Integrated WEC System Optimisation – Achieving Balanced Technology Development and Economical Lifecycle Performance

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Abstract— **Successful development of economical wave energy converter (WEC) systems requires an integrated and balanced research technology development process and a thorough understanding of the economic performance criteria over the system lifecycle. Core performance attributes are associated with WEC concept, technology, operation and wavefarm economics and include survivability, power output, availability and cost. Both integrated system optimisation and successful research technology development routes require appropriate WEC system assessment tools.**

The paper describes the structure of an integrated techno-economic WEC system performance assessment framework. This comprises a WEC engineering analysis and a wavefarm lifecycle analysis. Both are presented in content and structure. Six core sub-models of the wavefarm lifecycle analysis are described and generic example results are provided. It is shown how the WEC system performance assessment framework provides a solid foundation for implementation of an integrated techno-economic WEC system optimisation. Finally, the importance of the assessment framework for identifying shortcomings in the development programme and in achieving an objective, efficient and successful research technology development process is discussed.

Keywords— **Wave Energy Converter (WEC), WEC performance assessment framework, WEC engineering analysis, wavefarm lifecycle analysis, WEC system optimisation, research technology development process.**

I. Introduction and Motivation

The progression of the ocean wave energy industry towards commercial operation of WEC device has been slower than desired and a number of WEC technology developments have suffered considerable setbacks. The persisting range and variation of WEC species under development is a testament of the status of the industry and the challenge of satisfying economic performance requirements.

Aside from demanding funding needs, methodological reasons are often associated with the belated consideration of key performance criteria. A consistent and simultaneous consideration of all important performance features is required. This includes conceptual, technological, operational and economical considerations.

Technology Readiness Levels (TRLs) are increasingly becoming established in the wave energy industry. These provide a basis for the identification of the development status of a particular technology and support the development process by the definition of requirements along the development path [1]. Rightly, the TRL definitions require core technology stipulations for commercial operation including survivability and power output, also however, manufacturability, deployability, reliability and maintainability to be addressed at early to intermediate stages of the development process.

The need for performance appraisal procedures of WECs is increasingly being recognised amongst investors and in the industry [2] and a number of processes are underway internationally delivering valuable protocols, standards and tools for the measurement and evaluation of WEC performance and technology status [3], [4], [5].

In [6] the authors propose the concept of an integrated system development approach, towards a simultaneous consideration of key techno-economic performance features, over the more traditional sequential development approach, and a range of relevant modelling, simulation, evaluation and optimisation tools are presented.

In this paper an integrated techno-economic wave energy converter performance assessment framework is presented. The structure of the assessment framework is described, highlighting the complexity of the task. Preliminary generic wavefarm performance results show its usefulness. The assessment framework is shown to serve the needs of both the directing of an effective Research Technology Development (RTD) process and the implementation of an integrated techno-economic WEC optimisation, by providing a blueprint for relating the economic objective function to the technical system parameters. Both supports accelerated development towards commercial wave energy application and increasing economic performance of WEC technology.

II. TECHNO-ECONOMIC WAVE ENERGY CONVERTER PERFORMANCE ASSESSMENT FRAMEWORK

The top level components of the integrated techno-economic WEC performance assessment framework are firstly an engineering analysis of the WEC device and secondly a lifecycle analysis of the wavefarm. The engineering analysis of the device comprises hydrodynamic absorption, body dynamics, moorings, Power Take-Off (PTO) and other subsystem performance. The outputs of this analysis include information on power production, reliability and CapEx drivers which are passed on to the wavefarm lifecycle analysis. The wavefarm lifecycle analysis comprises model representations of manufacturing, deployment, operations, maintenance and productivity, subjected to marine operations environment models. In combination these models deliver in-situ estimates of CapEx, OpEx and annual energy yield, all of which are then fed into a discounted cash flow analysis. Because the framework relates the technical parameters to the economic performance it can then be used to assess the sensitivity of the economic performance to the input technical parameters. This feedback of the review of the wavefarm lifecycle analysis and the economic technology performance under commercial application conditions over a wavefarm lifecycle to the WEC technology parameters facilitates both

- guidance for an effective, focused and objective research technology development process, and
- implementation of an integrated techno-economic WEC system optimisation.

