# *Wave Energy Scotland and US Department of Energy Joint Workshop on Metrics Used for Measuring Success of Wave Energy Converters*

## ICOE 2016

## $26^{th}$ February 2016

**This report presents the process and outputs from a workshop held to begin a process to identify and agree a measurable set of suitable metrics with minimum numerical thresholds, which can support a list of wave energy converter system requirements.**

# Contents

# 1. Abbreviations

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|---|---|
| CAPEX | Capital Expenditure |
| DOE | United States, Department of Energy |
| FMECA | Failure Mode, Effects and Criticality Analysis |
| FOA | Funding Opportunity Announcement |
| HSE | Health, Safety and Environmental Management |
| LCOE | Levelised Cost of Energy |
| MTTF | Mean Time To Failure |
| NREL | National Renewable Energy Laboratory, Colorado, USA |
| O&M | Operations and Maintenance |
| OPEX | Operational Expenditure |
| PTO | Power Take Off |
| SNL | Sandia National Laboratories, New Mexico, USA |
| TPL | Technology Performance Level |
| TRL | Technology Readiness Level |
| WEC | Wave Energy Converter |
| WES | Wave Energy Scotland |
| TRIZ | The Theory of Inventive Problem Solving (Teoriya Resheniya Izobretatelskikh Zadatch) |

## 2. Overview

This document summarises the outcomes of the Wave Energy Scotland (WES) and US Department of Energy (DOE) joint workshop for key stakeholders within the wave energy industry, held in Edinburgh following ICOE on February 26$^{th}$ 2016.

The main objectives for the workshop were to review and agree on a list of capabilities and functional requirements for a Wave Energy Converter (WEC), to identify which functional requirements could be associated with capabilities, and to identify and agree on a measureable set of suitable metrics to support a list of WEC requirements. An additional objective was to identify appropriate numerical thresholds for each metric.

The outputs for the workshop will form a valuable input to the on-going joint effort between WES and the DOE to define technology requirements and stage gate metrics for WEC technology development.

The workshop was led by Jonathan Hodges, Research and Business Development Manager for WES, and Jochem Weber, Chief Engineer for the Water Power Programme at NREL. A further 52 key stakeholders from 10 countries and 37 different companies were present, covering a broad range of competencies including technology development, supply chain, research, policy making, test facilities and technical verification.

This report has been created to capture the outcomes of the joint workshop, by providing:

- A summary of the discussions taking place within each group during each break out session,
- A summary of the metrics and numerical thresholds which had been agreed within each group,

As a result, this report will also act as a valuable resource which can be referenced in the on-going activities within WES and the DOE to define metrics.

This document reports the views and opinions expressed by individuals attending the workshop. While it is acknowledged that there may be differing views for certain topics, the themes and discussion reported will support future workshops and development of proposed metrics.

# 3. Introductory Session

During the introductory session, Henry Jeffrey, Head of Research and Strategy for WES, and Alison LaBonte, Marine and Hydrokinetic Technology Manager for the US DOE, set out the aim of the workshop, which was to begin the process of setting quantitative metrics and benchmarks for the development of wave energy technology, and highlighted the international nature of the relationship between Scotland and the United States, with Jonathan Hodges from WES, Jochem Weber from NREL and Diana Bull from SNL all involved with the organisation and implementation of the day's activities.

The overall objective for the workshop was to agree on a list of system requirements before identifying suitable metrics to measure success, and providing minimum thresholds where possible.

**Workshop Overview**

Jonathan Hodges, Research and Business Development Manager for WES, and Jochem Weber, Chief Engineer for the Water Power Programme for NREL, then gave an overview of the reasoning behind the workshop. The topics covered included:

- Why do we need a requirements definition and metrics?
- Why are the US DOE and Wave Energy Scotland collaborating on this?

Jonathan explained that the definition of requirements is required to get a clear understanding of the design challenge. A common and consistent set of requirements will enable integration of a 'system of systems', and projects can then be effectively managed using a systems engineering methodology to ensure a rigorous, structured, engineering approach. The systems engineering approach is an established toolset for complex system development, and facilitates a complete set of system requirements to be defined through engagement with a large number of stakeholders and industry experts.

There is a synergy between the work being conducted by Wave Energy Scotland, the DOE, SNL and NREL. Both WES and the DOE are running stage gated innovation calls, these being the Novel WEC programme and the Wave Energy Prize respectively. NREL and SNL, with funding from DOE, are performing the WEC Structured Innovation project. This project investigates first targeting improvements the technology performance level (TPL, how well the technology performs) before focusing on the technology readiness level (TRL, how commercially ready the technology is). The methodology of refining TPL before TRL may be more time, cost and risk efficient in achieving market readiness, while allowing flexibility towards IP and enabling structured innovation techniques, such as TRIZ, to be employed.

This was then followed by a presentation by Jochem Weber, outlining the requirements and motivation behind this work. He explained that due to the current LCOE of WEC technologies being a significant way from cost effectiveness, we should be aiming to reduce LCOE in the order of a factor of 4. To enable this, it is essential that the problem statement of wave energy is precisely formulated, system requirements are identified, and that suitable metrics are quantified with minimal thresholds stated. This will allow new and developing technologies with high techno-economic potential to be readily identified with increased confidence.

A number of the system capabilities and functional requirements had been identified prior to this workshop. The first breakout session would be for groups to review this list and provide feedback to allow its completion. This would be followed by sessions which defined metrics to measure performance of the technical implementation of each system requirement, and to define a typical numerical threshold for each metric. It was accepted that defining a definitive target may not be possible at this early stage.

**Attendees**

The range of delegates invited to the workshop covered key stakeholders to WEC development. These included policy makers, technology developers, funders, researchers, test facilities, test sites and supply chain companies.

On arrival, all attendees had to identify whether they were either involved in the sector through government, technology development, funding, or research. The six groups for the Breakout Sessions where not predetermined, and the organisers ensured that there was an even spread of the four categories within each group. The discussions which took place were facilitated by WES, DOE and other select representatives.

The full list of attendees is included in Annex B.

**Definitions**

For the purposes of the Breakout Sessions, the key terms were defined as:

- Capabilities – things a system much be; "*A condensed version of the stakeholder needs that identifies the high level goals, independent of how achieved."*
- Functional requirements – things a system must do; *"Something a system does independent of a specific design; behaviour system has to perform."*

# 4. Breakout Session 1 – Agreement of System Requirements

## *4.1 Introduction to the Breakout Session*

Breakout Session 1 was designed to:

- Review and complete lists of capability and system functional requirements, which had been identified prior to the workshop.
- Prioritise capabilities against functions on a 2-dimensional matrix.

These activities would then inform the decision on which system requirements would be used for metric definition in Breakout Sessions 2 and 3.

## *4.2 Methodology*

All groups were supplied with a list of the functional requirements, definitions of capability and functional requirements, and a copy of the capabilities-functions matrix.

Initial activities would focus on reviewing the functional requirements for the system and their definitions and agreeing that these were appropriate. Further functional requirements or capabilities could be added if required.

Groups would then review the matrix and identify the functional requirements which appropriately matched against a capability, prioritising these functional requirements if possible.

As well as introducing the concept of systems engineering, the terms capabilities and functional requirements, and the group members to one another, the feedback from Breakout Session 1 would be used to shape the activities which would take place during Breakout Sessions 2 and 3.

