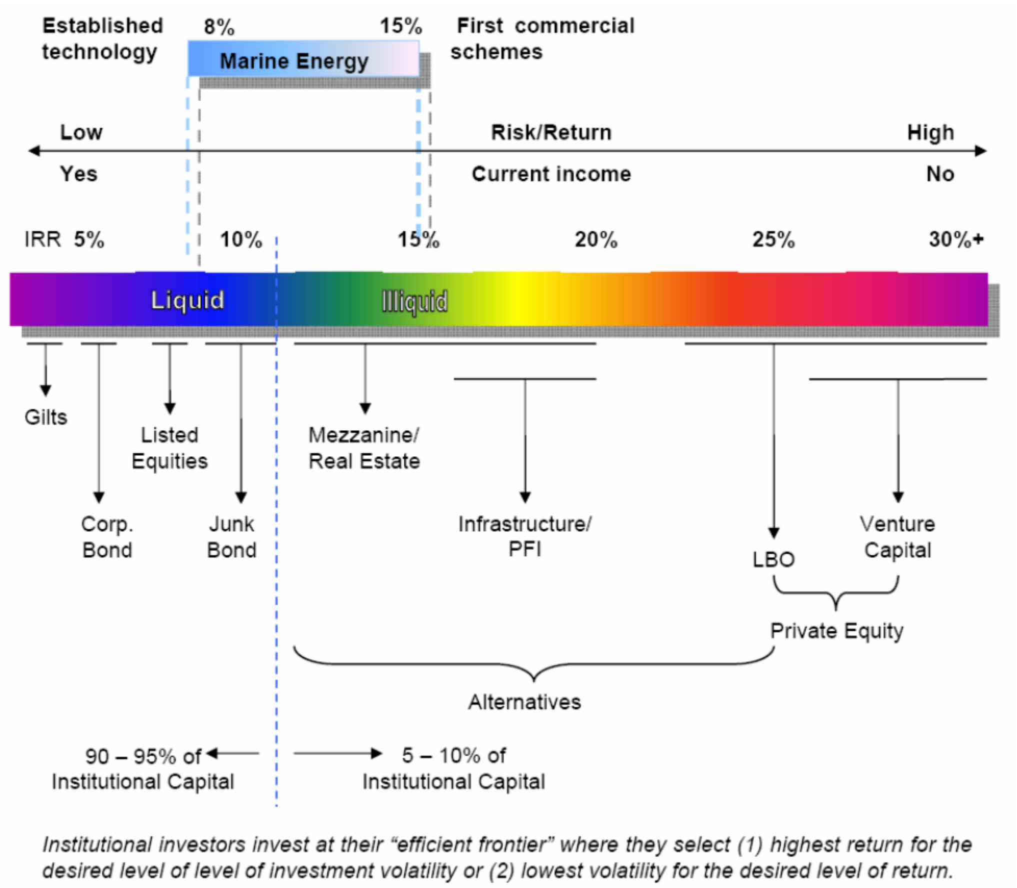
Table 2.1 How investors might think about discount rates[1]

Risk	An investor who puts money into a project expects a return on the investment. If the investment is risky then they expect a higher return. For a given level of risk the investor might set a minimum return that they are willing to accept. This could be called their 'hurdle' rate.
Opportunity	Investors often have several choices of where to place their money. For example an investor may choose to leave their money in the bank. This would provide them with a modest return. If they place their money elsewhere then they lose the 'opportunity' to make the return from the bank. An investor would then compare other investments against the 'opportunity' that they would lose. In most cases they would expect a greater return.

[1] Further reading: Corporate Finance, Brealy, Myers, Allen, McGraw-Hill International Edition, ISBN 0-07-111551-X

Discount rates can represent either the project return or risk. Different industries carry different levels of risk and are often assigned different discount rates. We consider that the discount rate for the first commercial marine energy schemes would be around 15% whilst 8% might be applied to it when the technology matured and became established in the market.