The circumstances are schematically depicted in Fig. 1.

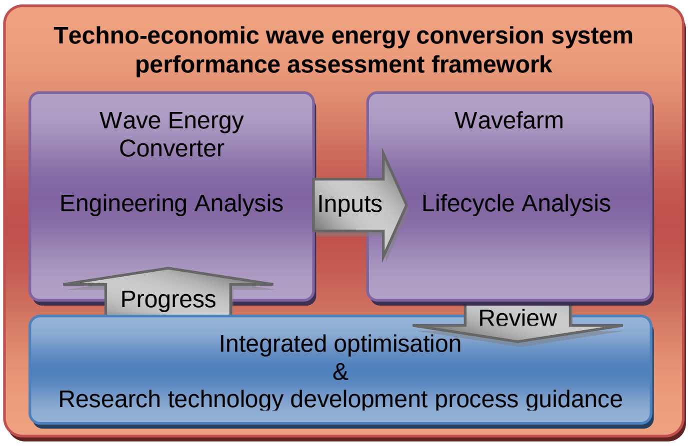

Fig. 1 Schematic of techno-economic WEC performance assessment framework

III. WAVE ENERGY CONVERTER ENGINEERING ANALYSIS

The Wave Energy Converter Engineering Analysis (WECEA) comprises three core elements, namely the analysis of the system dynamics, subsystem engineering analysis and the design assessment. It is applied to the particular WEC concept under consideration.

A diverse range of development tools and methods is required in the engineering analysis. This includes system simulation, empirical modelling and testing, various engineering design processes through to technology evaluation and certification as were described in [6]. A considerable subset of these can be numerically implemented in reasonable representation. Other processes are based on empirical testing, require considerable operational expertise or rely on expert knowledge and judgement in design reviews.

Fig. 2 shows the schematic of the WEC engineering analysis as implemented in the integrated numerical WEC system optimisation.

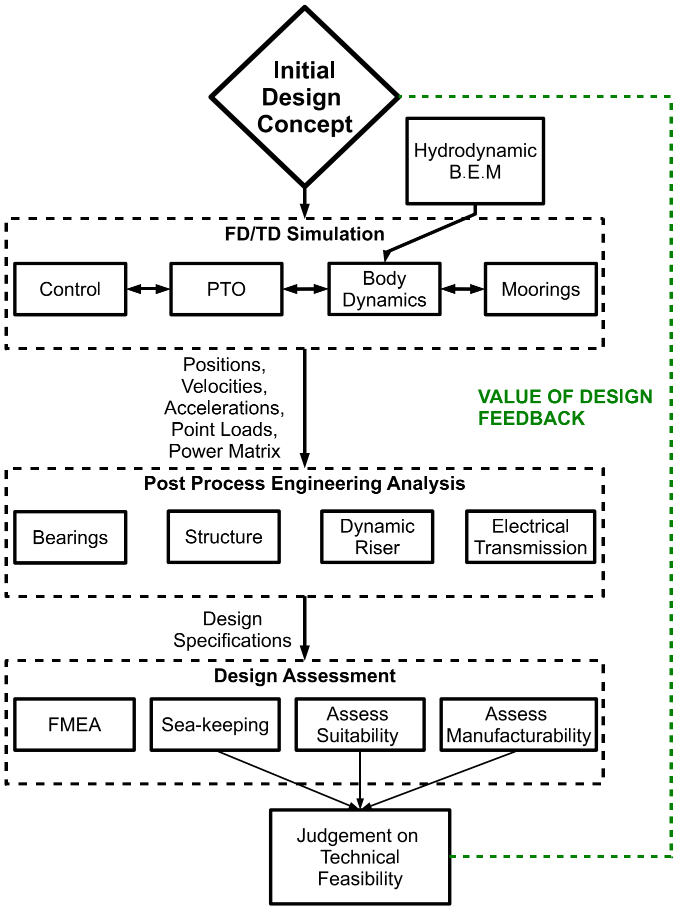

Fig.2 Schematic of the WEC engineering analysis, as implemented in integrated WEC system simulation

In particular, the system dynamics simulation provides hydrodynamics, mooring and internal loads, system control, absolute and relative motion, PTO dynamics and power conversion. Simulations are conducted at different complexity levels depending on targeted outcome. Representation of the system response is, amongst others, provided in form of performance distributions i.e. power matrix, motion and load distributions i.e. description of load profiles dependent on operational conditions.