### 4.2.1 List of Functional Requirements

A list of the pre-identified functional requirements and their definitions was provided to all the groups for review. This list was as follows:

- **Capture wave power**
  - The system must intercept the incoming hydrokinetic power in the ocean and convert it into some form of power that is available to be converted into electricity. Eg. The primary absorber (wave energy to mechanical energy).
- **Convert to electricity**
  - The system must transform the captured power into electricity. Eg. The Power-Take-Off (PTO).
- **Aggregate power from the different sources**
  - The system must combine the captured wave power or the converted electricity before delivering the electricity. Eg. Electrical Substation.
- **Deliver electricity**
  - The system must convey the electricity to the continental electrical grid. Eg. Electrical Cable.
- **Provide structural support**
  - The system must provide a physical entity that may enable the capture of wave power, convert electricity, control position, adapt to different environments, and/or perform survival actions. Eg. Supporting Structure of WEC.
- **Adapt to different sea conditions/states**
  - The environment in which the system will be deployed will be composed of variable height, frequency, tidal regimes, and incoming directions. The system may need to adjust operation to these varying conditions. Eg. Turret Mooring.
- **Supply energy to operate the plant**

    - The system may need to accept external energy to monitor the system, operated sensors, and potentially execute control over the system. Eg. Powering the data acquisition system.
- **Control position**
    - The system must provide a mechanism for station keeping. Eg. 3-point mooring.
- **Perform control actions**
    - The system must be able to accept external and internal communications / commands and execute upon them. Eg. Change state from operation to shut-down.
- **Perform survival actions**
    - The system must be able to execute a survival strategy to achieve an acceptable system response to forces that may be 100x's larger than operational forces. Eg. Pelamis diving through waves.

## *4.3 General Discussion Themes*

The first Breakout Session triggered the following discussion themes:

**Scope**

- There was uncertainty initially about whether the matrix was focusing on device or plant scale development. A number of the capabilities appear more technology themed and therefore appropriate to device scale (scalability, survivability, modular), while some of the functions appear appropriate for a farm or array scale (aggregate power from different sources).
- Similarly, the metric or numerical threshold used to assess the technology may change as it moves along the TPL/TRL scale. For example, the measure of success for a number of metrics may change depending on whether it is a preliminary scaled prototype or a pre-commercial full-scale device.
- There was some debate about having functional requirements involving control actions, as this made it difficult to be fully agnostic toward different technologies. A passive control device, active control device, or large structure with no need for control will all behave very differently and have different impacts upon CAPEX, and also upon OPEX following design development. “Perform survival actions” was also felt to be too descriptive, as some WECs can be inherently survivable without requiring special control strategies.

**Additional functions/capabilities/system requirements**

- When discussing system requirements, some groups felt that operation in a marine environment; data recording; and compliance with HSE regulations were not captured.
- Safety does not appear to be explicitly considered on the capabilities-functions matrix. There was some debate as to whether this should be a function (operate safely) or a capability (be safe).
- A number of groups reported that they felt “Design for Modularity” should be a further function of the system, although unanimous agreement upon the wording was not achieved amongst the attendees on the day.
- It was difficult to differentiate between the affordability with respect to CAPEX and with respect to OPEX, as there is a high level of interrelation between the two. For example, a high CAPEX may lead to a lower OPEX over the lifetime of the WEC.

**Rewording of functions**

- The wording of the functions required some modification to be generic and applicable to all WEC types. For example, the use of the phrase “Adapt to different sea states…” implies the WEC should have some form of adaptive control/shape change. The view of some groups was that this isn’t an essential requirement and that the operating window of WEC may be large enough to capture energy over a large proportion of sea states. It was suggested changing this function to “Operate over a range of different sea state conditions”.

### *4.4 Capabilities-Functions Matrix*

The objective was to define which functional requirements are associated with a capability, such that the following sentence could be completed:

- In order to be "x", the system must do "y", (where "x" is a capability, and "y" are the functional requirements).

This was not made explicitly clear at the outset however, and so it was unclear to some groups how the matrix should be interpreted. A number of the statements could be construed very differently if capabilities were associated with functional requirements, rather than functional requirements associated with a capability. Once this had been clarified, the sheer volume of information to discuss and agree on meant that most groups were unable to fully complete the capabilities-functions matrix worksheet, focusing instead on identifying the associated functional requirements to only a select few capabilities.

On reflection, specifying 3 capabilities for each group to complete during this session would have been more effective and would have resulted in complete a set of results to disseminate and use to inform future work on this topic.

The matrix itself is included in Annex D. There was not an agreement of the most appropriate functions to match with capabilities, but the following summarises some of the key outcomes from the discussion on the matrix:

- The function "Provide structural support" could be associated with most of the capabilities.
- Nearly all the functional requirements could be associated with Affordability with respect to OPEX and CAPEX.
- Affordability with respect to OPEX is closely linked to the function "Provide structural support", as this would help with survivability/reliability. Some also felt it would be appropriate to link it against "Performing control actions" in order that the WEC would be able to accept remote control commands from shore. The function "Supply energy to operate the plant" is therefore by definition also appropriate, in order to be able to transmit remote commands.
- Affordability with respect to CAPEX was felt to be linked to all functions, with the exception of "Aggregate power from different sources" and "Supply energy to operate the plant". Once again, "Provide structural support" was universally agreed to be a prioritised functional requirement, as this will provide a large contribution of overall CAPEX. Control and survivability functional requirements will be challenging but critical to achieve while maintaining an affordable CAPEX.
- Be survivable over lifetime was felt to be linked most closely to "Perform survival actions" and "Perform control actions", as these both directly refer to survival of the WEC. Again, "Providing structural support" is important as it provides a load path back to the foundation, which ties in with importance of "Control position" as this refers to the WEC foundations. "Capture wave power" may also be important as being able to select when to capture energy and when to detune from storm waves/high energy waves will lead to an improvement in survivability.
- Be available will be linked to "Operation in different sea states", in order to increase availability through the year. Control and survivability are once again also important to minimise the chances of WEC being subject to conditions which may cause failure/ long term loss of availability.
- Be reliable is closely tied to the capability "Be available", and the two could conceivably be considered as one. The main difference is that for reliability it may be appropriate to consider the function "Convert to electricity", while availability was linked with "Deliver electricity". Conversion to electricity is critical, with many WEC's tested to date experiencing many reliability problems due to poor PTO reliability. The

topic of reliability did cause much debate however, with a question of how it should be interpreted – does it mean not breaking or doing what is expected? The definition is considered again in Breakout Session 2, although the change to this definition may make a substantial difference to the appropriation function.

- Be manufacturable would be linked with “Design for modularity”, as this would greatly assist manufacturability and assembly on site. Some also felt, through a number of relations, “Capture wave energy” would have an effect, as a greater energy rating would require a larger device, which in turn may prevent certain manufacturing techniques/processes from being followed, thus leading to increased manufacturing complexity and costs.
- Be transportable and installable would also be linked with “Design for modularity”, as modular components will greatly assist assembly, subsea installation and removal/replacement of subsea components. “Control position” will have an effect as different foundation systems will have vastly different installation times. Once again, “Provide structural support” was also considered to have an effect, as designing a smaller support structure will weigh less, be transportable and will enable easier installation.
- Be scalable/Be deployable at large scale was one of the few capabilities which could be linked to “Aggregate power from different sources” and “Supply energy to operate the plant”. There was little discussion on the detail behind this however.
- Be acceptable to society and Be maintainable were only discussed very briefly, and no consensus was reached on which functions may be associated to these capabilities.

During informal discussions following the session, it was felt that that several functional requirements appeared to be sub-functions of the core things a system must do, namely “Capture wave power”, “Convert to electricity”, and “Deliver electricity”. This may have contributed to the extended discussions on definitions and the apparent difficulty in being able to agree which functional requirements were associated to capabilities.

# 5. Breakout Session 2 – Developing Metrics Part 1

## 5.1 Introduction to the Breakout Session

The objective of Breakout Sessions 2 and 3 was to promote the identification of measureable metrics for the highest-priority system requirements, as agreed following the first breakout session. Where possible, it was hoped that minimum threshold values may also be given for the metric itself.

## 5.2 Methodology

During the break between Breakout Sessions 1 and 2, the organisers discussed the feedback and used this to prioritise a list of key topics which would be assigned to the groups during Breakout Session 2 and later Breakout Session 3. Each group would receive one topic to discuss for an hour, before presenting their findings to all attendees. For each topic, the goal was to define:

- A method for measuring success
- What practical challenges exist which may affect the ability to apply the metric to real projects/technologies
- How this approach could be applied to a sub-system, a WEC or a wave farm
- A numerical threshold for success for a scaled prototype and a full-scale prototype

Consideration was given to the proficiencies of the individuals who comprised each group when assigning topics, to ensure that there was an appropriate level of experience to provide an appropriate level of feedback to develop the metrics. The topics assigned during Breakout Session 2 were:

- Group 1 – Maintainability
- Group 2 – Capture wave energy/performance
- Group 3 – Reliability/availability
- Group 4 – Survivability
- Group 5 – Convert to electricity
- Group 6 – Manufacturability

It was also recognised that there were a number of multi-disciplinary considerations, namely:

- Affordability in CAPEX and OPEX
- Health and safety
- Modularity
- Station keeping

Based on feedback from Breakout Session 1, these were not distinct enough to warrant discussion to create further metrics. They should however, be considered as a matter of course during the process of evaluating the selected topics.

