Economic Assessment of Marine Energy Schemes

Stallard, T.[1], Harrison, G.P.[2], Ricci, P.[3] and Villate, J.L.[3]

[1]Joule Centre, School of Mechanical, Aerospace and Civil Engineering, University of Manchester, UK
E-mail: tim.stallard@manchester.ac.uk

[2]School of Engineering, University of Edinburgh, Mayfield Road, Edinburgh, UK
E-mail: gareth.harrison@ed.ac.uk

[3]TECNALIA-ENERGÍA, ROBOTIKER-Tecnalia: Parque Tecnológico,
Edificio 202, E-48170, Zamudio (Bizkaia), Spain
E-mail: pricci@robotiker.es

Abstract

Although many marine energy technologies are presently being developed, only a small number of devices have generated electricity from the marine environment. From such a small experience base it is difficult to independently assess the economic feasibility of alternative technologies for large-scale electricity generation. With a few notable exceptions, much of the published work on marine energy costing concerns relatively small deployments (up to around 100MW rated capacity) with a strong emphasis on costing the components of individual marine energy conversion devices. A review indicates that there is considerable variation of unit electricity cost estimates even for similar technologies. In part, this can be attributed to different end-user applications and input assumptions. Comparison between individual marine energy technologies is therefore not straightforward, particularly for non-technical groups such as potential investors or policy makers concerned with future electricity generation scenarios.

Informed by consultation with stakeholders and the 22 partners of the EU FP7 EQUIMAR project, we present a summary of alternative approaches used to evaluate the economic viability of a marine energy scheme. For several technology types, the main factors affecting the capital cost, operating cost and revenue associated with a commercial scale marine energy project are identified. To aid identification of high-risk cost areas, indicative quantities are assigned to the uncertainty and scale-dependence associated with several key inputs. This provides a framework for equitable assessment of diverse technologies.

Keywords: Economic Assessment; Uncertainty; Risk.

1 Introduction

Much of the past research effort in marine energy has focused on the solution of different scientific and technical problems. Novel methodologies for analysis, simulation and engineering have been defined and improved but yet the design of these technologies is far from being established and it is rather difficult to perform an economic assessment of a marine energy concept, particularly because of the large number of existing device types and possible deployment sites.

Device developers need reliable tools for cost assessment in order to take decisions under proper economic criteria. Investors need properly recognised economic performance indicators for a fair comparison between different technologies (even if still at early stage). Utilities and policy makers need economic appraisal at a different level since the funding of future development projects will depend on the proper estimation of the economic impact of large scale deployments.

Considering the reasons given above, it is clear that economic assessment methodologies should be included in the same framework as technical considerations in order to evaluate or compare different marine energy technologies. Large scale research projects are increasingly focused on developing methods that allow robust and equitable comparison of technologies. This is the objective of the EU FP7 EquiMar project. This is a three year (commenced April 2008) collaborative R&D project funded under the Energy programme and involving a consortium of 23 partners. The main outcome of the project will be a suite of protocols for assessment of marine energy technologies. These documents will cover several technical areas and will be defined through the co-ordination of the partners in parallel work packages.

The content of this paper is the result of preliminary activities developed by the authors during the first year of Work Package 7 that will propose methods for

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assessing how the economic viability of the main types of marine energy technology may change with increasing scale of deployment. To distinguish between technologies the focus will be on evaluating the essential infrastructure costs associated with different types of marine energy device and the scope for reducing cost of electricity by optimisation of device performance. The expectation is that this will provide a framework for assessing the long-term viability of designs that are at differing stages of development. These tools will be of considerable use to policy makers and marine energy investors. Guidelines for appraising a given combination of technology and site will be developed and reported through protocols. Early work in this package has included the evaluation of existing economic assessment methods with the intention of preparing guidelines on the conduct of economic assessments. This paper represents a brief critical review of current methodologies and an outlook on their importance and validity in stakeholders' perception. First motivations for conducting economic assessment of marine devices are identified and exposed. Since a wide range of costs have been published for the same type of device, comparison of technologies is not straightforward and therefore improvements on this aspect are required.

Through consultation to stakeholders and project partners, the information needed to perform economic assessment is defined. Two different types of assessment are proposed: economic assessment of a specific device technology and assessment of a specific marine energy project (including choice of the deployment site). A brief review of existing literature concerning measures of economic viability and methods for calculation of cost factors is proposed and limitations of the existing approaches are specified and analysed. Finally, possible evolutions to overcome these constraints are addressed. Suggestions for methods for accounting of uncertainties are given and a view on the influence of number of devices and scale of the project on installation and operational costs is outlined.

2 Stakeholder Views

As a first dissemination event for EquiMar and for preliminary feedback on the organization of the project, a workshop was organised in coincidence with the 2nd International Conference on Ocean Energy in Brest in October 2008 with about 30 people, including partners and stakeholders external to the project but active in marine energy, that were invited to take part by EquiMar partners. Discussion was held with four focus groups to identify the main areas of uncertainty associated with economic assessment. Views were sought on what information should be provided in a protocol for economic assessment. The discussion areas included: Operation and Maintenance activities, the influence of scale of deployment and market size, ranges of unit costs, learning rates, insurance and the role of market conditions on economic viability. Key points were that:

- Headline figures (e.g. €/kW or €/kWh) are useless unless the inputs and assumptions employed are clearly stated.
- Economic info is used by variety of people and the methods employed are different.

