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

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Identification of Limitations of the Current Practices Adopted for Early Stage Tidal and Wave Device Assessment

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Identification of Limitations of the Current Practices Adopted for Early Stage Tidal and Wave Device Assessment

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Summary

Wave and tidal energy technologies are in there infancy in commercial deployment and operation. Although many devices exist in concept, only a small number have progressed to scale testing either in test tank or scaled sea conditions. With a number of devices existing at the concept stage and all seeking resources to progress prototype models, it is important to establish what current practices are adopted to appraise the performance of concept devices and the quality checks implemented to ensure a degree of accuracy is attained when undertaking this. In addition to the assessment processes undertaken, it is also important to understand how data produced from this early assessment is presented and used in order to establish appropriateness and fit for purpose. In order achieve this for both wave and tidal energy devices respectively they have been treated as two separate entities and as such this reports the current practices being adopted for wave and tidal devices and identifies the limitations inherent with current practices. The report is structured in a format which treats wave and tidal devices separately due to the different architecture associated with the devices and the physics of operation. Part A reports the limitations associated with current practices adopted in the early stage assessment of tidal devices, while Part B reports the limitations of current practices adopted for the early stage assessment of wave devices.

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Section A: Tidal Device Assessment

Tidal stream technology assessment processes

Tidal stream technology is in its infancy with a broad range of devices either at the conceptual, model or full-scale demonstrator stage. Meaningful power generation (defined as input to the electrical grid) may well be achieved in the medium term thus it is critical that methods and criteria are set in place imminently to assess the tidal devices that will receive public funding and that eventually may see full-scale production and deployment. A robust assessment criteria is required to identify the strengths, weaknesses and potential risks associated with any device and to ensure due diligence is exercised at each development stage. These assessment criteria will involve both experts in the subject area to conduct the assessment and also a set of tools (methodologies, numerical simulation etc.) to be used to complete the assessment tasks. If this is achieved the following benefits would be realised:

- Better allocation of public funding
- A more robust tidal energy sector
- A clear pathway for developers to follow to market

The following report attempts to identify the limitations of the current practices adopted to undertake **initial conceptual appraisal of tidal devices**, specifically with regard to: power capture; conversion and power take off; and station keeping.

It is hoped that once present limitations are clearly defined, enhanced assessment criteria can be set in place to benefit the industry. This document summarises the results arising from information provided by tidal energy device developers with regard to current appraisal and assessment processes.

1. Methodology

Information was gathered from a very wide range of tidal developers (see 0). The limitations of current practice identified will later be used to produce a set of guidelines that will in future allow developers or assessors to more efficiently progress tidal technologies to market. All information submitted was treated as strictly confidential and therefore all responses are summarised and made anonymous in this report.

Initial concept appraisal would seem to be very broad and highly dependent on the developer's needs with regard to satisfying their own demand for concept viability. To gain the maximum expertise and experience from those who have developed tidal devices each known developer was asked a series of questions related to initial tidal device assessment. This was undertaken by means of a personal email invitation, an online information request (see 0), and follow up telephone calls were necessary.

The information request was based around the commonly used assessment subsets of: power capture, power take-off and power conversion, station keeping, computational methods, and general topics such as risk and economic viability. However some questions were left open-ended to allow for any variation from the assumed norm.

2. Outcomes

5.1 Summary of Responses

The status of all the developers approached (refer to 0) was not entirely known, and indeed it is thought that a small number may not presently be operational. Feedback was very quickly received from 12 of the 36 listed developers including a number who would be widely recognised as the market leaders in this emerging industry.

Those who responded are developing a very wide range of technologies including single and multi-rotor horizontal turbines, vertical axis turbines, vertically oscillating foils and horizontally moving hydrofoils. Additionally the devices are both devices fixed (piled or other structure) to the seabed and those floating (moored) within the water column or at the sea surface. The information submitted and the comments made are therefore representative of a very wide proportion of tidal experience and innovation.

5.1 RESPONSES CONCERNING NOVELTY AND FACETS ASSESSED AT CONCEPT APPRAISAL

Every respondent had made a search to determine novelty before any early appraisal was made. Novelty was almost always determined by means of a patent search, and otherwise by analysis of any existing devices. The specific areas of early concept appraisal and evaluation are summarised in *Figure 1* as a percentage of all those replying to the information request. All developers who responded were extremely aware that commercial viability was the bottom line of any appraisal, although the early assessment of the technical merits was normally the basis on which this would be judged – as reflected by the figures in *Figure 1*.

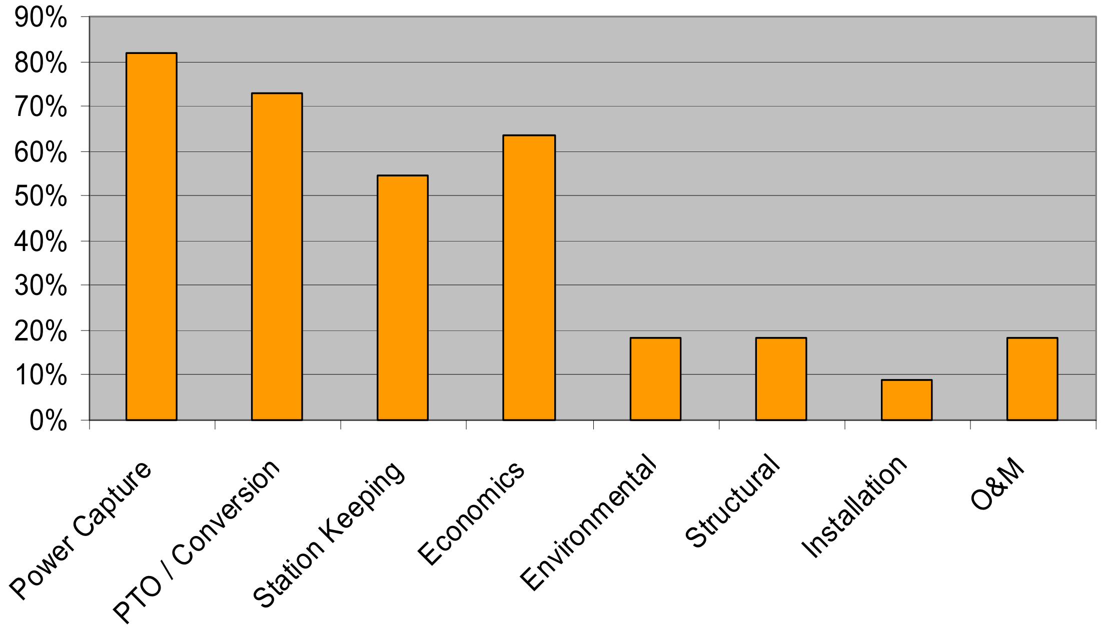

Figure 1: Factors Assessed during Early Stage Device Appraisal

Interestingly, 91% of respondents had undertaken informal model testing as a part of their initial concept assessment. The reasons given for this were linked to basic confirmation of operation, risk reduction, and basic physical proving which was seen to be more easily (reliably?) undertaken than computational modelling.

5.1 RESPONSES CONCERNING POWER CAPTURE, TAKE-OFF AND CONVERSION

The very early conceptual stage assessment of power capture, power take-off and conversion was generally undertaken for the following reasons (all eventually related to commercial viability – see *Figure 2*):

- To produce an approximation of a likely tidal stream to estimate and optimise system performance.
- To evaluate the prime mover full operational envelope power output characteristics and so identify the most suitable power-take off system
- To calculate the full water-to-wire efficiency of the system
- To identify the primary design drivers

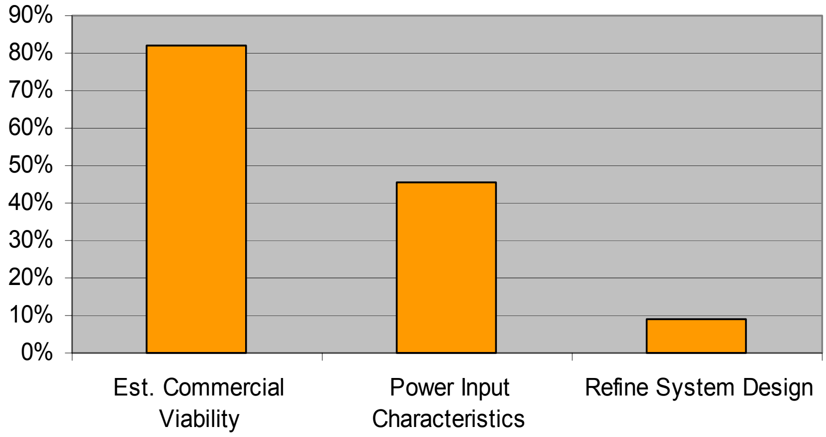

Figure 2: Reasons for Power Capture Assessment

With respect to power take-off and conversion, commercial viability continues as the main reason for assessment, however *Figure 3* also shows that these evaluations begin to influence the basic design decisions, for example, type of power take-off and conversion system best suited for grid connection, reliability, O&M etc.

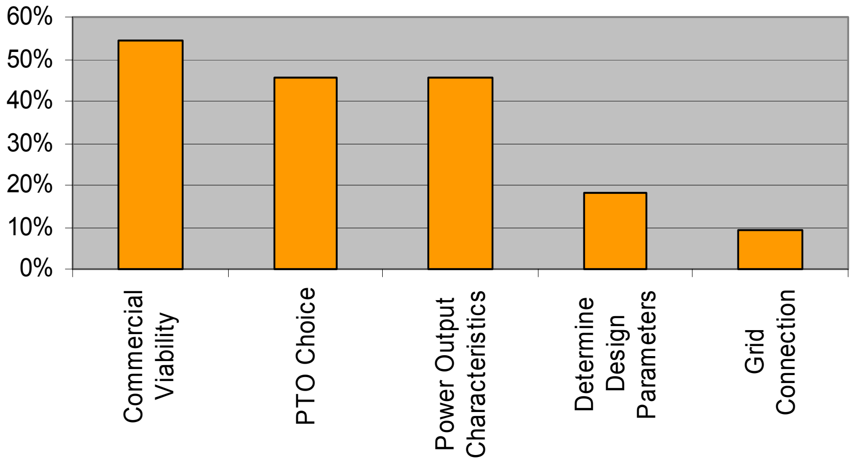

Figure 3: Reasons for Power Take-off and Conversion Assessment

A number of interesting points were made with respect to the level of detail, accuracy and limitations of the power capture, take off and conversion parameters evaluated:

- Conservative design assumptions should be used to avoid overly optimistic technology evaluation.
- Sensitivities in flow velocity make for large differences in performance evaluations.
- Effects of surface waves and turbulence are noted as being difficult to quantify both in real terms and in terms of power output.
- Complexities in scaling accurately (subsequently noted with scaled models).
- That the entire system should be optimised as a whole to determine all primary design sensitivities.
- To aid accurate evaluation and costing even at the earliest stages, advice and data from expert equipment manufacturers should be used where possible.

5.1 Responses Concerning Station Keeping

Station keeping refers to the method by which the tidal device retains its position (or limited movement) with respect to the tidal stream. Those responding that this was an important part of their assessment (10/12) had a very wide range of methods proposed, however this study finds a number of agreed areas of importance for early stage assessment as outlined in *Figure 4*. The level of assessment undertaken was generally conceptual (quasi static force calculations) at the early stages of device development, and was later refined during tank and sea tests.

