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Technology Performance Level Assessment Methodology

Version 3.01

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CONTENTS

1 BACKGROUND

This Technology Performance Level (TPL) Assessment Methodology version 3 has evolved from the initial TPL methodology version 1 presented in [1, 2] and the subsequent version 2 used for the Wave Energy Prize [3]. The initial forms of the TPL assessment and its corresponding metrics were developed based solely on experience in the wave energy sector, and knowledge of the key performance and cost attributes needed for wave energy converter technology to be economically viable and commercially successful. The revised TPL assessment methodology and formulation of requirements and associated WEC farm capabilities are key elements that can be used to identify the necessary innovations to yield high performing wave energy farm solutions.

Given that the Wave-SPARC project has strived to achieve technology independence, the performance of any specific WEC design is measured through the TPL assessment. The scoring criteria associated with each query rank the performance of the solution, considering only the single capability or sub-capability. Hence as the TPL is assessed on a holistic level, trade-offs are embedded. For example, if one chooses to favor small amounts of material they will receive a high score in this criterion (for having low material costs), but it may be counterbalanced by a low score in power generation.

Technology development progress, technology value, and technology funding have largely been measured, associated with, and driven by technology readiness, measured in technology readiness levels (TRLs) [4] & [5]. Originating primarily from the space and defense industries, TRLs focus on procedural implementation of technology developments of large and complex engineering projects, where cost is neither mission critical nor a key design driver. The key deficiency with the TRL approach in the context of wave energy conversion is that WEC technology development has been too focused on commercial readiness and not enough on the economic viability required for market entry.

To compensate for this deficiency, technology performance levels (TPLs) have been introduced in [6], and further detailed in [2], as a techno-economic performance assessment metric for WEC technologies. The detailed content of a techno-economic performance metric has been derived applying systems engineering techniques, completed for a wave energy farm detailed in [7]. Systems Engineering is a disciplined approach to evaluating, holistically, the goals that must be achieved by a technology and the fundamental elements of the solution that enable achievement of the goals. This involves analyzing customer and stakeholder needs to develop the requirements that will enable technical solutions that comprehensively address these needs. Each of these aspects—refinement of TPL and functional requirements—are complementary.

These outcomes are key goals of the Wave-SPARC Project sponsored by the US DOE and led by NREL and SNL with collaborators at Wave-Venture Ltd., Ecole Centrale de Nantes, Ramboll, and Det Norske Veritas - Germanischer Lloyd (DNV GL).

2 INTRODUCTION

The technology performance level (TPL) assessments can be applied at all technology development stages and associated technology readiness levels (TRLs). Even, and particularly, at low TRLs the TPL assessment is very effective as it, holistically, considers a wide range of WEC attributes that determine the techno-economic performance potential of the WEC farm when fully developed for commercial operation. The TPL assessment also highlights potential showstoppers at the earliest possible stage of the WEC technology development.

Hence, the TPL assessment identifies the *technology independent* “performance requirements.” In order to achieve a successful solution, the entirety of the performance requirements within the TPL must be considered because, in the end, all the stakeholder needs must be achieved.

The basis for performing a TPL assessment comes from the information provided in a dedicated format, the Technical Submission Form (TSF). The TSF requests information from the WEC developer that is required to answer the questions posed in the TPL assessment document.

Chapter 3 in this document presents the guiding questions for TPL assessment at appropriate readiness levels TRL 1-2, TRL 3-4 and TRL 4-5. For each capability, a number of questions are asked and three responses are provided for each question. These characteristic example responses are associated with quantified metrics to justify a high, medium or low TPL score. These are associated to TPL scores of two, five and eight, respectively, whereby the assessor can allocate scores of all integer values from one to nine.

Chapter 4 in this document presents the mathematics behind the calculation of a final system TPL score from the individual scores.

As the Wave-SPARC program progresses and the TPL assessment method is implemented, it is expected that the TPL assessment method (including the questions and scoring criteria) will be updated and published as new versions. The present version is comprehensive, and revised versions may provide improved efficiency and reduced complexity.

3 TECHNOLOGY PERFORMANCE LEVEL ASSESSMENT

The stakeholder needs developed through the systems engineering approach as described in [7] are met if the WEC farm has the right capabilities. This list of capabilities now forms the basis of the TPL assessment described in this chapter.

Analysis of stakeholders' needs leads to the specification of seven high-level stakeholder requirements to be met by seven capabilities groups. Five of these have been split into sublevel requirements. Some of the sublevel requirements have been split into sub-sublevel requirements. Satisfaction of a requirement at a higher level depends on the satisfaction of the requirement at the sub and sub-sub levels. For example, the sub-capability 'C1.1 Have as low a CAPEX as possible' is achieved by: being a low cost design (C1.1.1), being manufacturable at a low cost (C1.1.2), being inexpensive to transport (C1.1.3), and being inexpensive to install (C1.1.4). The full taxonomy is shown in Figure 1 and the seven highest level capabilities are given below:

- C1: Have market competitive cost of energy.
- C2: Provide a secure investment opportunity.
- C3: Be reliable for grid operations.
- C4: Benefit society.
- C5: Be acceptable to permitting & certification.
- C6: Be safe.
- C7: Be globally deployable.

A detailed explanation of the life cycle stages, stakeholders, and stakeholder needs can be found in [8].

Tradeoffs in the overall design manifest themselves in the competing capabilities. The assessment guidance that is associated with the capabilities query the technical solutions that a technology has chosen, i.e. they identify which tradeoffs have been selected. For instance, in order to be a low-cost design a device should not require a lot of material. However, in order to be able to generate a large amount of electricity the device may have to be large. Hence as the TPL is assessed on a holistic level, if a WEC designer chooses to favor small amounts of material this will receive a high score in this criterion (for having low material costs), but it may be balanced by a low score in generation.

