Summary of performance limits and guidelines for assessing devices in terms of performance increase required to attain a target unit electricity cost

Citation for published version (APA):
Stallard, T. (2011). *Summary of performance limits and guidelines for assessing devices in terms of performance increase required to attain a target unit electricity cost*. (Summary of performance limits and guidelines for assessing devices in terms of performance increase required to attain a target unit electricity cost), (EU FP7 Grant No. 213380). European Commission.

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

Grant agreement number: 213380

EquiMar

Deliverables D7.5.1-2

Summary of performance limits

&

Guidelines for assessing devices in terms of performance increase required to attain a target unit electricity cost

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Deliverable D7.5.1-2

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Guidelines for assessing devices in terms of performance increase required to attain a target unit electricity cost

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April 2011

Summary

The objective of this study is to estimate the maximum capital cost of a marine energy project such that electricity is generated at a target levelised cost of electricity. A capital cost is evaluated for alternative wave energy technologies at a particular site. The approach taken is to employ the standard Net Present Value method to quantify the budget that is available for all expenditures that can not be quantified at the present stage of development. A positive net present value is typically required to justify investment in a marine energy project. Positive NPV is only obtained if the present value of all revenues is greater than the present value of all expenditures over the project life. Initially, project revenue is estimated based on site resource and device performance. Subsequently, the present value of each of the expenditures associated with the site and technology are subtracted to estimate the budget available for outstanding capital costs. Several idealised devices are considered at eight different wave sites to quantify the number of devices in a project and hence estimate the capital cost per wave device that would result in a positive Net Present Value. The idealised devices considered are types of heaving point absorber. One of the device types is assumed to operate at the point absorber limit in all wave conditions that occur at each site. This limit is dictated by the resource not the device dimensions and so represents the maximum power output that could be achieved by a heaving device.

Application of this method to a range of sites would allow identification of the maximum device cost for each site so represents a capital cost 'budget'. If applied to a technology at an early stage of development it can be used as a method of identifying the market size for different technologies.

This report forms D7.5.1 and D7.5.2; the outputs from Task 7.5 as described below:

Task 7.5: The cost per unit of electricity is strongly influenced by the electrical output generated and by the value of this output. Accurate prediction of the power that can be generated by prototype designs is a key objective of many device developers and is the subject of WP4. However, a comparison between technologies must consider the extent by which device output may be increased without significant alteration of the design or infrastructure requirements. The present understanding of the limits to device performance - in terms of individual device optimisation and device interaction - will be reviewed and the economic implications assessed for different types of device.

7.5.1: Summary of performance limits of different device types to provide a method for investors and policy makers to assess the potential of early-stage designs against more developed technologies.

7.5.2: Guidelines for assessing technologies in terms of the performance increase required to generate electricity at a target unit cost.

1 INTRODUCTION

At present (2011), all tidal stream and wave energy devices are at an early stage of development. It is widely assumed that the levelised cost of electricity associated with these technologies will reduce with increased experience of design, manufacture and operation of these devices. The extent of cost reduction due to accrued experience is often based on the experience curve approach with progress ratios of 10 – 15 % assumed (see EQUIMAR D7.3.3 for further discussion). For any electricity generating technology, economic viability (based on a discounted measure such as the levelised cost of electricity or net present value) can only be improved through one of three mechanisms: decrease of either capital or operating costs or increase of revenue. The cost associated with farms of devices is the sum of many individual quantities (e.g. number of components, of materials, of days of vessel time) and a unit cost associated with each quantity (e.g. component cost, material cost, process cost and vessel day rate). To decrease the capital or operating cost it is necessary either to reduce the quantities required or to reduce the unit cost of each quantity. Similarly, revenue is dependent on the quantity of electricity generated and the unit value per quantity.

EQUIMAR deliverables D7.3.1 – 7.3.3 and D7.4.1-2 indicate that the expenditure required to install large farms of marine energy devices is a function of the number of devices installed. Thus, it is important for policy makers to consider how further development could lead to changes of the number of devices required in a farm and to evaluate how this will affect expenditures, installation and operation strategies. In EQUIMAR D7.3.3 mechanisms that may result in changes of capital expenditure are reviewed. These include changes due to elapsed time, due to scale of project and due to scale of cumulative capacity manufactured or installed to-date. In D7.4.1-2, the effect of site-access constraints on installation and maintenance expenditures are reviewed. In this report, the factors which limit the quantity of energy produced by individual devices and groups of devices are reviewed. The objective is to identify limitations to the reduction of cost of electricity that could occur from increased performance alone (i.e. increased energy production without change of expenditures). For wave energy devices and, to a lesser extent, for tidal stream systems there are several fundamental aspects of design that will influence, and perhaps limit, the extent of cost reduction that could be achieved. These factors are discussed in Section 2 and several idealised wave energy systems are considered in Section 4.

2   LIMITS TO DEVICE PERFORMANCE

If all other parameters remain equal, a percentage change of revenue has a larger influence on the net present value (NPV) of a project – and hence its economic viability – than the same percentage change of any expenditure or of discount rate. Increase of power output is therefore an important factor in the reduction of overall expenditures and reduction of both net present value and levelised cost of electricity (COE). For many technologies, increased power output is likely to be achieved by increased reliability (hence increased availability) but can also occur due to improvements in device design to optimise output for the resource. Furthermore, as the average power output per device increases, both the number of devices and quantity of associated infrastructure required for a particular project size will reduce. For example; a simplified expression for the power output from a wind turbine is

$$P \sim \tfrac{1}{2} C_p \rho A U^3 \qquad\qquad\qquad\qquad\qquad \text{Equation 1.}$$

where Cp denotes the power coefficient; i.e. the fraction of the kinetic energy flux of the undisturbed flow which is converted to mechanical power across the plane of the rotor. It is widely known that the power coefficient for a wind turbine in unconstrained flow cannot exceed the Lanchester-Betz limit such that maximum Cp = 0.592. Improvements of blade design and rotor control allow this limit to be approached but not exceeded. The electrical power output from a turbine is subsequently the mechanical power of the rotor minus generator, conversion and transmission losses. For a given wind speed (the resource), mechanical power capture can only be increased by improving the power coefficient (Cp) or increasing the swept area of the rotor (A). Typically, power coefficients are around 0.35 – 0.45. For a given turbine size, electrical power output may be increased by improving efficiency of mechanical to electrical conversion. Over the period 1980 to 2005, wind turbine rated power increased from around 50 kW to 5 MW and wind turbine size increased from 15 m diameter to 124 m diameter (Fossdal et al. 2007, Windblatt, 2007). These figures indicate that increased power output per wind turbine has occurred principally due to increase of rotor diameter. The increasing rated power of individual wind turbines has allowed reduction of the number of turbines per farm and so reduced the number of foundations required for a particular installed capacity.

It is therefore important to understand which factors may limit the power output of individual devices so that the extent of, for example, infrastructure cost reduction can be assessed. For wave devices and, to a lesser extent, tidal-stream turbines, there are several constraints that will limit the average power output of individual devices to relatively small magnitudes. These are discussed in the following sections.

2.1   TIDAL STREAM DEVICES

Energy production from an individual tidal stream device is typically obtained as the sum product of power output $P(U)$ due to a mean flow velocity U and the annual duration $T(U)$ of the same flow velocity. i.e.:

$$E \sim P(U) \cdot T(U) \qquad\qquad\qquad\qquad\qquad \text{Equation 2.}$$

The duration of each mean flow velocity is site dependent and will be obtained by conduct of a resource assessment. However, various studies have shown that flow conditions at the site may be altered due to large-scale energy extraction (Garrett & Cummins 2005, Couch & Bryden, 2007)

The variation of power output with flow speed varies with device type but several factors affect the maximum power output. If the device is small relative to the water depth and is located far from both the free-surface and the seabed flow may be considered as unconstrained and so the Lanchester-Betz limit is applicable as for a wind turbine as Equation 1 with Cp = 0.59. The depth of possible tidal stream sites is typically of the order of 40 – 80 m (Black & Veatch, 2005) and the devices presently in development are of the order of 16 – 20 m in diameter. A 20 m diameter tidal stream turbine would therefore generate around 1.5 MW during a steady tidal flow of 2.5 m/s. Larger devices may be possible for some sites but both blade design loads and support structure design loads will become increasingly onerous design constraints as the diameter is increased.