Further captured under the numerical implementation of the subsystem engineering analysis are representative engineering design implementations of subsystems including structure, key mechanical systems, PTO, mooring, dynamics riser, onboard electrical equipment and electrical transmission; delivering a system design specification.

The design assessment in the WEC engineering analysis comprises a range of checks, verifications and evaluations involving some application of codes, standards, guidelines and assessment methods. Examples include offshore engineering standards, failure mode effect analysis (FMEA), assessment of operational suitability through key system states and modes, assessment of manufacturing processes, evaluation of deployment procedures and analysis of maintenance and repair requirements.

The outcome of the design assessment provides valuable feedback within the engineering analysis and triggers system adjustment if system functionality and performance threshold criteria are not satisfied. The output of the engineering analysis is provided to the wavefarm lifecycle assessment in form of a power matrix, FMEA register and design specification with key characteristics of CapEx drives, manufacturing and deployment requirements.

IV. Wavefarm Lifecycle Analysis

The Wavefarm Lifecycle Analysis (WLA) seeks to quantify the CapEx and OpEx associated with all important aspects of the wavefarm lifecycle; manufacture, installation, production, maintenance and finally decommissioning [7], and also attempts to quantify the energy productivity. These quantities allow for financial calculations that give a measure of the economic value of the wavefarm [8], [9], [10].

In order to simulate each phase of the lifecycle, the analysis encompasses six models using one hour time steps, namely:

- Marine Operational Environment Model (MOEM)
- Manufacturing Model (MM)
- Deployment Model (DM)
- Operational and Maintenance Model (OMM)
- Productivity Model (PM)
- Financial Model (FM)

Inputs for the WLA rely on the WEC design specifications, reading of wave measurements as well as the previous engineering analysis outputs. The diagram in Fig. 3 shows how the components of the WLA are articulated.

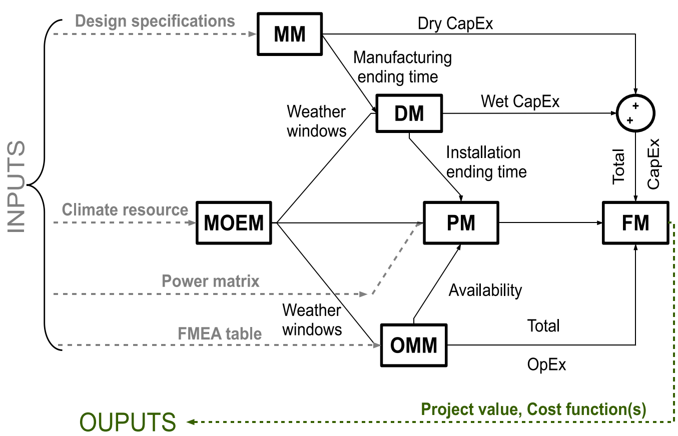

Fig. 3 Framework of the wavefarm lifecycle analysis

A. *Marine Operational Environment Model*

Given readings of the climate measurements of a specific location (e.g. wave height, wave period and wind speed), the MOEM provides the weather conditions over time.

A number of criteria can be used to determine whether the weather conditions are favourable or not for marine operations. One threshold widely employed is the significant wave height criterion which commonly ranges from 1 to 1.5 meters.

Ultimately, the model returns an hourly history of the significant wave height and the energy period over the project lifetime. Furthermore, the starting time of each Permitting Weather Window (PWW) along with their durations is computed.

For instance, the model delivers results such as those shown in Fig. 4. These are based on raw wave elevation measurements gratefully supplied by the Marine Institute (Ireland) of a wave rider located off Belmullet, Ireland over the whole year 2010 [11]. Here, a wave height threshold of 1.5 meters is chosen.

