COMMISSION OF THE
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COOPERATION

Equitable Testing and Evaluation of Marine Energy Extraction Devices in terms of Performance, Cost and Environmental Impact

Grant agreement number: 213380

EquiMar

Deliverable D7.1
Summary of Attributes of Cost Models used by different Stakeholders

DRAFT

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Summary of Attributes of Cost Models used by different Stakeholders

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Summary

This report presents a short summary of current existing methodologies for economic assessment and cost estimation applicable to marine energy technologies.

Through the analysis of a fundamental references in the field, general cost models are briefly summarised and explained with reference also to risk and uncertainties estimation. An insight of the different cost factors possibly to be accounted for during the assessment of marine energy technologies is also given.

Finally, the results of a request for information to the developers involved in the project are proposed and summarised, underlining the importance of the estimation of the cost of the energy produced for marine energy technology assessment and showing the relatively widespread use of the Net Present Value approach for economic evaluation. Uncertainty ranges for different cost items estimated by the respondents show relative sensitiveness to the development stage of the technology. Increase of installed power of future marine energy projects is seen as a possible way of reducing capital and operating costs although in a different magnitude depending on the items involved.

CONTENTS

1 INTRODUCTION

1.1 THE ASSESSMENT OF MARINE RENEWABLE ENERGIES

Electricity generation from marine energy conversion has made constant progresses in the recent years but has not yet come to the stage of a fully mature industrial sector. Although notable research effort has been put in this area and more and more private and public organisations are contributing to its development, only a few technologies have actually proven electricity production and even less have been operating while connected to the grid.

It is clear that, from such a limited experience, a comprehensive and reliable economic assessment of marine renewables is very difficult to be addressed. However, considering the increasing development of marine renewables and the growing interest of investors and policy makers, tools and methods for estimation of the economic performance should be defined also for allowing comparisons between the technologies and identifying key factors for cost reduction and improvement.

Design of such methodologies would require a harmonised approach between research institutions, developers, utilities and investors. Previous studies (see chapter 2) have already attempted to involve as much stakeholders as possible but there is still a relevant lack of information on the economic models utilised by different users.

The EquiMar project will take into account the definition of appropriate procedures for the economic assessment of marine energy technologies.

1.2 THE EQUIMAR PROJECT

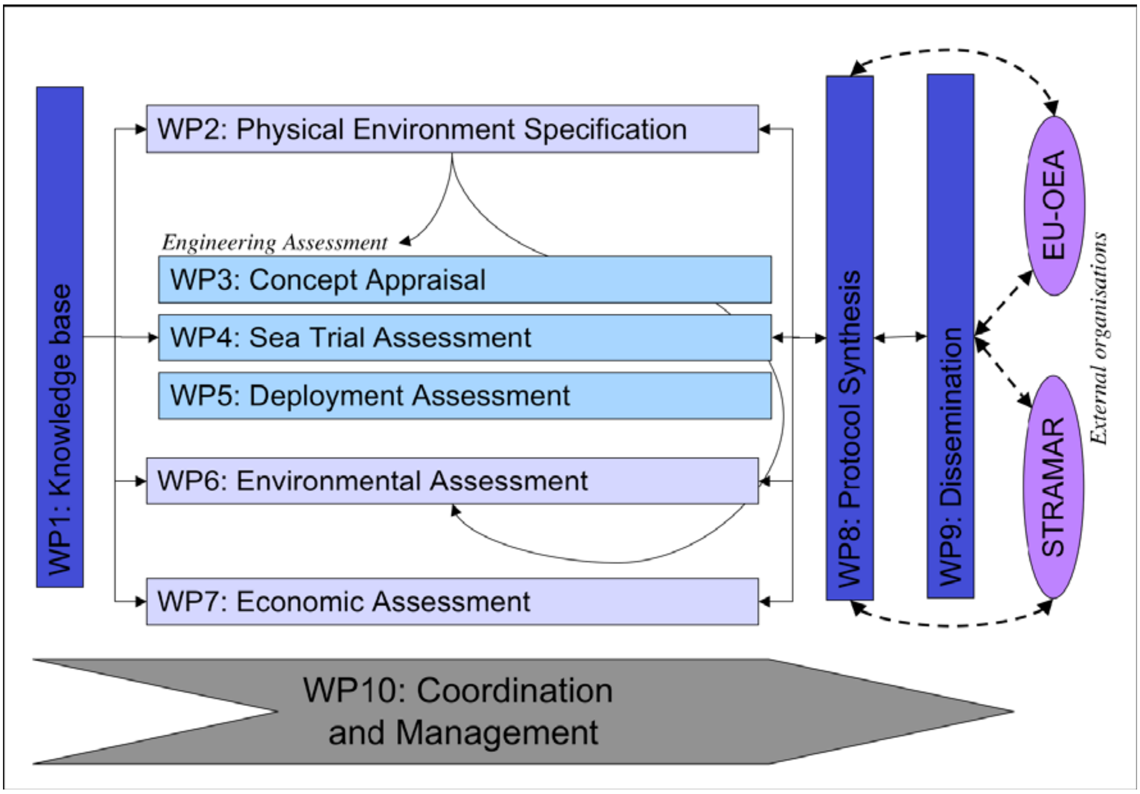

Figure 1.1 EquiMar project work package structure.

1.2.1 Structure of the project

The EquiMar project is funded by the European Commission as part of its 7th Framework programme under the Energy topic. It is a collaborative research and development project involving a consortium of 23 partners and will run for three years from the 15th of April 2008. A list of the partners involved is given below:

1. **The University of Edinburgh (UEDIN)**, United Kingdom
2. **Fundación Robotiker (TECNALIA-RBTK)**, Spain
3. **University of Strathclyde (UOS)**, United Kingdom
4. **Electricité de France SA (EDF SA)**, France

5. **EU Ocean Energy Association (EUOEA)**, Belgium
6. **University of Exeter (UNEXE),** United Kingdom
7. **University College Cork (UCC)**, Ireland
8. **Wave Energy Centre (WAVEC),** Portugal
9. **The University of Manchester (UniMAN),** United Kingdom
10. **Southampton University (SOTON),** United Kingdom
11. **Institut Français de recherche pour l'exploitation de la mer (IFREMER),** France
12. **Consiglio nazionale delle ricerche: Istituto di Scienze Marine (CNR-ISMAR),** Italy
13. **Det Norske Veritas (DNV),** Norway
14. **Teamwork Technology (TT),** The Netherlands
15. **Pelamis Wave Power Ltd (PWP),** United Kingdom
16. **European Marine Energy Centre (EMEC),** United Kingdom
17. **Wave Dragon (WD),** Denmark
18. **Uppsala University (UU),** Sweden
19. **Sea Mammal Research Unit (USTAN),** United Kingdom
20. **Scottish Association of Marine Sciences (SAMS),** United Kingdom
21. **Feisty Productions Ltd (FPL),** United Kingdom
22. **Aalborg University (AAU),** Denmark
23. **Actimar (ACTIMAR),** France

The aim of EquiMar is to deliver a suite of protocols for the equitable evaluation of marine energy converters (based on wave or tidal energy). These protocols will harmonise testing and evaluation procedures across the wide variety of devices presently available with the aim of accelerating adoption through technology matching and improved understanding of the environmental and economic impacts associated with the deployment of arrays of devices. EquiMar will assess devices through a suite of protocols covering site selection, device engineering design, the scaling up of designs, the deployment of arrays of devices, the environmental impact, in terms of both biological & coastal processes, and economic issues. The protocols will be developed through a robust, auditable process and disseminated to the wider community. Results from the EquiMar project will establish a sound base for future marine energy standards.

The activity within the project is structured through the definition of ten different Work Packages (including the project management), each one covering a specific part of the project with specific objectives. Six of them (WP2, WP3, WP4, WP5, WP6 and WP7) are mainly focused on technical issues, WP1 is intended to build a knowledge base for marine energy systems, WP8 will deal with the synthesis of the protocols and the organization of the documentation while WP9 will focus on dissemination of the project activity through the wider community. Finally WP10 will include all the coordination and management issues.