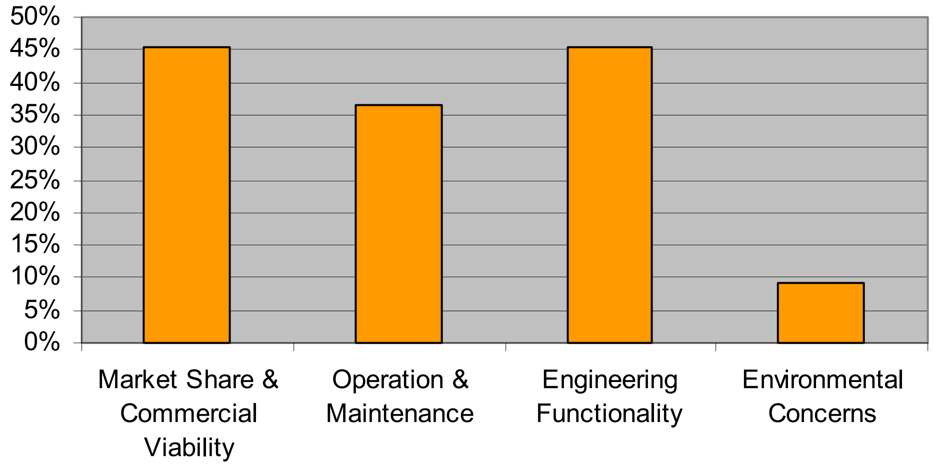

Figure 4: Reasons for Station Keeping Assessment

5.1 RESPONSES CONCERNING COMPUTATIONAL METHODS

All tidal device developers responded that they had undertaken computational modelling, although only 60% had developed their own mathematical models or codes. It should be noted that due to the constantly evolving nature of each device's development it was difficult to determine the level to which this had been undertaken for early stage device evaluation. The later stages of device development use very complex and complete models, of which very little information is publicly available due to commercial sensitivity.

Responses however suggest that spreadsheet based models are commonly used as initial assessment tools to determine the sensitivity of basic design parameters, although these tend to be focused on each device developers own preferentially chosen factors and assumptions as alluded to in the previous sections on power capture, take-off and conversion.

Efficiency of power capture (and hence assessment of commercial viability) is the primary reason for additional modelling (CFD, BEM, Vortex Theory, Streamtube Models) at the early concept evaluation. The majority of such modelling (often undertaken in partnership with R&D partners) used either commonly available commercial packages or packages previously developed for other sectors, for example, wind turbines. Such modelling is most often used to inform the design of future small scale demonstrators and to provide the early scaled predictions for the commercial viability of full-size devices.

A secondary reason for computational methods is structural integrity, although this tends to be focussed on the later stages of technology development/design and will therefore not be further discussed here.

Verification of the early stage conceptual modelling is rarely undertaken at this stage, with the vast majority of respondents only being able to quantitatively verify any outputs during or post the scaled test programme and particularly once sea testing had been undertaken at a reasonable scale.

The early concept appraisal limitations of the current state-of-the-art modelling (outside of very device specific issues) from respondents are generally:

- The issue of relevant and accurate scaling factors.
- Modelling techniques are not adapted or specifically defined for underwater (hydro-dynamic) systems.
- The lack of widely available tidal data sets or a generally accepted proxy to use in the modelling of a device.
- Research organisations are often very cynical of new innovative ideas that do not lend themselves to established modelling techniques.
- A major concern is the lack of relevant publicly available research and literature - which leads to each developer producing their own state-of-the-art models.
- A lack of defined and accepted terms, for example with regard to turbulence, blockage, solidity etc.

Further additional concept development limitations of the current state-of-the-art modelling identified include:

- Evaluation of wake effects and their impacts for tidal arrays.
- Dynamic loads and stability issues.
- Lack of vigorous and defined environmental procedures and factors.
- Modelling of materials in the sea – particularly composite materials.

5.1 Responses With Regard to External Advice and Mitigating Risk

73% of respondents indicated that they undertook a risk assessment of the initial assessment methodology and technology. A small number of developers (36%) claimed to use formal methods such as FMEA, HAZOPS at a very early stage; however risk assessment was usually informally undertaken on a conceptual level at a very early stage of the development in order to identify possible "showstoppers" as well as to focus and correctly sequence the R&D effort.

Much uncertainty and hence risk was noted as being associated with possible and rarely defined environmental objections - despite having what was thought to be a technically competent device. This was underlined as of great concern even at the conceptual appraisal stage.

5.1 Responses Concerning Other Issues

It should be noted that all developers contacted could be noted as serious contenders and visible in the field by their experience and state of development. Thus the experience of the academic and test facilities becomes important at the very early appraisal stage as this is often where initial ideas are first sent for a basic concept appraisal. It is our experience that Government and development agencies often pass on many such early stage technology appraisals to such entities as they have some experience in the field without the obvious commercial self-interest of other developers.

Advice or guidance on how to proceed with device appraisal was externally sought by half of all developers surveyed. Of those receiving advice, all except one had turned to the academic sector for help. The actual feedback concerning academic advice was that very often the academics had a limited understanding or willingness to tackle innovative concepts.

This may explain why so many developers attempt to build basic conceptual devices before any computational or formal modelling takes place. Issues that cannot be modelled tend to be tackled by empirical methods during testing. With this are used "*sound engineering experience, analysis, judgement and innovative problem solving*".

As a foil to the novelty argument the words of a very experienced tidal developer would also seem important: *"novelty is not a virtue, it just increases the risk of failures. Therefore novelty needs first and foremost to be justifiable in terms of possible benefits (i.e. lower cost, better performance, etc) to outweigh the increased risks. It is a business; engineering and financial judgement based on whatever analysis can reasonably be carried out."*

3. Limitations Identified for Early Concept Appraisal

With regard to guidelines or standards for early stage concept assessment, a theme ran through many of the developer responses which could perhaps be summarised as scepticism because:

1. there are not enough experts /expertise to set or evaluate these,
2. tidal devices tend to be highly varied or unconventional at the conceptual stage and may not fit into a set of guidelines.

However a couple of respondents noted that the "hype produced by some developers" with regard to technical and commercial status will lead to a breakdown of trust between investors and the tidal industry. This presumably adds to the argument that it is necessary to deliver a suite of protocols for the equitable evaluation of marine energy converters, however it is noted that a wide inclusive expertise and approach to innovative technology must be retained.

This work package of EquiMar therefore seeks to identify the current limitations with respect to initial tidal concept appraisal and notes the following general limitations with respect to current equitable technology evaluations.

Limitation 1 – Lack of standardised experts to provide full initial concept appraisal

The scientific community active on the subject is very narrowly populated and unconvincing (in the experience of some developers) particularly with regard to unconventional concepts and innovation. It would be best assessed by people with genuine relevant experience of real tidal device technology. By its nature marine energy technology requires expertise in many disparate areas which are unlikely to be accessible to any single person or institution.

Suggested measure - a list of neutral experts using some of the appraisal schemes suggested below might begin to enhance the expertise base.

Limitation 2 – Incomplete or partial system concept submissions

In the words of a developer: “rigorous evaluation before moving through stages should be mandatory if any public money is involved”.

Suggested measure – a ‘gated’ checklist of general assessments completed by recognised neutral experts requiring some basic evidence for all system components (and system integration) to ensure that the developer has a complete and viable concept or system.

Limitation 3 – Lack of a general tidal dataset for early concept appraisal

Various developers were critical of those who utilise the best possible tidal sites to make their devices look more attractive than is either realistic or honest.

Suggested measure - perhaps an initial generalised standard set of trustworthy tidal site data against which all early stage concepts may be appraised. This would not provide a definitive energy output or cost-benefit answer, but would allow an early filter for technologies that are not realistically appraised.

Limitation 4 – A lack of standardised modelling know-how and published information

There is a perceived lack of published fundamental marine turbine research and few publicly available agreed definitions of fundamental properties.

Suggested measure – further fundamental research should be undertaken and published. An accessible general explanation of, and published methodology for various fundamental properties and common modelling issues, e.g. solidity, blockage factors, the scaling of tidal devices, generalised wake modelling, etc., etc.

Limitation 5 – Incomplete appraisal of non-technical factors

Technologies are noted by developers as often not taking into account the physical, environmental, commercial and regulatory realities in their assessment.

Suggested measure – standard and accepted general guidelines / checklist for initial concept appraisal before public money is granted. Could be an additional part of the general technical early concept assessment?

Limitation 6 – Lack of resource to complete a robust early concept appraisal

The aforementioned proposed measures should help to improve and bring forward serious well thought through technology innovation, however cost will be incurred. Although it can be argued that the private sector should be entirely responsible, the best ideas will not necessarily reside with those who have early financial access. Therefore to bring forward the greatest economical benefit to all concerned it may be appropriate for some (matched) state aid to incentivise innovation and prevent unnecessary monetary wastage at a later stage.

Suggested measure - a small ‘hands-off’ ‘inspiration’ fund (€2000 maximum) for each conceptual appraisal (particularly expert engagement) provided once an interview and online form /spreadsheet checking the very basic physical and economic parameters have been completed. The requirement would be to adhere to the general appraisal guidelines therefore providing an excellent lead-in to gaining informed follow-up investment from the public and private sectors.

4. Further Work and Conclusions

The six major limitations of equitable evaluation identified by developers during early concept assessments are outlined in the previous section but may be summarised as:

1. Lack of standardised experts to provide full initial concept appraisal.
2. Incomplete or partial system concept submissions.
3. Lack of a general tidal dataset for initial concept appraisal.
4. A lack of standardised modelling know-how and published information.
5. Incomplete appraisal of non-technical factors.
6. Lack of resource to complete a robust early concept appraisal.

General suggestions are made as to how to reduce these inequalities for fair concept appraisal and informed investment. These would make use of a two-way flow of information to the benefit of all, specifically: better published research and technical definitions of common comparators; checklists of necessary evaluations (technical, regulatory, economic, environmental) to prove general system integrity; the training of and access to neutral experts for sound evaluation and advice; and a small resource to incentivise innovation along these lines.

The next stage of this EquiMar work package will attempt to add detail to these suggestions in full consultation with the tidal community. The over-riding principle being to incentivise the widest possible innovation while providing equitable evaluation of all types of tidal technologies in a non burdensome manner.

SECTION B: WAVE DEVICE ASSESSMENT

5. INTRODUCTION

This information request from tidal device developers and technology assessors attempted to identify the limitations of the current practices adopted to undertake initial wave energy device concept appraisal, specifically with regard to: power capture; conversion and power take off; and survival issues. In this instance *'Early Stage*' refers to the concept validation section of Phase 1 of the Development & Evaluation Protocol being introduced in this project. The full structured test programme is as follows:

- **Phase 1**: Validation Models (Concept, Performance, Optimisation)
- **Phase 2**: Design Model
- **Phase 3**: Process Model
- **Phase 4**: Prototype
- **Phase 5**: Demonstration

The information was kindly submitted by a significant number of current wave energy device developers including those at the leading edge of their field. The information they provided will be used to identify the limitations of current practice so as to produce a set of guidelines that will in future allow developers or assessors to more efficiently evaluate and progress wave energy technologies to market.

5.1 INFORMATION GATHERING

All information submitted was treated as strictly confidential and made anonymous in this report. The information was gathered due to the participants kindly giving their time to either fill out the questionnaire online or completing the survey that was sent to them via email. This resulted in an initial return of 13 completed forms from the 36 wave energy developers contacted. Additional to this, 14 other interested bodies, such as utility companies and engineering consultants, were contacted in relation to this information request, however most of these felt they had no contribution to make. Subsequently follow ups involving personal communications was undertaken to increase the level of respondents.