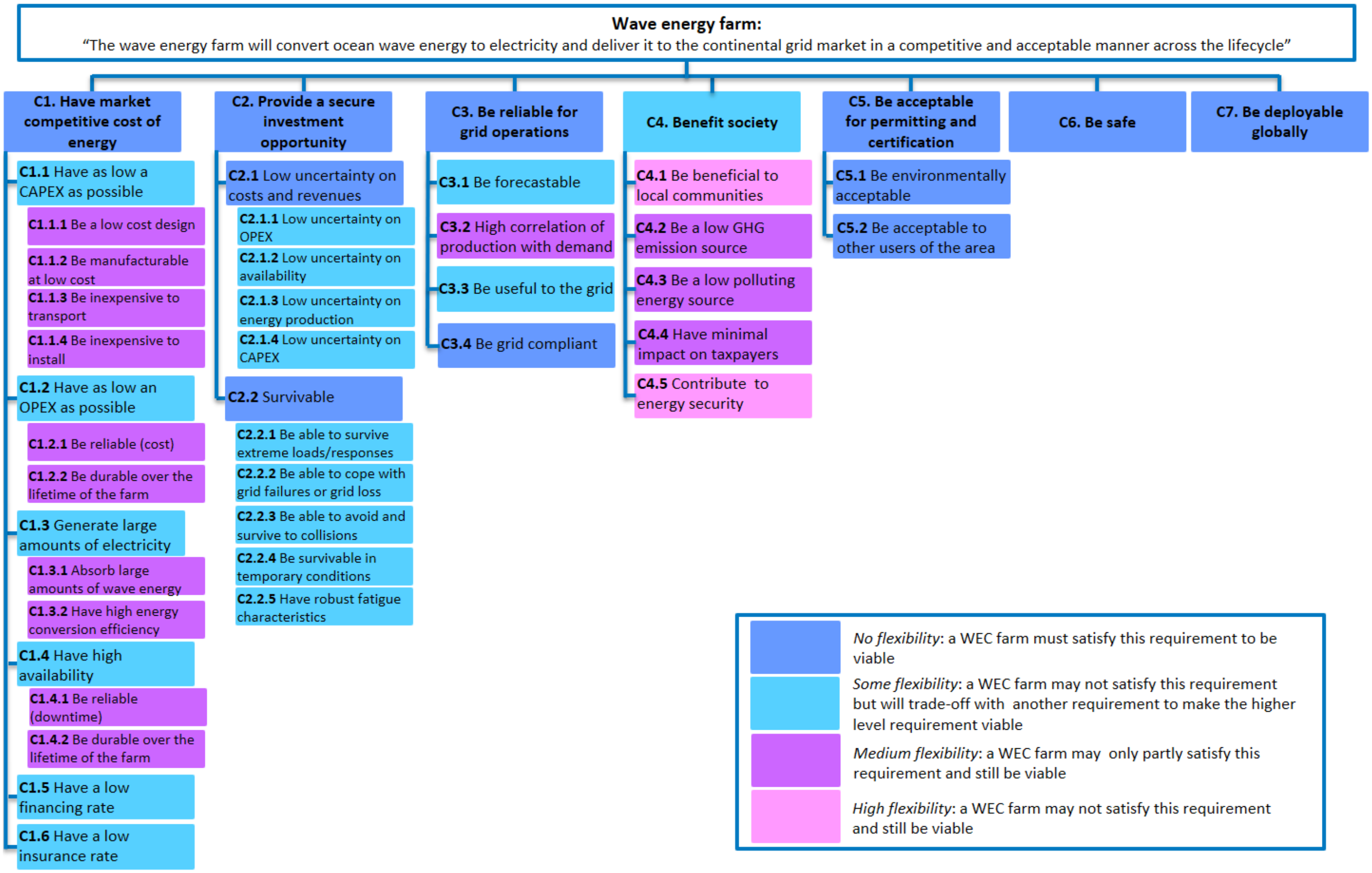

Figure 1. TPL taxonomy.

Note: This figure is hyperlinked. Press the Control key and click on any capability to be directed to the text that fully describes the capability and details the questions and scoring criteria by which to assess the capability. Where pictured, click ⮝ *to return to Figure 1.*

The capabilities are customer focused rather than technology focused which is in keeping with the Systems Engineering philosophy. The later sections of this chapter cover these capabilities and provide a series of detailed questions with scoring guidance to be answered by the TPL assessor under the capabilities and two nested levels of sub-capabilities. In each case the capabilities and the questions are intended to address the customer needs and so be independent of any technical solutions. This version 3.1 of the TPL assessment methodology provides question of appropriate levels of detail at different TRL levels. The assessment questions are grouped according to three levels of TRL. The most basic questions are to be addressed for TRL1-2 technologies. An expanded more detailed set of questions is to be addressed for technologies at TRL3-4 in addition to updating the answers to the TRL1-2 questions where requested. Finally, technologies at TRL5-6 and above must present quantified and verified evidence for expected techno-economic performance. Again lower level TPL scores are also considered where requested.

The TPL is designed to be an assessment of the suitability of the technical solution for satisfaction of the customers' needs. As such it is focused on technology assessment to a much greater extent than it is on project assessment. However, in certain questions it is necessary to consider a typical or target deployment location and typical or target wave farm project at that location since these are the context for the ultimate use of the technology and its value creation mechanism. In general, when answering the questions in the assessment at TRL1-2 & TRL3-4 the technology promoter should give information for some notional "typical" deployment, plant size (MW) distance from shore, etc., while at TRL5-6 the assessment needs to have a real world example of target deployment location and wave farm project.