A scheme of the structure of the project is given in figure 1.1.

1.2.2 Work Package 7 - Deployment assessment: Performance of multi-megawatt device array

This work package will develop methods for 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. 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 the protocols of WP8.

The work is divided into different tasks:

1. Evaluation of existing cost methodologies
2. Cost of electricity procedure
3. Variation of infrastructure costs with deployment scale
4. Influence of site accessibility on technology scale
5. Scope for cost reduction through performance optimisation
6. Procedure for technology comparison

This report is the result of part of the work carried out within task 1.

2 COST MODELS

2.1 BACKGROUND STUDIES

Marine energy conversion is a relatively recent technology field as it evolved from a purely research subject to practical applications only in the last two decades. For this reason the amount of information on economic assessment methods and procedures is not exhaustive and particularly limited if compared to other renewables. Previous economic studies on the viability of marine energy technology have indeed been carried out, often based on standard economic methodologies, but they usually lacked, apart from usable historical data, a uniform and consistent approach and an appropriate account for uncertainties related to device and site type.

Estimation of cost factor weights led in some cases to different results, perhaps due to a different number and type of devices considered and account for operation and maintenance costs appeared to be extremely difficult considering the scarce experience of full-scale tested technologies.

A key aspect of the costs estimation performed by previous researchers has been also the account for financial and technical risks. A typical procedure used by many is the application of a specified discount rate to each cash flow but the choice of the appropriate value and its range of variation could seem arbitrary. Discussion on how consider this factor is still ongoing and it should be reminded that the difference between the various technologies complicates the adoption of recognised values for comparative assessment.

Some previous studies have also applied learning rates or equivalent coefficient for account of economies of scale to future cost estimation in order to provide a wider scenario for marine energy development. Outcomes given by these procedures generally agree in showing future competitiveness of marine energy technology on the market assuming a relevant value of cumulative installed capacity will be reached. The learning rates applied are usually similar to the ones recorded by similar industries (such as wind energy). However, slight differences might change dramatically the level of competitiveness assessed making estimation for return from future large scale deployments particularly vague.

A general summary of existing literature on this subject can be found in the chapter 6 of the Deliverable D1.1 ([1]) of the EquiMar project.

2.1.1 WaveNet Report

The WaveNet was set up as a European Commission Thematic Network to share understanding and information on the development of ocean energy systems. A global report was issued in 2003 as a result of this project ([2]).

Chapter D of this document addresses financing and economics of wave energy projects. The report does not take into account tidal technologies but since most of the technical issues involved in cost estimation are common to both wave and tidal, the methodology outlined should be applicable to any kind of ocean energy device.

This section proposes an approach for economic evaluation of marine energy technology based on the estimation of the cost of electricity generated. This is found through application of a Net Present Value Approach (see section 2.2) with a discount rate equivalent to the 10%. This number, corresponding to a minimum Required Rate of Return (RRR) on a wave power project, took into account risk factors related to market assets through application of the Capital Assets Pricing Model (CAPM) plus a specific proportion of leverage derived by typical values for similar industrial sectors.

Procedures to accounting for risk are explained in details but only a single discount rate is finally applied to all the cash flows. Indicative capital cost breakdowns, obtained through parametric methods, are shown for several types of devices. Some of the operation and maintenance costs are assumed to be equal to a percentage of the capital costs (e.g. repair costs and spares) while parametric models are used to estimate repair time and frequency of failures.

2.1.2 The Marine Energy Challenge

The Marine Energy Challenge (MEC) was an 18-month programme of directed engineering support to accelerate the development of marine renewable energy technologies that was completed in summer 2005. The study was principally aimed at assessing the present and future costs of wave and tidal electricity generation and determining the possibility of an effective cost-competitive development. Different engineering consultants were asked to evaluate the feasibility of different wave and tidal energy technologies.

Results from this evaluation process were published in a report ([3]) in 2006, where current and future cost of energy generation is estimated through the NPV (Net Present Value) approach. Lower and upper bounds were considered for different cost factors thus current costs of energy were found to be within a relatively wide range of values. Estimation of future evolutions was based on the application of learning curves where different values were used for different possible scenarios. A gradual reduction of the discount rate was also considered for these long-term estimations to account for the different risk level associated respectively with early-stage and matures technologies.

The costing methodology applied was described in another report ([4]) where the principal key cost factors are listed and explained in details and main drivers are briefly stated. Additional information can be found in a document prepared by Black and Veatch ([5]), where the different cost components of the global capital cost of a marine energy devices are analysed and possible mechanisms of reduction are identified and listed.

2.1.3 The analysis of the Electric Power Research Institute (EPRI)

A global economic assessment procedure has been also defined by the Electric Power Research Institute (EPRI) and summarised in two distinct reports concerning respectively wave ([6] in 2004) and tidal ([7] in 2006) energy technologies The EPRI studies focused on the North American (United States) market and legislation and took into account specific taxation and incentives corresponding to federal and state regulations. Different methodologies were proposed for utility generators (UG) and non-utility generators (NUG).
Key differences are in the obligations set by the Grid Operator since this determines its position on the market and arise in the financing assumptions (i.e. capital structure and taxes) leaving practically all the other factors unchanged.

Cost methodology is based on cash flow analysis with fixed discount rate and evaluation is based on different indicators such as Net Present Value, Internal Rate of Return and Discounted Payback Period.

2.1.4 Comparisons with other electricity generating technologies

The models applied to estimate the cost of generating electricity with marine renewables are very important to attract investments and induce policy makers to support its development through appropriate actions.

In order to represent a reasonable alternative to conventional technologies, marine energy has to prove its economic competitiveness against them and to this aim the cost models defined for ocean energy should be consistent with the same ones historically used for fossil-fuel and other renewables.

Several reports on energy generating costs have been issued in the latest years and some of them are beginning to evaluate wave and tidal energy conversion with the same tools applied to conventional technologies. The methodology used is basically the same for almost all the documents analysed. Future costs are discounted through the use of a properly defined discount rate and integrated in the calculation of the net present value of the total cost. Dividing the total cost by the foreseen energy output an estimation of the cost of energy is obtained.

The main differences between the methodologies are often due to the kind of detail entailed in the calculation of different cost factors (some items may be listed in different categories depending on the approach) and discount rates (different financial assumptions on the structure of the company might severely affect this parameter). Confidence of the results is strongly dependent on the amount of available historical data.

The International Energy Agency publishes periodically reports on projected costs of generating electricity ([8]). In a document of 2005, different generating technologies are compared utilising data collected from several countries. Estimations on cost of energy and other cost factors associated with a specific conversion are given for each country for two different discount rates (5% and 10%).

Most of the methods do not take into account the dynamic variation of the power output that is typically associated with renewable energy and could create problems in an energy market regulated by the instantaneous power demand. A report issued by the Royal Academy of Engineering in 2004 ([9]) tried to account for the intermittency due to fluctuations of wind energy supply by considering additional costs of standby generation (i.e. cost of operating conventional power plants to generate surplus capacity to cover wind energy falls).

A detailed report from UKERC in 2007 ([10]) includes a discussion of the present methods with an extensive explanation of the risk factors involved in these calculations and gives a general overview also on the limit of the methodologies currently being applied. It is suggested that a deeper treatment of risk should be carried out when performing cost analysis of electricity generating technologies since, for example, current approaches do not take into account revenue risks associated with electricity price fluctuations and volatility.

Comparison with previous experiences in wind energy (especially offshore plants) might be largely beneficial to improving current cost models for marine renewables. Indications on operational costs breakdown and key factors could be particularly useful as well as the applicability of techniques for account of uncertainties (see [11], [12] and [13])

2.2 Economic Appraisal: Estimation of the Cost Of Energy (COE)

Almost all of the procedures briefly outlined within the previous section consider as principal measure of the economic viability of a project the cost at which energy generated by this project could be offered (with appropriate account for return).