The survey is broken down into nine sections, which deal with the obstacles that a device developer may be faced with at the early stage of concept validation or device development. These sections are as follows:

- General Device Information
- Concept Appraisal
- Computational Methodology
- Performance Assessment
- Conversion & PTO Assessment
- Station Keeping Assessment
- Seakeeping & Survival
- Operation & Maintenance, Deployment
- Risk Assessment

Each of these assessments were further broken down into whether it was considered in the device concept appraisal, what tools or information were used during the appraisal and mostly what were the limitations of the process. Throughout, there was sufficient opportunity for further comment on issues that may need to be addressed further. A copy of the questionnaire is included in the appendix.

6. GENERAL DEVICE INFORMATION

The introductory section of the questionnaire was aimed to get an overall feel of the device types and how the concept of validation and novelty is addressed by the device developers. The questions covered device type, the number of patents filed and how novelty of the device was determined. Figure 5 shows the distribution of the device type.

The other device types that were included by the questionnaire participants was attenuator type devices. The results of this are indicative of the current concern regarding wave energy and the multiple device types that exist and the consequent problem in drawing up standards that can accommodate each type in detail. This is further exacerbated by the fact that over 70% of the devices included in this survey are new concepts.

Before device validation got under way, the novelty of the concept had to be verified and this was done by either a search of the patent records or of the internet. The results of this are shown in Figure 6, which indicates that in fact both mediums were searched extensively. The novelty of the concept was determined through in-house expertise and experience, and subsequently through the successful award of patents.

Once the novelty of the device was established, patents were filed by all the participants internationally and at least half of the developers filed patents in their resident countries also. This and the number filed are shown in Figure 7. The average number of patents filed is between approximately six, although some devices have had a very large number of successful patent applications.

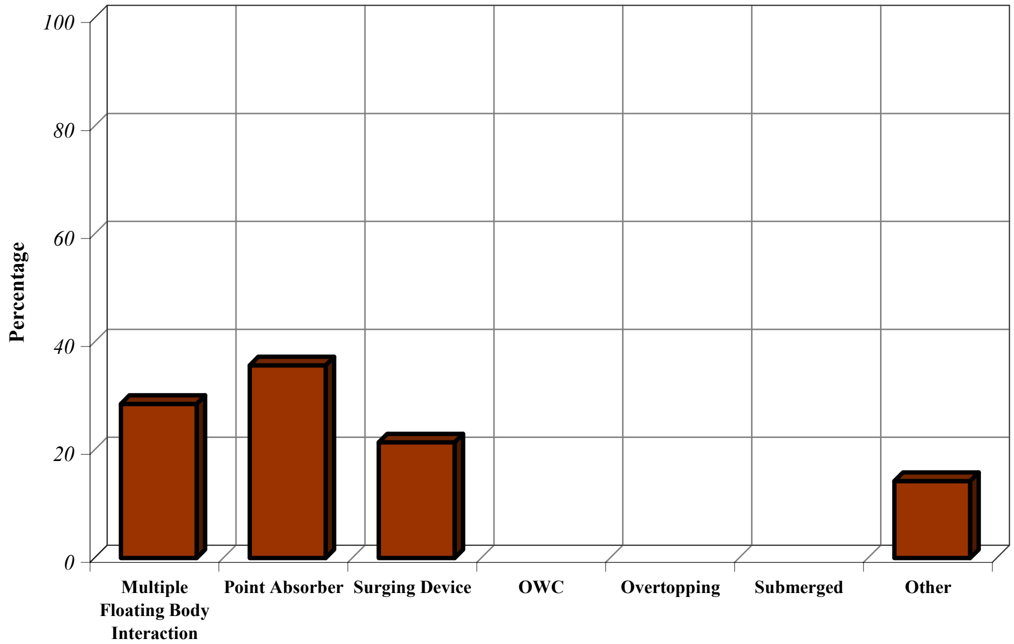

Figure 5. Device Type

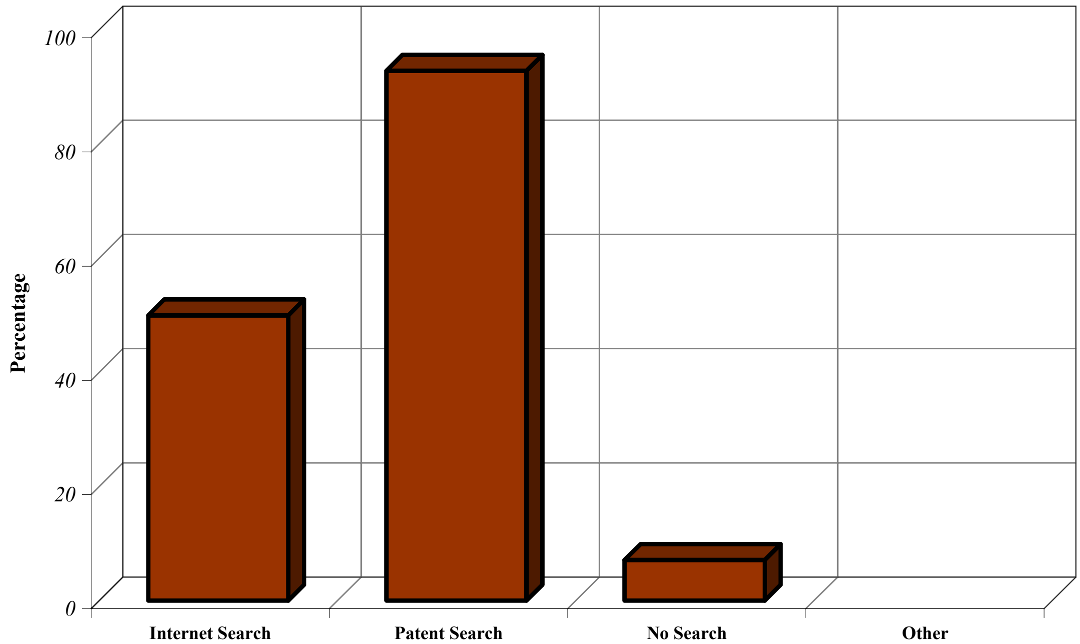

Figure 6. Databases Searched For Concept Novelty.

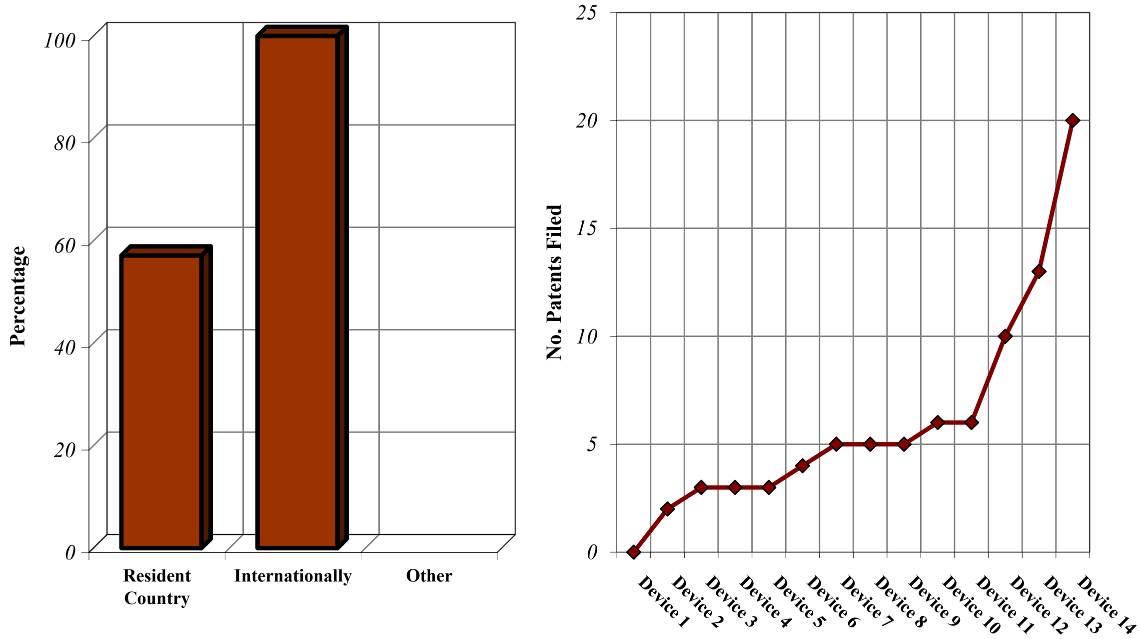

Figure 7. Patent Application Location & Number of Patents that Apply to Each Device

7. CONCEPT APPRAISAL

This section focused on the most important aspect of the device, and the subsequent methods of validating and studying it. Several options were available to the participant developer and more than one option was available for choice. The results of this selection process are shown in Figure 8. Interestingly, no one topic stands out, with power capture, seakeeping and survival being the main concerns to device developers. Obviously, the economic potential of the project is also of extreme importance at this early stage of development.

Having identified the areas of the device that were of most concern, it was asked how this was studied. Over 80% of the participants undertook some form of physical model testing in order to appraise the concept and validate the theory. It is assumed that those developers who didn't engage in physical small scale tests were limited by the complexity of their devices' operation. For the majority of developers that did conduct physical trials, the reasons are shown in Figure 9. It is clear from this plot that the main reason for the model testing was to validate a mathematical model of the theory and complexity of the device in question. Outside of the options given in Figure 9, the participants also indicated that physical modelling was conducted to verify the device power output, array interaction, shallow draft motions and the measurement of efficiencies.