The highlights of the revised TPL assessment methodology are:

- New structure and equation formulation more clearly represents energy economics.
- More complete inclusion of investment security and risk.
- More accurate integration of LCoE structure in calculation into the TPL.
- Integration of TPL for specific TRL (different TPL assessment questions at different TRL).
- Harmonization of TPL with terminology of certification and IEC standards.
- Reconciliation of TPL with Systems Engineering.
- TPL is now assessed using a list of detailed questions and scoring guidance.
- Significantly expanded depth of coverage.

The TPL assessment coupled with the scoring criteria identifies TPL value of the *technology independent* "performance requirements". In order to achieve a successful solution, the TPL assessment and associated scoring criteria need to achieve a high TPL value. This TPL is designed to assess the *techno-economic performance* of the proposed technology based on the holistic entirety of the TPL assessment and scoring criteria considering all the stakeholder needs.

The TPL score could be used by private investors and public funding agencies to make informed decisions when allocating resources to wave energy technology developers. The TPL metric could also be used to perform benchmarking studies between different WEC technologies. Such studies would be much more comprehensive than other recent studies such as [9], [10], [1], [11], and [12] that essentially used proxies for cost of energy or energy performance. In the long term, it is believed that using a TPL metric based on the present or improved list of stakeholder requirements may prove helpful toward WEC technology convergence. The intended uses of the revised TPL include:

- 3rd party technology assessment e.g. public funding bodies or technical due diligence.
- In house technology assessment for choosing between innovative product alternatives focused allocation of development efforts.
- Finance community and OEMs as investors in WEC technology.
- Finance community and OEMs as investors in WEC farm deployments.

BRIEF INSTRUCTIONS FOR USE

The TPL assessment should follow these broad steps:

- The technology must be described by its “promoter” in the technical submission form with an indication of the appropriate TRL level to be used for the assessment.
- The assessor must use the information in the technical submission form to assign a score of 1-9 to each question presented in this TPL assessment guide. Guiding scoring criteria are given in the form of High (score 8), Med (score 5), and Low (score 2). It is up to the assessor to determine the exact value of the score based on how much better or worse than the scoring criteria guidance the technology performs.
- For each numbered capability or sub-capability the assessor must weigh all the scores assigned to the answers in that section and assign one overall score on a scale of 1-9 to the capability (or sub capability). It is recommended to evaluate the distribution of scores for all the answers within that capability group when assigning the combined score. Note it is not recommended to average the scores within a capability group—some questions are more important than others for particular technologies. The assessor must use expert judgement to determine relevance of the criteria within a capability group to determine the final combined overall score.
- The assessor should enter the score for each capability in the scoring spreadsheet. Chapter 4 discusses the calculations that are performed in the scoring calculator which determine the final TPL score of the wave farm system.
- Finally, feed-back as to improvement of the assessment methodology can be send to the maintenance team of this document.

TPL: assessment and evaluation criteria

C.1. Have market competitive cost of energy

Electricity from the wave energy farm may be sold on the day-ahead wholesale electricity market or through a PPA. In both cases, the **sales price** of the produced electricity shall be **competitive with other energy sources**. However, note that market price may vary among energy sources in some countries. There may be feed-in tariffs, renewable energy certificates, or renewable obligations for wave energy or renewable energy sources. Some countries may also require that a certain percentage of the energy portfolio of utility companies is from renewable energy sources. The subtier stakeholder requirements below identify the variables in the LCOE equation. The LCOE of the wave energy farm is needed to determine if the project will have a market-competitive cost of energy.

The LCOE assessment is required at TRL 5-6 if possible with an assessment of uncertainty.

At lower TRL levels go to sub-capability C.1.1

TRL 5-6

- Using cost estimates of CapEx (C1.1), OpEx (C1.2), energy production (C1.3 and C1.4) calculate the LCOE of the wave energy farm according to the following equation:

$$LCoE = \frac{ICC \times FCR + O\&M}{AEP}$$

$LCoE$	Levelized cost of energy (\$/MWh)
ICC	Initial capital cost per installed capacity (\$/MW)
AEP	Annual energy production per installed capacity (MWh/MW/year = hours/year)

$$AEP = CF \times 365 \times 24$$

FCR	Fixed charge rate

$$FCR = 10.8\ \%$$

$O\&M$	Operations and maintenance costs, including all routine maintenance, operations, and monitoring activity (i.e. non-depreciable) (\$/MW/year)
CF	Capacity factor, averaged over typical year (%). Note: Must be strictly consistent with the estimated “initial capital cost per installed capacity”

High: LCOE ≤ \$0.20/kWhr.
Target for TPL is 9 LCOE ≤ \$0.05/kWhr
Target for TPL 8 is LCOE ≤ \$0.10/kWhr
Target for TPL 7 is LCOE ≤ \$0.20/kWhr
Med: \$0.40/kWhr ≤ LCOE ≤ \$1.60/kWhr
Low: LCOE≥ \$3.20/kWhr

C.1.1. Have as low a CAPEX as possible

CapEx includes **all costs** that occur in the development and construction of a WEC farm **until it starts producing electricity**. It should also include decommissioning costs. The WEC farm should have as low a CapEx as possible. **Drivers** of CapEx are **design, manufacturability, transportability, and installability**. It includes costs related to grid connection.

C.1.1.1. Be a low cost design

A WEC farm should have an elegant design and as few components/sub-subsystems as possible with many suppliers for the components and sub-subsystems. It should minimize the required material quantities and it should make use of low-cost material types. It may maximize recycling opportunities to provide additional revenues at the end of the WEC farm's lifetime.