The meaning of this economic indicator is indeed particularly clear to understand to a broad audience and represents an efficient parameter for communication with investors and policy makers. Moreover, results from a recent enquiry showed that a majority of the stakeholders considers the predicted present value per unit of generated electricity (€/kWh) among the best parameter for comparison of different technologies.

In this section the common approach to estimate this value will be briefly presented. It has to be noticed that the cost of energy by itself should not be the only determinant for an investment choice as capital expenditures and future revenues might be also decisive in deployment decisions. This is particularly true if one observes that operational future costs are extremely difficult to estimate for marine energy.

2.2.1 The Net Present Value Approach (NPV)

Industrial and financial projects are usually evaluated through a cash-flow basis. The cash flow is the balance of the amounts of cash being received and paid by a business during a defined period of time.

The Net Present Value is defined as the total present value (PV) of a time series of cash flows. It is a standard method for using the time value of money to appraise long-term projects and is widely used for assessment of differentiate investment opportunities. Interpretation of its meaning might be different depending on the parameters accounted for and the type of end-user or investor but the calculation procedures is roughly the same.

Also the NPV might not be the final result of an economic assessment but an intermediate result to derive other more interesting indicators (e.g. the cost of the energy generated). The same approach could be used as well for calculation of different economic quantities (for example the rate of return or the payback period).

Ignoring uncertainty, and assuming that money for the investment can be borrowed at a risk-free rate r, a single up-front capital investment cost I and annual cash inflows c_i in a period of n years, the NPV can be calculated as:

$$NPV = \sum_{i=1}^{n} \frac{c_i}{(1+r)^i} - I$$

In reality many elements of the project finances will be uncertain. In principle each uncertain element of the cash inflow c_i should be replaced with a certainty-equivalent amount s. The value of s in year i is chosen such that it has the same present value as the uncertain cash inflow when they are discounted at the appropriate (risk-adjusted) rate:

$$PV = \frac{s_i}{(1+r)^i} = \frac{E(c_i)}{(1+k)^i}$$

Where $E(c_i)$ is the expected (mean) value if the uncertain cash inflow c_i, and k is the opportunity cost of capital (or risk-adjusted discount rate) for projects of that class of risk. Then the NPV under uncertainty can be written as:

$$NPV = \sum_{i=1}^{n} \frac{s_i}{(1+r)^i} - I$$

This certainty-equivalent approach disaggregates the effects of time value of money under certainty from the effect of risk. Equivalently, one may define a risk premium as the expected value of the cash flow in a given year minus the certainty equivalent cash inflow. The risk premium should reflect the overall market risk premium for that class of project. Under a very general approach, the cash inflows in each period may be subject to a different level of risk, requiring a different risk premium to be used for each period. A more detailed account for uncertainties would require different elements of a single annual cash flow to be discounted using different risk premiums (see [10] and [14]). Usual practice, however, consists in the simplifying assumption to represent both risks and time value of the money by a single risk-adjusted discount rate k:

$$NPV = \sum_{i=1}^{n} \frac{E(c_i)}{(1+k)^i} - I$$

Use of an internal rate of return (IRR) avoids the need for a detailed assessment of the value of k by choosing its values such that the NPV becomes equal to zero. The IRR measures the effective cost of capital that the project could be charged, and still be expected to break-even.

If the discount rate is assumed constant, an alternative evaluation criterion consists in finding a solution for the number of years *n* that would make the NPV equal to zero. This solution represents the Discounted Payback Period (DPP) and might be an important parameter for marine energy technologies investors.

In principle any kind of cash flow could be included in a NPV estimation but, since the main objective is typically the comparison of a range of investments that could possibly be made by a firm, account is generally made for material and financial costs and not for internal costs related to the operation of the firm itself (e.g. personnel, management etc.). This could be justified considering that the same costs would be afforded by the company no matter what investment decision would be taken.

Anyway, for the sake of comparison between different marine energy technologies, some developers pointed out that these factors should be taken into account at some level of the cost model calculation. One might suppose to allocate to each cost factor calculation the exact amount of management, engineering and labour costs sustained during the specific task related to that (e.g. the salary of a structural engineer could be part of the structural cost of the device) but this could be very complicated to estimate on a parameterised basis valuable for all the technologies.

2.2.2 The estimation of the cost of energy through the NPV

Cost of generating electricity can be calculated straightforward from the equations above once that all the cost elements related to the installation and operation of a power plant are known.

Typically investors are used to distinguish between capital costs and operation and maintenance costs. The former ones are generally related to the production, installation and all the possible additional elements necessary for the start-up of the plant. Since they are generally sustained before the start of the life cycle of the project, they are computed as a fixed quantity not dependent on any discount ratio or timely factor. Operation and maintenance costs account for all the costs required by the plant to efficiently operate over its expected life, including monitoring, insurances, licenses and, clearly for the case of thermoelectric generation, also fuel.

A third factor, which could be ascribed to capital costs as well, is represented by decommissioning costs. For marine energy technologies operating at large distances from the coast these costs might be relevant. However, traditional approaches considered also that these costs could be partly balanced by additional revenues derived by re-use or sale of the remaining equipments and materials.

The Cost Of Energy (COE), for example expressed in € per kWh, could be determined ([4]) from the division between the global NPV of the projects over its whole service life and the NPV of the expected energy production along this time:

$$COE = \frac{NPV}{EP} = \frac{PV(\text{capital cost}) + PV(\text{O \& M costs}) + PV(\text{Decommissioning costs})}{PV(\text{energy production})}$$

Other references ([3] and [6]) use an annual basis for this estimation through amortisation of the capital cost over each year:

$$Ann = \frac{\text{capital cost} \cdot r}{(1-(1+k)^{-n})}$$

In such a way, if O&M costs can be considered recurrent every year and, the simple estimation of the annual output can be given by the equation:

$$COE = \frac{Ann + \text{O \& M costs}}{AEP}$$

Assuming constant O&M costs and constant annual productions, it can be shown that the two procedures give the same result. Calculating the cost of the energy with the former, however, might be preferable when, for example, maintenance interventions are required only at few times along the duration of the project and are not easily accountable since the second calculation would require an allocation of the cost along the whole time span.

Wave and tidal energy technologies, being generally capital-intensive conversion devices, will indeed aim at achieving high reliability and limited requirement for maintenance operations, possibly intensifying redundancy and monitoring. Capital cost per MW unit could be therefore another important indicator for comparison between different concepts.

3 MAIN COST FACTORS

Once the methodologies outlined above have been assumed, the calculation of the cost of energy of a particular device is not particularly complicated from the mathematical point of view and the main difficulties consist in the estimation of each cost component and the proper account for uncertainties related to these assumptions.

As mentioned before, analysts tend to distinguish between capital costs and operation and maintenance costs. Within these two large categories, several different cost centres can be subsequently recognised but there exist differences in literatures between the type of factors included and the specific weight they have on the global cost.

Indeed, due to the large range of different competing concepts in marine energy, it is rather difficult to define a generally applicable composition of the costs and most of the previous studies have focused on the identification of a reduced number of types of device for which more precise data on cost breakdown could be deduced.

The determination of the relevant O&M cost factors appears to be particularly hard and prone to large uncertainties since operational experience is very limited and knowledge coming from offshore oil and gas extraction and wind energy is not easily transferable. Even the definition of maintenance schedules is rather complicated because several components installed on marine energy devices are often commercial products designed to operate in very different conditions or are completely newly designed technologies and lack of historical failures data.

Another key aspect in defining the cost of energy of a generating technology is the accurate estimation of its revenue, i.e. in this case the electrical power output. The reliability of the annual energy production calculations depend on the degree of development of the technology and on the accuracy of the site resource assessment. Thus it is clear that a calculation of the cost of the energy, to be really indicative in terms of numbers (and not only used for comparison purposes), should be site-specific or at least related to a well-defined wave or tidal resource.