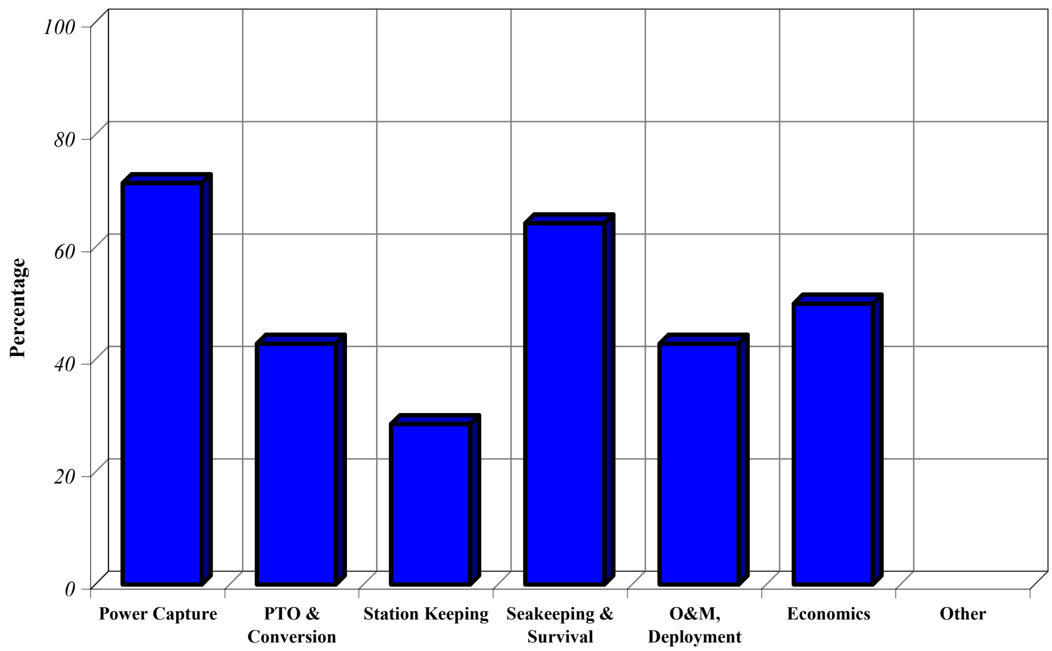

Figure 8. The Most Important Elements of Early Concept Appraisal

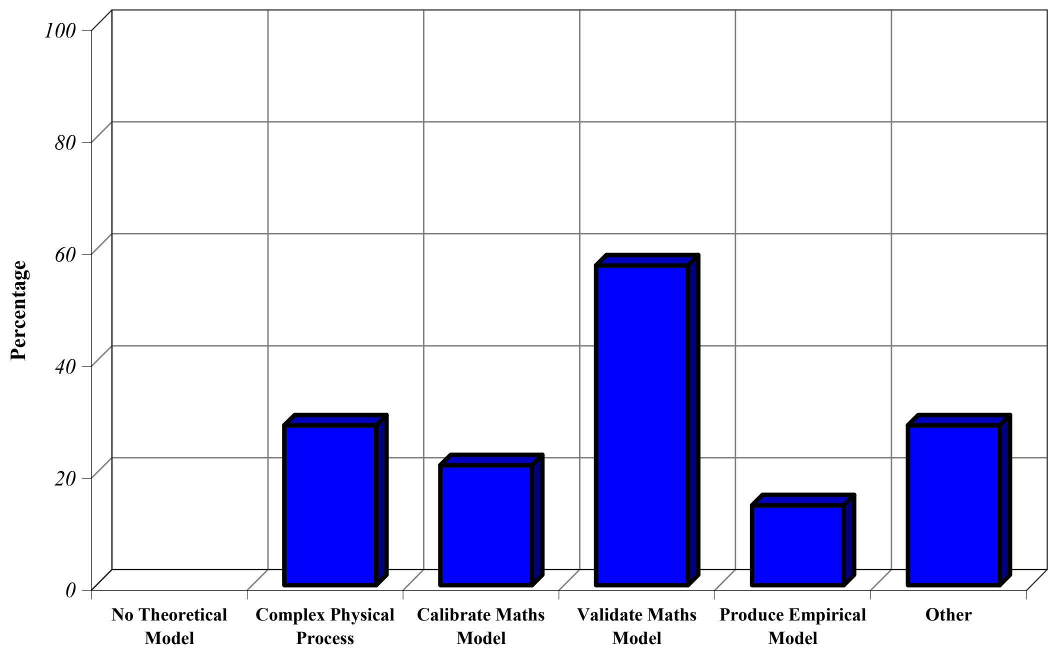

Figure 9. Purpose of Computational Models

8. COMPUTATIONAL METHODS

In most cases of wave energy converter concept assessment, complex physics are involved which can be adequately modelled by presently available mathematical packages. However, it is important to realise that these computational methods have assumptions and limitations, and that the coupling of these with the outcome of physical modelling is important at this early stage of product development. The aim of this section was to ascertain who is employed to carry out this numerical modelling, what commercial packages are used and if the numerical programs were found to be satisfactory. Figure 10 shows that for those developers who carried out testing in the computational domain (85%), the majority of it was conducted within the confines of the company (57%). Figure 11 shows that if external expertise was sought, it came from a mixture of consultancy firms and university groups.

The domain in which these numerical packages are run is also of importance, and the general consensus was that it was best practice to operate the mathematical models in both the time and frequency domain, although the theory of operation of the specific device would tend to dictate which was more favourable. For instance, some developers found that computation in the time domain was sufficient for their devices. As expected, due to the diversity of the technology, a third of the companies have developed device specific code for their respective wave energy converters. It was generally found that numerical modelling constitutes both sinusoidal waves and irregular sea states, of varying wave height and period, and of differing spectral shapes. These codes or models were used to determine wave structure interactions, optimisation, and power production. Control design was generally performed in the time domain. The products that were used for this evaluation is shown in Figure 12. The most popular choice for computational modelling was WAMIT, a frequency domain based wave structure interaction tool. The percentage attributed to 'Other' in Figure 12 is mooring design software such as ORCAFLEX and Flexcom.

Figure 13 shows which performance matrices were established from the use of the mathematical packages. Multiple answers were allowed and it is clear from the plot that power performance, body motions and loads were ranked as important as the next. As expected, power performance is of the greatest concern to developers at this early stage of concept appraisal as it is a key factor in the economic viability of the project. More details of this aspect are discussed in the next section. Mostly, the numerical modelling is used to validate the code against the physical testing, to optimise the device design, and verify the economic projections.

The participants were asked to comment on the present 'state of the art' of computational modelling techniques and if any limitations to the process were noted. The general consensus is that, while linear theory models are adequate for this phase of device development, the non-linearities involved are not well understood and care should be taken of the assumptions made. The importance of validating the models with physical trials was also stressed. It was mentioned that specialist training is required to use these numerical packages, and especially in the case of CFD, they are extremely time consuming. Defining the boundary conditions can also be a challenge. Finally, concerns were raised about the difficulty of modelling survivability in extreme waves, and the non-linearities associated with this, i.e. wave profile and characteristics. The limitations of the tools available for array interaction, especially in the time domain was also expressed.

The participants were asked their opinion on the present perceived lack of clarity in relation to wave energy terminology and definitions. Mostly there is agreement that there does exist a confusion in relation to the characteristic terms in use and their definition, especially in the frequency domain. The two prominent topics of discussion were regarding the wave periods being used and their subsequent definition, either temporally or spectrally, but also what characteristics and definitions should be used for the measured output performance? It was suggested by some that single parameter device rating is not enough and that the average power output of a given sea state should be used in the form of power curves. Also, as wave energy is an intermittent resource, yearly output rather than installed capacity should be used as a defining characteristic of the device.

It became apparent that at least half the participant developers were able to achieve detailed design parameters without the use of sophisticated numerical packages, and that the output of the computational programs were verified with results from scaled physical trials. For the case where the mathematical computer programs was not able to model the novel design aspects of the device concept, the participants indicated that these novel aspects of the device were addressed through extensive physical model testing and the subsequent development of suitable numerical simulation packages.