To provide a basis for comparison it is important that an economic assessment of a technology is based on inputs and measures of uncertainty that provide a realistic estimate of the economic viability. Guidelines on an economic assessment should therefore aim to clearly identify the inputs and assumptions employed.

Two categories of economic assessment were defined for the purpose of: a) identification of the preferred design option (comprising a number of devices deployed at a particular site to provide a target electrical output) or b) prediction of how the economic viability of a particular marine energy technology will change to allow comparison with other generating options. In relation to economic assessment of a *project* it is important to:

i) Provide or identify the information that is needed to conduct a cost assessment. It was noted that the information that is presently available in the public domain is not very useful
ii) Identify the underlying processes that affect cost and high risk cost areas: operation and maintenance, manufacturing and installation are the highest cost points.
iii) Account for the uncertainty associated with operation and maintenance costs. These remain very uncertain and there is likely to be variation with both scale of deployment and site characteristics. Manufacturing & installation processes are subject to similar issues.

In relation to economic assessment of a particular *technology* it is necessary to understand how the following factors may change economic viability as that technology is developed and deployed:

i) Change of maintenance strategy.
ii) Optimization of power output. Realistic expectations of power density limits should be employed.
iii) Transfer of technology and expertise from other technologies or industry sectors.
iv) Mass production over a scale that is appropriate for that technology.
iv) Change of wave-farm infrastructure requirements with scale of farm deployment (e.g. the variation of station-keeping and transmission infrastructure, such as number of moorings, length of cables) should be considered. Associated installation and maintenance should also be considered.
v) Supply chain dependencies should be highlighted where possible. For example: comparisons should be drawn between the rental of existing vessels or development and purchase of special purpose vessels.

Project Assessment

In relation to economic assessment of a project, stakeholders were asked about the type of information device developers should provide to allow comparison between design options (i.e. between alternative marine energy technologies) when planning a commercial marine energy project at a predetermined location. The options given were: “Predicted present value per unit of generated electricity (€/kWh)”, “Capital cost of present device design (fabrication) inc. station keeping”, “Predicted installation cost”, “Statement of installation tasks”, “Average output (e.g. per sea-state)”, “Variability of output (e.g. per sea-state)”, “Statement of maintenance requirements (task duration and occurrence)” and “Operating cost”. Results are summarized in Figure 1. The three most chosen items were “Predicted present value per unit of generated electricity” (21%), “Average output” (17%) and “Operating cost” (16%).

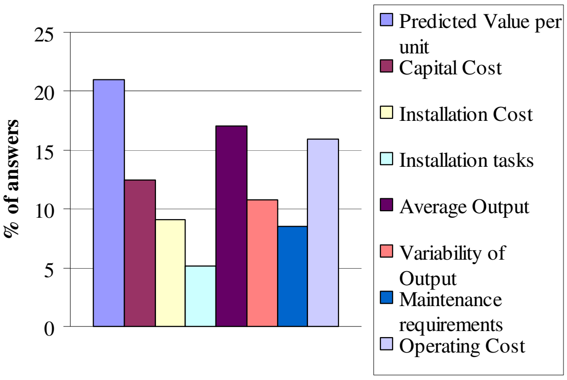

Figure 1(a): Key economic indicators for comparison of alternative marine energy devices. (Q10)

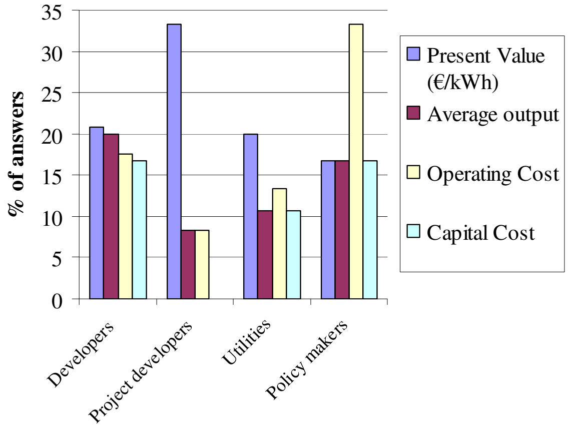

Figure 1(b): Key indicators used economic assessment split by respondent type. (Q10)

Responses to this question are quite spread indicating that a range of methods are typically employed to assess a project. However, the majority of responses identify the predicted net present value of the cost of electricity (COE) as the most widely used approach. Procedures for calculating this indicator are discussed in Section 3. Power output and operation and maintenance costs are also seen as key measures by which to compare alternative designs. It is interesting to note that capital cost is considered less useful than either operating cost or average output. This could be due to the (in general) higher level of uncertainty associated with operating costs and device performance. Only a small number of respondents suggest that the type and number of installation tasks and the type of maintenance requirements are important. This data is required to estimate the operating cost but the type of tasks is not considered important. The same responses are shown in Figure 2 as distributed per type of respondent. Present value per unit of electricity is considered as the most important information for comparison for most of the profiles with the exception of policy makers who seem to regard operating cost as a critical parameter for assessment. It is interesting to note that average output is particularly highly rated by developers and research institutions whilst investors and policy-makers assign lower relevance. This presumably follows from the fact that cost of electricity is more sensitive to net output than any other input and supports the use of summary economic indicators for policy decisions.