3.1 CAPITAL COSTS

Capital costs of marine renewables are usually broken down into two major components:

- Production cost (associated with the construction of the single unit itself)
- Put-into-operation cost (associated with deployment and all the operation required for the plant to produce)

These two main drivers are common to almost all of the technologies currently being developed, although their relative magnitude is dependent on the type of device considered. Some misunderstanding might arise for fixed onshore devices where construction and installation operations are basically the same (i.e. the device is produced and assembled directly in situ).

Cited reports ([2] and [4]) subdivide further on these two components. Under a rather general approach capital cost could be separated in four main drivers:

- Structural costs
- Installation costs
- Station-keeping costs
- Mechanical and electrical equipment costs

A brief introduction to each one of these components is given but it is clear that this subdivision is questionable and one might find useful to include separate items related to the connection to the grid while another could consider installation and station-keeping as part of the same item (indeed fixed tidal devices will be built and installed on site).

3.1.1 Structure costs

The cost of the structure is often cited as one of the largest cost factor for a marine energy device. The structure of a marine energy device has the dual aim of withstanding wave and tidal loads and securing the integrity of the equipment.

Preliminary estimates for this cost component can be given by the product of the mass of the material required times the cost per unit volume of the material utilised. For relatively simple geometries this approach might work (especially if applied to an optimisation procedure or for comparison of similar geometries with different parameters) but complexity in the design could complicate the estimation considerably.

An accurate estimate should account also for the cost related to manufacturing every element but it is clear that such calculation would be largely influenced by the number of units considered.

From a technical point of view, structural costs are perhaps among the easiest factors to be parameterised since they mainly depend on the device design and specific models could be built for different device types.

3.1.2 Installation costs

Installation costs present as well relevant device-specific characteristics. Moreover they might also suffer influence from the chosen deployment site (not only distance to shore but also seabed conditions could complicate installation operations).

However, some similarities might be found in cost estimation for particular typologies of devices. For example, most of the offshore floating wave energy converters currently being developed could be towed to the deployment site through the use of vessels generally operating for offshore oil and gas industry.

Costs associated with these vessels, however, might be changing depending on demand. The Marine Energy Challenge ([3]) used long-term average rates for estimation of these costs and additionally considered the possibility in the future to obtain lowest rates for long-term operations (large scale farms will require several units to be installed and therefore a large number or vessels or a long hiring period).

Installation costs could include also grid connection infrastructure installation and laying of the electrical cables, especially for large scale projects. However, transmission costs are not considered in detail within this Work Package because they are expected to be similar irrespective of the generating technology deployed at the offshore site.

3.1.3 Station-keeping costs

Station-keeping costs include all the components required to hold the device in place. Depending on the design, the structure of the device might effectively work itself as station-keeping element. Horizontal axis tidal turbines are typically installed on a monopole that represents also the main structure of the device.

For offshore floating converters, mooring are usually separate systems that allow the device to move independently within a limited range and are required to prevent its drifting. Design of foundations and moorings has been common practice for decades in offshore oil and gas extraction and therefore many standards on mooring design criteria are available and cost accounting procedures of mooring systems have been defined. However, the difference of the scale of the projects implies choices that would not be cost-effective at all if applied to marine renewables. Moreover typical safety coefficients defined for the offshore industry are generally quite conservative.

Mooring system for wave energy devices should also be designed not only to withstand extreme loads but also to interfere as less as possible with the nominal working operation of the device. Since there is still scarce experience on this subject, estimation of costs related to this factor is rather difficult and cost reduction mechanisms could appear in the future as large scale arrays might allow application of more efficient purposely designed configurations.

3.1.4 Mechanical and electrical equipment cost

Mechanical and electrical equipment costs include all the items that convert energy from a prime mover (water flow, air pressure, the device itself etc.) to electrical energy.

In a general tidal design this would include the blades of a tidal turbine, the gearbox, the electrical generator and the power converter while for a wave energy device we could consider hydraulic components, linear generators etc.

Mechanical and electrical costs are strongly device specific and generally sized according to the peak power output of the device. Generally speaking, marine energy converters are designed to operate at an optimum power level that does not correspond to the maximum power possibly encountered. This is because uneconomic oversize would result otherwise since highest power levels are rare to occur.

The choice of the adequate rated power for conversion mechanism should follow economic and engineering optimisations. A wide range of different conversion principles have been applied to marine energy technologies but most of the more advanced concepts make use of the same types of systems. Tidal conversion is usually performed through a turbine connected to a gearbox and subsequently to a generator. Wave energy conversion, depending on the type of device, is usually performed through hydraulic systems, linear generators, air turbines (in case of Oscillating Water Columns) or hydraulic turbines (mostly used on overtopping devices).

Some of these conversion mechanisms are indeed composed by standard commercial components in such a way that a preliminary costing estimate is possible (for example it is relatively easy to obtain pricing for hydraulic equipment like accumulators, motors and valves) but in most cases purposely designed solutions make difficult the definition of a uniform cost model.

Mechanical and electrical equipment include, within the present frame, also all the necessary items for monitoring, control and communication of the plant as well as additional electronic devices for grid-connected generation (power converter).

3.1.5 Other cost items

Some references define also additional cost items that might fall into the “capital costs” category.

Grid connection costs, for example, are considered aside by some analysts. One might also make a distinction between grid connection infrastructures (i.e. the set of elements required to perform power transmission from the deployment site to the chosen connection point to the grid including substations, transformers etc.) and the proper electrical interconnection equipment of the device (umbilical cable, connector and possibly power converter). Some of these elements could be included in one of the categories explained above. For instance, umbilical analysis is somehow related to moorings while other kinds of elements could be easily included in the “electrical equipment cost” item.

Project management is another cost item that should be considered since some level of management will be, at a certain point, required by any project. However, it might be difficult to give an estimate for this component. Moreover, it is likely that the same level of management will be needed for similar projects in such a way that, for the sake of comparison of different marine energy concepts, its account is not expected to have a large impact on the results.

Some references ([6] and [7]) include also distinction between engineering costs and development cost. For mature technologies one might think to include a specific factor accounting for labour expenses for the production of a single unit. This would be different from the corresponding labour effort required by operation and maintenance of the device.

Spare provisioning should be also included in the estimation but for preliminary assessment it could be considered as belonging to one of the four categories outlined above and estimated as a percentage of the total hardware cost.

3.1.6 Capital cost breakdown

Considering the different types of costs listed above, it would be interesting to understand in which percentage they actually contribute to the whole capital cost and whether this composition could be applicable to several device typologies.

Existing literature has proposed such figures based on responses from enquiries or engineering appraisal of the technologies. As it is understandable, tidal and wave technologies have quite a different capital cost composition.

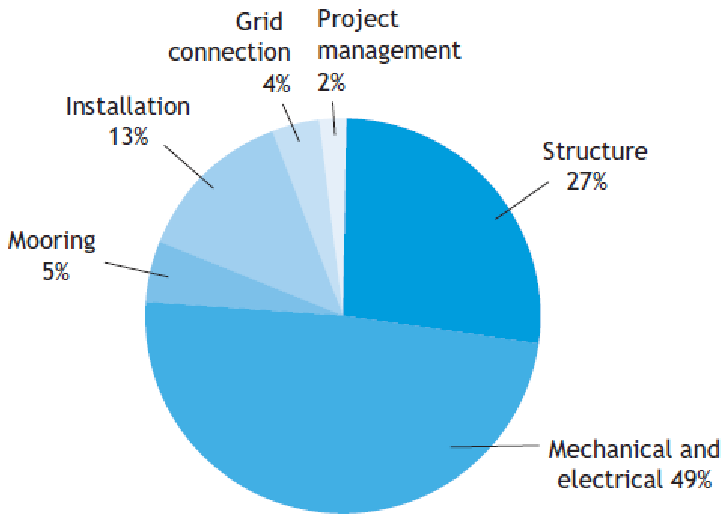

Figure 3.1 Breakdown of capital costs for a wave farm ([3])

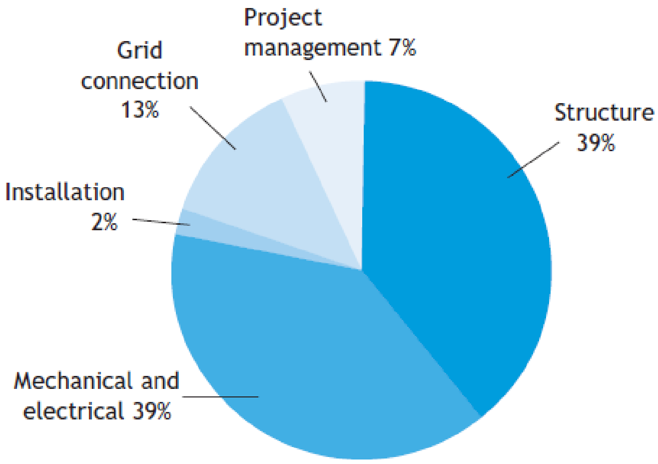

Figure 3.2 Breakdown of capital costs for a tidal farm ([3])

Illustrative examples, taken from the MEC report ([3]) are shown in figure 3.1 and 3.2. It has to be said that such data cannot be representative of marine energy as whole but are just based on data gathered during the project and engineering analysis performed by consultants.