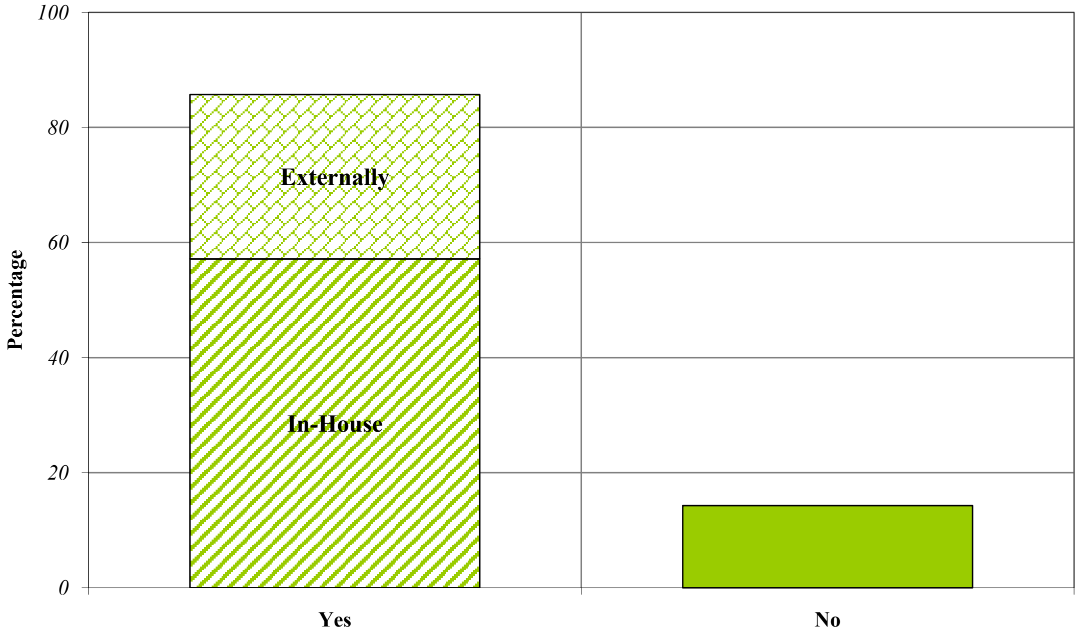

Figure 10. Proportion of Mathematical Modelling Done Internally and Externally

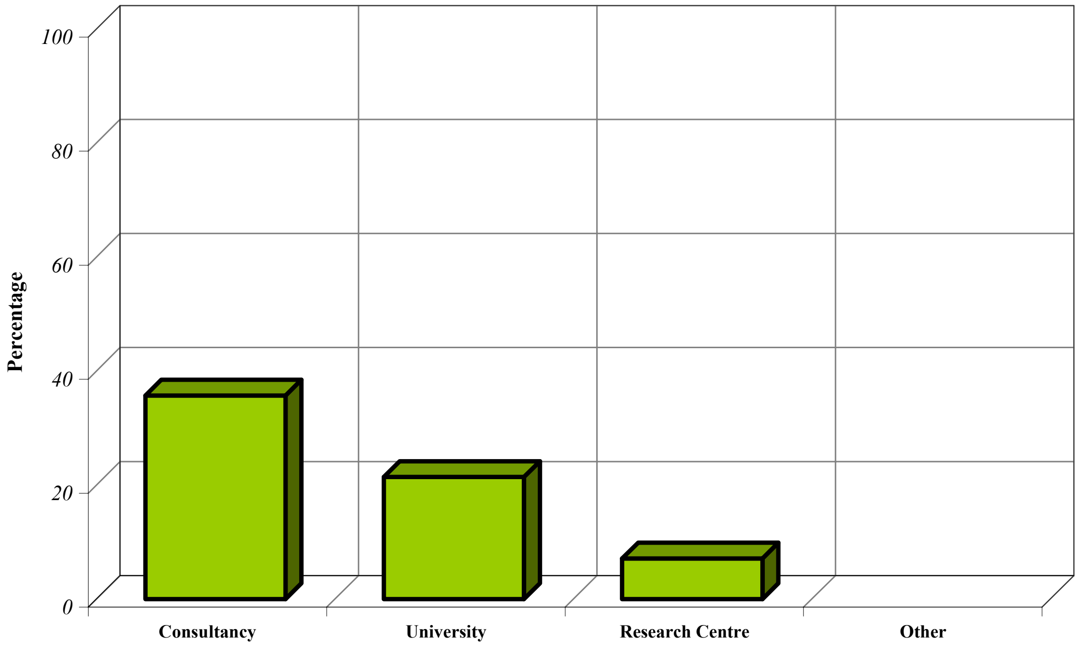

Figure 11. Percentage of External Expertise Sought

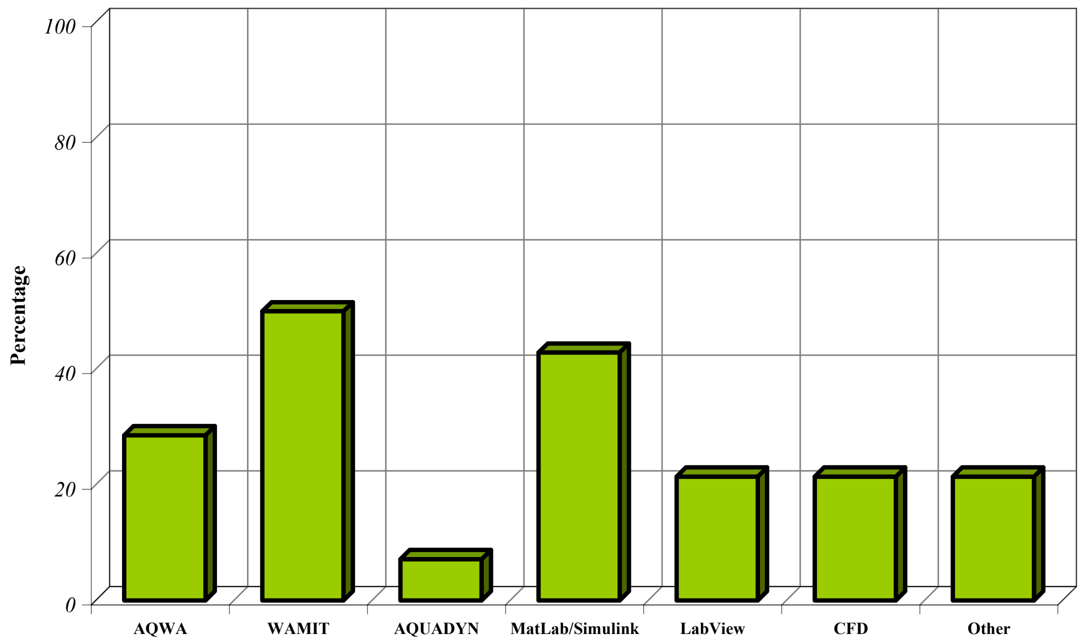

Figure 12. Computational Packages Used for Mathematical Modelling

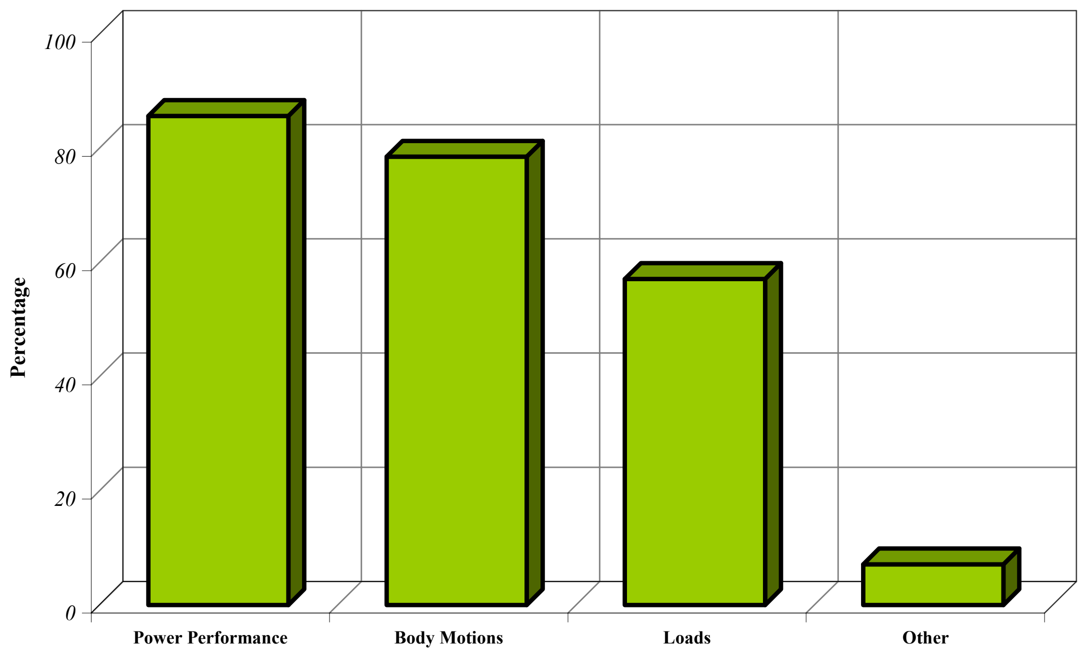

Figure 13. Items Modelled by Mathematical Methods

9. PERFORMANCE ASSESSMENT

All those developers who completed the survey participated in the assessment of their devices power capture. The objectives of this study are shown in Figure 14 and it is clear that power absorption and the impact on the economic viability of the device are at the forefront, while the analysis of significant design changes to power output and the measurement of efficiencies were also investigated. Figure 15 shows in which wave regime the performance assessment was conducted with the majority of the developers incorporating trials in both regular and irregular waves but also including directional sensitivity and wave grouping analysis.

The following is a list of some of the areas and parameters investigated during this phase of the testing schedule:

- actual power output and damping levels
- inter body forces, velocities and displacements
- conversion efficiencies and capacity factors
- wave parameters, frequency spectrum distributions and directional spreading

The limitations and perceived accuracy was deemed to be somewhat device specific, where there was a general difficulty in getting detailed wave data, i.e. the spectra of the wave measurement as opposed to just the summary statistics. Scaling effects were also of concern to some device developers, especially scaling device performance from this initial concept verification phase to the full scale.

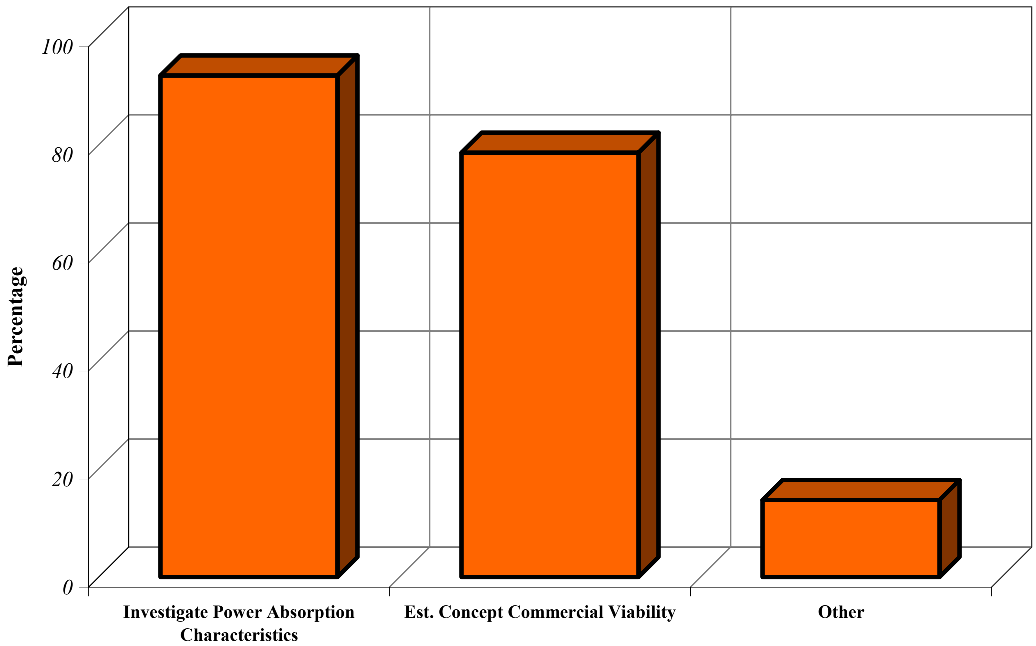

Figure 14. Objectives of Performance Assessment

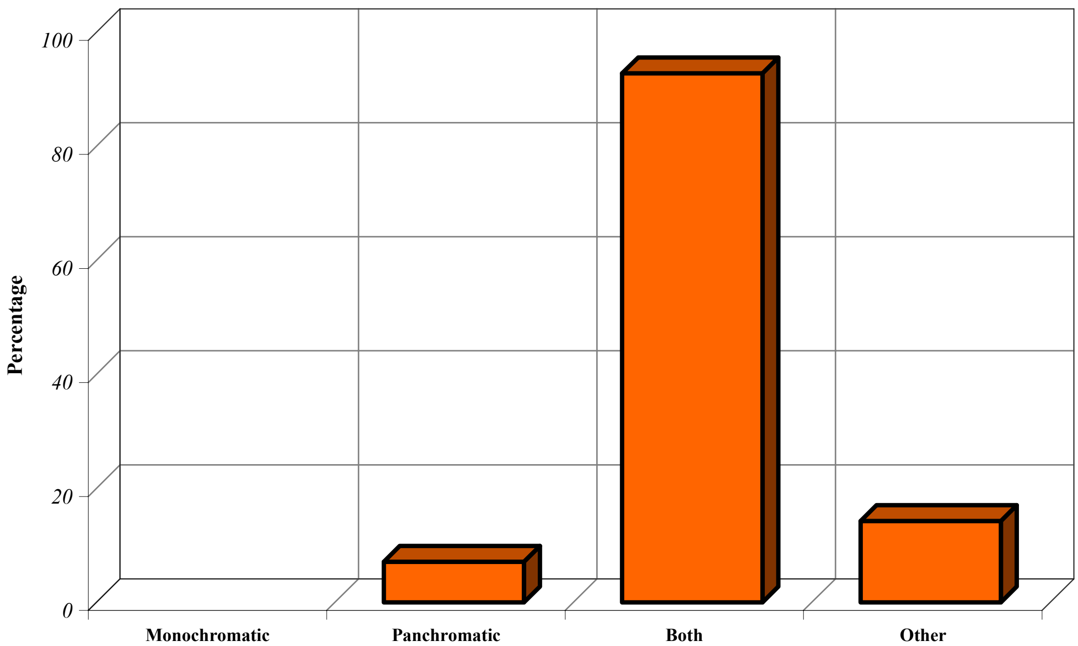

Figure 15. Level of Wave Detail Required for Performance Assessment

10. CONVERSION & POWER TAKE-OFF ASSESSMENT

Again, all the participants undertook this assessment in the early stage concept appraisal, however there was no general consensus on the primary objective of this task. This can be seen in Figure 16. It is clear that at this development stage, the economics of the project are the most important factor. Second to this the method to be chosen for power take-off and the incorporated control strategy. However at this small scale the developers found it difficult to assess the efficiencies and accuracy of the envisaged PTO system, as estimates and output from the validated numerical models were used, although it was felt that this issue can be addressed at larger scales.

Figure 17 shows the topics of concern during this aspect of concept validation. Obviously, the one thing that the large range of device types have in common is the PTO. Therefore it should be no surprise that largest proportion of interest is in ascertaining the PTO forces (71%). Power quality is also a considered factor during these trials, but other topics such as energy storage, speeds and instantaneous loads are also being investigated.

The limitations of this exercise was gathering the required information and measurements at these small scales, and subsequently the reliability of the scaling of these calculations to full scale. The majority of the developers indicated that a lot of this work is based on estimates from the simulation packages, and that the results can not be validated until the testing is conducted of a larger model to verify the numerical results.