Figure 2.1 Range of discount rates applicable to different types of project



Adapted and reproduced with permission from Tom Murley at HgCapital

This means that when we calculate the cost of energy using this present value approach we incorporate the project return into the cost of energy. Thus a scheme that produces energy at a cost of 5p/kWh at 8% discount rate might produce electricity at a cost of 6p/kWh at 15%[2]. This is the same scheme working in the same way, but with two different interpretations of project risk or investment return.

Alternatively, if this same scheme secured a power purchase contract and was paid 5p/kWh for all the power it produced over its life then it would make a return of 8%, but if the contract paid 6p/kWh it might make a return of 15%.

[2] These figures are purely to illustrate the point about sensitivity to rate of return. Details of the costs of marine energy systems can be found in the Carbon Trust report 'Future Marine Energy'.

The Marine Energy Challenge used a range of discount rates between 8-15%. These covered the likely range of financing options for technically proven products first entering the market through to well-proven products in wide deployment.

3. Performance

3.1 Device characteristics

The first stage in assessing the performance of a marine energy project is to characterise the performance of the device in terms of the wave or tidal current loading. For some devices this calculation can be achieved using linear mathematical models and coefficients derived from computer codes. Test data can be used to verify the model tests and provide better estimates of the coefficients. In some cases, perhaps because the wave-device interaction is highly non-linear, testing may be the only way to determine performance.

The Marine Energy Challenge used test data when these were available and developed numerical models in all other cases. Mathematical models are important even where test data are available because if they are well understood they can be used to calculate loads, design parameters, find optimum sizes and to try different configurations. Validated numerical models make good design tools.

3.2 Resource

The available resource is then measured or estimated. At a tidal stream site the most important measurements will be of tidal current velocity. For wave sites both wave height and period are important. For both technologies the amount of time for which each sea condition occurs must be estimated. An estimate of the annual energy output can be calculated by multiplying the power output of a device in each sea condition to the annual occurrence of that condition.

The energy production will vary depending on the site and, in general, devices placed in more energetic climates will produce more energy. However, if the devices are poorly matched to the climate then the energy output could be lower. Alternatively, the benefits of additional income from increased output may be offset by the cost of increasing the device strength to tolerate more severe wave loads or increased maintenance requirements. Either case would result in a higher cost of energy.

3.3 Losses

Once the theoretical energy output has been calculated some account is taken of the various energy losses. The power curves and power surfaces include some account of inefficiency. These include, for example, the conditions when the device is deliberately turned off when the incident energy is too low. Other losses must also be accounted for; these include losses in the electrical cable to shore, and lost energy due to an imperfect match between incident energy direction and device orientation. Many of these losses can be accounted for by applying a simple reduction factor to the energy generated by the device. For example if the cable losses are assumed to be 2% then for every 100kWh supplied to the cable 98kWh are delivered to the electricity grid on the shore, the remaining 2kWh is generally lost as heat to the sea. Many of the losses of this kind apply equally to all levels of power produced and are often assumed constant in the high-level cost of energy predictions used in the Marine Energy Challenge.

3.4 Availability

The availability of a device is a measure of the amount of time that it is running without fault. This time does not include periods when the device is working but is not generating due to a lack of waves or tides. Availability is a measure of the reliability of the device.

During the Marine Energy Challenge, several methods for calculating availability of marine energy devices were considered. These used various combinations of the following—

Estimates of servicing requirements

Most technologies will require routine servicing. Servicing involves a combination of inspection and replacement of consumable parts (such as oil and brake pads). Mature technologies have well-defined service intervals. These might be fixed time periods, such as every six months, or they might be conducted after a certain amount of electricity is produced. Many modern systems have sophisticated systems to calculate when servicing is required, depending on the time that has elapsed, the load on the system during the interval, the environmental conditions and other data from the monitoring of the condition of the system, e.g. of wear rates.

Estimates of failure rates

A reliability model is built from known or estimated failure rates for each of the components in the device (MTBF). The failure analysis of systems is a well-refined and widely used technique. In the Marine Energy Challenge the failure rates analysis was simplified in many cases so that different configurations of system could be assessed readily. Modelling such systems can often be conceptually straightforward but obtaining sensible operational data is impossible without building the entire system.