TRL1-2
• What is the technology class for each subsystem in the WEC Farm? **High:** All or predominantly Class 1. **Med:** Predominately Class 1 and 2 with no or few Class 3. **Low:** Any significant number of Class 3 or 4. • For the subsystem that collects wave power, please answer the following questions: a. Where in the water column is this subsystem located? **High:** Subsystems submerged far below the free surface will experience the smallest loads on the structure provided the pressure inside is equal to the hydrostatic pressure. **Med:** Minimal surface expression or only submerged minimally below the free surface. **Low:** Surface expression indicates susceptibility to higher global loads, slamming and greenwater loads, and additionally collisions with other users of the area. b. What is the displaced volume? **High:** Displaced volume less than 500m^3/MW. **Med:** Displaced volume between 500 and 2500m^3/MW **Low:** Displaced volume greater than 2500m^3/MW c. What is the dominant material type and what is its raw cost? **High:** traditional cheap material types in agreement with typical raw cost

Med: traditional expensive material types
Low: novel material types with uncertain raw cost data

d. What is the mass for structural members that are not intended to collect wave power, i.e. e.g. structural elements whose main purpose is not to provide surface area for wave power absorption?
For example: Internal reaction masses, structural linkages such as beams, lattice structures, tie bars.
High: a small fraction <10%
Med: between high and low
Low: a large fraction >50%

e. How many sets of point loads (heave plate, mooring lugs, PTO, end stops) affect the subsystem that collects wave power? Note: Point loads occur when two bodies connect for which the forcing profiles are distinct (general hull withstands hydrostatic pressure combining with the PTO attachment at which thrust forces must be mitigated); special structural solutions may be employed to distribute the point loads across a wider area. Identify the type and number.
High: Only one set of point loads (for instance mooring attachment points or PTO attachment points)
Med: Three sets of point loads (for instance mooring attachment points, end stops, and heave plate)
Low: More than three sets of point loads

f. What is the total number of distinct physical/structural configurations, i.e. can the subsystem that collects wave power alter its physical profile by changing: the water plane area, swept volume of motion by more than just the limitations of the PTO, etc.)?
High: Only one distinct physical/structural configuration
Med: Two distinct physical/structural configurations that differ by less than 50%
Low: More than two distinct physical/structural configurations or two distinct physical configurations that differ by more than 50%

- Where in the water column is the subsystem that aggregates power?
  High: Both the collect wave power and the aggregate power are attached to the ground and hence there is no dynamic motion between them.
  Med: One of the subsystems is floating and one is tied to ground.
  Low: Both the collect wave power and the aggregate power are floating and hence there could be significant dynamic motion between them.

• For the subsystem that controls position, please answer the following questions: a. For cable based subsystems: what is the technology class and what is the ratio of the expected footprint (length to anchors, L) to the expected watch circle (largest characteristic excursion of subsystem that collects wave power, w)? **High:** technology class 1 or 2 AND L/w < 0.1 **Med:** technology class 1 or 2 AND 1.8<L/w<2.8 or L/w ~1 tension (≤ class 2) or catenary (≤ class 2) with a larger footprint **Low:** technology class 3 or 4 OR L/w>2.8 any mooring concept with > class 3 b. What deployment depths are required by the concept? **High:** Onshore / on coast allows for many installation techniques or no requirements are placed on depth from the subsystem that controls position. **Med:** Depths between 20 – 50 meters. Shallower depths are cut-off location for certain installation techniques. **Low:** Depths greater than 70 meters c. How many total connections points are there on the collect wave power subsystem and on the sea floor? **High:** 2 or less per MW installed capacity **Med:** 4 or less per MW installed capacity **Low:** more than 4 per MW installed capacity
TRL3-4
Update the answers to TRL1-2 plus answer the following questions: • What is the technology class for each sub-subsystem in the WEC Farm? **High:** All or predominantly Class 1. **Med:** Predominately Class 1 and 2 with no or few Class 3. **Low:** Any significant number of Class 3 or 4. • For the subsystem that collects wave power, please answer the following questions: a. Considering assembly, installation, and operations what estimation has been provided for the needed material type, volume, and cost to fabricate structure that collects wave power. **High:** The volume and cost estimates for the structure that collects wave power are approximately \$500 k\$/MW **Med:** The volume and cost estimates for the structure that collects wave power are approximately \$1,100 k\$/MW **Low:** The volume and cost estimates for the structure that collects wave power are approximately \$2,400 k\$/MW

b. For power producing forces (i.e. forces translated to the structure due to power production, like at the PTO attachments) what are the magnitudes of the point loads identified previously in TRL1-2? What modeling technique was used to identify these magnitudes? (Use highest values where multiple power producing point loads exist)
High: Non-linear dynamic modeling applied and the ratio of the average annual P95 of the point loads to the average annual P50 power producing force is < 6 in a typical deployment climate
Med: Linear dynamic modeling applied and the ratio of the average annual P95 of the point loads to the average annual P50 power producing force is < 10 in a typical deployment climate
Low: Static modeling only and the ratio of the average annual P95 point loads to the average annual P50 power producing force is > 12 in a typical deployment climate

c. Considering the structure that collects wave power what are the following: the design utilization factor and the smallest return period of the sea-state(s) that corresponds to the production of the characteristic structural load? The design utilization factor is the ratio of the characteristic structural load (stress, force, moment, etc.) to the average annual P50 structural load. Note. The characteristic structural load is the basis for the structural design—to this load a factor of safety will be applied to achieve a desired safety level.
High: Design Utilization Factor < 10 & return period ≥ 60 years
Med: Design Utilization Factor < 20 & 40 < return period < 60 years
Low: Design Utilization Factor > 30 & return period < 40 years

d. Considering the structure that collects wave power identify how many cycles the structure must be designed to for the top five most highly flexed areas.
High: flexion cycles < (number of waves in a year * lifetime of structure)
Med: flexion cycles ≈ (number of waves in a year * lifetime of structure)
Low: flexion cycles > (number of waves in a year * lifetime of structure)

e. Considering the sub-subsystem that converts absorbed power into useable power what are the following: the design utilization factor and the smallest return period of the sea-state(s) that corresponds to the production of the characteristic sub-subsystem load? The design utilization factor is the ratio of the characteristic sub-subsystem load (stress, force, moment, etc.) to the average annual P50 sub-subsystem load. Note. The characteristic sub-subsystem load is the basis for the structural design—to this load a factor of safety will be applied to achieve a desired safety level.