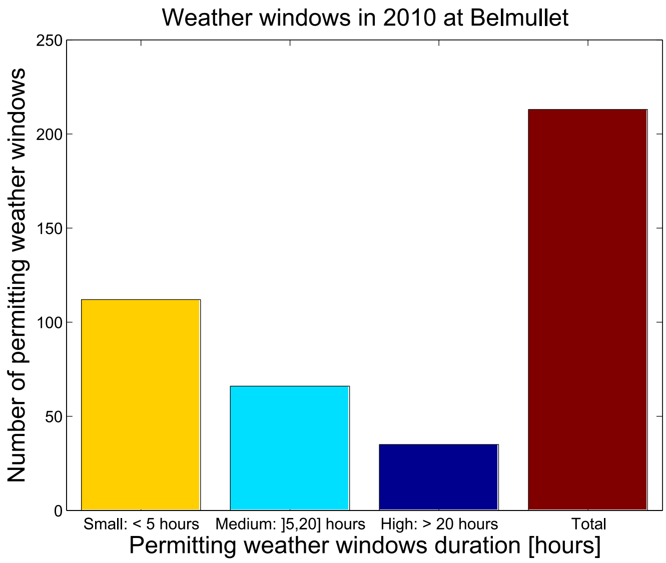

Fig. 4 Number and size of Permitting Weather Windows (PWW) at Belmullet, Ireland in 2010.

B. *Manufacturing Model*

In parallel to the MOEM, the MM can be independently treated. Given the design specifications and numerous cost estimates, it essentially provides two separate sets of information:

1. The yearly number of units manufactured.
2. The yearly dry CapEx.

Both the unit production rate and the unit dry CapEx may be subject to a learning curve.

The calculation of the dry CapEx is related to physical parameters such as: the volume of concrete, the surface area of steel, the PTO maximum force and stroke, the mooring design, the electrical equipment etc. It is good custom to breakdown the manufacturing cost into few categories as depicted in Fig. 5. In this pie chart, a generic point absorber was considered.

In addition, an initial investment covers the cost to set up all the production lines considered and an initial purchase of equipment.

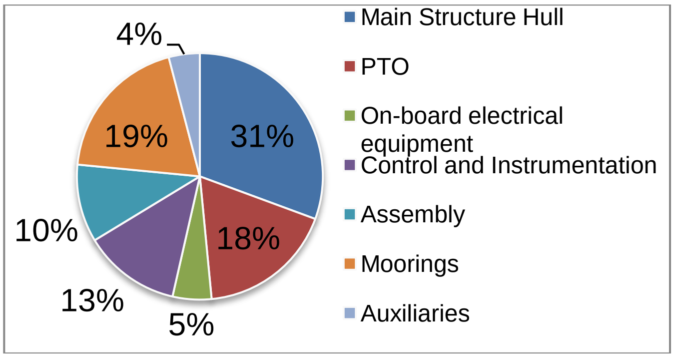

Fig. 5 Manufacturing unit costs breakdown

C. *Deployment Model*

Similarly to the MM, the DM generates a financial evaluation as well as an operational feature:

1. The yearly number of units installed.
2. The yearly wet CapEx.

The DM determines the time required for the deployment of one unit according notably to the distance between the site and the port and the vessel speed.

While various types of marine operations are handled by the WLA, a global approach can describe the methodology to deal with any type of marine operations as shown in Fig. 6.

Once again, an initial investment is accounted for acquiring suitable vessels and implementing the grid connection. The whole WLA is limited to two types of boats e.g. one for on-site operation and one designed for towing the device.