Technology Assessment

Marine energy conversion is, presently, not economically viable when compared to other generating options. It is widely known that costs must fall and performance must increase to improve economic viability. In another question, six options were given and respondents were asked to rate each of them from 1 (very little affect) to 10 (significant affect) on future economic viability. Results are shown in Figure 2. All options were highly rated, from 6,66 to 7,47 (mean values), being “Design changes resulting in reduction of capital cost of each marine device” (7,47) and “Reduction of scheduled maintenance” (7,46) the options with the highest marks, followed by “Increased average power output per device” (7,36). Four people did not answer this question. Since the rankings are quite similar for all the options, it could be said that they all are felt important in determining the future generating cost of marine energy. It is interesting also to notice that stakeholders acknowledge the relative degree of immaturity of these technologies by assuming design changes likely to have a positive effect in the future. Comparing to other factors, stakeholders seem to believe that changes in station-keeping design (moorings and foundations) and installation cost reductions will have less impact on future generating costs.

Respondents were also asked to identify the main design requirements that should be satisfied by the next generation of devices in order that they reach commercial viability. Results are shown in Figure 3. The two leading factors were “Reliability and low maintenance requirement” (30% responses) and “Guaranteeing continuous electrical power output for long times (high availability factor)” (24% responses).

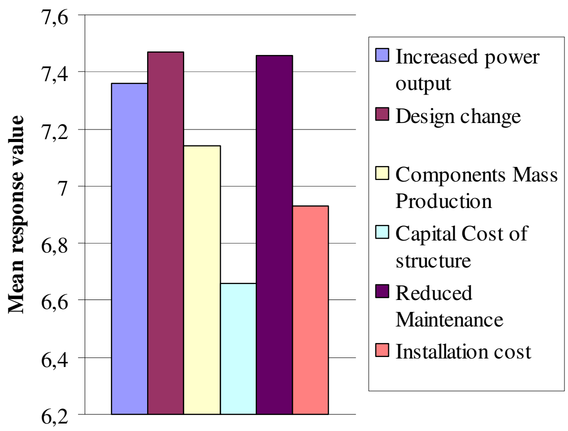

Figure 2: Factors expected to influence the future unit costs of electricity from marine energy. (Q11)

The importance of reliability and availability for future commercialisation of marine energy converters is in marked contrast to the lack of consensus on other design objectives. Ease of operation (and installation) and economic efficiency were considered to be important by around 12-14% of respondents. Adaptability of design (in terms of its suitability for multiple deployment sites), robustness and level of environmental impact were not considered important requirements. However, robustness is perhaps implicitly assumed in the requirement of high reliability. Indeed high reliability and availability are closely related since, aside from downtime due to inoperable wave conditions, availability will be strongly influenced by component reliability and the resultant downtime due to waiting on weather conditions for access and repair time.

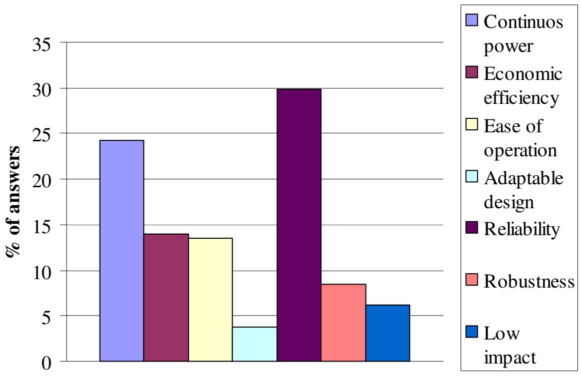

Figure 3: Design requirements that should be satisfied by a commercially viable marine energy device. (Q4)

Major improvements in economic viability are expected to occur due to reduced maintenance requirements (costs), design changes and increased performance (power output). These are supported by the views that next-generation designs should have high availability and reliability. In Section 5 we briefly consider the implications of increased power output and of reduced maintenance requirements on economic viability.

3 Project Assessment Methods

There are a wide range of approaches used for assessing economic feasibility of electricity generating technologies which reflect the even greater range of methods used for economic and financial appraisal generally. Common measures include: payback period, cost of energy, Net Present Value (NPV) and Internal Rate of Return (IRR). Expressions for calculating these parameters are given in [1-5].

A common measure is payback period, the time it takes for the revenue from a project to match the initial investment. It is very simple, readily understandable and offers a crude measure of investment risk (the faster the investment pays back the less 'risky'). Its limitation is that it does not account for the timing of costs and revenues, the size of the investment nor the overall return. It is commonly used as a screening method prior to the use of more credible methods.

Present value methods account for the timing as well as the magnitude of costs and revenues. The basis of these methods is the idea that a lower value – a greater discount – should be placed on cash flows in the future than on those occurring today as there is a risk that future cash flows may not occur. A higher perceived risk attracts a higher discount rate. The discount rate is typically the investor's overall cost of capital or may be adjusted for project-specific risks. Typical discount rate values suggested for marine energy in the UK are between 8 and 15%, with the higher rate applying to less developed technologies [1] to represent the greater uncertainty associated with both design and cost estimation. This connection between discount rate and design uncertainty requires further consideration.