For devices that are large relative to water depth, or that are located close to either the water surface or the seabed, power output could exceed the Betz limit for unconstrained flow due to the effect of blockage. Considering the free-surface as a rigid wall (e.g. Garrett & Cummins 2005, Batten et al. 2007), it has been shown that power coefficient will increase with the blockage ratio defined as the swept area (A) to channel area (Ac) such that:

$$C_{p,\,max} \sim 0.592\,(1\text{-}\,A/Ac)^{-2} \qquad\qquad\qquad\qquad \text{Equation 3.}$$

This suggests that for blockage greater than 20%, the maximum power coefficient may exceed 1.0. Whelan et al. (2009) account for blockage of a flow with a free surface and show that maximum power coefficient depends on both blockage and the Froude number of the flow. For 10% and 20% blockage, Cp maximum is approximately 0.7 and 0.95 respectively. High blockage values will only be observed for devices that are installed at close lateral spacing.

Tidal Stream: Array Interactions

A brief review of the present understanding of marine energy device interactions is given in Section 4.1 of EQUIMAR D5.4. To-date only a few studies have been published of rrays of tidal stream devices. Small scale experiments have been conducted employing porous discs to replicate rotors and numerical studies have been presented by several authors. A combined experimental and numerical study of tidal stream systems at scales ranging from individual devices through farm (array) scale to coastal scale is presently ongoing (ETI PerAWaT). Due to the lack of published information specific to tidal stream arrays, some comparison can be made with the literature on wind-turbine interactions. This suggests (see EQUIMAR D5.4):

1. Power losses due to interaction effects are large in multiple row wind farms
2. Numerical and analytical models tend to under-predict power losses as the number of rows increases

However, tidal streams are different from wind and EQUIMAR D5.4 demonstrates that it is important not to make strong generalisations, or carry over results from similar technologies or other device types.

2.2 WAVE DEVICES

An estimate of annual energy output from wave energy devices are typically obtained by the sum product of a device-specific power matrix and a site-specific sea-state occurrence matrix, typically:

$$E \sim P(\text{Hs, Tp}) \cdot T(\text{Hs, Tp}) \qquad \text{Equation 4.}$$

The duration of each sea-state ($T(H_s, T_p)$) is site dependent only and would be obtained by a resource assessment (e.g. EQUIMAR protocol IA). The power output during each sea-state is dependent on many aspects of device design (e.g. EQUIMAR Protocols IIA-IIC). The following discussion is restricted to wave devices which comprise one or more oscillating floats or surfaces. This is therefore applicable to the vast majority of wave devices with the exception of overtopping type devices. Only one such device presently exists in the form of the WaveDragon. Power density limits – i.e. the maximum power output that can be achieved from a given wave condition – are well-known for particular modes of motion of one or more floating bodies. 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.

For a heaving float in regular waves, of amplitude α and frequency ω, it is known that the maximum power output is a function of the incident wave power and wave length:

$$P_{max}(a,\omega) = P_{wave}(a,\omega)\, L_{wave}(\omega)\, / \, 2\pi \qquad \text{Equation 5.}$$

This power output is only obtained if device response is resonant and if a sufficiently large response amplitude is developed. A small device would need to oscillate with greater amplitude to obtain the same power output as a larger device. Typically response amplitude is limited by the float draft or some multiple of the incident wave amplitude. Maximum power output in irregular waves has been shown to be the sum of the power output to each regular wave frequency within the irregular wave-field (McCabe and Aggidis, 2009). However, this is only applicable if the device response response is optimised for all conditions. Typically, power output from irregular waves is sensitive to the device control strategy employed (see e.g. Falnes, 2003 and Thomas, 2008).

It is widely expected that commercial wave energy projects will comprise large numbers of individual devices installed in arrays. The configuration of arrays will be dependent on several factors including the spacing required for vessel access, on mooring considerations and on device design (see EQUIMAR Protocol IIC).

Wave Device Array Interactions

Theoretical studies have shown that array interactions may increase absorbed power, particularly at certain wavelength to spacing ratios (Thomas 2008). This effect is often summarised in terms of an interaction factor q, defined as the power output from an array of N floats divided by the power output of the same number of isolated floats. For a linear array of five heaving semi-immersed spheres Thomas & Evans (1980) calculated a maximum interaction factor of q = 2:25. This only occurs at a particular ratio of device size to wave length. For the same device size and wavelength, Fitzgerald & Thomas (200&) showed that a pentagonal configuration can attain an interaction factor of up to q = 2:77. However, if an array attains an interaction factor greater than unit value due to waves from one heading it must yield lower interaction factors when waves approach from other headings. When averaged across all headings (i.e. from bearings of 000 to 360°), the average interaction factor will be q = 1.

In many of the theoretical studies of wave device array interactions the unique case of optimal response is considered. In practice this is not straightforward to engineer, even in regular waves, since optimal power output requires that an external force (non-hydrodynamic) that is dependent on the motion of all other floats. Studies of small arrays undergoing sub-optimal response due to regular waves (e.g. Justino & Clement, 2003; Bellew et al., 2009) suggest that interaction factors for such arrays are likely to be less than 1.3 and often less than 1.0. To-date there has been limited research completed regarding interaction factors in irregular waves but studies are ongoing concerning both closely spaced arrays (deBacker et al. 2009 and Weller et al., 2011) and floats at wide spacing (Babarit 2010). However, a need for further guidance in this area has been identified (EQUIMAR D5.5).

3   REVENUE

It is important to identify technologies that will be economically viable at commercial scales of deployment. These may not be the same technologies that are economically viable at small-scales. For marine energy projects, revenue is due to the sale of electricity. Therefore only two factors affect the magnitude of revenue: the quantity of energy delivered to the market and the value of each unit of that energy. Throughout this study the commercial value of a unit of electricity is assumed to be 5 €c/kWh (e.g. 0.05€/kWh or 50€/MWh). The magnitude of subsidies such as Feed-in Tariffs and Renewable Obligation Certificates are not considered since they will not exist in a commercial market. For simplicity, possible variations of market value between locations and markets, due to output predictability and due to scale of the project are not considered (see EQUIMAR D7.2.1). Revenue is thus proportional to energy production. The assumptions of a constant (levelised) value of electricity and of a market value of €50/MWh are of course simplifications. Note that for higher market values, the resultant CAPEX and OPEX of the project would be increased proportionally.