Estimates of time to repair

The mean time to repair (MTTR) depends on the nature of the fault. For example some faults can be rectified using remote control systems, whereas others will require visiting the device. When visits are required, repair time is dependent on the nature of the work, for example whether access for personnel is needed or whether heavy equipment or parts must be transferred. Each type of intervention is affected to a greater or lesser extent by the prevailing weather. Remote intervention might be immune to weather conditions whereas transferring personnel with cumbersome loads may incur significant 'waiting on weather' delays.

The overall availability is a function of the rate of anticipated failures and the time to repair them. Because the number and timing of failures cannot be predicted, and because failures are often interrelated, the assessments make use of various statistical techniques to estimate availability. For example, Monte Carlo analysis allows simulation of numerous scenarios with different random combinations of faults and fault interactions and prevailing weather conditions. This produces an estimate of the most likely availability for the complete system whilst accounting for the main knock-on effects of the various faults on the overall operation of the farm.

The methods for estimating reliability can rapidly become very complex and they rely on much accumulated operational experience. When a large number of complete systems have been in operation for many years the availability can be observed.

Ultimately the availability of the system is shown as a single representative number. An availability of 100% would mean that the machine was always able to generate electricity when the conditions were right. A more realistic availability level would be say 95%, when about 5% of the time the system would be under repair or suffering a fault that stopped it generating.

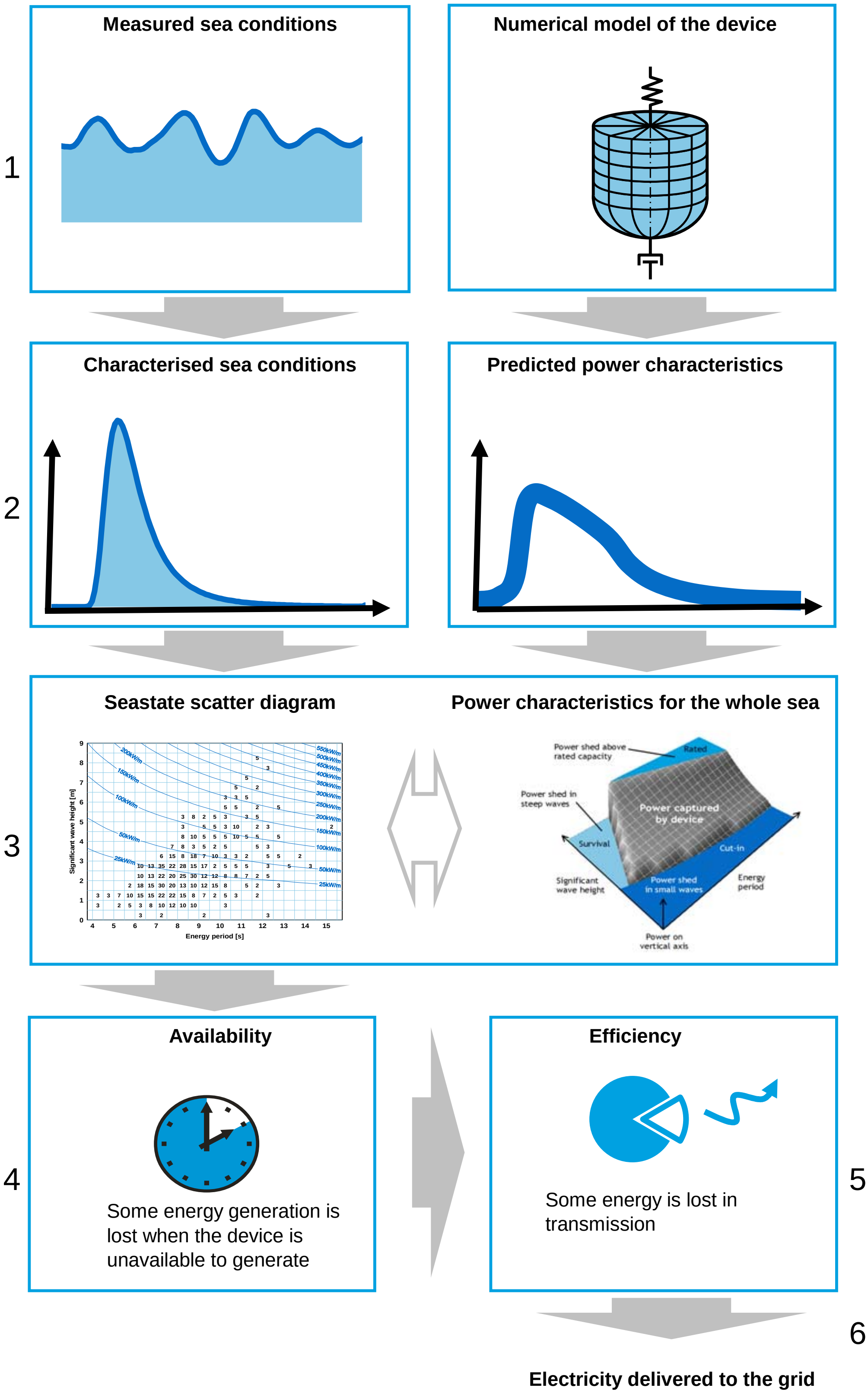
A more sophisticated, and less conservative, measure of availability would consider the time variation of energy production. This would mean that if all servicing could be undertaken at times when the device would not be generating anyway, such as when there are no waves, the availability could reach very high levels.