## 5.3 General Outcomes

The ability of a group to readily identify a specific benchmark number for the metric was largely dependent on the topic assigned. For some topics, the appropriate value was less obvious, and in some which were highly subjective in nature, the most appropriate metric itself was difficult to identify.

The majority of the conversations within the groups tended to prioritise targeting improvements in survivability and reliability over performance and efficiency.

The Breakout Sessions did not conclude whether separate metrics should be established for the prototype stage, or if it would be sufficient to either quantitatively or qualitatively illustrate a path to full-scale metric targets.

## *5.4 Group Discussion Themes*

### 5.4.1 Maintainability

Early group discussions considered the benefits of maintenance at sea compared to bringing the WEC ashore to maintenance. Maintenance at sea presents significant challenges with regard to HSE, and there is an increased risk of weather implications for the activity. It was accepted that there were more practical challenges than those recognised; however it was difficult to quantify all these in the allotted time.

The following metrics were identified for each system level:

- Sub-system and component – Mean Time To Failure (MTTF), time to repair, potential for cascading failures
- WEC – Cycle time (the total time from failure to repair), including estimating weather windows and wait times (such as when the entire WEC is not delivering electricity)
- Plant – % availability per year

A number of other metrics were considered, including a measure of the system accessibility (which would compare the sea states in which devices could be accessed for maintenance), and the level of common modular componentry (the ability to 'hot swap' either an entire WEC or components). To aid maintainability, the importance of an appropriate spares inventory was also identified, although a method of quantifiably measuring this was not recognised.

As evidenced by the metrics identified, there is a strong association between maintainability and reliability, and differentiation between the two became more difficult as the session went on.

The final choice was to use a similar metric to offshore wind, OPEX per MW capacity. This allows the cost and frequency of the interventions to be captured. The target annually for this would be £100k/MW capacity. It may be more appropriate to measure this against MWh rather than MW capacity, and calculated OPEX as a percentage of CAPEX could lead to an incomplete metric, as it allows more expensive devices a larger OPEX budget.

### 5.4.2 Capture wave energy/Performance

It was agreed that capture width ratio is not the best metric for measuring performance, although with more consideration there is the potential that capture width ratio/size of machine could be used in an effective way.

Wind energy metrics are well established, and something similar to those may be suitable for wave energy. Following discussions however, the group identified a suitable metric of kWh/tonne. This metric will need further consideration as it doesn't capture device cost, and the group was also unable to reach a consensus of whether this should be per tonne of material or tonne of displaced volume.  No specific targets were discussed to measure success of this metric.

### 5.4.3 Reliability/Availability

It was agreed that reliability should be related to componentry and fatigue failure, rather than a single large event which can cause total device failure.

The power industry has accepted rates of % availability, gained over years of operational experience, and it was felt that it would be sensible to follow a similar strategy to these. Given the nascent stage of WEC technology, the availability should also consider the likely significant increase when moving from a prototype WEC (~50%) to a wave farm (~90%).

Fundamentally, availability modelling is an effective way of capturing this up front in order to inform design on required redundancy and possible maintenance/spare requirements. Modelling will also mitigate against the risk of subsea testing, where failure of the prototype is just one single data point and hardly enough to extrapolate for a reliability estimate of a large wave farm. Interpretation of the modelling should be considered in parallel with LCOE as required improvements in availability may have an adverse effect on the ability to be cost competitive.

Much of the discussion focused on when this modelling should start, with a consensus learning towards as early as possible (Stage 1, <TRL 3). Early modelling should use data from handbooks/standards to gain an appreciation of the potential, and this should be refined with real test and operational data when moving up the TPL/TRL scale in order to reduce the uncertainty and error margin in earlier models.

The methods identified to measure success were to use:

- Monte Carlo simulation/FMECA, with inputs from industry data, codes and wave data. This should be completed at an early stage at a high level, with more detail added during stage progression.
- Testing either at scale in the wave tank or using a test rig to improve reliability of input data and determine MTTF.
- Record the number of days not operational following installation.

As each site identified by developers has different characteristics, developing a metric which enables comparison may be challenging, and may penalise those working at a high energy site which has a greater probability of failures. To develop an effective model, it is also important to understand component design life, so that the correct values are input.

The metric used to measure reliability/availability may be either:

- Days operational/Days installed – although this will be skewed by days not operational in low power seas for extended maintenance. This equation does not take into account that a large proportion of energy will come during winter months, which may have been captured by the WEC.
- ΣPower captured/ΣPower at site (where the 'Power at site' is related to the maximum possible energy which can be captured by the installed devices). This would acknowledge that power may be captured in high energy seas, and that extended summer maintenance may have little effect on overall energy captured for the year.

The numerical threshold for a wave farm should be in excess of 95%, although this should be lower for early developments to reflect a lower TPL/TRL (as stated previously).

### 5.4.4 Survivability

The group considering survivability took a step back from methods to measure success, and first focused on what the appropriate definition should be for survivability. Having agreed that it would be the "ability to recover following a disturbance or unexpected event", and that this should be an ability to recover from total loss rather than small failures (which is consistent with the group considering Reliability/Availability), the conditions that these disturbances may take were then discussed.

The group ran out of time before progressing onto possible metrics, but given the valuable background work completed during this breakout session, it was agreed that another group would investigate survivability during the next breakout session.

### 5.4.5 Power Conversion

Efficiency was the first consideration, as an ideal PTO would present a force proportional to velocity. Waves come in different sizes and ideally we would like to vary the force, wave-by wave. The extreme case of not doing this is called manifolding, where different devices have to pump against the same common pressure. Quite good approximations can be made if it is possible to do some time-sharing by connecting to the constant force at variable amounts of time with planned times for the change chosen to get velocity and force close in phase. In large waves the connection would start earlier and go on later than in small ones.

The other extreme is to have complete control of the force at all times, which would allow the developer to retro-fit advanced control strategies which are extremely likely to be developed in future. Controllability is a good attribute to have, although it will improve with experience and further data collection. Success of the solution can be judged in productivity curves in real spectra. The comparison measure is the deviation of actual forces or torques from the theoretical ideal.

A numerical threshold to define the metric was not agreed, but the group reported that they believed it would have been possible with a little more time.

### 5.4.6 Manufacturability

There are a number of different factors which should be considered as part of manufacturability. These include the uncertainty, novelty and risk associated with choices made during the design and build process, and also the capability to do large scale production. It may be possible to identify innovations which allow for better manufacturability, but there needs to be a set of metrics to reflect the choice of new, innovative materials and processes.

A suitable metric should assess any innovation in the correct way, looking at the following elements of the manufacturing process:

- Supply chain
- Experience of supply chain
- Materials
- Manufacturing process itself
- Infrastructure
- Location
- Large scale production options
- Operation duration

The issue of getting a metric appropriate for all technologies at a varying TRL appeared again, as large scale, small scale and volume manufacture are all very different and will make it difficult to define what the ‘reward’ of using the innovative technique will be for each developer. It may be possible to balance the options against each other on a plot with a success line, with TRL possibly used to normalise the axes.

A number of options were considered, although no clear metric or any numerical thresholds were identified.

# 6. Breakout Session 3 – Developing Metrics Part 2

## *6.1 Methodology*

During the break following Breakout Session 2, the organisers discussed the outcomes of the previous session and agreed the most appropriate topics for each group to tackle during Breakout Session 3. It was felt that the topic of survivability was an important one, and would benefit from further discussion. As a result, it was included again in Breakout Session 3. Each group would again receive one topic to discuss for an hour, before presenting their findings to the rest of the assembled attendees. The methodology to be followed was the same.