3.1   PRESENT VALUE OF REVENUE

Neglecting time variation of unit electricity value, the present value of the revenue from a project which generates an average output of 100 MW is both technology and site independent. Annual revenue from such a project during each year i is simply:

$$R_i = 8760 \cdot 100 \cdot 10^3 \cdot MV \qquad\qquad \text{Equation 6.}$$

where MV the market value of electricity. Hence the net present value (NPV) of this revenue over an operating period of N years and for a discount rate of r is given as:

$$PV(R) = R \cdot (1 + r)^N / r(1 + r)^N = Ann(R) \qquad\qquad \text{Equation 7.}$$

Thus, at a constant discount rate of 8 % the NPV of revenue generated over 20 years will be 430 €M (Figure 1). Present value of all revenues increases proportional to any feed-in tariff or subsidy provided in addition to the market value per unit and decreases with increasing discount rate. Discount rates of 10 and 12% correspond to present value of revenue of 373 €M or 323 €M respectively. For a rated power of 250 MW, the capacity factor of this generic project is 0.4 and so the net present value per MW of installed capacity for 8% and 12% discount rate is 1.72 €M/MW and 1.31 €M/MW respectively (Figure 2). For a given rated power, energy production is proportional to capacity factor and so capacity factors in the range 0.35 to 0.45 correspond to a net present values in the range 1.51 – 1.94 €M/MW (i.e. 1.72€M/MW ± 12.5%).
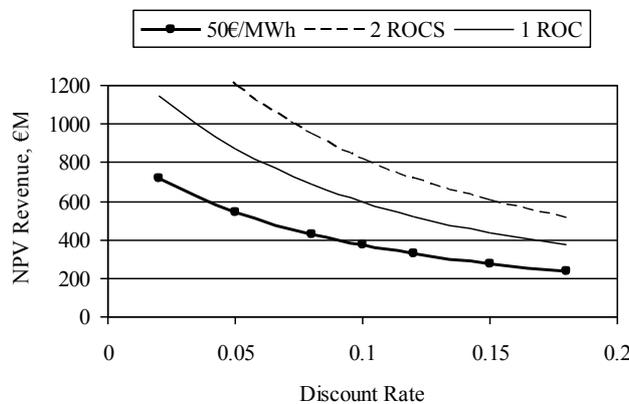

Figure 1: Net Present Value of revenue from arbitrary project generating average output of 100 MW over a range of discount rates. Project operating life of 20 years and market value of electricity of 50 €/MWh assumed.
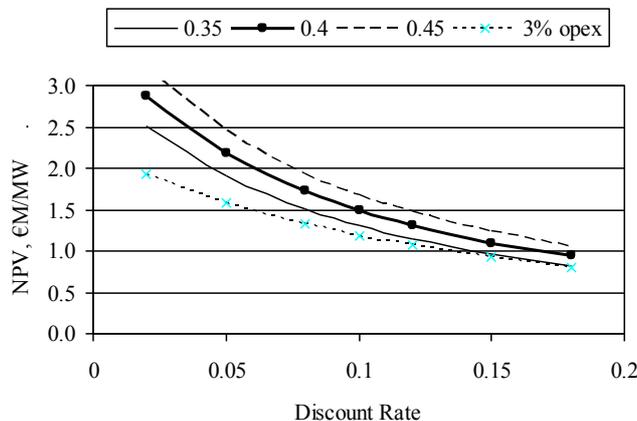

Figure 2: Net Present Value per MW of installed capacity for capacity factors in the range 0.35 to 0.45 for a project that would generate average power output of 100 MW during each year of a 20 year operating period.

3.2   CAPITAL COST

The total expenditure of Figures 1 and 2 must include all capital expenditures incurred prior to commissioning and all expenditures incurred during the operating life of the project. A simple approach for estimating annual operating expenditures (OPEX) is as a fixed percentage of the capital expenditure. Thus for OPEX = p x CAPEX, the present value of all expenditures can be reduced to:

$$PV(Ex) = CAPEX (1 + Ann(p)) = PV(R) \qquad\qquad\qquad \text{Equation 8.}$$

So, for example; consider a project at 8% discount rate; the net present value of all expenditures over the design life of the project must be less than 1.72 €M per MW of rated capacity installed if the average capacity factor of the project is 0.4. If the operating expenditures are 3% or 8% of CAPEX respectively then the capital cost must be less than 1.33 €M/MW or 0.96 €M/MW respectively for the project to return a positive Net Present Value (Figure 3).
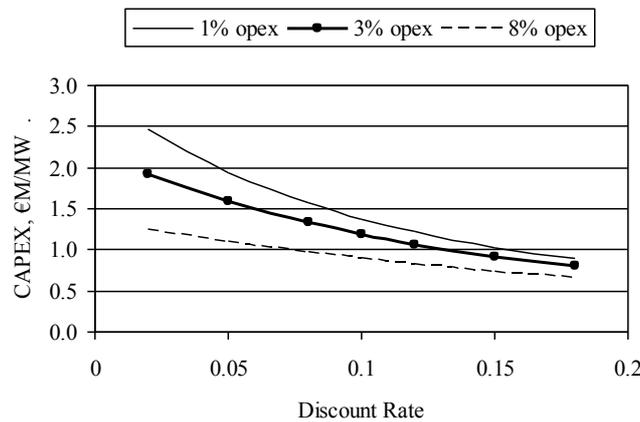

Figure 3: Specific capital cost (€M/MW) assuming annual operating costs in the range 0 to 8% of capital cost.

The values shown in Figure 3 are in a similar range to values suggested by the recent ETI & UKERC (2010) roadmap which suggests that a CAPEX of around 1900 €/kW would be required to produce a cost of electricity of 0.05 €/kWh by 2050), Table 1.

Table 1: CAPEX and OPEX of prototype, production and commercial marine energy technologies estimated by the Carbon Trust (2006) and UKERC & ETI (2010). Values in € obtained by 1GBP = 1.5€ and 3% inflation per annum.

		~ €/kW (2010)
Carbon Trust (2006)	First prototype wave	7250 – 15200
	First production wave	2900 – 7250
	First prototype tidal	8100 – 13500
	First production tidal	2350 – 5000
UKERC & ETI (2010)	CAPEX by 2050	1900 – 2500
	OPEX by 2050	4 – 12.5 €/MWh

The foregoing is for an arbitrary project that generates an average power output of 100 MW. In the following several types of device are considered to understand how this capital cost budget varies between sites and with technologies. Wave energy projects are considered since a range of published resource information is available. Wave occurrence scatter plots for eight sites are obtained from FugroGEOS (2001). Summary characteristics of each site are listed in Table 2. The following steps are taken:

1) Site resource and device performance dictate the number of devices in the project that are required to generate an average power output of 100 MW. The device types considered are briefly described in Section 3.4 and details of the model used for each device are given in Appendix A.
2) Transmission expenditures are estimated based on an a rated capacity of 250 MW (i.e. capacity factor of the project is 0.4) and on the distance from site to shore as described in Appendix B.
3) Operating costs are estimated based on two approaches; as a fixed percentage of capital cost and based on a simple assessment of vessel requirements. It is assumed that one day of vessel use is required per year per wave energy device. In addition both the transit time from site to shore and the duration of accessible conditions at each site are considered. Further details are given in Appendix C.
4) Capital costs for each device – comprising the three subsystems suggested in EQUIMAR D5.3 and associated infrastructure – are thus obtained as:

$$CAPEX = [PV(Revenue) – Ann(OPEX) – PV(transmission)] / NMEC$$

Table 2: Summary characteristics of eight sites based on wave data of FugroGEOS (2001).

Location	Shetland	N North Sea	South Uist	C North Sea	Irish Sea	S North Sea	Cornwall	Hebrides
Site code	14533	14541	15609	15138	15920	15512	16700	15354
Transmission Distance	200	90	110	75	30	75	50	350
Vessel Transit Distance	200	90	110	75	30	75	50	350
Depth (m)	130	100	110	110	40	25	85	200
Av. Peak Period, T_{Site} (s)	9.6	7.5	9.6	6.9	5	5.7	8.8	9.8
Av. Signifiicant wave height H_{site} (m)	2.64	2.25	2.79	1.79	0.96	1.33	1.9	3.16
Av. Power, P_{site} (kw/m)	33	19	37	11	2	5	16	49

For all projects considered, the CAPEX per MW is shown in Figure 4 for a project with constant OPEX of 8% of CAPEX and after considering transmission cable costs as discussed in Appendix B.
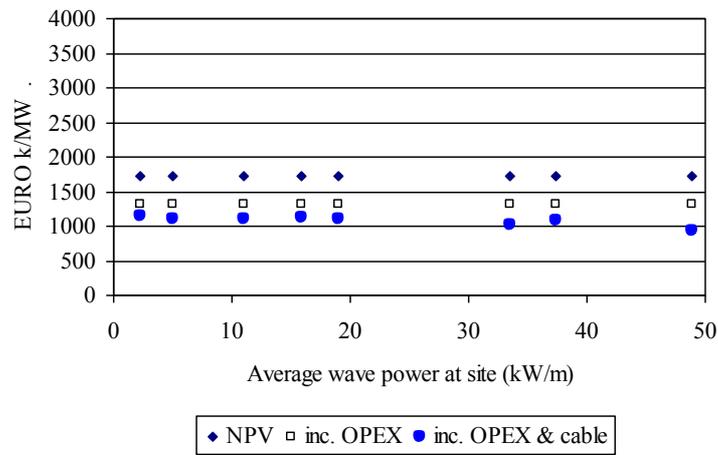

Figure 4: Specific capital cost (€ per kW of installed capacity) for wave energy projects assuming negligible OPEX (NPV), OPEX at 8% of CAPEX and after deduction of capital cost associated with transmission cable.