3.5 Annual energy production

The annual energy production is calculated by combining all of the above analyses.

1. The device characteristics for a range of sea conditions are defined based on numerical modelling and testing.
2. The number of times that each sea condition occurs in an average year is estimated for a given site and these are combined with the performance characteristics to estimate the gross energy output.
3. The likely losses incurred transmitting the energy within the farm and to the shore are calculated based on the location and distance to shore. The estimated energy output is reduced to account for these energy losses.
4. The sea conditions, system complexity and repair procedures are considered to estimate the amount of generation lost to planned and unplanned maintenance. The energy output is reduced once again to account for this lost generation.
5. The energy produced by the farm is then calculated as a long-term yearly average.

Figure 3.1 Simplified process for calculating the energy production of a marine energy project



4. Cost

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

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

The cost of energy is an important parameter, but it is not a static one. As technologies develop their cost of energy will alter. Some technological advances may reduce the overall cost of energy, some may increase it. The aim is to produce an overall reduction over time. There can be many routes to achieving this. Whichever is taken the cost of energy should be reviewed and managed routinely. This means that technology developers and energy farm operators need to revise their estimates often, as part of continual product development.

4.1 Key factors affecting cost of energy

The costs of energy of marine renewables technologies depend on several factors. Principally, these include capital costs, operating and maintenance (O&M) costs and the amount of electricity produced (performance). There will also be costs of decommissioning. Current estimates indicate these will be small compared to initial capital costs, and because they fall at the end of a project, the present value in a discounted cash flow analysis is low and has only a marginal effect on cost of energy. Like wind energy, wave and tidal stream energy are free at source so there is no fuel cost.

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

4.2 Capital costs

The capital cost of marine renewables technologies can be broken down into: the cost of the generation device itself (materials, components and labour in manufacturing and fabrication processes); the costs associated with installing it (deployment); the costs of keeping it on station (foundations or moorings); and the costs of connecting it to the grid (electrical cables and switchgear). Some of these costs are more dominant than others, and the relative distribution of cost centres varies between different device concepts and site locations.

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

This section describes the approach taken in the Marine Energy Challenge to estimate these costs. Figure 4.3a shows an example of a cost breakdown for a wave energy device.

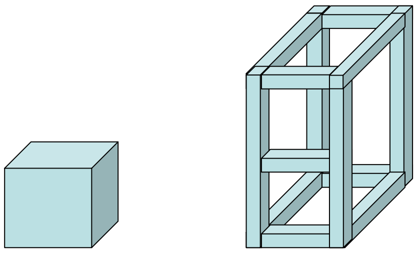
4.2.1 Structure costs

In many cases the structure forms the largest cost of any marine energy device. It usually has to both interact with the waves or tides and support the power conversion equipment such as gearboxes, hydraulics and generators.

The cost of the structure can be a simple product of the material weight and the cost of that material. For example a large steel structure with a mass of 20 tonnes might cost around £20,000 based on a steel cost of say £1000/tonne.