The topics assigned during Breakout Session 3 were:

- Group 1 – Survivability
- Group 2 – Scalability
- Group 3 – Installability
- Group 4 – Acceptability
- Group 5 – Deliver electricity
- Group 6 – Controllability

## *6.2 Group Discussion Themes*

### 6.2.1 Survivability

The group took the survivability definition agreed in the previous session, “to continue to function during and after an unexpected event”, and looked to develop a metric around this. It was decided that survivability should not be focused on continuing to operate in conditions following an unexpected event, but rather to be able to survive without significant damage or loss of the device.

A common design lifetime is 20 years, with an event defined as a 1 in a 100 year storm. The ‘unexpected event’ may cause an unplanned loss of the expected lifetime, and may take the form of a collision or a freak weather event (wave, tsunami, hurricane, ice, etc). Safety factors determined from engineering standards are used in the design to account for this, although the lack of standards for wave means that offshore wind or oil and gas are commonly used. There are different strategies for achieving an affordable survivability and an economic failure rate, such as load shedding, load avoidance and load reduction through active or passive control.

The group recognised that device survival is relative. The loss of the only installed prototype WEC represents a significant loss, but the impact of a single device loss in a large wave farm would be harder to quantify. More information is required about the probability of achieving design life following certain unexpected events. This is an area where destructive testing would be of benefit, but it is yet to be completed in wave.

Verification and certification for devices is also needed, as used in other industries, and as a result, this metric will largely be the undertaking of certification bodies and insurance companies. By association, to obtain certification/insurance, it can be assumed that an independent review has been completed upon well-defined and evolved load cases, FMECA analyses, etc.

The insurance cost will have an impact upon LCOE, although it wasn’t possible to put a figure on what % of CAPEX or OPEX this would be. The group also questioned whether the requirement for a 20yr design life can be reviewed, if it has a positive effect upon LCOE.

The benchmark target settled upon was the ‘Total Loss Insurance at 0.5% of CAPEX per year premium’.

### 6.2.2 Scalability

Initial discussions revolved around what scalability meant to each member of the group. It was quickly evident that this could mean different things to different people, including:

- Physical scaling up a prototype device to full scale,
- Scaling by way of array, to build more of a single device,
- Increasing the level of market share.

For the purposes of the discussion, it was chosen to define Scalability as increasing power on the grid through arrays and an increase in market share.

There are a number of key drivers for the scalability, which include:

- Lease area (can maximise production over a large set area)
- Balance of plant
- Balance of the energy left behind
- Economies of scale
- Manufacturability, transportability and maintainability
- Impacts of rating on scale (can only go so large).

There may be decreased CAPEX with increased scale and reduced risk of economic loss associated with down time of a single device, but this may come at the expense of potentially increased OPEX and installation cost.

With reference to the definition of scalability being used, grid connection and grid acceptance will also have an impact on scaling. Factors to be considered here would include grid interconnection, ability to shed power, maintenance scheduling, storage, ancillary services.

Given all the points raised within the group, it was felt that the metric will be ultimately determined by array effects and specifics of the technology. An appropriate metric which balanced scale and power was not agreed, although it may be suitable to use MW capacity per unit array area. The group had intended to agree upon a defined metric and threshold, but ran out of time during session.

### 6.2.3 Installability

The group first considered a number of issues which would directly impact on the ability to install. These included:

| Issue | Description |
|---|---|
| **Safety** | There may be the need for divers, or variations in wave conditions could affect the security of hardware. A neutral observer should be present to ensure that the agreed method statement and risk assessment is followed and there are no last minute changes to procedure. |
| **Time** | Quick disconnect methods for station-keeping (eg. Pelamis) should be recognised and rewarded as part of a metric. Towing time and installation of seabed ancillaries should also be included in overall installation time. |
| **Cost** | Reductions in cost are important, unless there is a very high safety risk to be addressed (eg. Loss of life). The use of specialist vessels should also be considered, which may lead to a short term loss, long term gain. |
| **Design** | Understand and mitigate the possibility of free-surface effects which could lead to device instability. |
| **Operating weather windows** | Consider issues like device draught, maximum wave height for installation, wave directionality. |

| | |
|---|---|
| **Minimise operational steps** | Eliminate repeat handling and use of specialist equipment to save time. |
| **Site requirements** | Identification of any environmental issues |
| **Decommissioning** | Method for device removal must be identified during design, so required design features can be incorporated and not planned for retrofit. |
| **Repeatability** | Can be measured through tank testing, and will be of increased importance for array sites. |

The methods identified to measure success were to:

- Use a risk matrix to assess the high risk and safety implications of installation operations.
- Use knowledge of the site wave conditions and the maximum allowable wave height for installation to predict the maximum installed MW for a given time period (eg. Year)
- This could be taken further and developed into the £(install) / MW (total capacity of devices installed) for a given time, as this also considers the possibility of multiple vessels/multiple working to increase the number installed in a given time frame.

No numerical threshold values were considered, but further interaction with developers and suppliers to understand the capabilities installation conditions would allow an appropriate target to be set.

### 6.2.4 Acceptability

The broad discussion within the group was on 'what is acceptability?' from the public perspective. It was deemed that this is determined more by the site location than by the specific technology.

A number of key issues were recognised which should be considered in order to produce an appropriate metric.

| Issue | Description |
|---|---|
| **Public** | ▪ Visual impact<br>▪ Perceived cost of electricity<br>▪ Disruption/noise – build and operation<br>▪ Job creation and economic benefit<br>▪ $CO_2$ emissions |
| **Fishing** | ▪ Impact on fishing areas and their quality<br>▪ Alternative employment |
| **Leisure** | ▪ Yachting<br>▪ Loss or amenity – possible metric: % energy extracted? |
| **Shipping** | ▪ Availability of port facilities<br>▪ Additional mileage to shipping<br>▪ Risk to shipping through debris/devices |
| **Environmental** | ▪ Protected marine species – birds and fish<br>▪ Noise during construction and operations<br>▪ Physical impact |
| **Military** | ▪ Interference with operations |
| **Coastal erosion and sediment transport** | ▪ Incident energy transmitted to shore |
| **Consenting bodies** | ▪ Project visibility<br>▪ Decommissioning<br>▪ Cumulative impact |

Due to the time given over to discussing the background to the issue, and the subjective nature of the topic, it was not possible to identify a clear measureable metric for acceptability.

### 6.2.5 Deliver Electricity

Attentions were primarily focused on the costs and specification of inter-array cabling, and how this might impact on O&M and CAPEX. The decision was that cabling would only be considered up to the collection point, as connection to the grid from this point (the cable to shore) is likely to be common between devices. The knowledge base for this subject will continue to expand due to evolution from offshore wind.

There was also some debate whether a hydrodynamically optimised array may not be the best option for a commercial array.

The metric proposed was the total distance (in Km) of export and inter-array cabling, as this it would also acknowledge optimisation of the required subsea ancillaries. Array capacity is not considered, and so similar sized arrays may inadvertently favour large designs with fewer devices, so more consideration is required and a weighting factor may need to be applied, such as MW capacity.

### 6.2.6 Controllability

The whole system needs to be defined at a farm, device and sub-component level, and with this in mind a number of elements were considered initially under the topic of controllability:

- Reaction times
- Fault tolerance of the control system itself
- Array level control
- Fail safe conditions
- Strategy for each different operation state

To define how the whole machine can be controlled there needs to be an understanding of the ultimate limit of energy capture, and this requires a consistent means to quantify the impact of control. There will be interactions between devices in a farm which must be defined, and the complete control system needs to be sufficiently complex to be able to handle everything which may be required from devices. The dynamics of the machine will be required, and so there may be an issue about the complexity of the response.

In order to be able to define success, the following questions need to be answered:

- Can you be grid code compliant based on farm size?
- Do you have energy storage at the device/PTO level, or at an array level?
- Is real time control needed?