In the following sections, stages 1 to 4 are applied to several idealised devices to provide an indication of the capital cost per device that may be possible if improvements in device performance allow power output to approach the point absorber limit. Estimates of average power production per device and site are given in Sections 3.3 and 3.4

3.3   ENERGY PRODUCTION

Useful energy, typically in the form of electricity, is the only marketable output from a marine energy farm. Inaccurate prediction of power output can significantly alter economic viability (see e.g. D7.2.1 and D7.2.2). It is therefore important for designers to understand the full-range of wave- or tidal-stream conditions expected at the design site and to understand the power output expected from each device within the farm due to these conditions. Revenue may be calculated via several methods depending on the stage of development of the technology.

3.3.1   Rated Power and Capacity Factor

The simplest approach to estimate revenue is to consider an average value per unit of electricity and estimate energy production on the basis of the installed capacity of the project.

$$Revenue = RatedPower \times CapacityFactor \times T_{yr} \times AverageRevenue$$ Equation 9.

The capacity factor is defined as the ratio between the average power output of the project and the rated power. Typically capacity factors are in the range 0.25 – 0.4 but since they are defined as a function of generator rating artificially high values can be created by a technology that is rated at a lower power than required for the design conditions. Although this approach neglects site specific conditions it is widely used for assessing early stage concepts.

3.3.2   Occurrence plot and performance surface

Perhaps the most widely used approach is based on the performance curve of a typical device e.g. Power(Variable), the cumulative duration of Metocean conditions suitable for operation, e.g. Time(Variable), and the mean value of electricity. The duration of conditions Time(Variable) may be expressed as a probability of occurrence, e.g. p(Variable), multiplied by the duration of the period of interest. For tidal stream devices, a 1-D performance curve, Power(U_C), and 1-D occurrence plot, probability(U_C), may be employed where U_C the mean current speed. For wave devices a 2-D performance matrix, e.g. Power(H_s, T_p) and occurrence matrix probability(H_s, T_p) are typically employed. For a wave energy project, annual revenue would therefore be calculated:

$$Revenue = \sum_{0}^{H_{s,\max}} \sum_{0}^{T_{p,\max}} \big[Power(H_s, T_p) \cdot Probability(H_s, T_p) \big] \times Availability \times T_{yr} \times AverageRevenue \quad \text{Equation 10.}$$

This approach is generally applicable since it accounts for both site- and technology dependence of energy production. Further dimensions to the performance curve may be necessary for some technologies to describe sensitivity of power output to additional environmental variables or design parameters. A similar approach is used here to calculated device energy production but a power matrix is not calculated for the device. Instead an annual wave power spectrum $S_{Ann}(w)$ is obtained from the probability of occurrence of different sea-states as described in Appendix A.

3.4   DEVICE AND SITE COMPARISON

Three types of device are considered:

    I.   A heaving point absorber optimised for all conditions that occur at the site

    II.   A point absorber tuned to the annual average conditions at the site

    III.   The PWP power matrix as employed by EPRI (2004-06) with rated capacity of 750 kW.

The definition of device types I and II is given in Appendix A. The average power output for each type of device at the range of sites considered is shown in Figure 5.

For a device optimised for all wave periods (Type I), average power output varies between 2.65 MW at the site with annual average power density of 50 kW/m approx., down to 350 kW at the site with annual average power density of 11 kW/m (Figure 5). The sites with average power densities of less than 10 kW/m yield average power outputs of less than 100 kW even from the device optimised for all wave frequencies and so do not seem practical. Devices that are designed to generate optimal power output at the annual average peak period of the site (Type II) generate less than half the power output of an optimised device. For this type of device, smaller devices generate power over a narrower frequency range than larger devices. For example; a 10 m diameter device generates average output between 135 kW and 675 kW (11 kW/m site and 49 kW/m site respectively compared to 200 kW and 1280 kW from a 20 m diameter device at the same location.
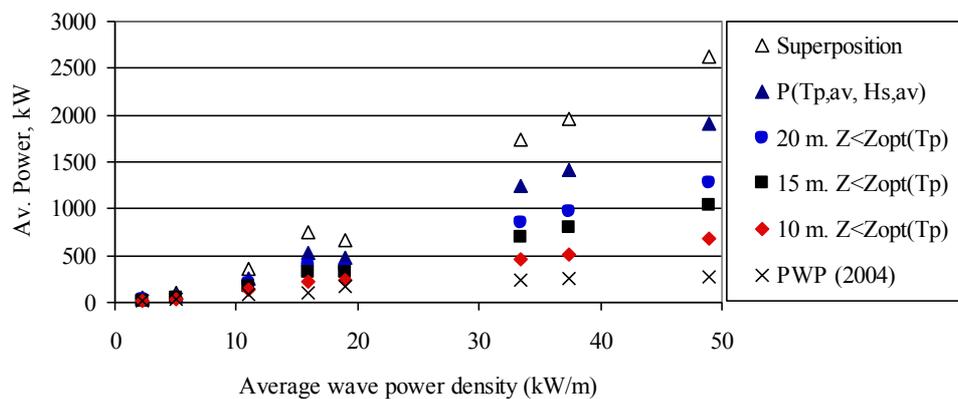

Figure 5: Average power output for a heaving float which attains optimal power output at all wave frequencies (Type I, see Appendix A) and for idealised devices of 20 m, 15 m and 10 m diameter that are designed to attain optimal power output at the peak period of the site (Type II, see Appendix A). Power output of Pelamis also shown for comparison based on performance matrix used by EPRI (2004)