Similar results for different type of devices given by the WaveNet ([2]) are shown in figures 3.3 and 3.4. It is interesting to notice how large sensitivity to the kind of device is assumed for different cost items.

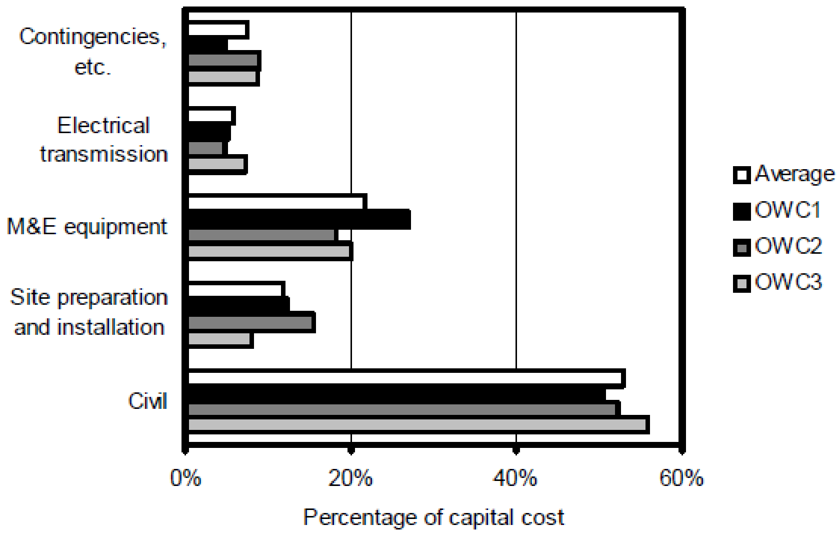

Figure 3.3 Breakdown of capital costs for Oscillating Water Column devices ([2])

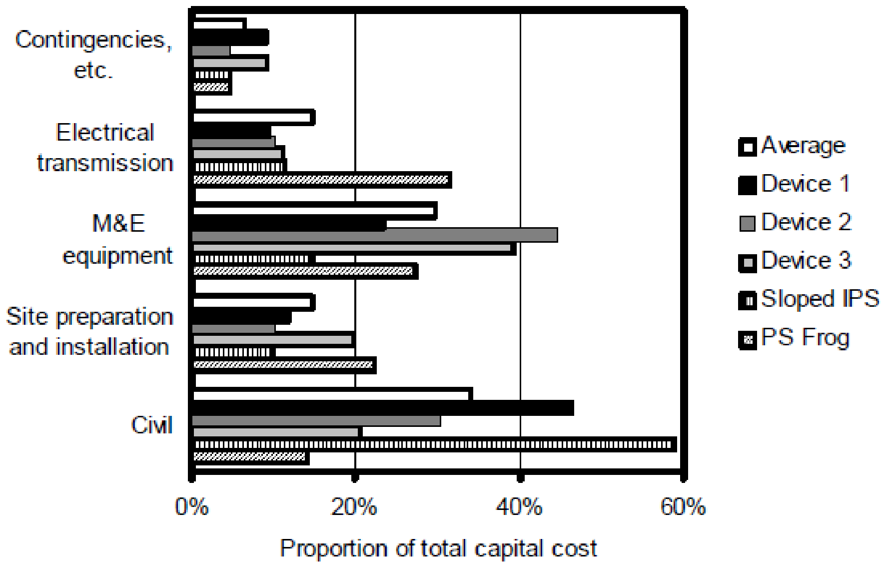

Figure 3.4 Breakdown of capital costs for Wave Point Absorber devices ([2])

3.2 OPERATION AND MAINTENANCE COSTS

Operation and maintenance costs can be also structured in several parts:

- Replacement parts
- Maintenance personnel costs
- Vessel and equipment for transportation and maintenance
- Monitoring
- Insurance
- Licences

Some prefer to include also a “refit” item that accounts for updates of the design and adoption of improved components.

Distinction is typically made for maintenance operations between planned and unplanned maintenance. O&M costs depend on the size and location of the installation and are at present extremely difficult to estimate for marine energy installations. Useful information on components life might be taken from offshore oil and gas industry experience.

Indeed a report ([15]) issued by the UK Department of Trade and Industry (DTI) in 2005 applied reliability data taken from the OREDA handbook ([16]) to evaluate failures modes and rates for several components. This document took also into account weather window influence on maintenance operations through Montecarlo simulation techniques.

A NORSOK standard ([17]) specifies also formulas and calculations of life cycle costs of components used in the offshore oil and gas industry.

Costs of vessels for maintenance are usually dependent on hiring day rates and might be largely changing depending on demand and weather conditions. It has to be noticed that maintenance interventions might be reduced through proper redundancy of critical components. This would increase capital costs but might be largely beneficial in terms of future operating issues.

3.3 POWER OUTPUT ESTIMATION

Calculation of the cost energy clearly depends on the expected power output estimation.

Technologies at an advanced stage are generally characterised by appropriate performance indicators that allow the calculation of the power output along the year through relatively easy calculations. Tidal devices usually make use of power curves depending on the tidal flow velocity while performance of wave energy converters is assessed through a matrix that specifies the expected output given by a sea state with determined significant wave height and energy period.

The accuracy of the calculation depends on the models utilised for performance assessment and/or on the amount of historical real data. Performance assessment is part of Work Package 3 and 4 within the EquiMar project and will not be studied in detail.

However, it has to be said that electrical power production could change a lot along the years and within the same year. For example, annual average power output for the case of wave energy could be subject to large variations due to the stochastic nature of the resource. This level of uncertainty should be properly assessed and taken into account when performing an economic analysis.

4 ACCOUNT FOR RISK AND UNCERTAINTY

Different studies use different definitions of risk. Some aim to distinguish between uncertainty and risk, by ascribing the term uncertainty to a situation where it is not possible to parameterise the variability of outcomes, and using risk when outcomes are variable within some expected probability distribution which can be parameterised.

The act of investment involves exchanging a lump sum of money now in return for an income stream in the future. Companies will make this exchange if the expected project returns are high enough to cover the initial lump sum as well as compensating them for taking on the project risks.

There are different approaches to take into account the risk associated with an investment. Some of the references previously cited have considered included within the choice of an appropriate discount rate risks and uncertainties. A standard method largely applied in economic and financial assessment is represented by the Capital Asset Pricing Model.

4.1 THE CAPITAL ASSET PRICING MODEL

In finance, the Capital Asset Pricing Model (CAPM) is used to determine a theoretically appropriate required rate of return of an asset, if that asset is to be added to an already well-diversified portfolio. The model takes into account the asset sensitivity to non-diversifiable risk (also known as systemic risk or market risk), often represented by the quantity beta (β) in the financial industry, as well as the expected return of the market and the expected return of a theoretical risk-free asset.

Even in the complete absence of risk the Required Rate of Return would be positive, because, in general, people prefer to consume now rather than later. If they are to forgo present consumption and channel the value of it into investment, they must be rewarded for doing so. The RRR is the rate of return that an investment should guarantee to attract investors.