The following topics arose and need to be considered in order to be grid code compliant:

- Diagnostics
- Fault tolerance and redundancy
- Maximise performance
- Reaction time
- Fail safe/protection
- Compatibility between PTO and control system
- Flexibility to change and adapt to new strategy and hardware
- Sensitivity to measurements and error in response of device/PTO to that

In addition, any control system needs to take account of survivability, by incorporating fault tolerancing which links to maintenance. The compatibility of individual components needs to be controlled, which led to the discussion progressing to consider hardware requirements and whether there would be a difference between the requirements for a standalone device or array devices. It is important to consider the sensitivity to measurements and error in sensors, and the impact on hydrodynamics of the WEC by the control system should not be overlooked.

The group felt that the optimised control methodology and failsafe controls should be differentiated, although they could not agree on the definition of a clear metric which would be technically agnostic. However, the discussion around the topic identified a number of questions which should be answered in order to deliver a suitable metric at a later stage.

# 7. Developing Metrics – Results

The metrics proposed for each of the topics during breakout sessions 2 and 3 are summarised below, along with a suggested numerical threshold (when given):

| Topic | Metric | Threshold |
|---|---|---|
| **Maintainability** | OPEX/MW capacity | £100/MW |
| **Capture wave energy/performance** | kW/tonne (undecided on tonne(material) or tonne(volume displaced)) | |
| **Reliability/availability** | ΣPower captured/ΣPower at site | >95% |
| **Survivability** | Total Loss Insurance at 0.5% of CAPEX per year premium | |
| **Convert to electricity** | | |
| **Manufacturability** | | |
| **Scalability** | MW capacity per unit array area | |
| **Installability** | £(install) / MW (installed capacity) for a given time | |
| **Acceptability** | | |
| **Deliver electricity** | Distance (in Km) of export and inter-array cabling (may require a weighting) | |
| **Controllability** | | |

# 8. Conclusions and Next Steps

Henry Jeffrey brought the session to a close, summarising the outputs of each of the breakout sessions completed and thanking participants for their involvement in a successful day. It was explained that a summary report would be produced, and that it is hoped that this was just the first in a number of workshops which will be held as part of a continued relationship between WES and the DOE to create a set of suitable and universally accepted metrics to measure the performance of possible technical solutions with respect to WEC system requirements. The outputs of this workshop, in terms of requirements and metric definition, will form a valuable input to this on-going joint effort.

# Annex A: Agenda

Agenda for the joint US Department of Energy and Wave Energy Scotland workshop on WEC technology requirement specification and performance metrics, held at ICOE on February 26th 2016.

| | |
|---|---|
| 8:30 – 9:00 | Registration |
| 9:00 – 9:20 | Workshop introduction by Jochem Weber & Jonathan Hodges |
| 9:20 – 10:30 | *WEC technology system requirement specification*<br>Breakout Session 1: System requirements<br>Introduction: Jochem Weber<br>Group discussion |
| 10:30 – 11:10 | Feedback by attendees |
| 11.10 – 11.30 | Break |
| 11:30 – 12:30 | *WEC Technology system requirement metrics and thresholds*<br>Breakout Session 2: System requirement metrics and thresholds 1<br>Introduction: Jonathan Hodges<br>Group discussion |
| 12:30 – 13:00 | Feedback by attendees |
| 13:00 – 14:00 | Lunch |
| 14:00 – 15:00 | Breakout Session 3: System requirement metrics and thresholds 2 |
| 15:00 – 15:30 | Feedback by attendees |
| 15:30 – 15:45 | Break |
| 15:45 – 16:20 | Conclusions: System requirements |
| 16:20 – 17:00 | Conclusions: System requirement metrics and thresholds |

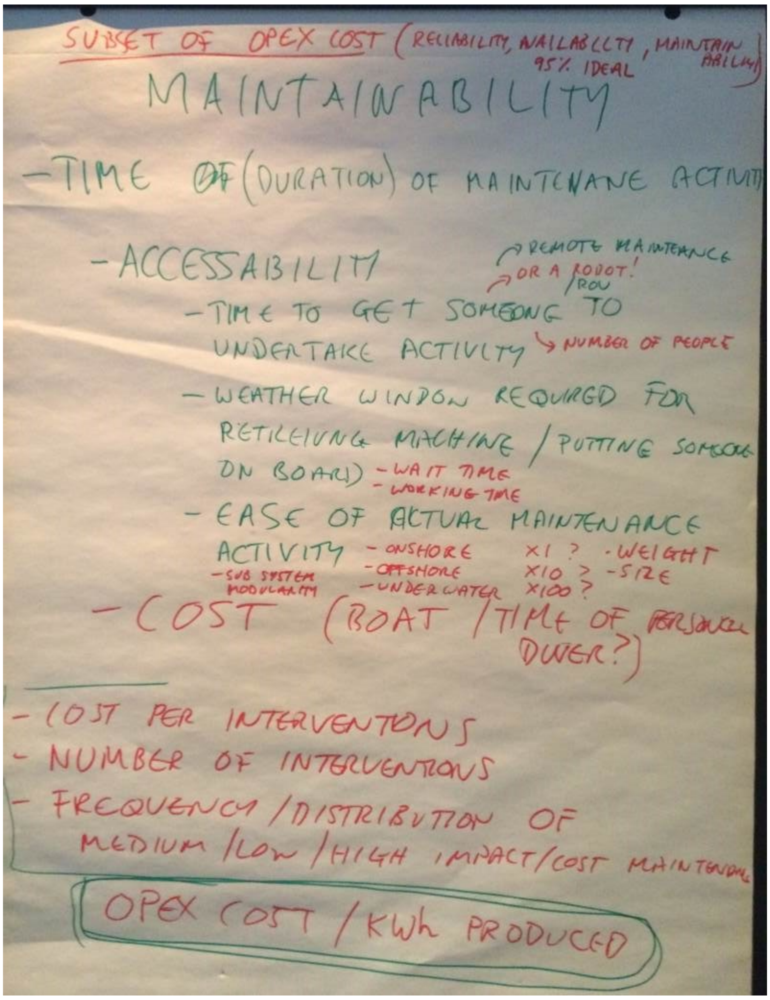
## Annex B: Attendee List

| Forename | Surname | Country | Organisation |
|---|---|---|---|
| **Henry** | Jeffrey | UK | Wave Energy Scotland |
| **Jonathan** | Hodges | UK | Wave Energy Scotland |
| **Elva** | Bannon | UK | Wave Energy Scotland |
| **Matthew** | Holland | UK | Wave Energy Scotland |
| **Ross** | Henderson | UK | Quoceant |
| **Beth** | Dickens | UK | Quoceant |
| **Chris** | Retzler | UK | Mocean |
| **Luca** | Castellini | Italy | Umbra |
| **Elaine** | Buck | UK | EMEC |
| **Brendan** | Cahill | Ireland | SEAI |
| **Ray** | Alcorn | UK | Exceedence |
| **Ray** | Hunter | UK | ORE Catapult |
| **Simon** | Cheeseman | UK | ORE Catapult |
| **Steve** | Packard | UK | Trident Energy |
| **Brian** | Holmes | Ireland | University College Cork |
| **Donald** | Naylor | UK | Pelagic Innovation |
| **Adrian** | de Andres | UK | University of Edinburgh |
| **Pablo** | Ruiz Minguela | Spain | Tecnalia |
| **Calum** | Kenny | UK | University of Edinburgh |
| **Paul** | Brewster | UK | Pure Marine |
| **Anna** | Stegman | UK | ETI |
| **Jochem** | Weber | USA | NREL |
| **Conor** | Haughey | Ireland | Bluepower Energy |
| **Cameron** | McNatt | UK/USA | Mocean |
| **Alison** | Labonte | USA | Department of Energy |
| **Rémy** | Pascal | UK/France | Innosea |
| **Claudio** | Bittencourt Ferraira | UK | DNV GL |
| **Kim** | Nielsen | Denmark | Ramboll |
| **Boris** | Teillant | Portugal | WavEC |
| **Alexandra** | Price | UK | Wave Energy Conundrums |
| **Alan** | Henry | Ireland | Rockall Solutions |
| **Robert** | Edwards | UK | DECC |
| **Colin** | McNaught | UK | Ricardo |
| **Owain** | Roberts | UK | University of Edinburgh |
| **David** | Bramble | UK | DECC |
| **David** | Rubie-Todd | UK | Wavepower |
| **David** | Findlay | UK | Albatern |
| **David** | Campbell | UK | Albatern |
| **David** | Ogden | UK/France | Innosea |
| **Daniel** | Petcovic | Sweden | CorPower |
| **Diana** | Bull | USA | Sandia National Laboratory |
| **Tim** | Ramsey | USA | Department of Energy |
| **Tim** | Mundon | UK/USA | Oscilla Power |

| | | | |
|---|---|---|---|
| **Gregory** | Payne | UK | University of Edinburgh |
| **Andrew** | Baron | Canada | Dynamic Systems Analysis |
| **Paul** | O'Brien | UK | Scotent |
| **Keith** | O'Sullivan | UK | Black and Veatch |
| **Ronan** | Costello | UK | Wave Venture |
| **Ben** | Kennedy | UK | Wave Venture |
| **Tom** | Davey | UK | FlowaveTT |
| **Stuart** | Brown | UK | FlowaveTT |
| **Stephen** | Salter | UK | University of Edinburgh |
| **Max** | Carcas | UK | Caelulum |
| **Rebecca** | Sykes | UK | Lloyds Register |