The Cost of Energy (CoE, or levelised cost) aims to capture the lifetime costs of a generator and allocate those costs to the lifetime electrical output with both costs and output discounted to present value. It is expressed in €cents/kWh. The approach was developed for regulated monopoly utilities to provide a first estimate of the relative costs of plant. CoE is presently widely used by policymakers to indicate the relative merits of different generating technologies as well as in identifying the need for subsidy for developing technologies [6]. Although a useful measure, the CoE of high capital cost, low fuel cost technologies such as wave and tidal energy is very sensitive to variations in discount rates. Furthermore, the revenue side of the investment decision, i.e the influence of electricity prices and associated risks, and the scale of the investment is neglected.

The net present value is the sum of all the costs and revenues over the lifetime of the investment discounted to the present day. A project with an NPV greater than zero has a return exceeding the minimum expected rate and would be beneficial to undertake. For a generation project the NPV can be expressed in €/kW installed. As for CoE, NPV is very sensitive to the discount rate. Internal rate of return is related to NPV as it is the discount rate at which the NPV is zero, i.e., in which present value of all future expenditures balance the present value of all future revenues. In effect the IRR measures the cost of capital that the project could support and still break even. The project IRR is often compared to a hurdle (minimum) rate which may be the investors cost of capital or a risk-adjusted rate. Care must be taken with IRR as it implicitly assumes that returns can be invested at the same rate and that changes in net cash flows can lead to multiple project IRRs.

Assessment of Risk

Consideration of risk as well as return is vital in economic appraisal. While discounting methods like CoE, NPV and IRR attempt to encapsulate risk it is often in a non-specific way. For example, discount rate is typically the company's weighted average cost of capital which reflects the differing required rates of return for equity (shares) and debt as well as the balance of debt to equity (gearing). This does not fully capture the risks affecting specific projects or technologies particularly for new projects whose risk structure differs from existing activities.

It is common when comparing the CoE of different technologies that the same discount rate is applied across the board (i.e. to all cash flows) [7]. However, this implicitly suggests that the risk profile of (say) a wave energy converter is the same as that of a gas-fired power station. Common sense suggests this is not true since one has a largely predictable cost stream whereas the other is exposed to volatile wholesale gas prices. Specification of discount rates on the basis of exposure to specific risk factors has been suggested as a means of properly leveling the playing field [4]. This involves applying different risk-adjusted discount rates to different cost or revenue streams or classes of streams, e.g. a higher discount rate would be used for cash flow dependent on fuel prices than for long-term fixed value contracts). Identification of the risk premium for each risk factor is a significant challenge. However, mirroring practice in financial markets, the use of the Capital Asset Pricing Model (CAPM) to translate the required rate of return (i.e. discount rate) to the risk of specific cash flows has also been proposed [4]. A simplified approach is to define a single risk-adjusted discount rate for the project [4]. A difficulty with this approach is that risk is defined in terms of the correlation between a cash flow and the stock market and so limited data is available for emerging sectors such as marine energy. Assessment of risk-parameters for sectors that are 'similar' to marine energy [3] suggests that no risk adjustment is required. CAPM applied to individual cash-flows may therefore be more appropriate for assessment of marine energy devices.

Economic assessment of a specific investment may ignore the often important strategic benefits of a project. For example, the addition of a project to the investor's portfolio that has a different risk profile can offer benefits by spreading risk. This approach places a higher value on generating options that have predictable and low-variance power output (research is underway within the EPSRC Supergen Marine Energy programme).

Current Perceptions of Methods

Participants were asked to discuss their approaches and viewpoints on economic appraisal methods. Developers tend to consider the estimation of the CoE as an important parameter for investment decisions: three respondents from four considered it to have a greater than 50% influence with the other respondent expecting a smaller influence. The importance attached to this parameter may reflect a need to indicate economic viability in a simple fashion. This indicates a need for a recognised definition and methodology for CoE estimation for marine energy. Most of the respondents make use of NPV for economic assessment of their technologies while some also use IRR, both with and without accounting for gearing. One respondent pointed out that economic appraisal does not involve only a single project but also the whole company. This is the case as it is the developing company that is financed and therefore quality of management and business plan are a vital component.

Risk is taken into account through single fixed discount rates for two respondents. Another pointed out the use of range values by assigning confidence errors to estimates. CAPM has also been mentioned by a respondent as a mean for assessment of the whole financial project. Overall a need to improve assessment of risk specific to marine energy is perceived. To address this there is a need to better understand the risk and uncertainty associated with marine energy projects. The main uncertainties for marine energy can be grouped into capital costs, operating costs and revenues, which can then be further categorised as required. For example, revenue uncertainty is partly driven by resource uncertainty and reliability which affect the volume of output as well as price uncertainty from electricity sales, green certificates etc. More detail in these areas will allow better comparison between competing technologies. Methods that can be applied to consider uncertainty and risk include stochastic approaches.