High: Design Utilization Factor < 10 & return period ≥ 60 years

Med: Design Utilization Factor < 20 & 40 < return period < 60 years

Low: Design Utilization Factor > 30 & return period < 40 years

f. Considering the sub-subsystem that converts absorbed power into useable power identify how many cycles the sub-subsystem must be designed to for the top three most highly flexed areas.

High: flexion cycles < (number of waves in a year * lifetime of structure)

Med: flexion cycles ≈ (number of waves in a year * lifetime of structure)

Low: flexion cycles > (number of waves in a year * lifetime of structure)

g. Evaluate the specific capacity factors (a capacity factor is the average value divided by the rated value) by populating each element of the scatter diagram for each component within the sub-subsystem that converts absorbed power into useable power (i.e. generator, variable frequency drive, hydraulic cylinders, etc.). These average capacity factors should be determined through dynamic analysis in which efficiency dependencies (on velocity or flow rate for instance) are accounted for.

High: Capacity factors >0.5 for a majority of components in sea-states that comprise 90% of a typical year in the deployment climate

Med: 0.3 < Capacity factors < 0.5 for a majority of components in sea-states that comprise 90% of a typical year in the deployment climate.

Low: Capacity factors <0.3 for a majority of the components in sea-states that comprise 90% of a typical year in the deployment climate.

- For the subsystem that aggregate wave power, please answer the following questions:

a. What is the intra-array connection length (electrical cable, pressure conduit, etc.) per MW of installed capacity?

High: Total intra-array connection length is ≤1km per MW installed capacity
Med: Total intra-array connection length is ≤2km per MW installed capacity
Low: Total intra-array connection length is >2km per MW installed capacity

b. How many collect wave powers connect to one aggregator and what is the technology class of the connection?
High: ≥16 collect wave powers per Aggregator AND technology class 1 or 2
Med: ≥8 collect wave powers per Aggregator AND technology class 1 or 2
Low: <8 collect wave powers per Aggregator OR technology class 3 or 4

c. Evaluate the specific capacity factors for the conduit from collect to aggregate and the other sub-subsystems by populating each element of the scatter diagram. These average capacity factors should be determined through dynamic analysis in which efficiency dependencies are accounted for.
High: Capacity factors >0.5 for a majority of sub-subsystems in sea-states that comprise 90% of a typical year in the deployment climate
Med: 0.3 < Capacity factors < 0.5 for a majority of sub-subsystems in sea-states that comprise 90% of a typical year in the deployment climate.
Low: Capacity factors <0.3 for a majority of the sub-subsystems in sea-states that comprise 90% of a typical year in the deployment climate.

- For the subsystem that delivers wave power, evaluate the specific capacity factors for the conduit that transports power from the aggregators to the grid and the other sub-subsystems by populating each element of the scatter diagram. These average capacity factors should be determined through dynamic analysis in which efficiency dependencies (on velocity or flow rate for instance) are accounted for.
High: Capacity factors >0.5 for a majority of sub-subsystems in sea-states that comprise 90% of a typical year in the deployment climate
Med: 0.3 < Capacity factors < 0.5 for a majority of sub-subsystems in sea-states that comprise 90% of a typical year in the deployment climate.
Low: Capacity factors <0.3 for a majority of the sub-subsystems in sea-states that comprise 90% of a typical year in the deployment climate.

- Considering the sub-subsystem that controls position, please answer the following questions:
  a. Considering the sub-subsystem that controls position what are the following: the design utilization factor and the smallest return period of the sea-state(s) that corresponds to the production of the characteristic sub-subsystem load? The design utilization factor is the ratio of the characteristic sub-subsystem load (stress, force, moment, etc.) to the average annual P50 sub-subsystem load. Note. The characteristic sub-subsystem load is the basis for the structural design—to this load a factor of safety will be applied to achieve a desired safety level.
     High: Design Utilization Factor < 10 & return period ≥ 60 years
     Med: Design Utilization Factor < 20 & 40 < return period < 60 years
     Low: Design Utilization Factor > 30 & return period < 40 years

  b. Considering the sub-subsystem that controls position identify how many cycles the sub-subsystem must be designed to for the top 3 most highly flexed areas.
     High: flexion cycles < (number of waves in a year * lifetime of structure)
     Med: flexion cycles ≈ (number of waves in a year * lifetime of structure)
     Low: flexion cycles > (number of waves in a year * lifetime of structure)

  c. How will the control position connect to the sea floor and what is the technology class of this connection mechanism?
     High: Install using non-specialized vessels AND technology class 1.
     Med: Installation requires drilling or specialized vessels AND technology class 1 or 2.
     Low: Uncertainty relating to the solution OR technology class 3 or 4

  d. What geophysical conditions are required to deploy this concept?
     High: sand and soft clay
     Med: aggregated substance, i.e. gravel
     Low: solid rock

TRL5-6

- Materials and components costs = Sum of costs of materials and components/sub-systems required to make the WECs farm (unit cost and number of components/sub-systems) - recycling revenues