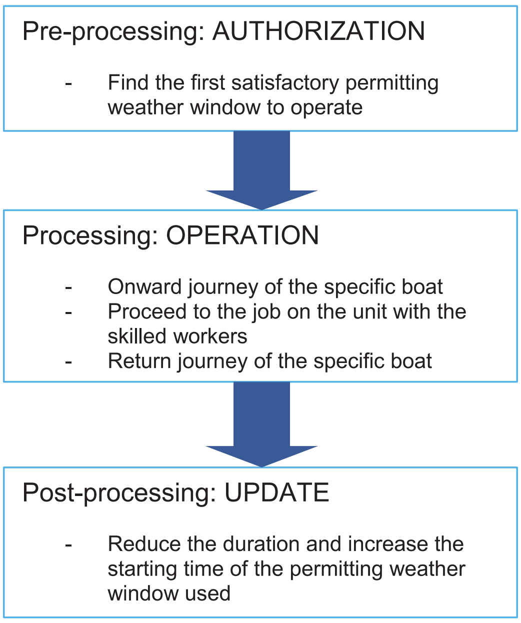

Fig. 6 Marine operation procedure

D. *Operational and Maintenance Model*

As soon as the first device is installed, the OMM is activated. The model plans the maintenance operations [12]. Following the nature of the failure and the availability of both the equipment and the teams, the type of operation and henceforth the recovery time is adjusted. At the end, the OMM returns:

1. The total yearly OpEx cost assessment.
2. The hourly farm availability for production over the lifetime.

Currently, the model includes two scheduled maintenance operations, namely the annual inspections and a midlife refit.

Finally, failure events occur randomly according to the probability rates evaluated within the FMEA table. A summary of all the different types of marine operations can be seen in Fig. 7.

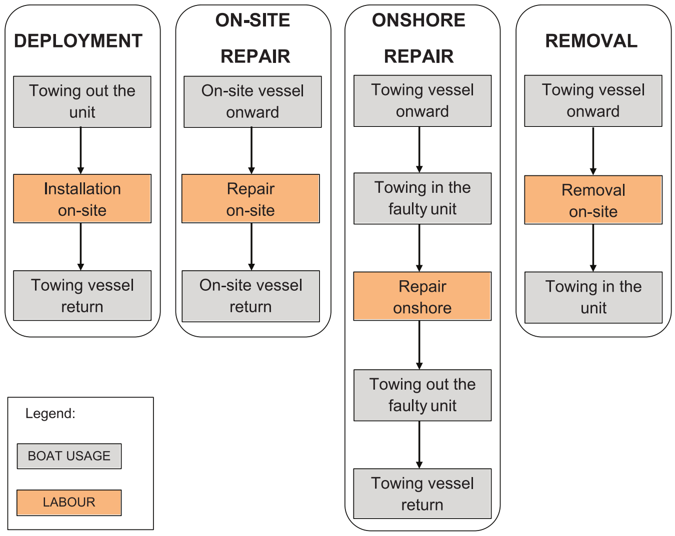

Fig. 7 Types of marine operations

Considering a project of 100 units with a device lifetime of 20 years, a plot of the wavefarm availability over the project lifetime is shown in Fig. 8.

E. *Productivity Model*

The PM produces the hourly wavefarm power production over the lifetime by combining the power matrix, the availability and the wave measurements.

For each hour, the model looks for the cell corresponding to the sea state used for the weather windows calculations in the power matrix. The hourly device power production is therefore constructed. Knowing the farm availability, the farm power production is straightforwardly computed. An efficiency learning rate can be applied to the power production on a yearly basis.

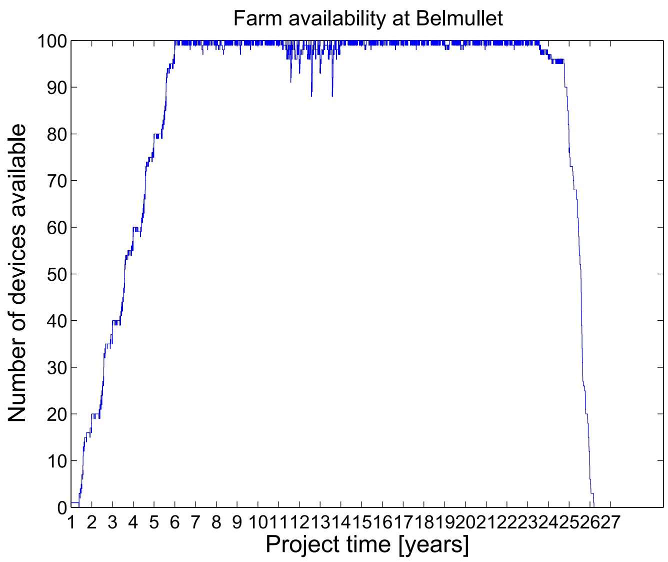

Fig. 8 Wavefarm availability for a project of 100 units with a device lifetime of 20 years