Capital Cost Estimation

Like other renewable technologies capital costs tend to dominate the cost of marine energy devices. Although the Oil and Gas sector generally deals with different project scales and cost magnitudes, some methodologies derived for economic analysis and comparison of different concepts might serve as reference for marine energy systems. NORSOK [8] developed a standard that describes a system for coding of cost and weight estimates and suggests classification and cost breakdown for offshore structures. Cocodia [9,10] describes a technique for estimating floating structure cost in which risk factors are taken into account by applying fuzzy logic. However, a key distinction to oil and gas developments is that there is virtually no historical data on which to base cost estimates for marine energy. Further, the balance between different elements of the capital cost will vary across concepts. This variation is identifiable in device-specific breakdowns of across several major cost categories offered by respondents (Figure 4). Broadly speaking, structural costs constitute a large part of the capital cost of each device. Variations can be observed on electrical and mechanical equipment cost since this reflects the type of power take off concept employed. One developer (A in Figure 4) aggregated installation costs within station-keeping costs. Other cost components include: labour, project management and engineering design.

Developer Views on Capital Cost

With relatively few technologies deployed at commercial scale, there is considerable uncertainty surrounding estimates of future costs. Generally, these uncertainties are taken into account by most of the developers but there is substantial divergence in terms of the scale of this uncertainty (Figure 5). One respondent consistently estimates that the uncertainty associated with the cost of their technology is relatively low; this could be attributed to some extent to the relatively advanced development stage. At the other end of the range, one respondent suggests much greater uncertainty. This could be a reflection of several factors: their role as a project sponsor and technology investor (greater distance from detail), their wider experience or that the technologies considered are at an earlier development stage. Overall the response suggests that cost uncertainties arising from the development status of a technology should be accounted for in future cost models. It is interesting to note that, particularly in the current economic climate, commodity price and currency exchange fluctuations may represent a similar level of uncertainty to those associated with design or specification!

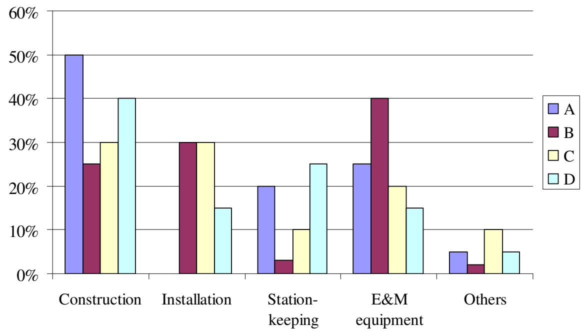

Figure 4: Major contributions to capital cost. (Q4)

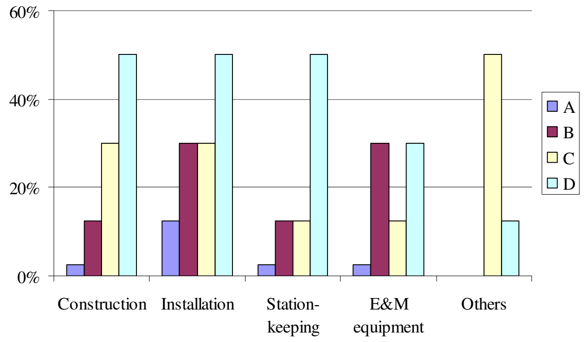

Figure 5: Percentage uncertainty associated with estimates of capital cost. (Q5)

Economies of scale or learning are traditionally quoted as offering cost reductions as greater volumes of devices are installed. Reductions of costs with greater installed capacity are expected by all the developers, with reductions of the order of 5-20% per doubling of the installed capacity (Figure 6). Only one respondent sees the possibility of increase of a cost item (station-keeping costs); the reason for this view is not known.

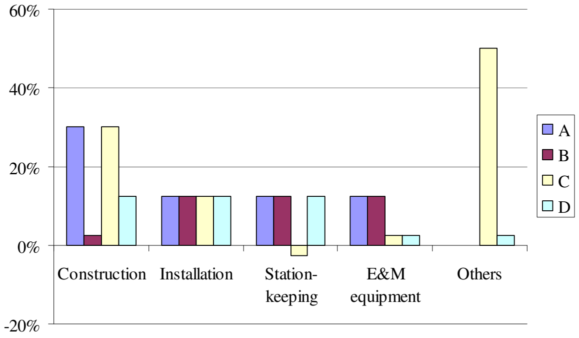

Figure 6: Expected variation of capital costs with scale of manufacture or deployment.

Operating Cost Estimation

The example of wind energy may be beneficial for marine energy in those aspects related to operation and maintenance costs of offshore plants. O&M cost breakdowns for offshore wind are given jointly with a list of possible cost-reduction factors by Garrad-Hassan [11]. Risk-based life-cycle approaches for optimal planning of operation and maintenance, based on Bayesian decision theory [12] and stochastic Monte Carlo methods [13] have also been presented. While generally regarded as a more modest cost factor, operating costs will be an important issue as the marine energy industry develops. Respondents were asked to rank three different factors in order of contribution to expected operating costs (Table 1). Developers see the cost of vessels (either hiring or purchase) and maintenance equipment as the most significant fractions of operating costs. It is interesting to note the relatively high value placed on insurance in contrast to most published studies. The cost of outage periods is related to the availability of the device and, by impacting annual energy production, affects both revenue and cost of energy. Respondents stressed that the scale of the project would have a strong influence on the ranking of the costs (question referred to an installed capacity of 50MW). Other comments included the consideration of licensing costs as an operation and maintenance cost and the inclusion of component refit costs as an independent item (in this case it has been considered as part of the cost of replacement parts).