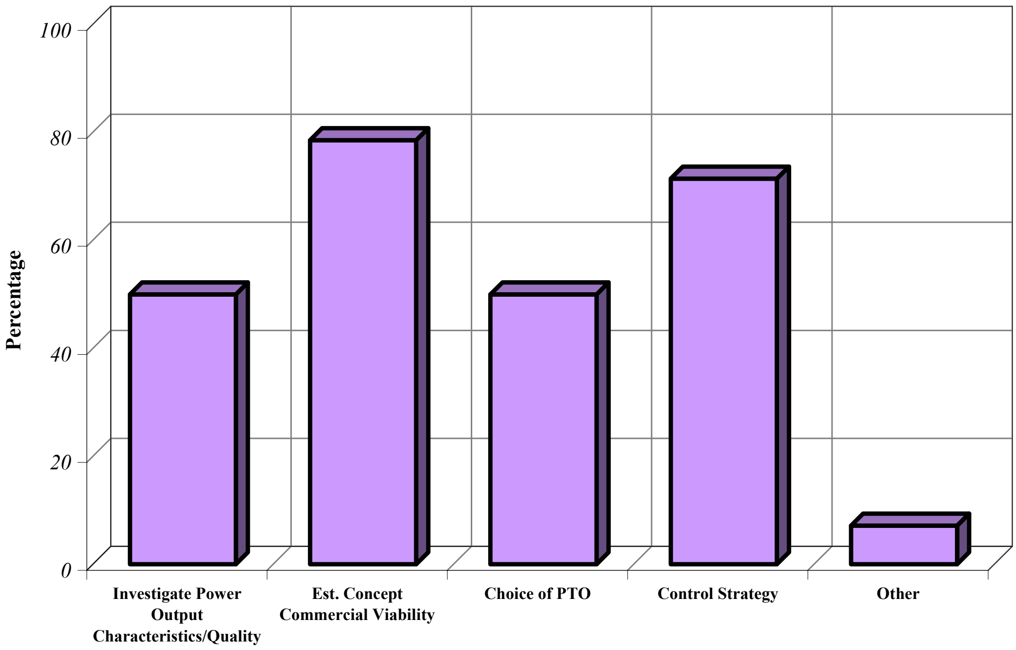

Figure 16. Objectives of Conversion & PTO Assessment

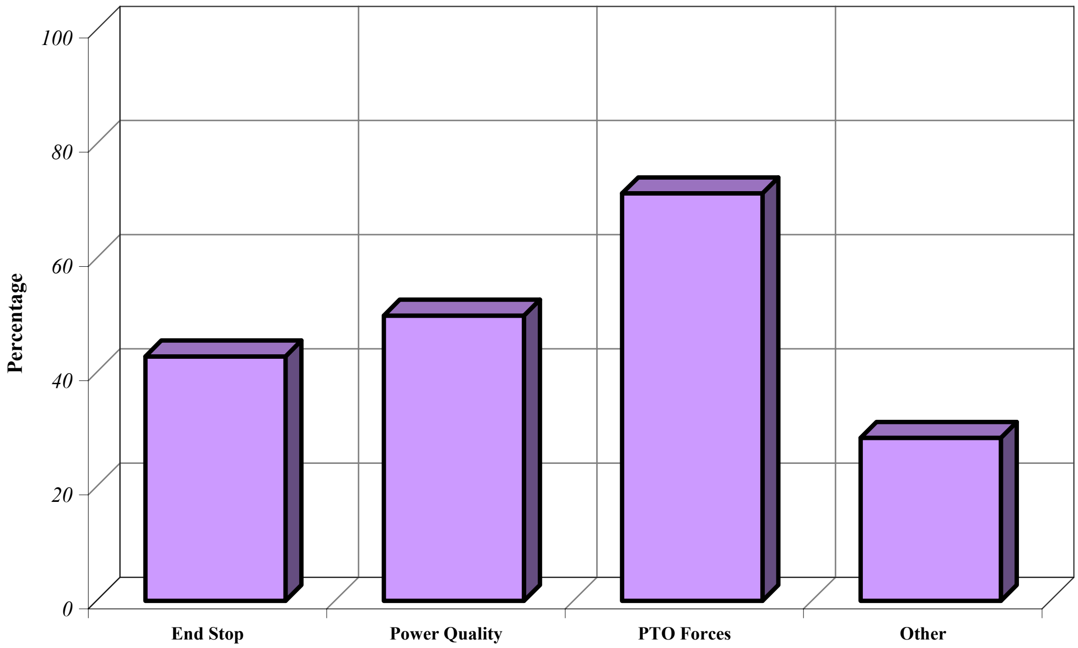

Figure 17. Level of Detail Required

11. STATION KEEPING ASSESSMENT

This aspect of the device performance was another that all the participants of the survey engaged in. The device developer required objectives of this study are shown in Figure 18. To operate in the sea environment, this is an important aspect of the viability of the device concept and the devices ability to generate electricity as proven by the results plotted in Figure 19. Depending on the device type, the station keeping method can be a significant contributor to the final costs of the project. According to the developers an accurate assessment of the mooring loads, drag forces, wave velocities and currents were undertaken for both normal operation and failure scenarios.

One of the major concerns for developers when conducting this assessment was the lack of accuracy of the design standards from the offshore industry. These were found to be very restrictive and experimentation was necessary in some cases. The costs associated with mooring and installations were also found to be excessive and largely unpredictable. Due to the erratic nature of the perceived costs and the demand of infrastructure vessels in the oil and gas industry, developers found it hard to predict installation cost of their devices.

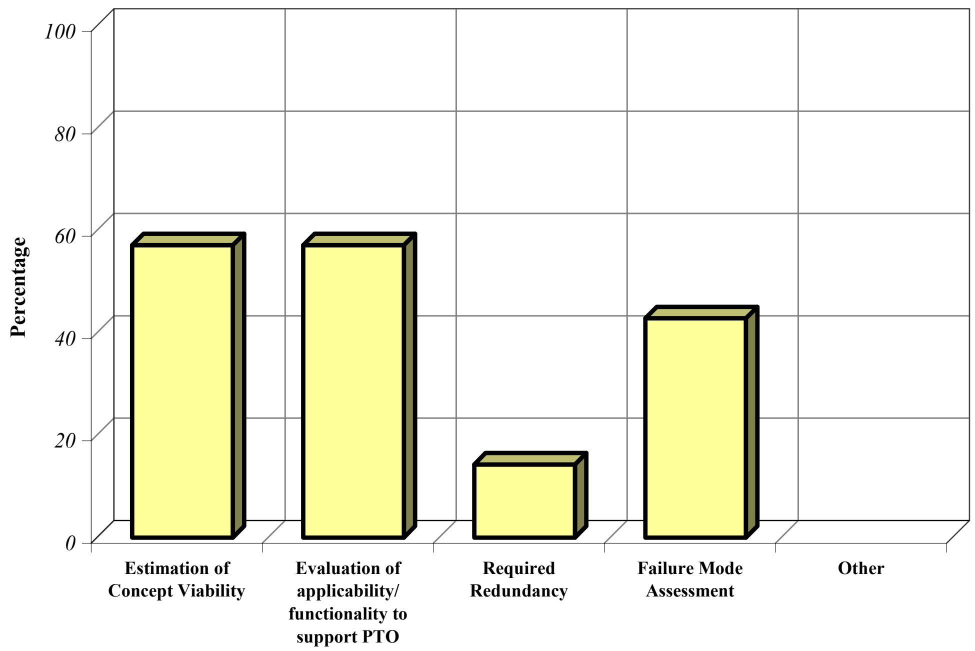

Figure 18. Objectives of Station Keeping Assessment

12. SEAKEEPING & SURVIVAL

Another important assessment of the device capabilities is conducted in this section. Of concern in this study are the extreme motions and loads experienced by the device and the mooring performance. This is shown in Figure 13.1. The measured investigated parameters are of the maximums and the extremes. The general consensus is that experimental trials are unavoidable for investigative work on this topic as it was found that the numerical packages were unable to resolve the non-linearities associated with extreme seas.

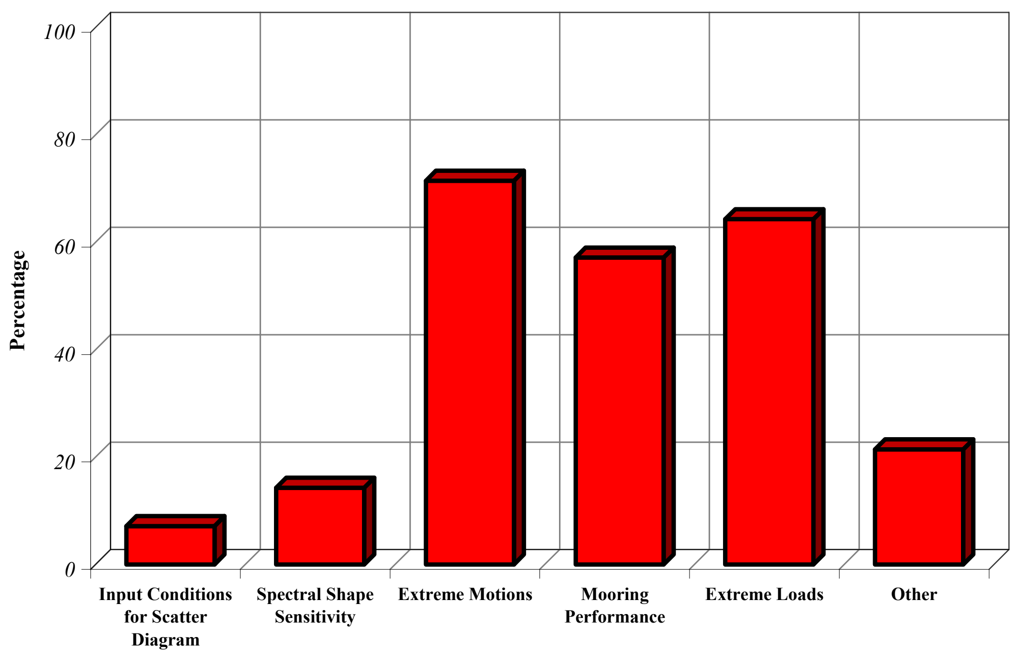

Figure 19. Objectives of the Seakeeping & Survival Assessment

13. OPERATION & MAINTENANCE, DEPLOYMENT

Figure 20 shows the percentage of the different objectives developers had in mind when conducting the O&M assessment, of which 90% of the developers took part in. Open water accessibility and prediction are of concern in the operation and maintenance phase, however of most interest is the requirement of service vessels and accompanying infrastructure. Intrinsically, a device is positioned in a hostile environment to capture the wave energy efficiently and economically. To combat this, the appropriate tools are required to operate a maintenance schedule safely, efficiently and cost effectively. Developers have conducted detailed studies of the design path to a high level, following standard naval architecture and engineering procedures, and have incorporated suitable design features into the device to reduce the risk of component failure.

The limitations associated with this analysis are the difficulties in the choice of a suitable weather window for O&M operations and the confidence levels of wave prediction and forecasting. Due to the technology specific nature of wave energy, the developers are finding it difficult to estimate the life time of components and at this stage assumptions have to be made about the MTBF (mean time between failures).

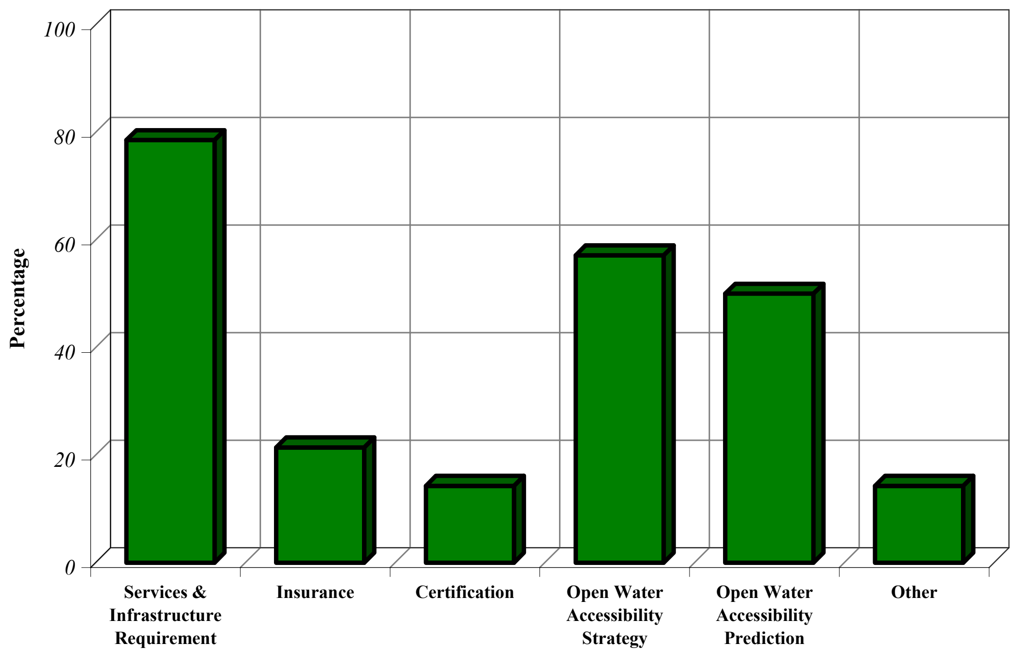

Figure 20. Objectives of the O&M and Deployment Assessment

14. RISK ASSESSMENT

Nearly one third of the participants of the survey undertook some form of risk assessment of the technology. Half of those that did conduct the analysis, performed a basic risk assessment while the other half conducted a more detailed analysis. This involved FMEA (failure mode and effects analysis) on all components for structural, PTO and mooring, and the subsequent identification of components that had a significant impact on viability, which was then fed into the O&M model of the previous section.