- For the subsystem that collects wave power, please answer the following questions:
  a. Considering the structure that collects wave power what are the following: the design utilization factor and the smallest return period of the sea-state(s) that corresponds to the production of the characteristic structural load? The design utilization factor is the ratio of the characteristic structural load (stress, force, moment, etc.) to the average annual P50 structural load. Note. The characteristic structural load is the basis for the structural design—to this load a factor of safety will be applied to achieve a desired safety level.
  High: Design Utilization Factor < 10 & return period ≥ 60 years
  Med: Design Utilization Factor < 20 & 40 < return period < 60 years
  Low: Design Utilization Factor > 30 & return period < 40 years

  b. Considering the structure that collects wave power what safety class will it be designed to?
  High: high safety class $<10^{-5}$ per annum resulting in a larger factory of safety being applied to the structural design
  Med: medium safety class $<10^{-4}$ per annum
  Low: low safety class $<10^{-3}$ per annum resulting in the smallest factory of safety being applied to the structural design

  c. Considering the sub-subsystem that converts absorbed power into useable power what are the following: the design utilization factor and the smallest return period of the sea-state(s) that corresponds to the production of the characteristic sub-subsystem load? The design utilization factor is the ratio of the characteristic sub-subsystem load (stress, force, moment, etc.) to the average annual P50 sub-subsystem load. Note. The characteristic sub-subsystem load is the basis for the structural design—to this load a factor of safety will be applied to achieve a desired safety level.
  High: Design Utilization Factor < 10 & return period ≥ 60 years
  Med: Design Utilization Factor < 20 & 40 < return period < 60 years
  Low: Design Utilization Factor > 30 & return period < 40 years

d. Considering the sub-subsystem that converts absorbed power into useable power what safety class will it be designed to?
High: high safety class $<10^{-5}$ per annum resulting in a larger factory of safety being applied to the structural design
Med: medium safety class $<10^{-4}$ per annum
Low: low safety class $<10^{-3}$ per annum resulting in the smallest factory of safety being applied to the structural design

e. What is the annual average capacity factor for useable power from the subsystem that collects wave power based on dynamic analysis?
High: Capacity factor > 0.4
Med: 0.2 < Capacity factor < 0.4
Low: Capacity factor < 0.2

- Considering the sub-subsystem that controls position, please answer the following questions:

a. What are the design utilization factor and the smallest return period of the sea-state(s) that corresponds to the production of the characteristic sub-subsystem load? The design utilization factor is the ratio of the characteristic sub-subsystem load (stress, force, moment, etc.) to the average annual P50 sub-subsystem load. Note. The characteristic sub-subsystem load is the basis for the structural design—to this load a factor of safety will be applied to achieve a desired safety level.
High: Design Utilization Factor < 10 & return period ≥ 60 years
Med: Design Utilization Factor < 20 & 40 < return period < 60 years
Low: Design Utilization Factor > 30 & return period < 40 years

b. What safety class will it be designed to?
High: high safety class $<10^{-5}$ per annum resulting in a larger factory of safety being applied to the structural design
Med: medium safety class $<10^{-4}$ per annum
Low: low safety class $<10^{-3}$ per annum resulting in the smallest factory of safety being applied to the structural design

- What techniques (experimental, numerical, etc.) were used to determine the characteristic loads for the sub-subsystems asked about above?
High:

Experimental Technique	*Modeling Technique*
Statistically significant testing in appropriate return period	Dynamic modeling including predominant nonlinearities

confirming characteristic load to within 10% of expectation

and capable of resolving impact events

Med:

Experimental Technique
Statistically significant testing in appropriate return period confirming characteristic load to within 20% of expectation

Modeling Technique
Dynamic modeling based on nonlinear assumptions

Low:

Experimental Technique
Statistically significant testing in appropriate return period confirming characteristic load to within 50% of expectation

Modeling Technique
Dynamic modeling based on linear assumptions

- What are the fatigue lives for the highest consequence elements of the farm?
  High: Majority of fatigue lives are greater than 1.5 the lifetime of the farm.
  Med: Several of fatigue lives are equivalent to the lifetime of the farm.
  Low: Majority of fatigue lives are less than the lifetime of the farm OR fatigue lives have not yet been fully considered.

- What is the annual average capacity factor for the aggregated useable power from the subsystem that aggregates wave power based on dynamic analysis?
  High: Capacity factor > 0.5
  Med: 0.3 < Capacity factor < 0.5
  Low: Capacity factor < 0.3

- What is the annual average capacity factor for electrical delivered power from the subsystem that delivers wave power based on dynamic analysis?
  High: Capacity factor > 0.5
  Med: 0.3 < Capacity factor < 0.5
  Low: Capacity factor < 0.3

- For the subsystem that delivers wave power, what is the typical distance to shore that the aggregated power must travel?
  High: <20km
  Med: between 20km and 40km
  Low: >40km

- What are the monitoring costs for the farm over the entire life cycle to ensure environmental acceptability?

High: insignificant portion of the Materials and components costs (1-2%)
Med: important portion of the Materials and components costs (4-6%)
Low: nontrivial portion of the Materials and components costs (>10%)

C.1.1.2. Be manufacturable at a low cost

The WEC farm should be easy and quick to mass produce. It should minimize the need for specialized tools and equipment, highly qualified workers, and dedicated or specialized infrastructure for manufacturing, assembly, and storage. The WEC farm may provide cost-offsetting by performing more than one service.

TRL1-2
• Of the technology class 3 & 4 subsystems (subsystems that collect wave power, aggregate power, deliver power, and control position), which must be custom-manufactured and at what level? . **High:** custom manufacturing for one subsystem at high numbers, ~100 (for any manufactured part trying to achieve mass production) or not custom manufacturing anything. **Med:** custom manufacturing two subsystems and some of them with low numbers (~20 or less) **Low:** custom manufacturing more than two subsystems and some of them with low numbers (~10 or less). • What is the expected manufacturing facility? Is this facility easily transferable to new locations? (including concepts of specialized manufactures that would not be able to set up shop in location) **High:** facility can be easily set-up close to deployment location (not needing transportation) (ex. any warehouse or concrete apron is sufficient). **Med:** need large warehouse with specialized needs (floor strength, clean requirements, etc.) or water-depth of harbor required to be deep **Low:** requires dry-dock or floating dock (very specialized locations that are not highly translatable); water depth of harbor required to be deep. • What expertise is needed from the workforce (dependent upon: material type, level of tolerances that must be achieved, specialized safety, customized molds, etc.)? **High:** majority of materials that do not require specialized skills or safety (pouring concrete over laid out rebar). **Med:** some material that requires specialized skill and safety covering small percentage of total manufactured mass (welded steel) **Low:** majority of material that requires specialized skill and safety (welded steel) • What is the dominant material type in the system that collects wave power? **High:** traditional inexpensive material types. **Med:** traditional expensive material types **Low:** novel material types