Uncertainty ranges for operating costs are generally perceived as being very high by developers (Figure 7). Most of the respondents perceived similar ranges for each category. Again, the development stage is obviously influential on the degree of certainty of the cost estimations since the respondent with experience of grid-connection indicates lowest uncertainties. Most respondents anticipated reduction of operating cost with increase of the installed capacity (Figure 8). Cost of personnel, vessels and equipment seem to be the factors that are expected to fall most significantly per doubling of installed capacity.

Table 1: Weighted average rank of operating cost category.

Rank	Operating Cost Category	Score
1	Vessels, transportation & on-site maintenance activities	9
2	Maintenance & monitoring personnel	5
3	Insurance	3.5
4	Costs related to long outage periods due to inaccessibility	3
5	Replacement parts	2.5
6	Organisation and finance	1

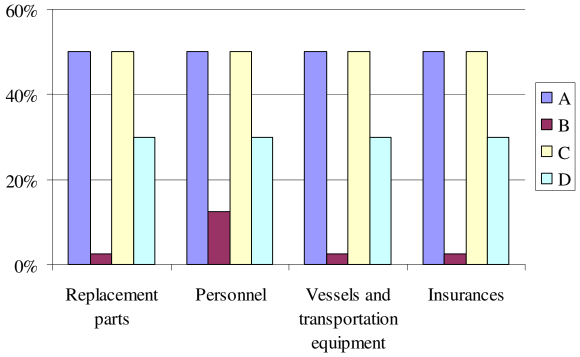

Figure 7: Perceived uncertainty of estimates of operating cost for a marine energy project.

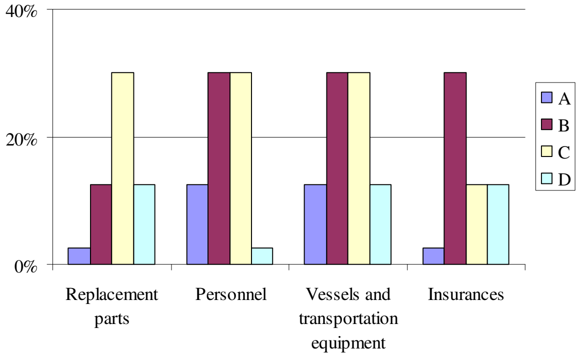

Figure 8: Expectation of cost reduction with increased scale of deployment at a single location (i.e. with doubling of rated power of a farm from 50MW to 100MW installed capacity).

4 Cost Reduction Mechanisms

None of the marine energy devices (wave or tidal stream) presently in development are commercially viable in their present form. To understand how this electricity generating option may contribute to future supplies it is important to predict how costs may change as the industry moves from demonstrator schemes to large-scale deployments. In many studies [2, 14-15, amongst others] it has been assumed that the cost of electricity will fall with the cumulative installed capacity. This approach is based on the assumption that increased experience of designing and using a technology reduces its cost. Details of the approach are given in various texts [17-18] and learning rates of between 10-15% have typically been assumed for marine energy [2, 14]. However, this approach is clearly only an approximation and must be used with caution since learning rates are difficult to transfer between industry sectors [17], are time-varying [18] and are particularly difficult to apply to technologies at an early stage of development [5, 17]. In a study focused on the investment required for marine energy learning [5] it is noted that experience does not lead to cost reductions until the installed capacity of a single technology type is greater than around 100MW (comparison to wind). Even when representative rates are applied it is difficult for learning alone to provide the cost reduction required for commercially competitive levels of CoE (presentations by Vattenfelde and ETI, ICOE 2008). Furthermore, this approach does not allow comparison between types of marine energy technology. This is of considerable importance for both policy-makers concerned with energy scenarios and to investors.

In the following, we briefly discuss the limitations to the main factors that influence the cost of electricity from marine technologies and consider how these limits affect the potential for future cost-reduction. For any electricity generating technology, unit electricity costs can only fall through one of three main mechanisms; increase of revenue or reduction of either capital or operating costs. Note that, as discussed in Section 3, discounted measures of economic viability will also reduce with reduction of the perceived risk but these processes are not considered further here.

Performance Limits

One method for comparing early stage concepts to more established concepts (e.g. lab-scale to offshore demonstrator scale) is to consider the limitations to economic viability based on theoretical models of idealized device performance. Although these idealized models will not be a true representation of present device performance they represent an upper bound to the output that cannot be exceeded even by continued development without change of device concept. This can be interpreted as a maximum power density and can be used as an indication of whether further development is worthwhile. Power density limits are well-known for certain device configurations. For example; the power output from individual devices that comprise a single wave activated body constrained by a power-take-off system is a function of the incident wave conditions (following point-absorber theory), float volume and allowable response amplitude [20]. If a (single) device can be designed to produce maximum output as defined by point absorber theory in all sea-states, the average annual output per device remains small (less than 1 MW at sites with annual power density greater than 35 kW/m, see Table 3 of [21]). More accurate predictions of maximum output can of course be made accounting for constraints on a particular device concept but this is a general limit for single devices. Knowledge of the maximum power density provides a basis for an investor to determine the potential improvement of economic viability that a particular technology type could achieve.