Less than 40% of those that conducted a risk assessment sought advice from an external source, although those that were contacted are shown in Figure 21. The 15% of the 'Other' is attributed to the DNV Certification Guidelines. Further to this information, over 40% indicated that there was some degree of communication and feedback between the developer and assessor to allow re-supply of data, calculations and justification.

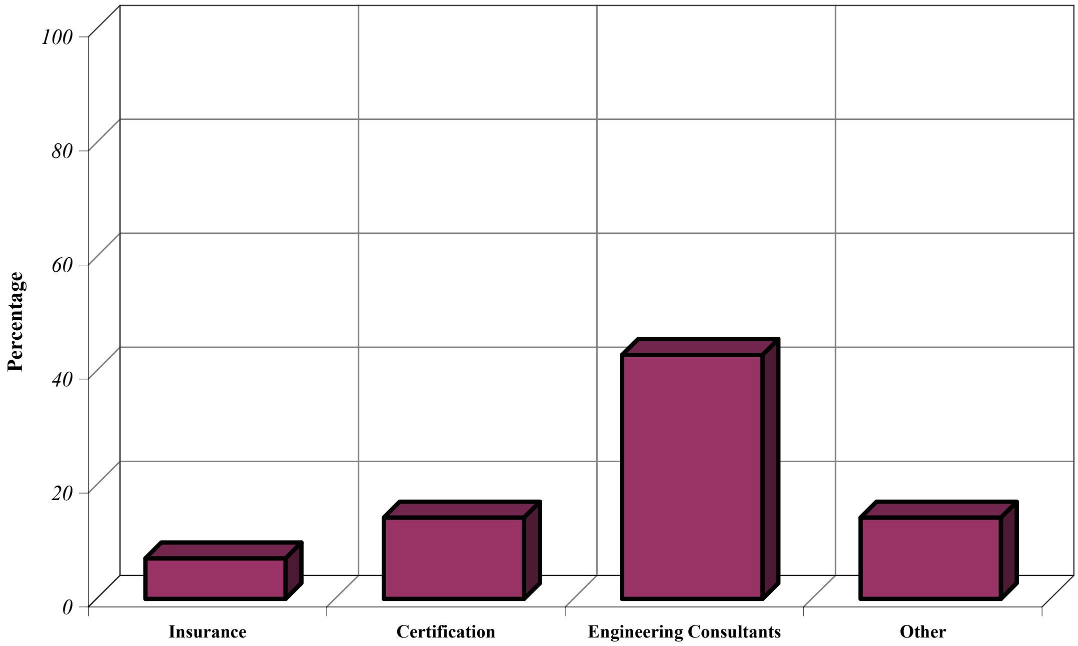

Figure 21. Groups Found to be Useful in Risk Assessment

15. FACILITIES

The final section of the questionnaire related to the availability of adequate facilities and testing environments for this early stage of concept appraisal. Less that 50% of those who contributed to the survey chose to give an answer to this question, but the general indications from the developers were that wave tanks to incorporate early device models have high work loads, therefore causing delays to project development due to waiting times.

Some of the technical requirements were to include a wave tank with variable depth and one that incorporated both wave generation and current flow. The cost to hire these facilities was also an issue that was raised. Another technical requirement was a medium scale facility to incorporate PTO testing, as this is usually unachievable at the small scales of concept validation.

16. GENERAL COMMENTS

At the end of the questionnaire, the participants were given the opportunity to raise any other issues that they might have with regard to the gaps or limitations of the current practices adopted for early stage wave energy device assessment. Some of the comments are displayed below.

> *The current understanding of waves, especially their spectral character, is based on very old data gathered for a different purpose. As a result, the conception of the waves from which conversion is to be done is quite primitive and different from the waves our machines will encounter.*
>
> *Standard guidance on how to carry out a WEC assessment and on the kind of analyses of both simulated and laboratory output data is required.*
>
> *I would strongly suggest that more funding mechanisms be put in place to support modelling and physical testing in the wave tank of smaller models to validate numerical models.*
>
> *Currently there is a far too theoretical an approach to wave energy conversion. This may limit and restrict the industrial development when the industry becomes more mature.*
>
> *Maintenance is essential, so the most important cost driver outlined is the open water accessibility strategy. Any operation is much more difficult and dangerous at sea than in the relatively calm water of a harbour: relative motion is a major hazard particularly for heavy lifting and the time to complete operations can be highly uncertain. Consequently, a policy of off-site maintenance was adopted from inception. Accessibility constraints*

then apply just to deployment/retrieval, i.e. what size (Hs) of sea state you can carry out the operations in, what Hs you can tow the machine to/from site and the length of weather windows you have at these Hs. Addressing other requirements follow from this strategy, with the continuing objective of minimising cost. In the absence of dedicated support vessels one is reliant on the offshore industry vessels and their cost is generally high and extremely volatile: oil price fluctuation is further multiplied by supply and demand mechanisms; the consequence is charge-out rates that can, over quite short periods of time, vary by more than an order of magnitude. Insurance will reflect this component of risk and cost.

Early stage work should address both the upper limit to device performance and the realistically attainable output. Much of the published concept assessment work focuses on just one of these aspects but they are both important. Best-practice specific to wave devices for extreme motions and displacements would be useful. An approach to studying array interaction and its impact in device performance and power quality needs to be quantified and qualified.

There does not appear to be a mechanism for assessing the ultimate potential of early-stage concepts and recommending support as appropriate. A framework for equitable comparison of devices would be useful. Assessment might include the potential of wave energy devices, eventually, to compete with (and complement) multi-megawatt offshore wind turbines.

17. CONCLUSION

The purpose of this information collection exercise is to use the gathered information to inform Work package 3 of the EQUIMAR project. At present no common practices are adopted to assess the performance and operational characteristics of conceptual and small prototype tidal and wave energy devices. Information acquired from this early stage assessment may be used to secure next stage development funding or promote a specific tidal or wave energy device. Because there are no standards/ common practices, the data produced may be easily misinterpreted or inaccurately presented, which in turn may lead to a failure in performance expectations as devices scale up in size. This work will feed the next stage of the work package which aims to deliver common practices to be adopted for the performance assessment of conceptual device performance and procedures.

It was envisaged at the beginning of this information request that a larger return would be received, but it is now felt that due to confidentiality concerns, especially as the developer's fear identification of their device through the answers of the questionnaire, this is unlikely to be achieved. As is core to this activity, every effort has been made so as not to compromise device identification. This fear is primarily due to the vast and varied concepts being investigated as each device type has some form of unique feature, as testified by the number of successful patent awards. This alone complicates the task of comparative study and evaluation and necessitates the need for projects such as EQUIMAR.

As a high proportion of these devices are new concepts, these require technical and economic validation. The majority of devices are investigated via initial concept appraisal using analytical methods then physical testing, which essentially is looking to establish the Power Capture, then put some metric against Seakeeping and Survival and Economic Viability, and mostly the physical testing was used to validate the numerical models. When computational simulation is employed, this is conducted in both the frequency and time domain, dictated by the device type, and as a consequence, 60% now have device specific code. As most of the mathematical models are based on linear regressive methods, the importance of validation against physical testing was highlighted. Both numerical modelling and physical testing have their limitations, but once these have been identified or are known, a successful outcome at this stage of the development path can be achieved.

Although both questionnaires have been broken down in to specific areas of interest, Power Output and Economic Viability are the common reason for undertaking conceptual evaluations. The uncertainty associated with this is the scalability of the results, both from the numerical models and the physical trials, however, there is confidence that this will be addressed at larger scales. Station Keeping is device dependant where in some cases it is a simple application of the knowledge and experience from the oil and gas industry, while in other cases it is a large proportion of the device cost. In relation to Operation and Maintenance costs, there is a general worry about the availability of the appropriate service vessels and infrastructure, and the associated costs of this unpredictability of supply. The final section asked about was Risk Assessment. Only 60% of the developers who answered the questionnaire considered this at this stage of development. Although most of the developers did not seek external guidance, those who did, maintained a dialogue with the external expertise. Finally, of the comments made by the developers, there was a general understanding of the importance of the small scale phase of the development path but there was also a requirement for guidance and funding to allow proper investigation.

APPENDIX 1

EQUIMAR WP3 WAVE ENERGY INFORMATION REQUEST

Name of Organisation/Company *:
Device/Concept Name
Contact Email Address *

1: **GENERAL INFORMATION** - What type or class of device(s) did your organisation have experience with?

- Multiple Floating Body Interaction
- Point Absorber
- Surging Device
- OWC
- Overtopping
- Submerged
- Other:

1.1: Was the proposed device:

- A new concept?
- A variation of an existing or historical device?

1.2: Was an internet/patent search carried out to determine concept novelty before device appraisal?

- Internet Search
- Patent Search
- No search carried out
- Other:

1.3: How was novelty determined?

1.4: Have patents been filed on your device concept? If so, how many?

- Resident Country
- Internationally
- Other:

  1.4.1: Number of patents filed:

2: CONCEPT APPRAISAL - Which concept elements did your organisation consider most important at the early stage of appraisal?

- Power Capture
- Power Take-Off & Conversion
- Station Keeping (foundations, anchors, & mooring etc)
- Seakeeping & Survival
- Operation & Maintenance, Deployment
- Economics
- Other:

2.1: Was an idealised physical model tested to appraise the concept and/or validate the theory? (Please note that this does not refer to formal and rigorous physical modelling.)

- Yes
- No

  2.1.1: Why was this physical modelling undertaken?

    - No theoretical model
    - Complex physical processes
    - Calibrate mathematical model
    - Validate mathematical model
    - Produce empirical model
    - Other:

3: COMPUTATIONAL METHODS - In undertaking the initial appraisal, did your organisation employ numerical or computational mathematical modelling?

- Yes
- No

If NO please skip to question 3.8.

3.1: Was this computational modelling carried out in-house or by an external body?

- Internally
- Externally
    - 3.1.1: If external expertise sought, was it a:
        - Consultancy
        - University
        - Research Centre
        - Other:

3.2: Was this computational modelling carried out in the frequency or time domain or both?

- Frequency Domain
- Time Domain
- Both

3.3: Has your organisation developed special mathematical (device specific) models or codes?

- Yes
- No
    - 3.3.1: If so, please describe them briefly, and how they have been applied.