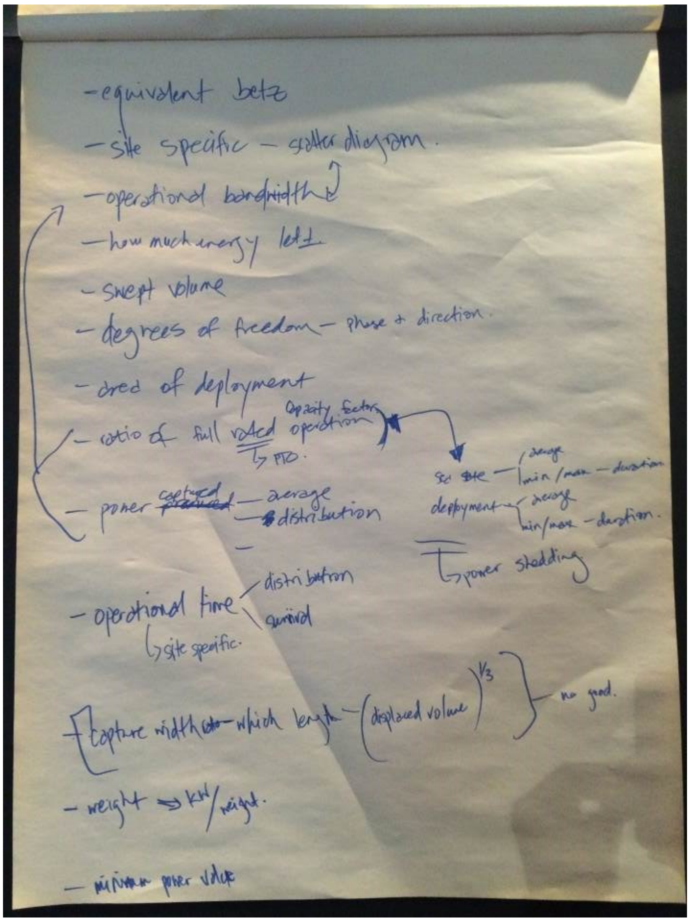
## Annex C: Flipchart Photos

A number of the groups used flipcharts to record their ideas during Breakout Sessions 2 and 3. These are recorded using the images below:

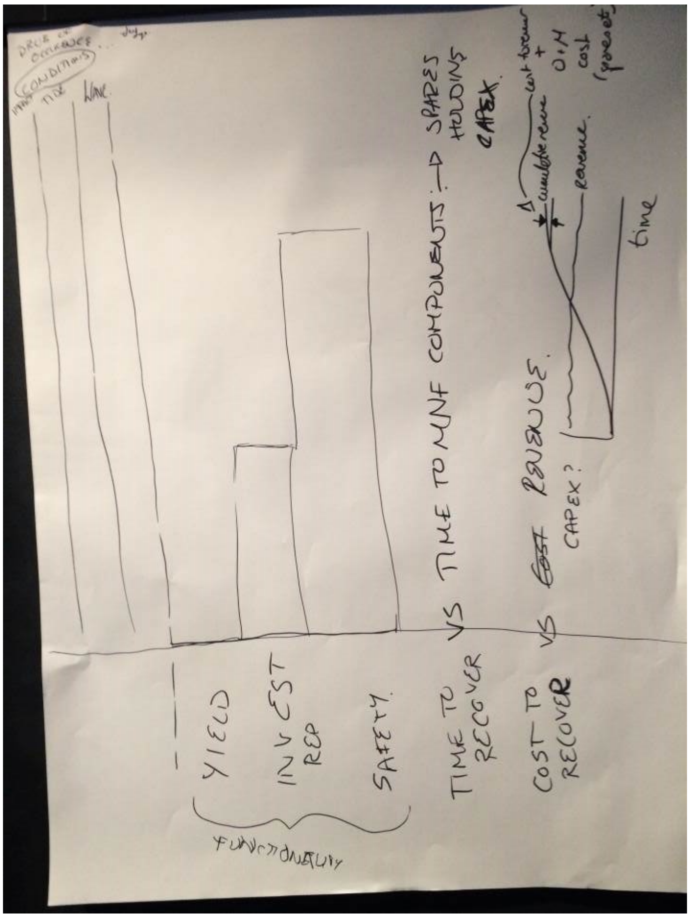



**Maintainability: Image 1 of 1**

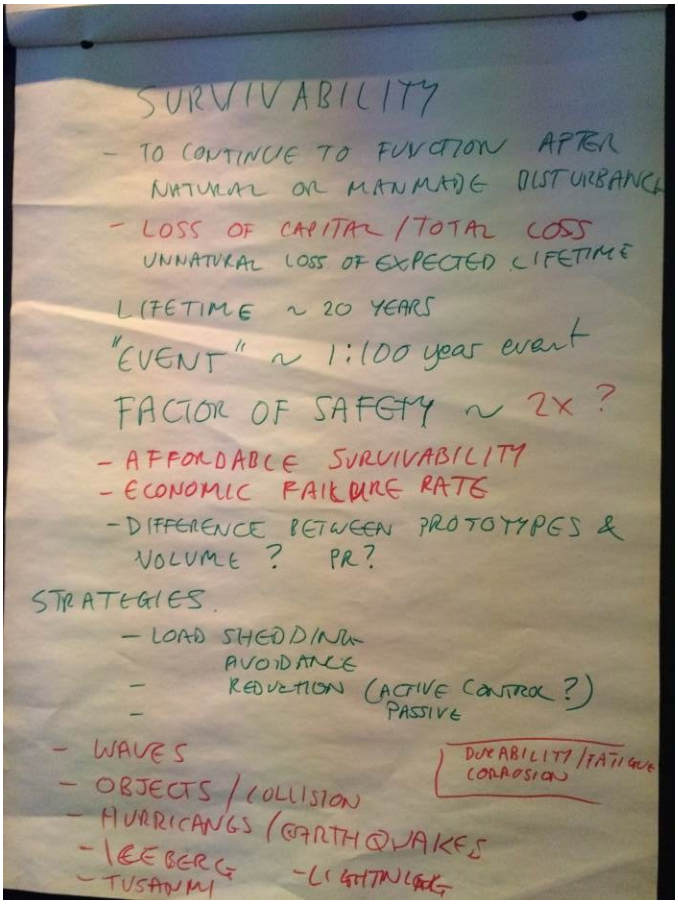

**Power Capture: Image 1 of 2**



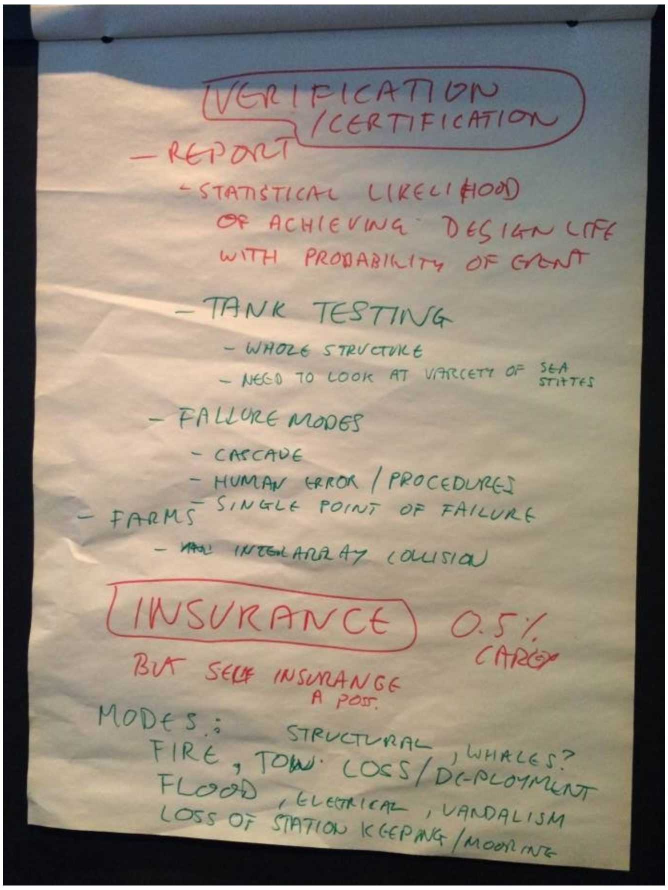

**Power Capture: Image 2 of 2**



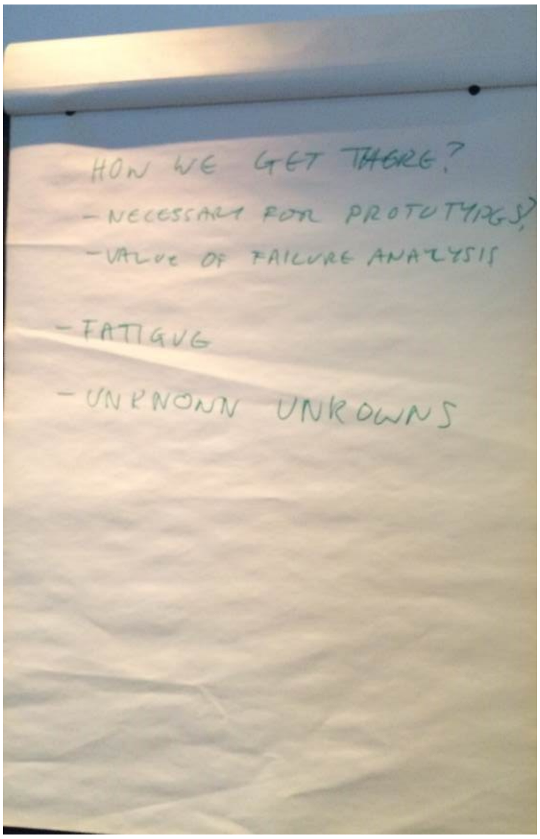

**Survivability (Breakout Session 2): Image 1 of 1**



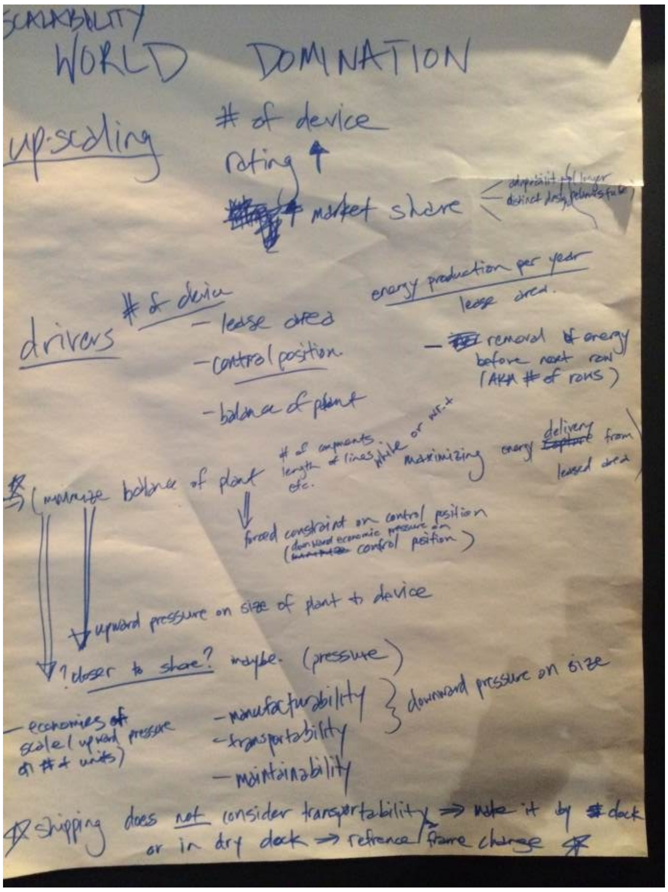

**Survivability (Breakout Session 3): Image 1 of 3**



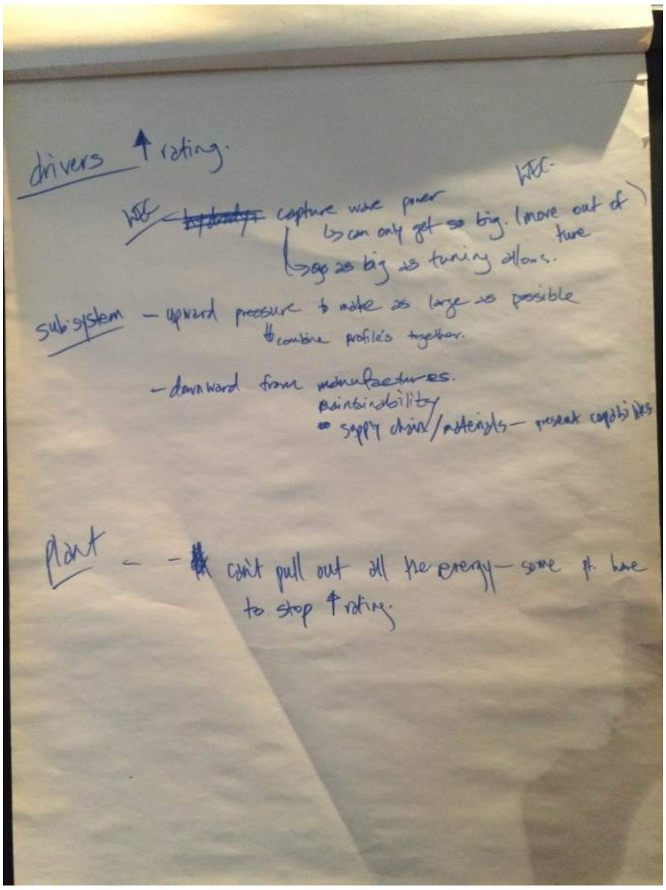

**Survivability (Breakout Session 3): Image 2 of 3**



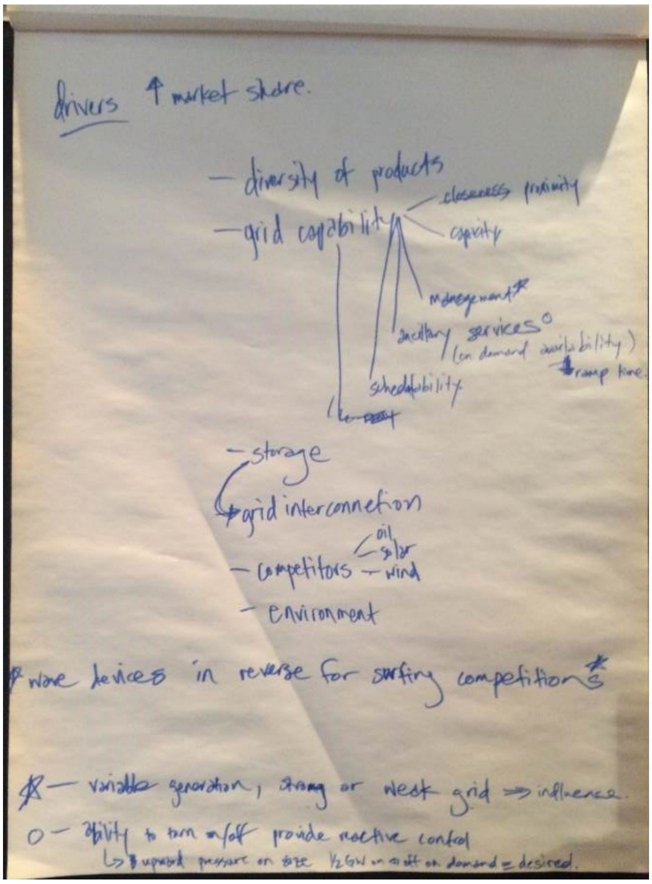

**Survivability (Breakout Session 3): Image 3 of 3**



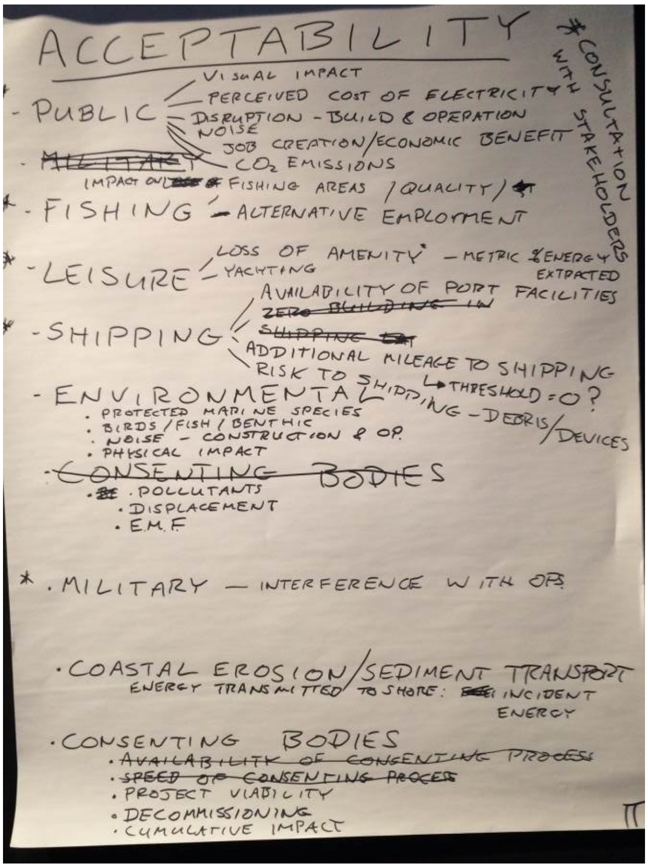

**Scalability: Image 1 of 3**



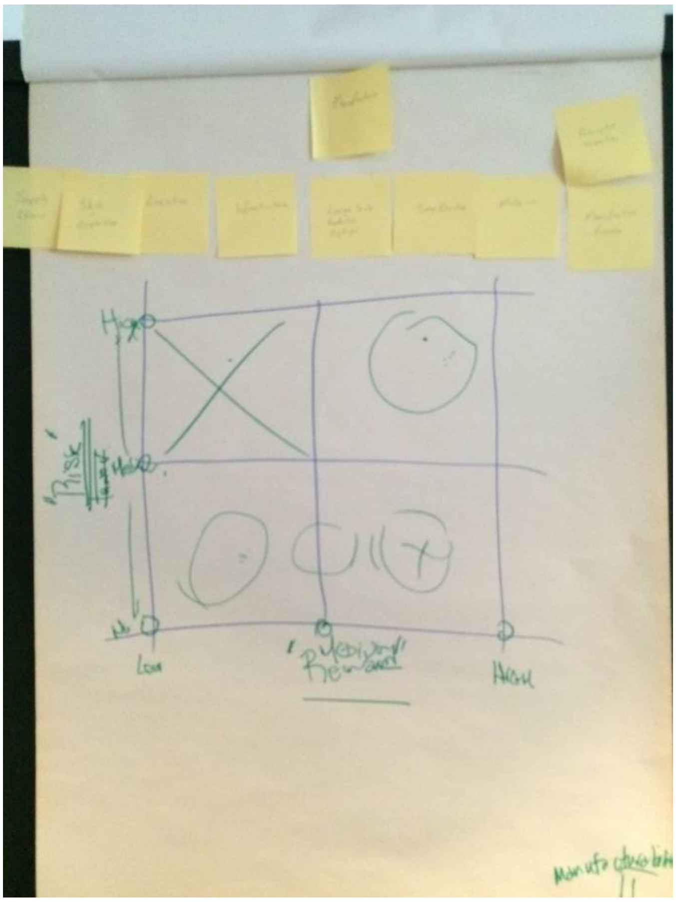

**Scalability: Image 2 of 3**



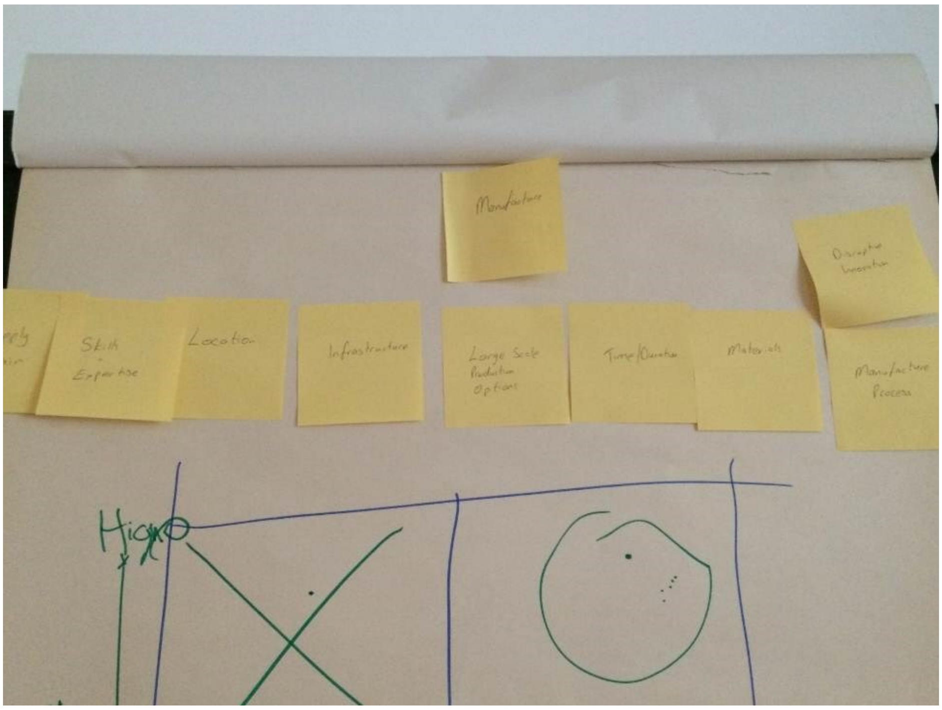

Scalability: Image 3 of 3




Acceptability: Image 1 of 1




**Manufacturability: Image 1 of 2**




**Manufacturability: Image 2 of 2**

# Annex D: Capabilities-Functions Matrix

Nb. Yellow cells refer to the functions which were associated with capabilities during Breakout Session 1.

| Function → Capability ↓ | Capture wave power | Convert to electricity | Deliver electricity | Provide structural support | Adapt to different sea conditions / states | Aggregate power from the different sources | Supply energy to operate the plant | Control position | Perform control actions | Perform survival actions | Design for modularity |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Be affordable with respect to OPEX | | | | | | | | | | | |
| Be affordable with respect to CAPEX | | | | | | | | | | | |
| Be survivable over lifetime | | | | | | | | | | | |
| Be structurally durable | | | | | | | | | | | |
| Be available | | | | | | | | | | | |
| Be reliable | | | | | | | | | | | |
| Be manufacturable | | | | | | | | | | | |
| Be transportable and installable | | | | | | | | | | | |
| Be integratable (sub-system, systems of systems) | | | | | | | | | | | |
| Be scalable/Be deployable at large scale | | | | | | | | | | | |
| Be environmentally acceptable | | | | | | | | | | | |
| Be acceptable to the other users of the area | | | | | | | | | | | |
| Be acceptable to society | | | | | | | | | | | |