• What are the sizes (envelope dimensions) and the mass of each sub-subsystem (structure, mechanism that creates transportable power, etc.) that will comprise the subsystem that collects wave power? **High:** No lifting by crane is required at sea AND lifting by crane to be <60t required on land. Envelope dimensions are approximately equivalent to a standard shipping container on at least 1 side of horizontal footprint. **Med:** No lifting by crane is required at sea AND lifting by crane to be <120t required on land. Envelope dimensions are approximately those of a standard shipping container on at least one side of horizontal footprint. **Low:** Lifting by crane is required at sea (any) OR lifting by crane>120t on land. Envelope dimensions are > a standard shipping container. • If it is anticipated to be manufactured, what is the dominant material type in the subsystem that aggregates wave power? **High:** traditional cheap material types. **Med:** traditional expensive material types **Low:** novel material types • If it is anticipated to be manufactured, what is the dominant material type in the subsystem that controls position? **High:** traditional cheap material types. **Med:** traditional expensive material types **Low:** novel material types
TRL3-4
Update the answers to TRL1-2 plus answer the following questions: • Of the technology class 3 & 4 sub-subsystems, which must be custom-manufactured and at what level? . **High:** custom manufacturing for only a few dissimilar sub-subsystems at high numbers, ~100 (for any manufactured part trying to achieve mass production) or not custom manufacturing anything. **Med:** custom manufacturing multiple dissimilar sub-subsystems per system (~ 5) and some of them with low numbers (~20 or less) **Low:** custom manufacturing many dissimilar sub-subsystems (more than ~5) and some of them with low numbers (~10 or less). • What is the expected manufacturing rate, in day / MW, for all complete subsystems? (Considering a single production facility / single production line.) **High:** less than 10 days / 1 MW (manufacturing at least 100MW in one season) **Med:** 11 -20 days / 1 MW

Low: greater than 21 days / MW

- In order to integrate distinct sub-subsystems, what mechanisms are employed to achieve and maintain necessary alignment (i.e. in the face of elastic deformation) or what steps are being taken to achieve self-alignment in the face of flexure?

  High: Design does not possess alignment concerns (small size, extremely rigid materials) OR design is tolerant of flexure.

  Med: small surfaces / interfaces requiring close (accurate) alignment OR multiple surfaces / interfaces requiring alignment

  Low: Large surfaces / interfaces requiring close (accurate) alignment. (ex. bearing surface on the stroke length difficult to obtain, or maintaining the air gap on a linear/rotary generator)

- To what level can the manufacturing techniques be automated for each sub-subsystem and subsystem? (levels: every piece must be hand welded, can use a mold, can use automated fiberglass winding, etc. Suitability of manufacturing process to achieving rounded edges?)

  High: Ability to automate a majority of the manufacturing steps, workers needed to implement a minority of manufacturing steps.

  Med: in between high and low.

  Low: Inability to automate a majority of the manufacturing steps, highly skilled workers needed to implement majority of manufacturing steps.

- How many distinct manufacturing techniques (rolling steel, welding steel, winding fiberglass, etc.) must be implemented to achieve the system that collects wave power?

  High: Minimizing the number of distinct techniques and material types is preferential; having a few at most.

  Med: Multiple techniques or multiple material types.

  Low: Multiple material types and multiple manufacturing techniques (multiple greater than 7).

- If the subsystem that aggregates wave power is anticipated to be manufactured, what are the sizes (envelope dimensions) and the mass of each sub-subsystem (structure, mechanism that combines transportable power, etc.)?

  High: No lifting by crane is required at sea AND lifting by crane to be <60t required on land. Envelope dimensions are approximately equivalent to a standard shipping container on at least 1 side of horizontal footprint.

Med: No lifting by crane is required at sea AND lifting by crane to be <120t required on land. Envelope dimensions are approximately those of a standard shipping container on at least one side of horizontal footprint.
Low: Lifting by crane is required at sea (any) OR lifting by crane>120t on land. Envelope dimensions are > a standard shipping container.

- Are interfaces for sub-subsystems and components easily identifiable / accessible?
  High: The majority of interfaces are easily accessible (e.g. can install/remove a high number sub-system at any time)
  Med: in between high and low.
  Low: A minority of interfaces are easily accessible (e.g. cannot install/remove a high number sub-system at any time)

- What steps will be taken to ensure that the integration of the sub-subsystems and components will achieve the quality required?
  High: Testing occurs early and continuously throughout the manufacturing process (expects a triangle of manufacturing)
  Med: Some crucial tests are performed late in the manufacturing process (by late we mean difficult to go back and fix/identify true cause of problem)
  Low: no testing is indicated or occurs late in the manufacturing process

- Are the procedures of assembly efficient and easily implementable?
  High: Assembly procedures result in smooth, orderly, logical integrations that reduce installation times.
  Med: Missing procedure steps that could jeopardize the assembly process.
  Low: Assembly procedures result in conflicting or impossible integrations, and/or be very time consuming

TRL5-6

- Manufacturing costs = sum of (labor hours * unit cost of labor + hours of use of tools and equipment/infrastructure * unit cost of tools and equipment/infrastructure + hours of storage * unit cost of hour of storage) - Cost offsetting

- What is the expected manufacturing rate, in day / MW, for all complete subsystems? (Considering a single production facility / single production line.)
  High: less than 10 days / 1 MW (manufacturing at least 100MW in one season)
  Med: 11 -20 days / 1 MW

Low: greater than 21 days / MW

- To what level can the manufacturing techniques be automated for each sub-subsystem and subsystem? (levels: every piece must be hand welded, can use a mold, can use automated fiberglass winding, etc. Suitability of manufacturing process to achieving rounded edges?)