3.4: What commercial or open-source codes did you use, and in what applications?

- AQWA
- WAMIT
- AQUADYN
- MatLab/Simulink
- LabView
- CFD
- Other:
    - 3.4.1: How were simulations conducted: e.g. size of domain, models used, kind of systematic analyses performed, and for what parameters?

3.5: What performance matrices were the models used to establish?

- Power Performance
- Body Motions
- Loads
- Other:

3.6: How has data from the modelling process subsequently been used?

3.7: Please comment on the present “state of the art” as you see it with regard to the limitations of the modelling methods presently available (i.e. non-linearities etc)

3.7.1: Please comment on the present “state of the art” as you see it with regard to the present lack of clarity over definitions and other terminology. (i.e. Tz, Te, Tp etc)

3.7.2: Please comment on the present “state of the art” as you see it with regard to the scope for inconsistencies and potential confusion. (i.e. max/rms power etc)

3.8: Has your organisation obtained detailed calculations of loads, outputs etc. without numerical models?

3.8.1: How are novel design aspects assessed (for which no numerical simulation package exists)?

4: PERFORMANCE ASSESSMENT - Did you undertake power capture assessment?

- Yes
- No

4.1: What were your objectives for the power capture assessment?

- Investigation of power absorption characteristics
- Estimation of concept commercial viability (power matrix)
- Other:

4.2: What level of wave detail was required for the assessment?

- Monochromatic (regular)
- Panchromatic (irregular)
- Both
- Other:

4.3: What parameters were considered in the performance assessment?

4.4: What did you perceive to be the limitations and accuracy of the appraisal? (For example assumptions made.)

5: CONVERSION AND POWER TAKE-OFF ASSESSMENT - Did you undertake this assessment?

- Yes
- No

5.1: What were the objectives of the power conversion and take-off assessment?

- Estimation of concept commercial viability.
- Investigation of power output characteristics/quality
- Choice of power take-off methodology (air turbines, hydraulics, direct drive, etc)
- Control strategy
- Other:

5.2: What level of detail was required, and which parameters were considered?

- End stop
- Power quality
- PTO forces
- Other:

5.3: What did you perceive to be the limitations and accuracy of the appraisal? (For example assumptions made.)

6: STATION KEEPING ASSESSMENT (foundations, anchors, & mooring etc) - Did you undertake this assessment?

- Yes
- No

6.1: What were the objectives of the station keeping assessment?

- Estimation of concept commercial viability
- Evaluation of applicability/functionality to support power conversion technology.
- Required redundancy
- Failure mode assessment
- Other:

6.2: What level of detail was required, and which parameters were considered?

6.3: What did you perceive to be the limitations and accuracy of the appraisal? (For example assumptions made.)

7: SEAKEEPING & SURVIVAL - Did you undertake this assessment?

- Yes
- No

7.1: What were the objectives of the seakeeping and survival assessment?

- Input conditions for bi-variate scatter diagram
- Spectral shape sensitivity
- Extreme motions
- Mooring performance
- Extreme loads
- Other:

7.2: What level of detail was required, and which parameters were considered?

7.3: What did you perceive to be the limitations and accuracy of the appraisal? (For example assumptions made.)

8: **OPERATION & MAINTENANCE, DEPLOYMENT** - Did you undertake this assessment?

- Yes
- No

8.1: What were the objectives of the O&M and deployment assessment?

- Services and infrastructure requirement
- Insurance
- Certification
- Open water accessibility strategy
- Open water accessibility prediction
- Other:

8.2: What level of detail was required, and which parameters were considered?

8.3: What did you perceive to be the limitations and accuracy of the appraisal? (For example assumptions made.)

9: RISK ASSESSMENT - Has a risk assessment of the initial methodology and technology been undertaken?

- Yes
- No

9.1: How was this undertaken, for example, have components/sub-systems been ranked in order of risk (least understood)?

9.2: Was advice or guidance sought as how to proceed with risk appraisal?

- Yes
- No

    9.2.1: Which specific groups, facilities and entities were approached and found most useful?

    - Insurance
    - Certification
    - Engineering consultants
    - Other:

    9.2.2: Was there communication and feedback between the developer and assessor to allow re-supply of data, calculations, justification etc.?

    - Yes
    - No

10: GENERAL - Were there any specific facilities that you feel are lacking and would be particularly useful in early concept appraisal?

11: Does your organisation have any other comments with regard to the gaps or limitations of the current practices adopted for early stage wave energy device assessment?

APPENDIX 2

TIDAL DEVICE ASSESSMENT: INFORMATION REQUEST

EQUIMAR Information Request to Identify Limitations of the Current Practices Adopted for Early Stage Tidal Device Assessment

Introduction

The following Information Request attempts to identify the limitations of the current practices adopted to undertake **initial conceptual appraisal of tidal devices**, specifically with regard to: power capture; conversion and power take off; and station keeping.

The information you kindly submit will be used to identify the limitations of current practice so as to produce a set of guidelines that will in future allow developers or assessors to more efficiently evaluate and progress tidal technologies to market.

All information submitted will be treated as strictly confidential. A summary of the feedback will be produced to all those completing this information request. No specifically attributable information will however be published or shared outside of the core work-package partners (*University of Strathclyde, IFREMER and University of Southampton).*

Please use this document for your organisation's response. To minimise time spent, please simply delete the answers that do not apply and type your text to the open ended questions in the boxes provided […]. Other or extra comments are also most welcome.

A) GENERAL QUESTIONS

1) What is the name of your organisation and which type or class of device(s) does your organisation have experience with? […]

2) Was a search made to determine concept novelty before concept appraisal? Yes/No

1) Was the device proposed:
   a. A new concept.
   b. A variation of an existing or historical device.
2) How was the novel aspects of your device determined? **[…]**

3) Which concept elements does your organisation consider in its early stage appraisal?

   a. Power capture
   b. Power take-off and conversion
   c. Station keeping
   d. Economic
   e. Other **[…]**

4) Was a very basic physical model/part-model informally tested to appraise the concept? *(Please note that this does not refer to formal and rigorous tank/ flume testing.)* Yes/No

1) Why was this undertaken? **[…]**

B) POWER CAPTURE ASSESSMENT

1) What were your **objectives** for the power capture assessment?
   a. Estimation of concept commercial viability.

   b. Investigation of power input characteristics.
   c. Other **[…]**
2) What **level of detail** was required, and which **parameters** were considered? **[…]**
3) What do you perceive to be the **limitations** and **accuracy** of the appraisal? For example, assumptions made. **[…]**

C) CONVERSION AND POWER TAKE-OFF ASSESSMENT

1) What were the **objectives** of the power capture assessment?
   a. Estimation of concept commercial viability.
   b. Investigation of power output characteristics.
   c. Choice of power take-off methodology.
   d. Other **[…]**
2) What **level of detail** was required, and which **parameters** were considered? **[…]**
3) What do you perceive to be the **limitations** and **accuracy** of the appraisal? **[…]**

D) STATION KEEPING ASSESSMENT

1) What were the **objectives** of the station keeping assessment?
   a. Estimation of concept commercial viability and market share.
   b. Evaluation of applicability/functionality to support power conversion technology.
   c. Evaluation of operation and maintenance requirements.
   d. Other **[…]**
2) What **level of detail** was required, and which **parameters** were considered? **[…]**
3) What do you perceive to be the **limitations** and **accuracy** of the appraisal? **[…]**

E) COMPUTATIONAL METHODS

1) In undertaking the initial appraisal, has your organisation experience in mathematical or computational modelling of power capture, conversion or station keeping? **Yes/No**

If YES

   a. Has your organisation developed mathematical models or codes? **Yes/No**
      i. If so, please briefly describe them, and how they have been applied. **[…]**
   b. What commercial or open-source codes have you used, and in what applications? How have simulations been conducted: e.g. size of domain, models used, kind of systematic analyses performed, and for what parameters? **[…]**
   c. What performance metrics have the models been used to establish? **[…]**
   d. What verification process has been undertaken to establish agreement/ accuracy with actual performance? **[…]**
   e. How has data from the modelling process subsequently been used? **[…]**
   f. Please comment on the present "state of the art" as you see it:
      i. the limitations of the modelling methods presently available; **[…]**
      ii. present lack of clarity over definitions and other terminology; **[…]**
      iii. the scope for inconsistencies and potential confusion. **[…]**

If NO

   a. Has your organisation supplied detailed calculations of loads, outputs etc.? **[…]**
   b. How are novel design aspects assessed (for which no numerical simulation package exists)? **[…]**

F) GENERAL ASSESSMENT AND OTHER COMMENTS

1) Has a risk assessment of the initial assessment methodology and technology been undertaken? **Yes/No**
   a. How was this undertaken, for example, have components/sub-systems been ranked in order of risk (least understood)? **[…]**
2) Was advice or guidance sought as how to proceed with concept appraisal? **Yes/No**
   a. Which specific agencies, groups, facilities and entities did you find most useful? **[…]**
   b. Were there any specific facilities that you feel are lacking and would be particularly useful in early concept appraisal? **[…]**
3) If concept appraisal has not been undertaken by the developer, was there communication and feedback between the developer and assessor to allow re-supply of data, calculations, justification etc.? **Yes/No**
   a. What caveats and details did the assessors require? **[…]**
4) Does your organisation have any other comments with regard to the gaps or limitations of the current practices adopted for early stage tidal device assessment? **[…]**

Thank you very much for your efforts in providing this information

2.1 Tidal Developers and Appraisal Organisations Approached

Technology Developers

Reference	Company	Country
TD1	Aquamarine Power (SSE)	UK
TD2	Atlantis Resources Corporation (Nereus and Solon)	Singapore
TD3	BioPower Systems Pty	Australia
TD4	Blue Energy Canada	Canada
TD5	Clean Current	Canada
TD6	CoRMaT	UK
TD7	Electricite de France	France
TD8	Edinburgh Designs (Polo?)	UK
TD9	GCK (Gorlov)	USA
TD10	Hydro Gen	France
TD11	Hydroventuri	UK
TD12	Inha University	Korea
TD13	Lunar Energy	UK
TD14	Marine Current Turbines	UK
TD15	Neptune Renewable Energy Company	UK
TD16	New Energy Corporation	Canada
TD17	Ocean Renewable Power Company	USA
TD18	Oceanflow Energy (Evopod)	UK
TD19	OpenHydro	Ireland
TD20	Ponte di Archimede S.p.A	Italy
TD21	Pulse Gen	UK
TD22	Sabella SAS	France
TD23	Scotrenewables	UK
TD24	Scottish Power / Hammerfest	UK
TD25	SMD Hydrovision (Tidel)	UK
TD26	Swann Turbines	UK
TD27	Teamwork Technology (Tocardo)	Netherlands
TD28	Tidal Generation Limited (Rolls Royce)	UK
TD29	Tidal Sails	Norway
TD30	Underwater Electric Kite	USA
TD31	Uppsala University	Sweden
TD32	Verdant	USA
TD33	Voith Siemens	Germany
TD34	Tidal Energy Limited	UK
TD35	VIVACE	USA
TD36	Tidal Stream	UK

Research and Development

Reference	Company	Country
RDD1	DNV	Netherlands
RDD2	Edinburgh University	UK
RDD4	EMEC	UK
RDD5	HMRC University College Cork	Ireland
RDD6	IFREMER	France
RDD7	Lancaster University	UK
RDD8	Maine Maritime University	USA
RDD9	NaREC	UK
RDD10	Robert Gordon University	UK
RDD11	Southampton University	UK
RDD12	Strathclyde University	UK