For all device types there is considerable variation of average power output between sites and so there is a considerable variation between the numbers of devices that would be required to generate an average output of 100 MW (Figure 6). Although the capital cost per MW (Figure 4) would be similar irrespective of technology and site, the difference between device numbers results in quite different constraints on the capital cost per device that would be required to generate electricity at a similar unit cost at each site. This is shown in Figures 7 and 8 for two device types and a range of operating costs.
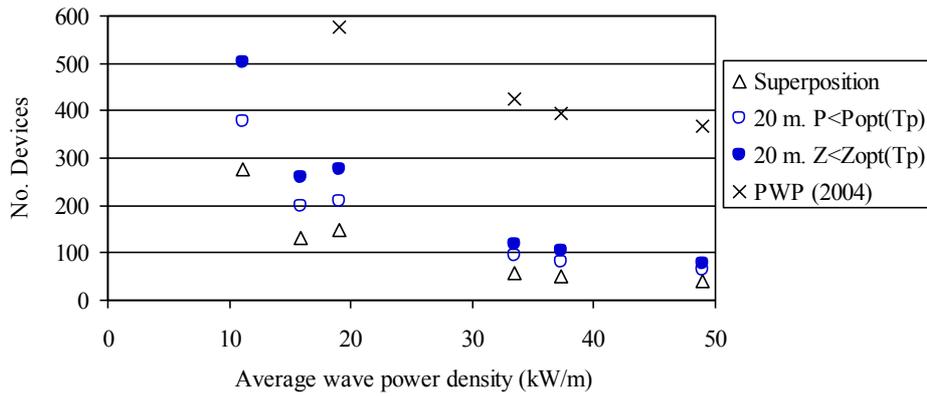
Figure 6: Number of individual heaving float wave energy devices required to generate a mean power output of 100 MW at eight sites. Devices shown represent optimal power output at all wave frequencies (Type I, see Appendix A) and a 20 m diameter system that is designed to attain optimal power output at the peak period of the site only (Type II, see Appendix A). Number of Pelamis also shown for comparison based on performance matrix used by EPRI (2004).
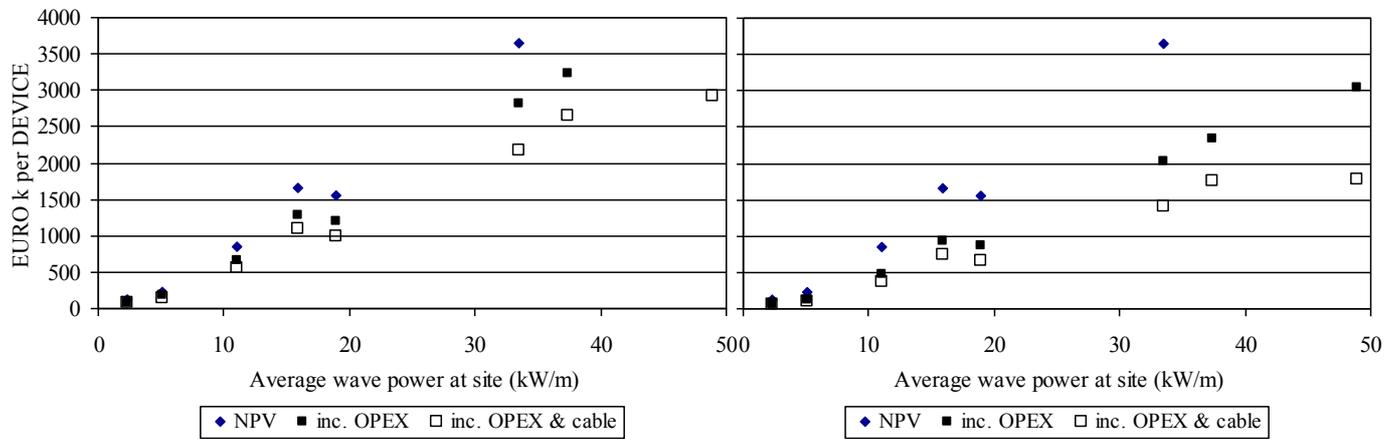

Figure 7: Net Present Value and Capital Cost associated with wave device designed to attain optimal power output at the peak period of the site (20 m diameter device of Type II, see Appendix A) at each of eight sites. Annual operating cost assumed as (LEFT) 3% per annum and (RIGHT) 8% per annum. Estimate of transmission cable capital cost as Appendix B.
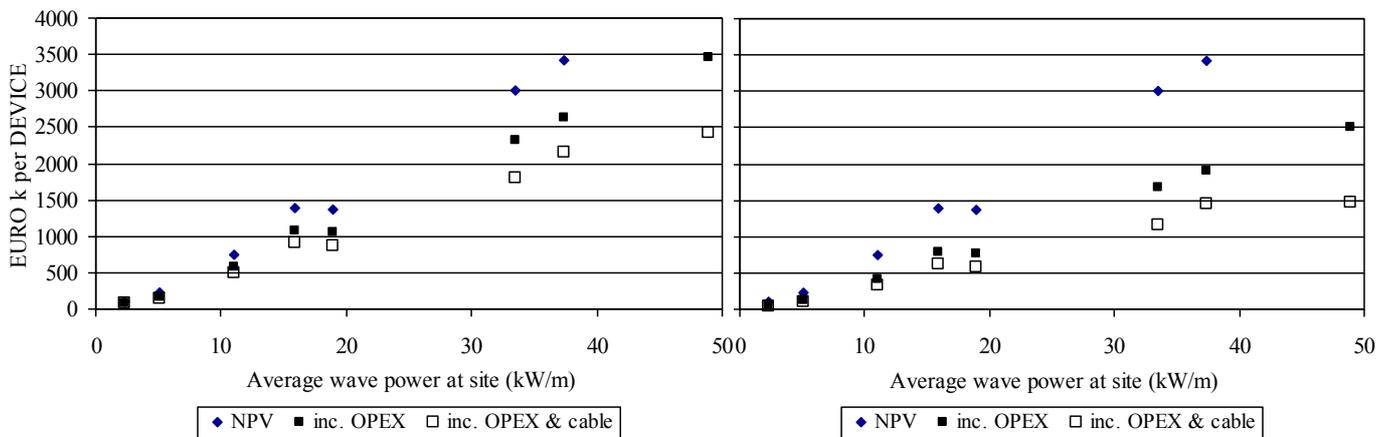

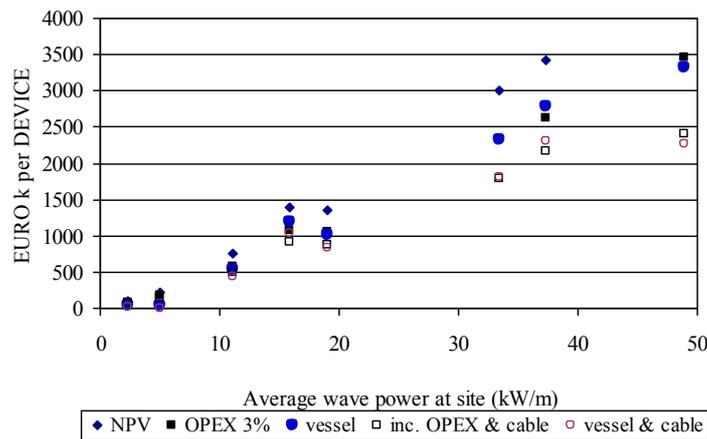Figure 8: As Figure 7 for device type II of 15 m diameter.

Figure 9: As Figure 8 for operating cost of 3% capital cost and for site- and technology dependent operating cost evaluated based on vessel access considerations as described in Appendix B. Average vessel-based operating cost across the eight sites considered is 3% of capital cost.

For each of the idealised devices considered the net present value of expenditure per device differs considerably between sites. This is entirely due to the different power output of devices at different locations. The net present value of all expenditures varies between around €750k to a little over €4000 k depending on the device type. After accounting for operating expenditures and transmission expenditures, the capital cost per devices varies between €500 k and €3000 k depending on operating cost assumptions and whether transmission costs are included in the analysis. The sites with higher average wave power are generally located further from shore and so transmission costs represent a significant fraction of the total expenditure at sites with greater than 30 kW/m average wave power. If operating costs are considered on the basis of a simple site access model, there is only marginal variation of the capital cost budget at each site (Figure 9) but this is substantially less than the variation due to individual device performance.

4 SUMMARY

For a marine energy project to yield a positive net present value, the present value of revenue must exceed the present value of all expenditures. A nominal 'commercial' value of electricity of 50€/MWh is considered to quantify the capital cost per MW of installed capacity and the capital cost associated with each device for a project of 100 MW average output. This project results in a positive net present value only if the total expenditure is less than 1700 €k/MW. After accounting for estimates of operating cost and transmission cable cost, this requires the capital cost of the project to be less than 1200 €k/MW. This value does not vary significantly with technology or site. However, the number of devices and hence the cost per device varies considerably with both site conditions and technology. Several idealised wave devices of the oscillating body type are considered to evaluate the capital cost per device that would allow electricity to be generated at an equivalent market value.