F. *Financial Model*

Finally, the analysis assesses the value of the project by implementing a discounted cash flow algorithm within the FM [13]. Numerous financial assumptions (tariff, retail price of energy, tax rate, depreciation pattern, etc.) are used in alignment with financial practice in related industries (offshore, renewable energy). An illustration of the cash-flow economics during the operational stage of the project is depicted in Fig. 9. On the top plot, from left to right, 4 vertical bars represent respectively the revenue, the OpEx, the future cash-flow and the discounted cash-flow for each year of the project. Between year 11 and 13, one can notice larger operational costs appearing due to the midlife refit. In addition, the net present value curve is included on the bottom and shows a positive final value. The initial investment which reflects the total CapEx can be seen at the first year of the net present value curve. In this scenario, the discounted payback period occurs around year 15.

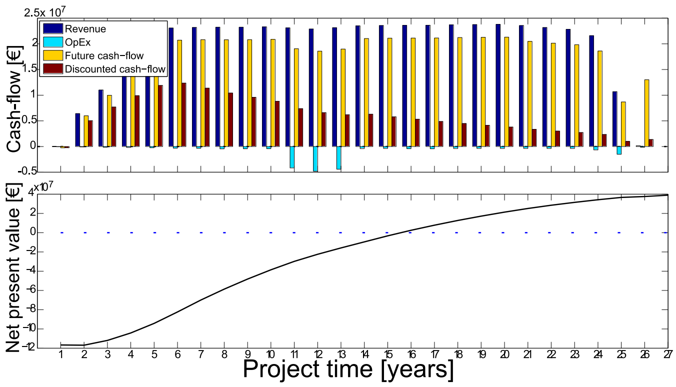

Fig. 9 Cash-flow economics and net present value for a project of 100 units with a device lifetime of 20 years

At this stage, many cost estimates and assumptions call for a refinement and some extra features could be implemented in the near future. However, despite the important uncertainty underlying the WLA, the analysis is already producing results that can help identify where significant effort needs to be undertaken for reaching the commercialisation stage as soon as possible.

V. Integrated Techno-Economic Wave Energy Converter Optimisation

Reflecting on Fig. 1 showing the schematic of the techno-economic WEC performance assessment framework, the feedback of the economical performance of the wavefarm lifecycle analysis on the technical system parameters is used to implement the integrated techno-economical WEC system optimisation. Certainly not in its entirety, however to a reasonable representation, the WEC assessment framework with its WEC engineering analysis and the wavefarm lifecycle analysis can be implemented in a numerical form via simulation. For a number of reasons, including computation effort, a nested architecture of the optimisation loops is employed. This ensures that, for instance, a number of PTO control parameter variations are exploited and accessed prior to introduction of WEC device geometric variations, as previously employed in [14]. This approach is here extended to a multiple nested optimisation architecture, which at a high level is illustrated in Fig. 10, distinguishing between geometry, equipment and wavefarm optimisation loops. The work here concentrates on WEC device technology optimisation under economical wavefarm lifecycle performance criteria. Different sets of wavefarm lifecycle operational conditions are considered, however a numerical optimisation of the wavefarm project parameters alone for a given WEC technology is not a priority under the current work. This is indicated in Fig. 10 by the exclusion of a feedback directly within the wavefarm lifecycle optimisation independently of the WEC technology equipment optimisation.

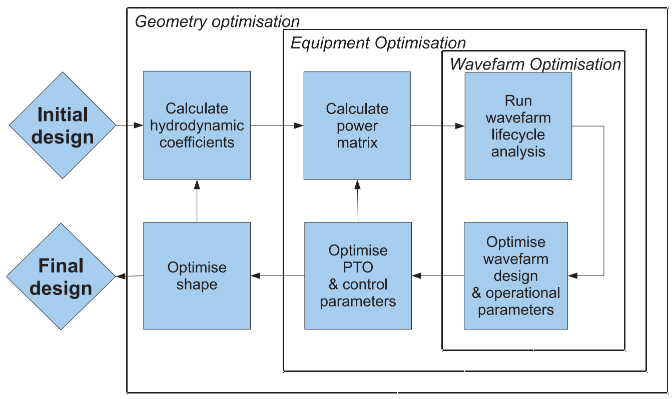

Fig. 10 High level schematic of nested techno-economic WEC optimisation based on performance assessment

With the inclusion of the wavefarm lifecycle assessment and the use of the economical wavefarm performance as the targeted object function, this approach goes beyond the widely employed selection of object functions for technology evaluation, e.g. annual average power levels over key CapEx drives like displaced volume, wetted surface or structural mass.