This approach is useful in some cases but quite often the complexity of the structure has a large overall effect on the cost. Thus a simple lump of material costs less than a complicated fabrication. Most often the unit costs for fabrication of relatively straightforward shapes are collated and then the number of each type of shape calculated. This usually results in the majority of the structure costing roughly the same per unit mass, but with a few components costing significantly more. Such components might include joints between parts of the structure or flanges and interfaces with other items of equipment.

Figure 4.1 Structural complexity



Simple 100-tonne structure

Complex 100-tonne structure

The Marine Energy Challenge used engineering experience and a build-up of unit costs, as well as quotes for the construction of the whole unit from experienced fabricators. Both approaches are needed. The first is simpler and allows the trade-offs between cost and performance to be made more readily and the second is suited better to refined designs.

The experience of the fabrication industry is essential to developing low-cost solutions. Often the most expensive manufacturing operations can either be simplified or eliminated completely without significant changes to the overall concept. The advice of experienced fabricators was particularly useful in the refinement of the Marine Energy Challenge devices' structural designs.

4.2.2 Mechanical and electrical costs

The mechanical and electrical costs include all the items that convert the movement of the device or the surrounding water to electrical energy. For example these can include the hydraulic systems between two moving parts of the structure, the blades of a water turbine, the gearbox that increases shaft speed, and the electrical generator that converts the motion to electrical power.

The mechanical and electrical costs are strongly device specific. These components are sized mainly according to the peak power output of the device. Thus a gearbox is sized such that the product of its rated torque and its rated rotation speed is roughly equal to the power of the device. Likewise the product of rated generator current and the rated generator voltage is roughly the rated power of the device.

Determining the optimum power level of the device is an iterative process. It is generally not economic to install a power conversion system that can convert the highest levels of energy in the sea. This is because these high levels do not often occur and thus the device would be underutilised most of the time. Instead a compromise is made and the device is rated at less than the highest power likely to be seen. Occasionally some of the energy is shed and not extracted by the device.

The ratio of the mean power output to the peak power is known as the capacity factor[3]. A capacity factor of 30% means that the generator will produce the energy equivalent to 30% of that produced if it could run at full load. The device cannot run at full load all the time because there is insufficient power in the sea.

$$\begin{aligned}\text{Capacity factor}[\%] &= \frac{\text{Energy output}[kWh]}{\text{Energy available}[kWh]}\\ &= \frac{\text{Annual energy output}[kWh]}{\text{Rated power of device}[kW]\times\text{time in the year}[h]}\\ &= \frac{\text{Mean power output}[kW]}{\text{Rated power output}[kW]}\end{aligned} \qquad \textbf{Equation 2}$$

In the Marine Energy Challenge the simplest approach used was to estimate roughly the best balance between installing a more expensive and larger generator with the additional income from the energy produced. This balance is different in each case. Once it is known, the sizing of all the mechanical and electrical systems can be calculated from the overall device size.

In many cases after the design had been developed the balance of output to installed capacity was reviewed. This led to either increases or decreases in capacity factor.

In reality the capacity factor of a scheme is **not** a design driver, but a consequence of the balance of output and cost. Thus some devices had capacity factors of below 10% and others above 50%. It is not possible to conclude which has the better overall economics from these figures alone.

In many instances the design of the mechanical and electrical equipment requires new systems and indeed some of the intellectual property inherent in the device designs involves these novel systems. Often only guesses of the performance of these components can be made. In several

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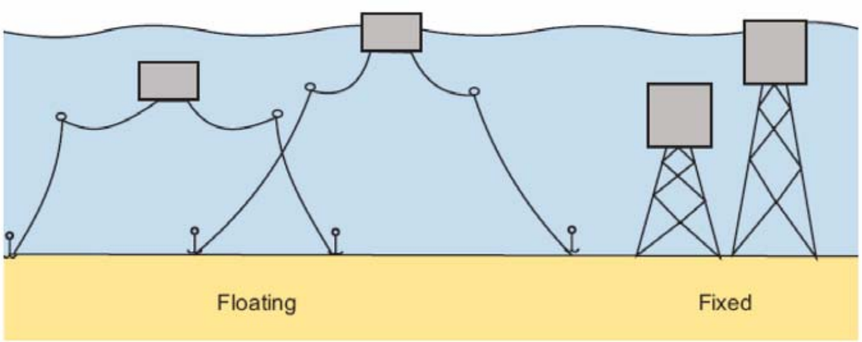
[3] In conventional power systems the concept of the **capacity factor** is also applied. In this case it is termed the **load factor**. The difference is that in renewable energy systems it is the *fuel supply* (e.g. the waves or tides) that varies, whereas for conventional system the fuel supply is constant but the *load* varies. The load varies as people turn lights and machines on and off.