For a single wave device that is designed to produce maximum output as defined by point absorber theory in all sea-states, the average annual output per device remains small (typically less than 1 MW at sites with annual power density less than 45 kW/m. More accurate predictions of maximum output could of course be made accounting for constraints on a particular device concept but this is a general limit for single devices of the heaving point absorber type. For tidal stream devices, dimensions will be limited by water depth and, as for wind turbines, by structural considerations related to blade and support structure design. Power output has not been quantified for these systems in this study but is expected to be of the order of 1-2 MW per turbine. Thus, as for wave farms, commercial deployments (e.g. 100 MW capacity and above) must comprise large numbers of devices. For the wave sites considered there is considerable variation of the number of devices required to generate an average output of 100 MW. For this reason, it is useful to consider the capital cost associated with each device (i.e. €M/device) rather than the capital cost per installed MW of capacity (€M/MW installed). The cost per device varies between around €500k to €3500 k depending on the device type, operating cost assumptions and whether transmission costs are included in the analysis. For sites with average wave power of around 30 kW/m, the capital cost per device would need to be less than €1250 – 1750 approx. to generate electricity at a levelised cost of around 50 €/MWh.

Throughout this study, all estimated values of revenue, CAPEX and OPEX are based on an assumed 'commercial' value of electricity of 50€/MWh. It is recognised that this is not necessarily a representative value for a commercially viable technology and does not include market incentives. The calculated values of CAPEX and OPEX shown in figures and in the text are proportional to the assumed market value of electricity and so the values shown can be scaled to consider different assumptions of electricity value.

A. IDEALISED DEVICES

Power output from a device at each site is calculated based on the principle of superposition. That is, power output of the device is defined for a wave of unit amplitude over a range of regular wave frequencies and response at each frequency subsequently scaled by the amplitude of each regular wave component as defined by a wave power spectrum. Average power output is the sum of the average power output in all wave frequencies that occur at the site during a year.

For each site, an annual power spectral density is obtained as the summation of a spectra associated with each combination of H_s and T_p that occurs at the site. For example; for a site where $i = 1$ to N combinations of (Hs, Tp) occur each with a probability of occurrence P_i, each sea-state is described by a spectra $S(\omega) = S_B(H_s, T_p)$ and the annual power spectrum is obtained as:

$$S_{Ann}(\omega) = SUM(\ P_i \cdot S_B(\omega)_i\ )$$
<div align="right">Equation A.1</div>

The corresponding amplitude spectrum is given by:

$$|A|(\omega) = [\ 2S_{Ann}(\omega) \cdot d\omega\ ]^{\frac{1}{2}}$$
<div align="right">Equation A.2</div>

In the following, a Bretschneider spectrum is employed to represent each sea-state and the resultant annual spectrum for each of the eight sites is illustrated in Figure A.1. It is acknowledged that this may not accurately describe all conditions (see comparison to JONSWAP spectrum in Figure A.1) but sensitivity to spectrum shape is not considered further at this stage.
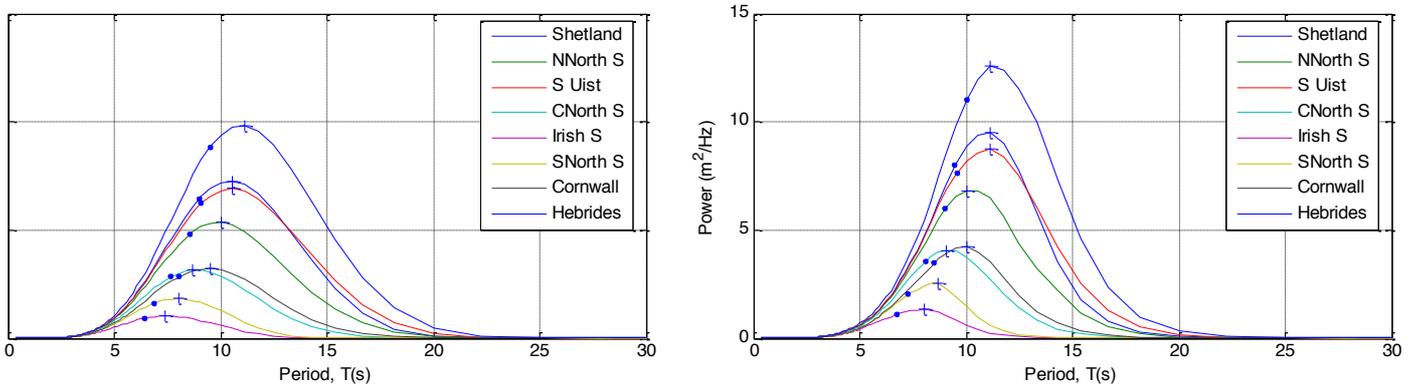

Figure A.1: Annual power spectrum obtained for each site by summation of (Left) and Bretschneider spectrum (Right) JONSWAP spectra with spectral peakedness parameter $\gamma = 3.3$, for each sea-state that occurs at the site. Annual peak period (+) indicated for each site. Bretschneider spectrum used for site comparison study.

Several idealised devices are considered as follows:

I. Optimal device, power at each regular wave of angular frequency ω ($= 2\pi f = 2\pi/T$ where f the frequency and T the period) is obtained for unit wave amplitude as:

$$P_{opt}(\omega) = \rho g^2/4\omega\ L/2\pi$$
<div align="right">Equation A.3</div>

This average power output is equal to

$$P_{opt}(\omega) = F(\omega)^2 / 8B(\omega)$$
<div align="right">Equation A.4</div>

Where F(ω) the wave-induced excitation force on the (stationary) immersed surface of the float due to regular incident waves of frequency ω. B(ω) is the component of the radiation damping force due to oscillation of the float at frequency w and unit velocity, w|A|. This is comparable to the system studied by McCabe et al. (2009) which operates at the point absorber limit at all wave frequencies that exist in an irregular wave field.

II. Device tuned to the peak period, of the annual power spectrum, ($T_{p,av}$):
A heaving device is considered as a single degree of freedom spring-mass-damper system (e.g. Falnes, 2003; Thomas, 2008) such that average power output is obtained in terms of applied mechanical damping (R) and response amplitude (Z):

$$P(\omega) = \tfrac{1}{2}\ R\omega^2 Z^2$$
<div align="right">Equation A.5</div>

$$Z(\omega) = F(\omega) / (\omega^2 M + \omega(B(\omega) + R) + S\ )$$
<div align="right">Equation A.6</div>

An axi-symmetric float with radius a is employed such that $S = \rho g \pi a^2$ denotes the hydrostatic stiffness. The total mass (M) is specified such that the natural period of the float is equal to the peak period of the annual power spectrum. i.e.:

$$M = S\ (T_{p,av}^2 / 4\pi^2)$$
<div align="right">Equation A.7</div>

Thus, the mass employed includes the added mass at the period T_p but frequency variation of added mass is neglected. Mass is also independent of displaced mass. As a result, the natural frequency of the float is $T_N = T_{p,av}$.