For instance, Fig. 11 and Fig. 12 display plots of the normalised annual average power absorption as functions of normalised structural mass and wetted surface, respectively, of self-reaction heaving point absorber – Wavebob type – device configurations. Sixteen shape families and a shortlisted subset are compared for two different sites with each curve parameterised by scale. The line colour coding in both sets of plots is in correspondence. Such performance indicators provide a basis for comparison, are however sensitive to the select CapEx drivers and only capture a limited subset of relevant performance features with respect to overall WEC system and wavefarm economics.

The assessment framework places expert judgement, evaluation of technical feasibility and technology design reviews effectively in the overall development process and combines such developer controlled improvement action with the numerical system optimisation efforts.

Where knowledge required for the evaluation and/or for the improvement of particular system properties is missing or affected by high uncertainty it is extremely valuable to evaluate the importance of such system properties on the overall techno-economical system performance through the application of the assessment framework.

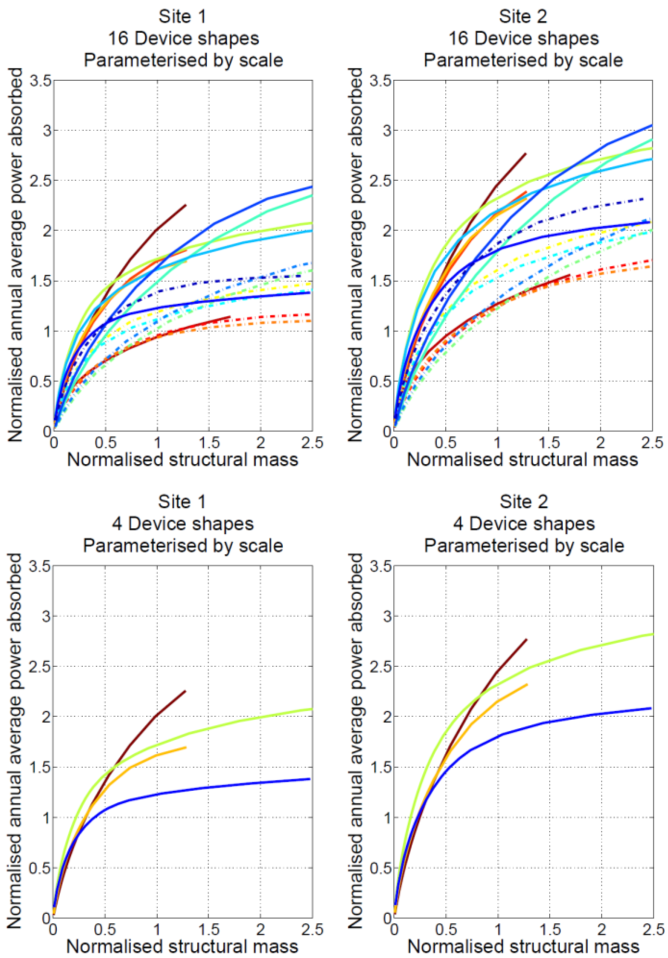

Fig. 11 Power absorption capability (normalised) versus structural mass (normalised). Comparison of different shape families (sixteen and shortlist) with each curve parameterised by scale.