If the outcome of a project is certain, so that it has no risk, there is no problem in deciding an appropriate RRR. It would be the interest rate on zero risk investments (typically government bonds). This is generally named Risk-Free Rate of Return (RFRR).

On the other hand, if the outcome of an investment is uncertain, the investors will need to be offered the prospect of a higher rate of return to compensate for taking on the risk involved. Clearly the RRR on a project should reflect this. Therefore the RRR on a project should be equal to the risk-free rate plus a premium for risk.

A company's risk manifests itself as variability in the returns it makes to shareholders. Variability can be split into market risk and specific risk, being the former one related to general market movements and the latter to events specific to the company and its sector.

In the CAPM approach, risk is generally accounted through the definition of a beta coefficient (β), representing the sensitiveness of the project risk to market changes, that often cannot be measured directly (such as the case of marine energy projects) but can be guessed by observation of published figures for companies or sectors. To obtain a measure of the return required for the risk taken in the investment, one needs also to define a Market Risk Premium (MRP), which is generally based on historical data of the equity market (i.e. the return is referred to possible similar risky investments).

Given these parameters, the return on equity can be defined:

$$ROE = RFRR + \beta \times MRP$$

Typically capitals will be funded through leverage and the company will be required to guarantee appropriate returns corresponding to the interest rate of the debt contacted. Considering a capital composed by a determined Proportion of Equity (POE) and a proportion of debt (DEBT) with a specified interest rate (IR), the RRR can be finally determined through the equation:

$$RRR = ROE \times POE + IR \times DEBT$$

This could be considered as the rate of return that would be capable of satisfying investors, shareholders, creditors and other capital providers.

The discount rates used in economic analyses and cost of energy estimations should be based on this estimate. An extensive explanation of this method with tables of data on risk coefficients is given in the chapter D1 of the WaveNet report ([2]).

5 COST MODELS APPLIED BY DEVELOPERS

One of the objectives of the Work Package 7 of the EquiMar project is to define a procedure for calculating the cost of electricity generated that accounts for design stage and uncertainty of performance.

With the scope of defining a methodology agreed by a large range of stakeholders and intending to identify commonalities between different cost inputs specified by developers and utilities, a request for information was sent to the developers within the EquiMar consortium to collect information on cost models currently applied and defined by stakeholders.

5.1 CONTENTS OF THE SURVEY

The survey was conducted through the preparation of a questionnaire. The questions included are specified in annex 1.

The questionnaire was structured in four parts:

- Importance of COE estimation (question 1)
- Assessment methods (questions 2-3)
- Capital cost estimation (questions 4-6)
- Operating cost estimation (questions 7-10)

There is also a first introductory question that identifies the actual experience in operating a marine energy power plant.

To date four developers have replied to the survey but additional data are expected to be collected through circulation of the questionnaire outside the consortium.

5.2 RESULTS

5.2.1 Background of the developers

All the developers are at a relatively advanced stage of development. Two of them have been operating grid-connected marine energy devices (one of these two both wave and tidal). A third developer is still at the stage of open sea scaled testing and has not experience of grid-connected operations. The fourth developer has been operating a large scale tidal power plant but the person who filled out the questionnaire has mainly an experience of technology watcher.

5.2.2 Importance of COE estimation

Developers tend to consider the estimation of the cost of the energy as an important parameter for investment decision. Three respondents out of four considered this influence superior than the 50%. Only one respondent assumed that the cost of energy would be decisive only for a limited percentage on an investment decision.

This points out to the effective importance of the definition of a recognised methodology for COE estimation.

5.2.3 Assessment methods

Most of the respondents make use of the net present value for economic assessment of their technologies. One respondent pointed also to comparative methods as efficient method for assessment. Also internal rate of return with and without account for gearing was mentioned.

Learning curves for future cost estimation are also widely applied (three out of four marked this option), especially at less advanced stages of development.

A respondent pointed also that economic appraisal does not involve only a single project but also the whole company as it is the developing company that is financed. In this frame, quality of management and business plan should be assessed as well.

Risk is taken into account through single fixed discount rate for two respondents. Another one 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.

A need for improving risk assessment is perceived. Suggestions are made to apply stochastic approaches to consider uncertainties.

5.2.4 *Capital cost estimation*

Responses to the first question of this section are summarised in figure 5.1.

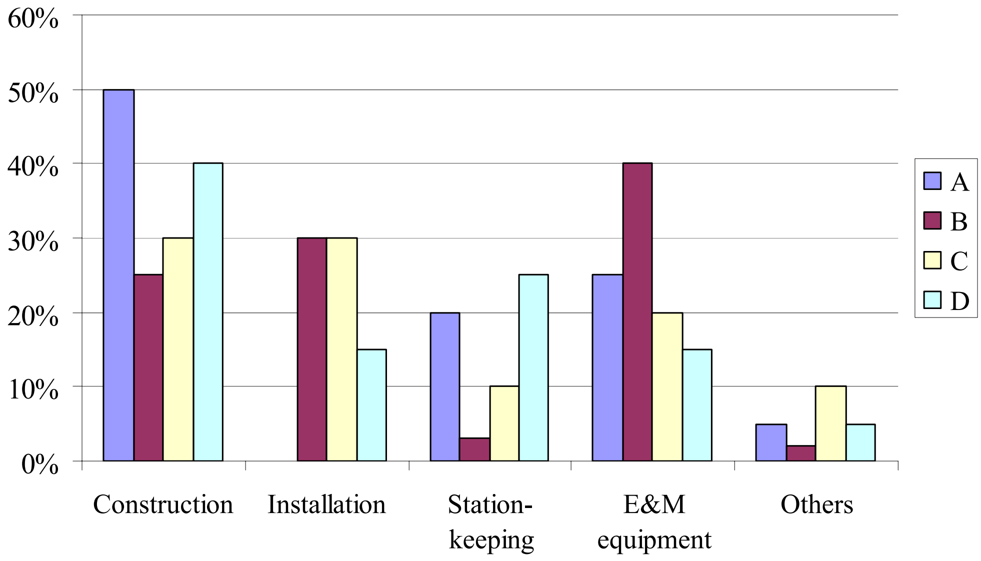

Figure 5.1 Responses to question 4 (capital cost breakdown).

A relevant difference in the influence of each cost factor can be observed. Broadly speaking, it can be said that structural costs constitute a large part of the whole capital cost of the device.

Deviations can be observed on electrical and mechanical equipment cost (as the PTO concept influences this factor). One developer estimated the installation costs included with the station-keeping ones.

Other cost components listed were:

- Labour
- Project Management
- Engineering and organisation

Figure 5.2 summarises the responses to question 5.

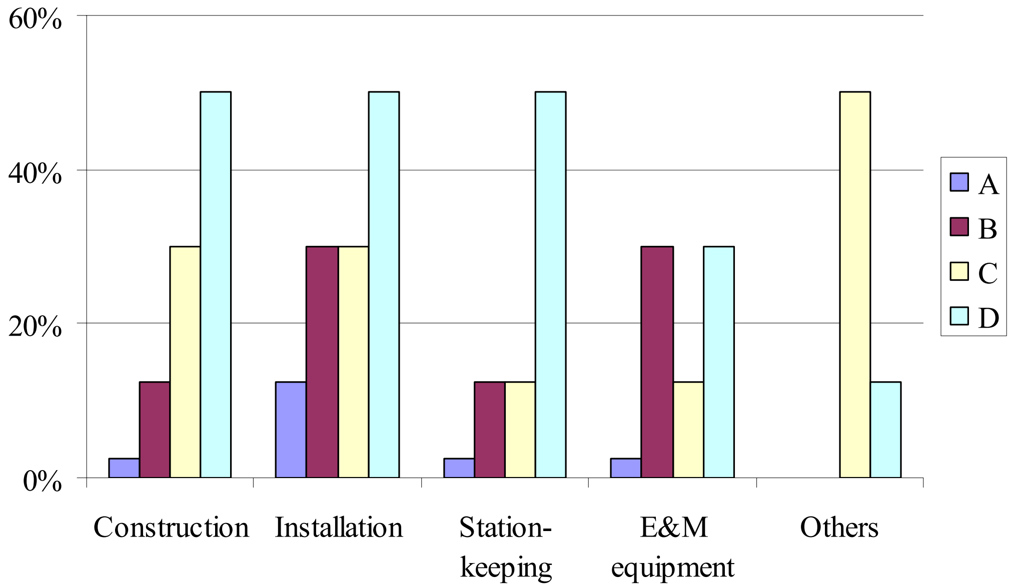

Figure 5.2 Responses to question 5 (uncertainties on capital cost estimation).