Rather than conducting a diffraction analysis for the float geometry, the excitation force is estimated as an approximation to the Froude-Krylov force only for all wave frequencies. A constant pressure is assumed across the (stationary) circular base of the float at draft 10 m such that:

$$F(\omega) \sim F_{FK}(w) = \rho g \pi a^2 \cosh(k(z-d)) / \cosh(kd) \qquad \text{Equation A.8}$$

Where k the wavenumber ($k = 2p/L$) and d the water depth at each site. Subsequently, frequency dependent radiation damping is obtained from the equivalence of optimal power output as obtained by Equation (A.1) and Equation (A.2). i.e:

$$B(\omega) = F(\omega)^2 / 8P_{opt}(\omega) \qquad \text{Equation A.9}$$

Where $P_{opt}(w)$ obtained by Equation A.3 as a function of wave frequency only. Figure A.3 shows the frequency variation of excitation force and radiation damping obtained using this approach for a water depth $d = 200$ m.
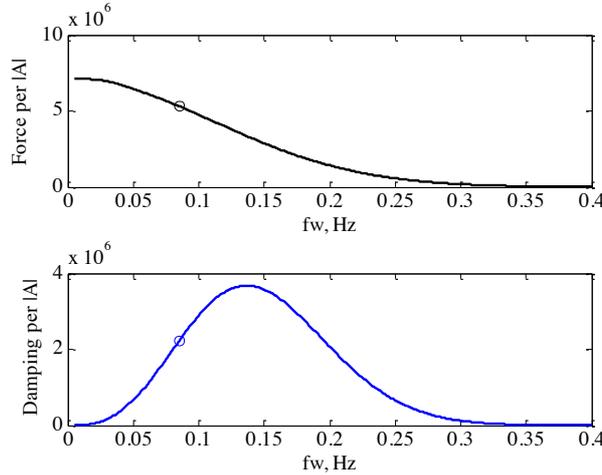

Figure A.2: Approximation to Froude Krylov force (Eqn A.7) and corresponding radiation damping (Eqn A.8).

The mechanical damping, R, is specified as equal to the radiation damping corresponding to the peak period:

$$R = B(T_{p,av}) \qquad \text{Equation A.9}$$

For each case two limits are imposed:

$$P(\omega) < P_{opt}(T_{p,av}) \qquad \text{Equation A.10}$$

  Power at all frequencies less than power obtained at the natural period of the system (or, equivalently, at the annual average peak period at the site).

$$Z(\omega) < Z_{opt}(T_{p,av}) \qquad \text{Equation A.11}$$

  Maximum response amplitude occurs at the natural frequency of the system.

The power, P(w), and response, Z(w), curves given by Equations A.5 and A.6 are dimensionalised for the site spectra by multiplication by the component wave amplitude $|A|(\omega)$ and square of component wave amplitude, $|A|(\omega)^2$ respectively: Where $|A|(w)$ obtained by Equation A.2 from the annual power spectrum associated with the site. The resultant response spectrum and power density spectrum are shown in Figure A.4.
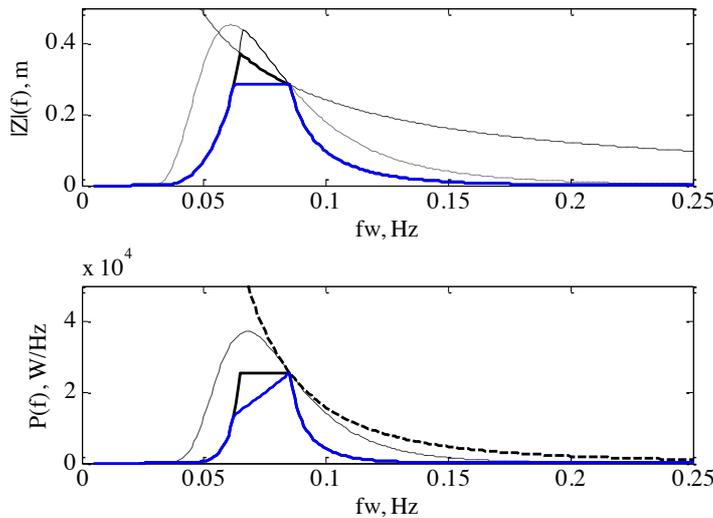

Figure A.3 : Response (Z, top) and power spectrum (P, btm) for 20 m diameter at Site 1. Optimal response curve (dashed curve) generates average power output 1738 kW; (solid black curve) power limited to Popt(Tp) generates average power output of 830 kW and (solid blue curve) response limited to Zopt(Tp) generates average output of 703 kW.

B. TRANSMISSION INFRASTRUCTURE COSTS

For a particular site, the cost of manufacturing and installing a transmission cable from the wave power plant to a grid connector is mainly dependent on cable capacity and so will be similar irrespective of generating technology if the mean output is comparable. For this reason, the cost of transmission is sometimes excluded from cost studies to facilitate comparison between alternative marine technologies. However, for commercial scale marine energy power generation schemes, the capital cost of grid connection and construction of fabrication facilities must be considered (D7.2.1, D7.6). Transmission costs should be considered because the costs associated with design, manufacture and installation of the system can represent a large fraction of the total capital costs and partly because two distinctly different approaches are employed. Perhaps the majority of device developers propose the use of an electric cable which may be similar to those used for offshore wind farms (HVAC) or, for higher capacity of more distant sides may employ High-Voltage DC systems (HVDC). In contrast, a minority of developers propose the use of a hydraulic pipeline to transfer energy to the shore combined with onshore electricity generation via, for example, low head hydro-turbines. For example; this approach is proposed for the Aquamarine Oyster system and CETO which are designed for deployment at relatively shallow sites close to a shoreline[1].

Many studies have been published of the costs associated with manufacture and installation of high-voltage electrical interconnections and associated infrastructure (Atkins, 1992; Garrad Hassan, 2003; Black & Veatch, 2004; Halcrow, 2005; EPRI, 2005, Lopez et al. 2010, Dicorado et al. 2011). Although direct cost comparison of AC and DC systems is not widely available, at present, installation of 33kV cables seems to be the cheapest option for distances up to 20km and power levels up to 200MW (Grainger and Jenkins, 1998). At greater distances, the appeal of this approach is reduced due to increasing cable laying costs and electrical losses. The appeal of HVDC cables increases with required power and transmission distance and, in the long term, installation of a direct DC link looks promising for arrays with rated power greater than 200MW located more than 25km from shore (Grainger & Jenkins, 2003). Other studies suggest that greater transmission distances or rated powers must be considered before HVDC is the lower cost option. EConnect (2005) suggest HVAC transmission are likely to exhibit lower lifetime costs when transmission distance is greater than 60 km or required capacity greater than 300 MW whilst Boehme et al. (2006) suggest that the costs do not breakeven until rated powers of 325MW and transmission distances of 250km are considered.

The capital cost of both types of electrical transmission system is dependent on distance to shore, electrical power generated in the farm and the choice of an AC or DC connection. The main costs for either type of electrical transmission system are represented by the foundations, generators and onshore (grid) connection. These costs increase with increasing distance to shore and water depth. In addition, the cost is sensitive to the composition of the seabed and cable landing facilities (EPRI, 2005). A summary of cost-estimates for specific sites and of general cost functions based on unit length are given in Table B.1. Here, the distance to site is taken as a straight line between the wave site and the nearest shoreline. No account is taken of variation of bed material. Clearly, estimated costs vary considerably but are a large fraction of project NPV for all sites (compare Figure B.1. to Figure 1). For comparison between sites (as Section , the cost functions of Boehme et al. (2007) are used as plotted in Figure B.1.
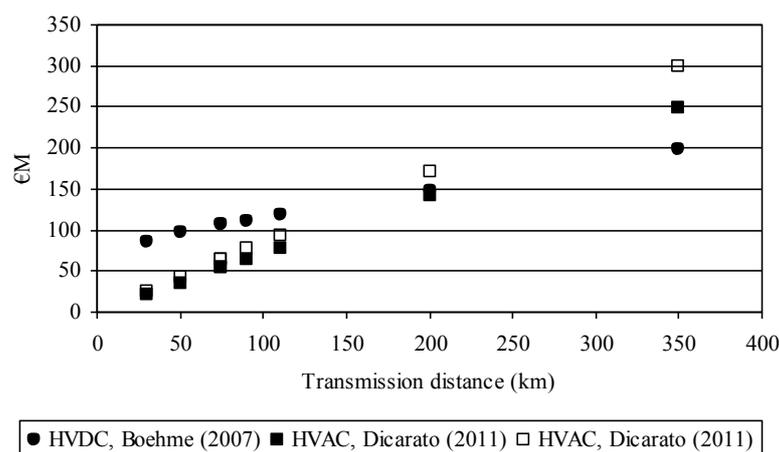

Figure B.1: Cost estimates for a High-Voltage cable of 250 MW rated power for the eight UK sites considered based on cost functions listed in Table B.1. Values adjusted from year of publication by 3% inflation.