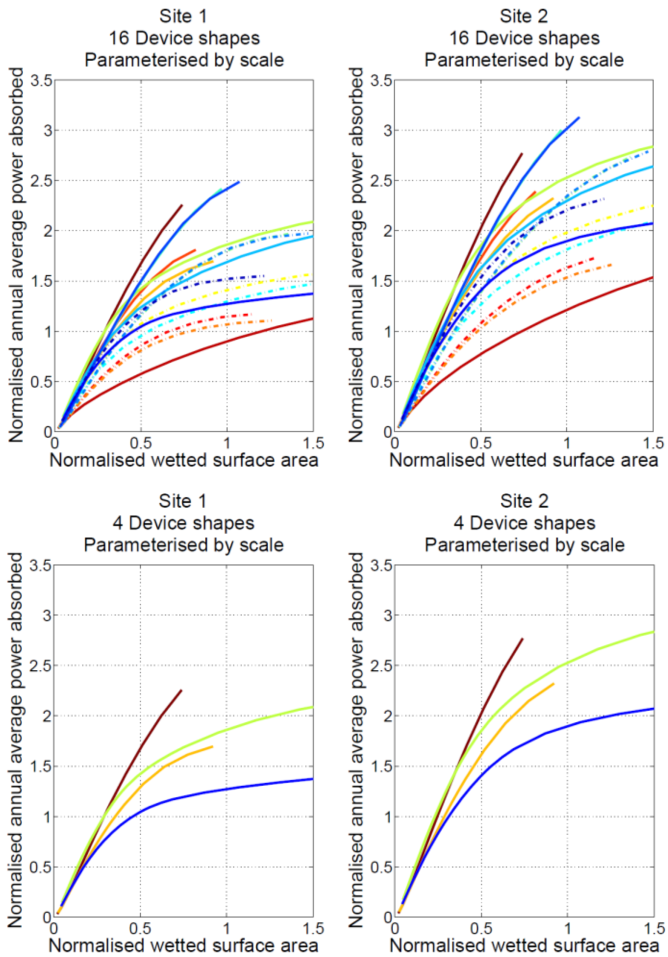

Fig. 12 Power absorption capability (normalised) versus wetted surface area (normalised). Comparison of different shape families (sixteen and shortlist) with each curve parameterised by scale.

VI. Technology Development Process

There are clear limitations to the numerical implementability of the overall WEC assessment framework presented here. This is particularly the case where expert judgement, evaluation of technical feasibility and considerable experimental or operational experience are required.

However, there are several ways in which the system of an integrated WEC assessment framework facilitates an effective and objectively balanced technology development process.

Uncertain base assumptions can be implemented and the relevance of associated system properties to the techno-economical system performance can be accessed through variation of these system parameters over relevant value ranges. For example the reliability statement in the FMEA of a WEC PTO or core mechanical systems, based on the interaction of an amount of mechanical components and their reliability is subject to high uncertainty. In assuming a reasonable value range for such uncertainty the impact and relevance on the overall wavefarm performance can be quantified by a sensitivity analysis on such system parameters. Where there is a knowledge gap in the behaviour of the system its relevance can be quantified. This information can directly be used, for instance, to introduce fundamental design changes into the system in order to lead to an increased certainty regarding the reliability of the system. Alternatively, system modularity and redundancy may be increased to improve availability or ease of failure mitigation during operation and maintenance. In other cases the relevance of the uncertainty of particular system properties may be low and no further improvement activity or changes are required.

In all cases the sensitivity analysis provides valuable and clear guidance for the definition of research technology development requirements with direct impact on the allocation of human and financial resources. Further und substantial importance is associated to such knowledge through its impact on the choice and development of the overall RTD consortium primarily comprising strategic, research and technology development partners [14]. This has significant impact on the commercial success of WEC technology development.

It is important to appreciate that an objective, well justified and effective WEC RTD strategy and program can be achieved by utilisation of such an integrated WEC system performance assessment framework. This clearly underpins the significance of the methodology presented here.

VII. CONCLUSIONS

The presented techno-economic performance assessment framework is progressively proving its value in serving the needs of the research technology development process by guiding allocation of development resources and also of the integrated techno-economic WEC optimisation by providing a blueprint for relating the economic objective function to the technical system parameters. Each of these in turn serves the purpose of achieving commercial wave energy application and increasing economic performance of the WEC.

At the National University of Ireland, Maynooth, implementation of an integrated techno-economic WEC optimisation for deployment on a high performance computing cluster is under way and at Wavebob, technology development is increasingly taking advantage of both modules of the described techno-economic performance assessment framework.

ACKNOWLEDGMENT

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