cases, manufacturers of similar systems were contacted for advice. This advice included advice on novel electrical systems, hydraulics, control systems and new materials.

4.2.3 Mooring costs

The moorings include all the components required to hold the device in place. For some designs the moorings and the structure are effectively the same item, for example the monopile used in a tidal energy turbine could also be considered as the main structure. However, in many cases the moorings are quite separate systems that allow the device to move independently and are required only to hold it on station and prevent it drifting. For many mooring systems their design depends on the mean and **extreme** (storm) loads placed on them by the sea. This contrasts with the design of the power take-off system that is optimised towards the **average** conditions in the sea. The water depth, the tidal current and the tidal range also all affect the design and cost of the mooring system. Moorings are therefore designed to suit both the technology and the deployment location.

Figure 4.2 Moorings



4.2.4 Installation

The method of installation will depend on the nature of the device. The choice of vessels, for example, will also change. Some devices can be towed to site using a tug and their anchors placed using an anchor-handling vessel. Others might be carried on a heavy-lift vessel or a barge. Piles and other structures might be positioned using stable platforms such as jack-up barges that can float out to the site and then 'jack' themselves up out of the sea to form a temporary platform.

- Heavy-lift vessels
- Jack-up
- Barge
- Tug
- Anchor Handler

The offshore and oil and gas industries have developed a large number of specialist vessels (such as those above) for completing all types of work at sea. Tugs and other non-specialist vessels are widely available and can be procured at less cost, whereas some of the specialist jack-up barges are much more expensive and are harder to charter. Generally the more specialised the vessel the greater the cost.

The costs associated with deployment are usually estimated with vessel charter rates. These are usually daily rates. The day rates for vessels change in response to the demand for the vessels. During the Marine Energy Challenge (2004-2005) costs for anchor handlers increased several-fold due to increased demand for their services in the oil and gas fields of the North Sea.

The Marine Energy Challenge used long-term average rather than spot rates for vessel costs. This means that some prototypes may well incur dramatically lower costs, or indeed unfortunate higher costs depending on their timing and their ability to negotiate good prices.

Marine energy systems though are slightly different to other offshore operations. Many marine energy systems are designed to be deployed in large numbers. This means that some will need longer vessel-hire periods and will ultimately be able to either negotiate lower day rates or indeed justify procuring their own dedicated vessel. Many of these options were considered in the Marine Energy Challenge.

Deployment costs are also strongly related to the location. The sea conditions, tidal ranges, etc. will dictate the choice and thus the cost of the vessel. The distance to port will also affect the transportation time and the duration of vessel charters.

4.2.5 Grid connection

Estimates during the Marine Energy Challenge included the costs of all electrical connections to the shore. They also included the necessary shore-based facilities to join the output of the marine energy system to the land-based electricity grid. In reality other costs may be incurred too, the shore based grid might need reinforcement or adaptation to absorb the new generation, but this is certainly not true for every site around the world. Thus shore-based electrical system upgrades were not included in the costs.

The grid connection costs include any cables, transformers and switchgear needed to connect the offshore farm to the land. Generally the costs depend on the distance to shore, the ground seabed conditions along any cable route and the power being transmitted.

4.2.6 Project management

All capital projects, such as marine energy systems, require project management. All the Marine Energy Challenge cost of energy estimates allowed for some level of project management for their schemes. Such costs are extremely difficult to estimate and so simple fixed proportions of the overall costs were allocated to management in most cases. These allowances cover the costs of managing the project as well as insuring some of the construction risks. Early projects are likely to have very high project management costs, though these will probably reduce to levels found in similar industries.