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[1] e.g. www.aquamarinepower.co.uk and www.carnegiecorp.com.au

Table B.1: Cost estimates for electrical transmission system between marine energy site and onshore grid connection point.

Cost	System Description	Reference
50 $M (Total)	8km 250MVA (90MW), California	EPRI (2005)
13.5 £M (Total)	20 km cable and 30 MW subsea transformer. Wavehub, cornwall	Halcrow (2005)
210 £/m	10 MW transmission cable	Atkins (1992)
1620 £/m	400 MW transmission cable	
100 £/m	Cable procurement	Black & Veatch (2005), Halcrow (2005), EPRI (2004)
60 £/m	Cable installation	EPRI, (2004)
225 £/m	Cable installation	GarradHassan (2003)
$47.6 + 4.063L$ for transmission distance L	HVAC (132 or 275kW) manufacture & installation	Boehme et al. (2006) Section 4.7.
$162.4 + 0.675L$ for transmission distance L	HVDC (150 kV) manufacture & installation	Boehme et al. (2006) Section 4.7.
$250 + 26.5\exp(380\text{Irate}/10^5)$	HVAC 132 kV k€/km	Dicorato et al. (2011)
$403 + 14\exp(462\text{Irate}/10^5)$	HVAC 230 kV k€/km	
52-72	Cable Transport k€/km	
286-463	Cable Installation k€/km	

All values in currency of year of publication.

C. MAINTENANCE RATES BASED ON SITE ACCESSIBILITY

Annual expenditures are required to ensure that the device availability and power output assumed in the revenue calculation are maintained. Annual expenditures will include insurance, conduct of maintenance, conduct of repair and several other costs. In many studies, the total operating cost is expressed as a percentage of the total capital cost (Dalton et al., 2010). UKERC & ETI suggest that operating costs must reduce to a levelised cost of less than 65 £/MWh to generate electricity at a levelised cost of less than 50 £/MWh.

Although straightforward to apply, OPEX written as a percentage of CAPEX is an oversimplification that neglects both site- and technology-specific constraints. Detailed analyses of specific projects consider the reliability of devices and accessibility of the site to obtain site- and technology-specific costs (EPRI, 2005). The operation and maintenance (O&M) schedule for an offshore renewable energy scheme influences both the period of individual device operation, hence the revenue from electrical output, and the periodic expenditure required to implement the designed schedule. Many studies of operational processes have been produced within the offshore wind industry (Herman, 2002; AMEC, 2001) but the greater energy density of waves at the design sites of marine energy schemes increases the importance of efficient O&M planning as demonstrated by D7.4.1-2. AMEC (2001) suggest that, for wind turbines at least, maintenance costs should be considered on a per device basis and this is a logical assumption for offshore devices where the time required to access individual floating structures is not insignificant.

Here, an estimate of one aspect of maintenance expenditures is considered for each of eight sites. The approach employed is to consider the number of vessel days required for each project if, on average, one day of maintenance is required per wave device per year. Site-accessibility data presented in D7.4.1-2 is employed to account for the reduction of site-accessibility associated with increasing power density. Application of this approach to eight UK sites indicated that a waiting on weather allowance was required prior to each day of accessible conditions. The number of days waiting required varies from about one day at sites with annual average power density of less than 10 kW/m up to six days at sites with average power density greater than 40 kW/m.

The approach taken here is as follows:

1) Select number of maintenance activities required per wave device, $N_{Task/MEC}$. (Note that these activities may be on project components such as support structures, mooring lines, cables or electrical infrastructure rather than individual devices)
2) Select number of maintenance activities completed during a single visit to the site, $N_{Task/Trip}$
3) Determine total number of maintenance activities, $N_{Task} = N_{MEC} / N_{TaskMEC}$
4) Determine total number of trips to site required, $N_{Trip} = N_{Task} / N_{Trip}$
5) Calculate total transit time, $T_{Transit} = N_{trip}$ x L_{Port} / V_{Vessel}. A nominal vessel speed of xx km / hr is assumed for all vessels based on REF.
6) Calculate vessel working time, $T_{Use} = N_{Trip}$ x 24 hrs
7) Calculate vessel waiting time, T_{Wait}, based on values given in wave-site accessibility study of D7.4.1-2.
8) Total vessel time required, $T_{Vessel} = T_{Transit} + T_{Use} + T_{Wait}$
9) Annual vessel cost, OPEX1 = T_{Vessel} x VR where VR a vessel day rate (€k).

Clearly, the annual vessel cost estimated by this method is dependent on assumptions regarding device reliability ($N_{Task/MEC}$), number of maintenance activities completed per trip ($N_{Task/Trip}$) and the vessel rate (VR). Identical assumptions regarding reliability are made for all sites to facilitate comparison. Barrett (2005) and Ragliano Salles (2003) studied the monthly variation of offshore vessel day-rates over a ten and five year period respectively for the North Sea fleet. They report mean day-rates in the range £5-7.5k/day for anchor handling, towing and supply vessels (AHTS), approximately £5k for offshore supply vessels (OSVs) and approximately £2.5k/day for crew supply vessels. Typically rates are observed to be lower for vessels that are widely available but considerable variation is typically observed due to local demand. ODE (2008) present a simple model for estimating vessel rate whilst accounting for supply and demand. However, to facilitate comparison between sites, the vessel rate is assumed equal for all of the projects considered. A nominal rate of €10k/day is assumed in this report based on average values of £5 k/day for typical OSV of 2003 inflated at 3% per annum to 2010 and converted to EUROs.

Application of this approach to each of the eight sites considered is shown in Figure C.1. This results in a range of vessel costs that vary by a factor of more than two over the six sites with power levels greater than 20 kW/m but are an order of magnitude larger for sites with particularly low power density (e.g. less than 10 kW/m). When expressed as a percentage of capital cost, vessel rates alone correspond to between 1.1-2.5% of CAPEX for each project. This increases to between 2.4-5.36% of CAPEX if a nominal vessel rate of €20k/day is assumed or, equivalently, if vessel rates are assumed to represent half of the total operating cost. In the
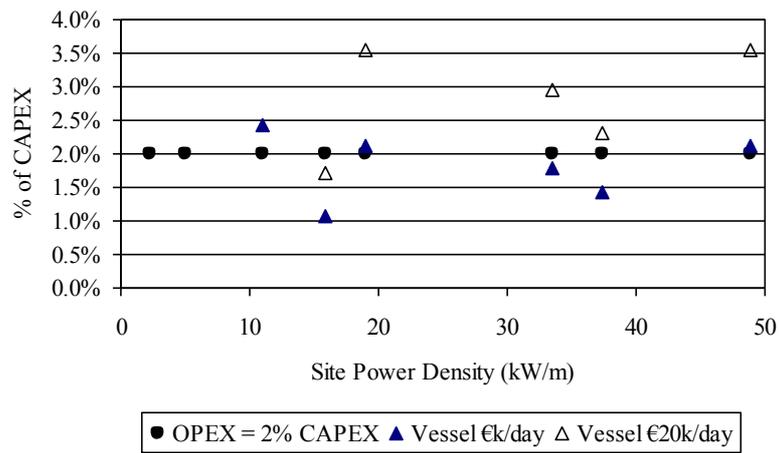
Figure C.1: Estimated vessel cost associated with each of the wave energy projects considered. All projects comprise sufficient wave energy devices to generate an average power output of 100 MW. The vessel day rate and the quantity of maintenance required is identical for all sites. Vessel costs are shown for device type II only (see Appendix A) for two day rates.

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