In addition to the power output of individual devices, and number of devices within a particular project, the possible extent of cost reduction is influenced by the number of devices that can be deployed; i.e. of the market size for a particular technology. Differentiation has been made between deployment location on the basis of water depth [14, 16], particular combinations of site- and technology [2, 15] and industry-wide estimates have been employed [22, 23] but there seems to have been limited consideration of how estimates of maximum market size for a particular technology may influence cost reduction. For example; deployment sites available for wave technologies that operate in nearshore waters of the UK are limited to 3 GW (capacity factor of 0.3 to produce 7.8 TWh/yr practical resource [14]) and this effectively limits the cumulative installed capacity over which learning may occur.

Capital Cost Reduction

As summarized in Section 2, the total capital cost of a marine energy project includes several main areas. The engineering components for which manufacture and installation costs are required are: mechanical & electrical equipment (i.e. conversion device), station-keeping infrastructure and transmission infrastructure. Site infrastructure consists of the civil engineering structures required to maintain the wave energy devices in their operating location and electrical connections required to transfer generated electricity from individual devices to the point of transmission. The civil works required will typically consist of mooring lines and anchors whilst the electrical connections will consist of cables and electrical conditioning equipment. For commercial scale marine energy power generation schemes, the capital cost of grid connection must be considered (see [24]). These costs are principally dependent on the rated capacity of the connection and so will be similar irrespective of the marine devices deployed at a particular site and can therefore be neglected when comparing different generating technologies.

The cost of both station-keeping and inter-array electrical equipment will depend on the number of devices to be installed, their configuration within an array and the inter-device spacing. Station-keeping systems vary with device type but typically either comprise a mooring for floating devices or support structure for bed-mounted devices. Although some cost studies have been completed for individual mooring systems, there is limited understanding of how the configuration or installation cost of mooring systems and support structures would vary with installed capacity at a particular site. Typically, a percentage reduction of unit cost has been assumed to represent bulk orders [2-3, 7] but these are not clearly justified and additional costs for construction of mass-fabrication facilities should also be considered [25]. One limitation to any station-keeping arrangement is the installation cost which is closely linked to site accessibility.

Operating Cost Reduction

A parametric estimate of the operating cost for a wave energy scheme would be based on the number and duration of maintenance tasks and would account for the availability of wave conditions and time required to access the site from a suitable port.

At present, very little is known about the reliability of alternative marine energy technologies due to the lack of offshore experience. It is perhaps reasonable to assume that more complicated devices will require more regular maintenance. As an indication of the target reliability of commercial wave energy schemes, it is instructive to draw comparison with commercial offshore wind farms. A baseline design for an offshore wind turbine requires between 1.5 and 2.0 maintenance visits during a typical year and a reliable design may only require a single maintenance task per year [13,26]. As for offshore windfarms [26], many of the maintenance costs for wave devices will be fixed per device and so increasing device output is advantageous for reducing cost. This is assumed by many of the workshop participants and by device developers (Figure 5.5). As noted above, the rated capacity per generating unit is subject to relatively low physical limits (order of 2 MW) and so the potential for reducing operating cost by increasing the rated capacity and output of individual devices is limited.

Whilst estimates of device reliability, task duration and travel duration have been included in several wave energy studies [2, 14], the influence of site accessibility has not been widely considered. For offshore wind, turbine accessibility has been a significant source of operating cost uncertainty (typically access requires significant wave-heights of 2 m or less, [26]), this has increased the perceived investment risk and this is likely to be even more important for wave energy sites (e.g. Figure 7). Furthermore, accessible conditions must persist for a sufficient duration to access the site and complete the relevant tasks. This information is site-specific rather than device-specific and can be estimated either from time-histories of significant wave height or from occurrence matrices. For access to tidal stream sites, the joint occurrence of accessible wave conditions and suitable flow velocities must be considered resulting in only very short intervals for access.

These site-access limitations have important implications for both installation strategies and maintenance strategies. For example; consider an array of 200 devices deployed near South Uist. At this location, accessible conditions persist for 24 hour intervals for an average of 16 times per month during the summer months (May-Sep) but only 5 times per month during the winter (time-series analysis of hindcast data over 5 years). Installation or maintenance activities must be completed within these times and this would require two vessels operating continuously during the summer months if a typical task requires 24 hr access (similar to offshore wind, [20]). Irrespective of maintenance task duration, maintenance time must fall within the range of accessible conditions and this provides a basis for considering maintenance cost for large scale deployments. At a site with lower average wave power density (kW/m), accessible conditions will be more persistent but at the expense of a lower average output from individual generators. (If power output is assumed to be optimal for a point absorber then four times as many devices would be required in Southern North Sea than at South Uist to generate the same mean output and more vessels would be required despite easier access). Both installation and maintenance strategies are therefore likely to change significantly with scale of deployment, particularly for large deployments of similar capacity to offshore wind (order 100MW+).