Four different indication of uncertainty were possible:

- **Level 1:** 0-5%
- **Level 2:** 5-20%
- **Level 3:** 20-40%
- **Level 4:** more than 40%

Generally speaking, high uncertainties are taken into account by most of the developers. The lower uncertainties estimated by one respondent (developer A in this case) could be related indeed to a more advanced development stage. This could give some indications on uncertainties on costs to be accounted in future cost models depending on the development status of a particular technology.

One respondent pointed out that commodity price fluctuations (especially steel) and currency exchange fluctuations can contribute larger uncertainty than design/specification changes.

Figure 5.3 summarises responses to question 6.

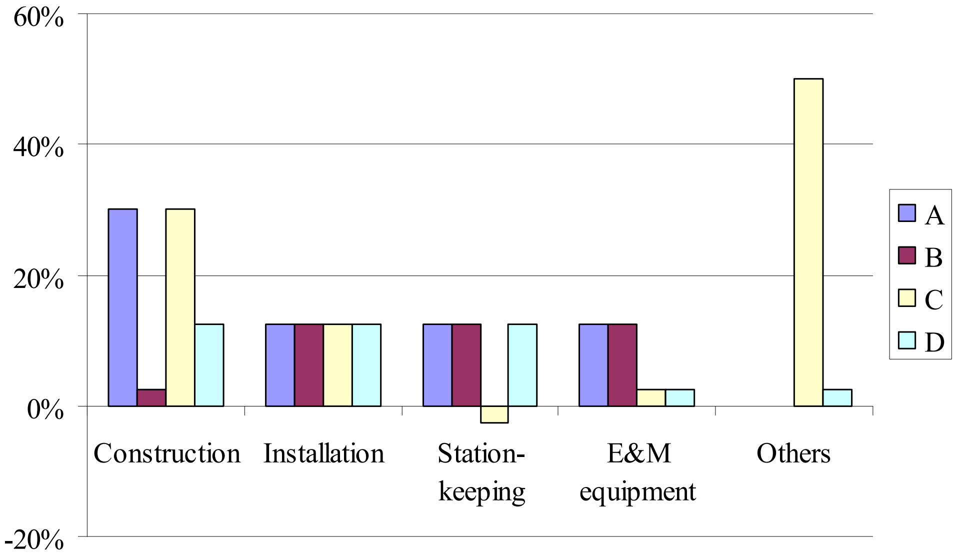

Figure 5.3 Responses to question 6 (scalability of the capital costs).

Reductions of costs due to increased installed capacity are agreed by all the developers. Expected reductions are often in the order of 5-20% per doubling of the installed capacity.

Only one respondent sees the possibility of increase of a cost item (station-keeping costs).

5.2.5 Operating cost estimation

Respondent were asked to rank three different factors in order of percentile fraction of the expected operating costs.

Through weighted evaluation of the responses, the results are:

1. Cost of vessels and equipment for transportation and on-site maintenance: 9 points
2. Cost of personnel for maintenance and monitoring: 5 points
3. Insurances: 3.5 points
4. Costs related to long outage periods due to unaccessibility: 3 points
5. Cost of replacement parts: 2.5 points
6. Organisation and finance cost: 1 point

It appears clear that developers see in the cost of hiring vessels and equipment for maintenance the principal cost source during the operation of the device (all the respondents named this option).

Additional cost factors mentioned by respondents include organisation and outage periods. The latter is indeed related to the availability of the device and would affect the revenue in terms of lack of output therefore it could be accounted within the estimation of the annual energy production (i.e. assuming a lower availability factor).

Respondents pointed out the importance of the scale of the project that would probably have a strong influence on the distribution outlined above. Within this frame the results above summarise the perception of O&M costs based on the current state.

Other comments included the consideration of licensing costs as operation and maintenance costs and the inclusion of refit of the components as an independent item (in this case it has been considered as part of the cost of replacement parts).

Figure 5.4 summarises the responses to question 8.

Four different indication of uncertainty were possible:

- **Level 1:** 0-5%
- **Level 2:** 5-20%
- **Level 3:** 20-40%
- **Level 4:** more than 40%

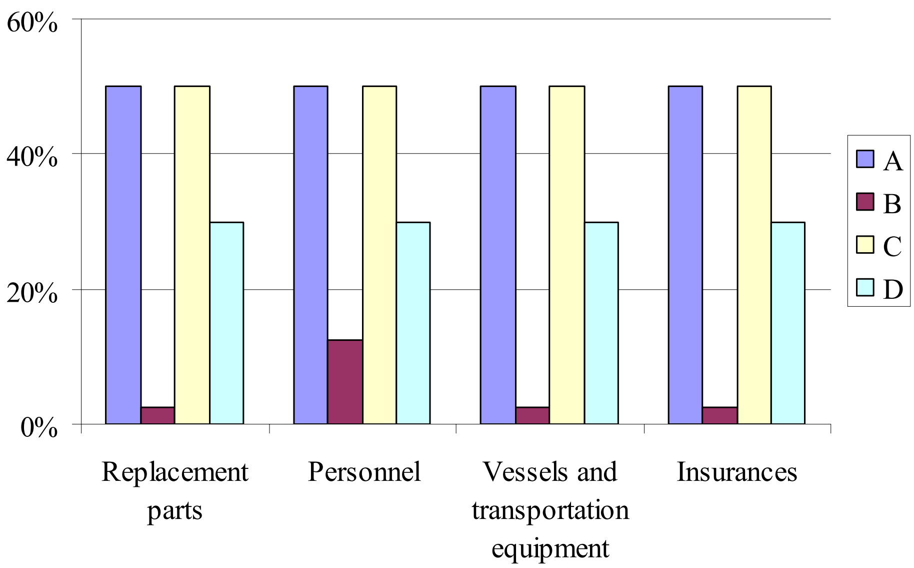

Figure 5.4 Responses to question 8 (uncertainty of the operating costs).

Uncertainty ranges for operating costs are perceived as very high by developers. Most of the respondents ranked each cost factor as having the same uncertainty of the others.

Again, the grade of development is obviously influential on the degree of certainty of the cost estimations. A respondent with a long experience of offshore grid-connection operation estimated lower uncertainties than the other ones.

Figure 5.5 summarises responses to question 9.

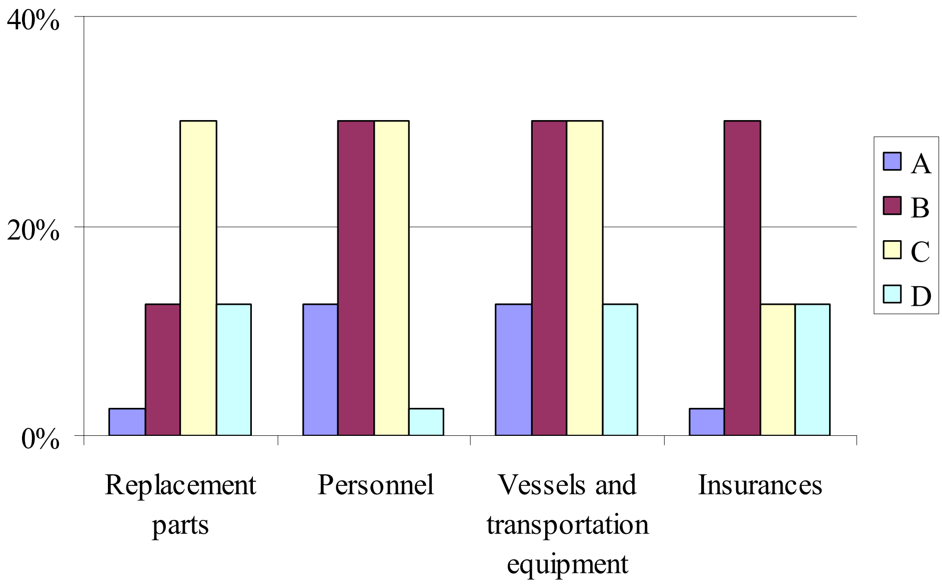

Figure 5.5 Responses to question 9 (scalability of the operating costs).