4.3 Deployment location

Many of the elements of the cost equation depend on the deployment location of the marine energy system—

Table 4.1 The influence of the deployment location on the cost of energy

Cost centre	Influences
Energy production	Energy density at the site
Foundations and moorings	Water depth, ground conditions, tidal streams, tidal ranges, energy density
Grid connection	Distance to shore, ground conditions along any cable route
Installation	Water depth, tidal streams, tidal ranges, distance to suitable port

The deployment location has a strong influence on the energy production and the costs of a scheme. Thus suitable target locations for each device were decided early on in the Marine Energy Challenge.

4.4 Operating costs

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

Figure 4.3b gives a breakdown of O&M costs for a specific wave farm envisaged. Like capital costs, O&M costs also depend on the size of the installations and the location, and are also likely to vary from year to year. At present, it is much more difficult to estimate O&M costs than capital costs due to the lack of experience in operating wave and tidal stream farms, although it is possible to infer costs from experience with upstream oil/gas installations and offshore wind farms.

Below we discuss planned and unplanned maintenance and how these affect energy generation and thus project income. Here we describe how we consider the costs of these activities.

4.4.1 Planned maintenance

The costs of planned maintenance include—

- Cost of consumable replacement parts (e.g. new brake pads, replacement oil)
- Cost of servicing the vessel in terms of the time and personnel required
- Cost of waiting on the weather conditions to be right to allow servicing to take place.

4.4.2 Unplanned maintenance

The cost of unplanned maintenance is considered in a similar way. Here though the costs are not known, it is not known which parts will fail and when. Therefore the costs are an estimate of the likely average for a project. The costs include—

- Cost of replacement parts (e.g. new brake pads, replacement oil)
- The costs of spares kept in case of failure (for small schemes only small spares are carried (e.g. a puncture-repair kit), but for larger farms maybe entire devices can be kept as spare (e.g. a spare racing car)
- Cost of servicing the system in terms of the time and personnel required
- Cost of having service equipment and personnel on stand-by in case of fault
- Cost of waiting on the weather conditions to be right to allow servicing to take place.

Of course there is much that can be done to minimise these costs, and as the industry develops equipment will become more reliable, the parts will be more readily available, more personnel and equipment will be available at short notice to make repairs and better operation efficiencies are possible.

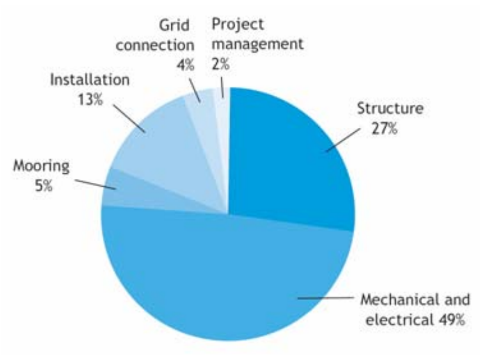
The Marine Energy Challenge estimated some of the likely costs of unplanned maintenance, but for the first few devices these costs were often very high. Since the Challenge was to estimate not only the costs today but the costs in the future some assumptions about increased reliability and operational efficiencies were needed. These assumptions were made by observing the development of other industries, by theoretically trading off capital and operation costs (e.g. including spare/redundant systems) and by investigating sophisticated options such as the purchasing of bespoke vessels rather than relying on hiring available systems.

Wherever possible evidence for these areas of efficiency improvement was found and demonstrated. Usually this resulted in either a reduction or an elimination of unplanned maintenance costs. It must be stressed though that these assumptions do not apply to the first few devices where we will still be learning about the reality of operating these new devices in the real sea environment.