5 Concluding Remarks

This paper presents a brief overview of motivations and methods for conducting an economic assessment of marine energy systems. Information presented is drawn from the literature, a stakeholder workshop and a small survey of device developers. Sample sizes are relatively small and so the quantities presented are somewhat indicative but provide insight into the widely differing perspectives of different end-users and of different developers. The purpose of this review was to identify the information that is considered and is perceived to be important for assessing the economic viability of marine energy technologies. Two distinct types of economic assessment can be identified for: a) the evaluation of a particular project (e.g. to identify a preferred combination of technology and site for commercial electricity generation) and b) for evaluation of how the economic viability of a technology may alter with increased development. Such an approach may be employed by an investor to understand whether an early stage technology could be competitive with more established generating options or by policy-makers using strategic planning models. For project assessment, several quantitative measures are briefly discussed and it is explained how environmental and design uncertainties can be linked to financial risk. For technology assessment, methods for estimating cost changes are outlined and the implications of the limitation to device power capture, resource extent and site accessibility are explained. Several of the uncertainties identified are the subject of ongoing activities within the EQUIMAR project.

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References

[1] Entec UK Ltd. commissioned by Carbon Trust. *Cost estimation methodology: the Marine Energy Challenge approach to estimating the cost of energy produced by marine energy systems*. 2006.

[2] Previsic M., Siddiqui O., Bedard R. *Economic Assessment Methodology for Wave Power Plants*. 2004. Available at: http://oceanenergy.epri.com

[3] Boud, R. and Thorpe, T. (2003) *WAVENET: Results from the work of the European Thematic Network on Wave Energy*.

[4] Awerbuch, S. (2003) Determining the real cost: Why renewable power is more cost-competitive than previously believed. *Renewable Energy World* 6(2)52-61

[5] Jeffrey, H. Learning rates in the marine energy sector. *Proc. 2nd International Conference on Ocean Energy,* Brest, Brittany, October 2008.

[6] Gross, R., Heptonstall, P. and Blyth, W., *Investment in electricity generation: the role of costs, incentives and risks*, UK Energy Research Centre, London, May 2007.

[7] IEA (2005) *Projected cost of generating electricity*, International Energy Agency

[8] NORSOK standard Z-014 SCCS, 2002.

[9] Cocodia E., *International Codes and Standards Applicable Cost Estimating Relationships for Floating Production Systems,* Proc of 27th Int. Conf. on OMAE, Estoril, Portugal, 2008

[10] Cocodia E., *Risk Based Fuzzy Modeling of Cost Estimating Relationships for Floating Structures,* Proc of 27th Int. Conf. on OMAE, Estoril, Portugal, 2008

[11] Garrad Hassan *Offshore Wind: Economies of scale, engineering resource and load factors*, 2003, DTI and Carbon Trust Report 3914/BR/01

[12] Sorensen J.D., *Optimal, risk-based operation and maintenance planning for offshore wind turbines*, Proceedings of the European Offshore Wind 2007 Conference, Berlin, December 2007.

[20] van Bussel, G.J.W. (1999) The Development of an Expert System for the determination of Availability and O&M costs for Offshore Wind Farms. In *Proc.European Wind Energy Conference (EWEC),* Nice, France, 1999, pp402-405

[14] Carbon Trust, The. *Future marine energy. Findings of the marine energy challenge: Cost competitiveness and growth of wave and tidal stream energy*. 2006. Available at: www.thecarbontrust.co.uk

[15] Bedard R.., Siddiqui O., Previsic M. and Polagye B. *Economic Assessment Methodology for Tidal In-Stream Power Plants.* 2006.

[16] Black & Veatch (2001) *The commercial prospects for tidal stream power.* ETSU T/06/00209/REP. DTI Sustainable Energy Programme DTI/Pub URN 01/1011.

[17] IEA (2006) *Offshore wind experiences.* International Energy Agency.

[18] Junginger (2004) *Learning in Renewable Energy Technology Development.* PhD Thesis, University of Utrecht.

[19] Chapman J and Gross R. *Technical and economic potential of renewable energy generating technologies: potentials and cost reductions to 2020*. Performance and Innovation Unit report, The Strategy Office. Crown Copyright; 2001.

[20] Falnes, J. A review of wave-energy extraction. *Marine Structures* 20 (2007) 185-201.

[21] Stallard, T.J. Rothschild, R. and Aggidis, G.A. A comparative approach to the economic modelling of a large-scale wave power scheme. *European Journal of Operational Research* 185(2) 2008. 884-898.

[22] DTI (2007) *Impact of banding the Renewables Obligation – Costs of Electricity Production.* URN 07/948. Ernst & Young LLP.

[23] RAEng (2004) *The cost of generating electricity.* PB Power report for Royal Academy of Engineering.

[24] de Alegria, I. M., Martin, J.L., Kortabarria, I., Andreu, J. and Ibañez E., P. (2009) Transmission alternatives for offshore electrical power. *Renewable and sustainable energy reviews*. 13(5) 1027-1038

[25] Atkins Oil & Gas (1992) *A parametric costing model for wave energy technology* ETSU-WV1685

[26] AMEC Wind (2001) *Monitoring and Evaluation of Blyth Offshore Wind Farm. Projected Operation and Maintenance Costs of UK Offshore Wind Farms Based on The Experience at Blyth*. DTI Report W/35/00563/Rep/5 URN 04/881