Most respondents see a concrete possibility of reduction of costs with the increase of the installed capacity of a specified power plant.

Cost of personnel, vessel and equipment seem to be the factors that most likely will experience large reductions for doubling of the installed capacity.

The last question asked the developer to rank three possible maintenance activities in order of decreasing frequency of intervention.

Responses were different and included several comments. One remark concerned the need of taking into account, at the current stage of development, of refitting needs that would require additional engineering and development activities (and costs).

Two respondents specified the benefit of redundancy and the need for designing proper redundant system to avoid criticality of failures. One remark particularly underlined the importance of assessing the importance of maintenance activities by a cross-matrix that accounts for risk of the failure and frequency of the failure.

Device component replacement and device maintenance were recognised as possibly most frequent activities required by marine energy devices.

5.2.6 Final remarks

All the consulted developers generally agree on the importance of Cost of Energy estimation as key parameter for assessment of marine energy technologies.

To perform economic assessment of their own products and projects, developers apply Net Present Value approach, often coupled with fixed discount rates. However, the importance of proper accounting for risk factors is generally acknowledged and most respondents insist on the necessity in improving risk assessment methods.

Capital cost breakdown is roughly similar for all the four developers interviewed. However, it is interesting to notice the different degree of uncertainty associated with its estimation for different respondents. This seems to be highly correlated to the development stage of the technology. Scalability of capital costs is also acknowledged by developers, although with some discrepancies in a few cases.

Costs for vessel and personnel for maintenance seem to be the most important operating cost items. Also it is interesting to observe the relevant importance given to insurance costs by developers. Respondents tend to consider operating costs very difficult to estimate with large uncertainty ranges given but also generally believe in the possibility of consistently decreasing their magnitude through the increase of the installed power.

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7 ANNEX 1: REQUEST FOR INFORMATION ON COST ASSESSMENT METHODS

7.1 BACKGROUND OF THE USER

The Equimar partners represent a majority of researchers active in marine energy research. The purpose of this pro-forma is to obtain an overview of the knowledge held by Equimar partners concerning cost assessment methods. Indicative quantities and explanations of methods used are required wherever possible. Where these are not available, references to other sources of information would be of use.

A) Briefly describe your experience of marine energy projects
   a. Experience of offshore wind energy project. Indicate MW scale.
   b. More than six months operation of a grid-connected full scale device
   c. One to six months operation of a grid-connected full scale device
   d. More than six months operation of a grid-connected reduced-scale device
   e. One to six months operation of a grid-connected reduced-scale device
   f. Six months operation of a not connected reduced-scale device
   g. One to six months operation of a not connected reduced-scale device
   h. Other … (Please specify)

7.2 QUESTIONS

General info on cost model perception and importance

1) If you are, or have been, involved in any marine energy project, how important would you rate the influence of predicted cost of electricity in an investment decision? (percentage from 1 to 100)
   - Less than 30%
   - From 30% to 50%
   - From 50% to 80%
   - More than 80%

Assessment methods

2) What assessment method do you use, or recommend using, for economic appraisal of marine energy technologies?
   - Net Present Value
   - Comparative method
   - Portfolio method
   - Future cost estimation (learning curves)
   - Other ... (Provide a reference or brief explanation of th e method used)

3) Which method do you use, or recommend using, for quantification of risk and uncertainty of a marine energy investment?
   - Single fixed discount rate
   - Capital Asset Pricing Model (CAPM) – discount rate dependent on a risk parameter related to financial movements
   - Different risk parameters to separate cash flows (Awerbuch)
   - Use of range values by assigning confidence errors to the estimates
   - Other ... (Provide a reference or brief explanation of the method used)

Capital cost estimation

4) Which fraction of the whole capital cost of a full-scale single marine energy device would you expect to be represented by each one of the following factors, based on your experience? Indicate a percentage of the total capital cost (Do not consider site to shore transmission infrastructure).

Cost factor	Percentile fraction of the total cost
Construction costs (material, structure, manufacturing)	□
Installation costs (deployment and connecting operation)	□
Station-keeping costs (foundations, moorings)	□
Electrical and mechanical equipment costs (power conversion, generator, umbilical etc.)	□
Others ……	□
Others ……	□

5) Considering your current state of development and/or degree of involvement in marine energy activities, which uncertainty range would you consider appropriate for each one of the following factors in a cost assessment?

Uncertainty range	0%-5%	5%-20%	20%-40%	>40%
Construction costs	□	□	□	□
Installation costs	□	□	□	□
Station-keeping costs	□	□	□	□
Electrical and mechanical equipment costs	□	□	□	□
Others ……	□	□	□	□
Others ……	□	□	□	□

6) Consider the influence of deployment scale, in terms of the installed capacity of the project, on each one of the cost factors previously identified. Starting from a hypothetical first deployment (say 50 MW) suppose to estimate the costs of a deployment with a doubled rated power (say 100 MW). How much would you expect each of the cost factors outlined above to change?

Percentile variation	Increase 0%-20%	Reduction 0%-5%	Reduction 5%-20%	Reduction 20%-40%	Reduction >40%
Construction costs (per MW unit)	□	□	□	□	□
Installation costs (per MW unit)	□	□	□	□	□
Station-keeping costs (per MW unit)	□	□	□	□	□
Electrical and mechanical equipment costs (per MW unit)	□	□	□	□	□
Others ……	□	□	□	□	□
Others ……	□	□	□	□	□

Operating cost estimation

7) Which three of the following factors represent the greatest fraction of the operating cost of a marine energy device? Specify the rank of each by writing a number between 1 and 3 (1=most important, 3= least important)
   - Cost of replacement parts

- Cost of personnel for maintenance and monitoring
- Cost of vessels and equipment for transportation and on-site maintenance
- Insurances
- Others ……………..

8) Which uncertainty range would you consider appropriate for each one of the following factors in a marine energy cost model?

Uncertainty range	0%-5%	5%-20%	20%-40%	>40%
Cost of replacement parts	□	□	□	□
Cost of personnel for maintenance and monitoring	□	□	□	□
Cost of vessels and equipment for transportation and site maintenance	□	□	□	□
Insurances	□	□	□	□
Others ……	□	□	□	□
Others ……	□	□	□	□

9) Starting from a hypothetical first deployment (say 50 MW) suppose to estimate the costs of a deployment with a doubled rated power (say 100 MW). How much would you expect each of the cost factors outlined above to change?

Percentile variation	Increase 0%-20%	Reduction 0%-5%	Reduction 5%-20%	Reduction 20%-40%	Reduction >40%
Cost of replacement parts (per MW unit)	□	□	□	□	□
Cost of personnel for maintenance and monitoring (per MW unit)	□	□	□	□	□
Cost of vessels and equipment for transportation and site maintenance (per MW unit)	□	□	□	□	□
Insurances (per MW unit)	□	□	□	□	□
Others ……	□	□	□	□	□
Others ……	□	□	□	□	□

10) Which three of the following options represent the most frequent maintenance activity for a marine energy device? Specify the rank of each by writing a number between 1 and 3 (1=most important, 3= least important)
- Device maintenance
- Device component replacement
- Electrical connection maintenance
- Mooring component maintenance
- Other: …………………………….
- Other: …………………………….