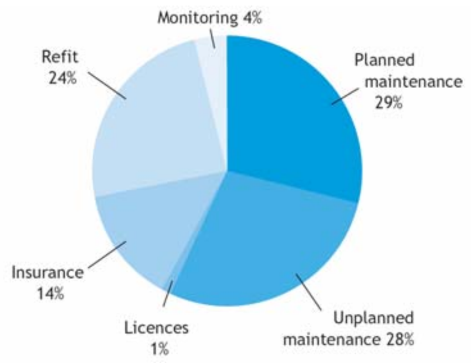
Table 4.2 Cost centres and cost drivers

Cost centre	Main drivers	Example measures and variables
Capital cost		
Structure cost	Material cost Extreme loads	Cost per tonne, tonnes of material
Mechanical and electrical costs	Rating of the machine (installed capacity)	Peak power output, mean power output
Moorings	Water depth Tidal range Tidal flow Storm conditions Compliance	
Installation	Type and availability of vessels required Distance to port Time taken for installation Time waiting on weather	Vessel day rates
Grid connection	Power transmission level Distance to shore	Cost per kilometre
Project management	Project management Insurance Permissions	Proportion of the total capital cost
Operating cost		
Planned maintenance	Cost of replacement parts Component design duty and known service intervals Time to complete service Distance to port Time waiting on weather	
Unplanned maintenance	Cost of replacement parts Cost of spares Time to complete service Time waiting on weather Cost of personnel and materiel standby	

Figure 4.3 Cost breakdowns for an example wave energy device a) capital b) O&M



a)



b)

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

5. Uncertainty in estimates

Only when much experience has accumulated, both of developing and running marine energy technologies, can good estimates of the cost of energy be made. Even then, estimates for particular projects will still be uncertain. It is good practice when making any estimates to estimate also the uncertainty in them. For example we might conclude that a particular item might cost about £1000, but in reality could cost anything from £900 to £1200. We would say that the £1000 middle estimate was our ‘best’ guess.

Some times we assign probabilities to these figures. For example we might conclude that there is a 90% chance that the item above would cost less than £1200, but only a 10% chance that it might cost less than £900. Sometimes we can work out these estimates using statistical techniques, but often we have to make our own estimates of the uncertainties instead. Whichever method is available, assigning a range with a nominal ‘confidence’ level provides much more useful information.

Narrow confidence bands show more certainty in an estimate than wide ones. For example if we were to estimate the cost of readily available raw material (e.g. steel) we might find it was in the range £995-£1010, whereas a similar value of a less common material (e.g. silicon) might cost £800-£1200. Both will cost the project around £1000, but we are surer of the steel costs than the silicon costs.

Uncertainty information helps us identify which areas we need to investigate further, e.g. where costs need to be calculated in more detail perhaps. It also shows where uncertainties will always exist and where these need to be managed differently. For example the estimate of the long-term energy output of a wave energy farm will always be uncertain because it depends on the weather and the weather is extremely difficult to predict for the whole life of the project. This means that project investors need to find other ways to deal with this uncertainty. One way is to treat it as a project risk, in much the same way as they treat the ‘market’ risk of other products.

Combining estimates and their uncertainties can be difficult. If the estimates are calculated with rigorous statistical techniques, then the best estimates and their uncertainties can be combined statistically too. However, more often the estimates are not based on statistical observations and additionally there are complex interactions and trade-offs between the different options. For example, it is quite unlikely that all the costs (if estimated properly) will all be at their lower end, neither is it likely that they will all be at their higher end. Thus adding all the low costs together does not give a reasonable low overall cost.

Additionally, if one parameter reduces the cost of energy it might influence another to increase it again. For example, if the wave resource turns out to be at the high end of the estimate, more energy might be produced and the cost of energy lowered, but this might also cause an increase in wear rates and thus more maintenance is required, hence raising the cost of energy again.

For very complicated systems models of the cost of energy can be constructed that allow for all of these interactions. Once again, techniques such as Monte Carlo analyses can be used to calculate both the best combined estimate and the uncertainty in that estimate.

It is good practice to make estimates of the uncertainty in all individual estimates as well as in combined estimates.

Appendix A
Sources of further information

1 Page

For more information see—

Carbon Trust
(http://www.carbontrust.co.uk)

Future Marine Energy – Results of the Marine Energy Challenge: Cost competitiveness and growth of wave and tidal stream energy
Available from (http://www.carbontrust.co.uk)

Carbon Trust Marine Energy Challenge Newsletters
(http://www.carbontrust.co.uk/technology/technologyaccelerator/marine_energy.htm)