  High: Ability to automate a majority of the manufacturing steps, workers needed to implement a minority of manufacturing steps.

  Med: in between high and low.

  Low: Inability to automate a majority of the manufacturing steps, highly skilled workers needed to implement majority of manufacturing steps.

C.1.1.3. Be inexpensive to transport (excluding install)

WEC farm components, sub-subsystems, and subsystems should be built close to the manufacturing and/or deployment site to minimize shipping and transportation costs. Alternatively, the sub-subsystems and subsystems should be of a size and modularity for which standard transportation is possible. They should be transportable in any weather conditions.

TRL1-2
• How will each subsystem (mechanisms that collect wave power, aggregate power, deliver power, and control position) be transported to the installation staging point (e.g. port location)? **High:** by non-specialized boat, railway and or road requiring no upgrade to existing infrastructure (such as widening roads) and no special permissions or precautions e.g. permission from local authorities or police, special speed limit, special escort. **Med:** by specialized boat, railway and or road requiring no upgrade to existing infrastructure (such as widening roads) but requiring special permission or precautions e.g. permission from local authorities or police, special speed limit, special escort. **Low:** any option that requires an upgrade to existing infrastructure
TRL3-4
Update the answers to TRL1-2 plus answer the following questions: • For each transported subsystem, answer the following questions: a. What are the mass and envelope dimensions? i. If the subsystem is being transported as sub-subsystems, identify the mass and envelope dimensions of the sub-subsystem as well as the number of independent transports required to assemble the subsystem. **High:** Mass and envelope dimensions fit within standard shipping containers: can fit under bridges, mass within common bridge limitations, etc. **Med:** Mass and envelope dimensions require careful selection of routes or require additional escort to ensure safe transportation **Low:** New infrastructure / transportation vehicles are needed to ensure safe transport b. What is the typical transport distance? **High:** Transportation distance on the order of 200 km **Med:** Transportation distance on the order of 2000 km (~vertical length of a US state) **Low:** Transportation distance on the order of 10,000 km (~1/4 of the circumference of the world) c. How many competing transport options are available?

High: Transportation can be accomplished by any mechanism (rail, flight, boat, or road) with competing companies within each category Transportation can be accomplished by a few mechanisms with few competing companies within each category **Low:** Only one mechanism with few competing companies • What is the anticipated number of transportation trips of custom manufactured subsystems, sub-subsystems, and components per farm rating? **High:** ≤10/MW **Med:** between high and low **Low:** ≥50/MW
TRL5-6
• Transportation costs = sum over all means of transportation of (hours/distance of transportation * unit cost of transportation) • How will each subsystem (mechanisms that collect wave power, aggregate power, deliver power, and control position) be transported to the installation staging point (e.g. port location)? **High:** by non-specialized boat, railway and or road requiring no upgrade to existing infrastructure (such as widening roads) and no special permissions or precautions e.g. permission from local authorities or police, special speed limit, special escort. **Med:** by specialized boat, railway and or road requiring no upgrade to existing infrastructure (such as widening roads) but requiring special permission or precautions e.g. permission from local authorities or police, special speed limit, special escort. **Low:** any option that requires an upgrade to existing infrastructure

C.1.1.4. Be inexpensive to install

WEC farm subsystems should be installable in most weather conditions, require minimal time to complete the installation, use readily available vessels, and minimize the need for skilled workers.

TRL1-2
• For each subsystem (mechanisms that collect wave power, aggregate power, deliver power, and control position), what are the masses and envelope sizes of subsystems being transported to and maneuvered within the installation area? **High:** No lifting by crane is required at sea AND lifting by crane to be <60t required on land. Envelope dimensions are approximately equivalent to a standard shipping container on at least 1 side of horizontal footprint. **Med:** No lifting by crane is required at sea AND lifting by crane to be <120t required on land. Envelope dimensions are approximately those of a standard shipping container on at least one side of horizontal footprint. **Low:** Lifting by crane is required at sea (any) OR lifting by crane>120t on land. Envelope dimensions are > a standard shipping container. • What typical distance must the installation vessel(s) travel? At TRL1-2 simply identifying the general range (on-shore, near-shore, off-shore) is sufficient. **High:** on-shore: implies short distance **Med:** near shore: implies an intermediate distance **Low:** off-shore: implies a long distance • How many assembly steps and how many connections must be made at the installation point? **High:** ≤6/MW (e.g. connecting one mooring leg, righting the device to vertical, connecting to aggregate) **Med:** between high and low **Low:** ≥24/MW or if there is insufficient justification • What is (are) the expected installation vessel(s), or alternatively is it clear that any installation vessels can be excluded? **High:** clear that only a few (less than 3) non-specialized vessels will be needed **Med:** clear that many (more than 5) non-specialized vessels will be needed or a few non-specialized and less than two specialized **Low:** clear that a majority of specialized vessels will be needed • What are the weather window requirements for installation? **High:** access ≥ 70% during the year

Med: 30% < access < 70% during the year **Low:** access ≤ 30% during the year
TRL3-4
Update the answers to TRL1-2 plus answer the following questions: • How many MW of rated power at point of grid connection can be installed per year considering the weather windows (but independent of manufacturing / supply limitations)? (Note: Answer must exclude the possibility of multiple installation teams working in parallel b/c we are attempting to assess rate of installation.) **High:** More than 70MW **Med:** More than 30MW **Low:** less than 30MW • How many trips from the staging point to the installation point for all subsystems must be completed per installed MW? **High:** 5 or less trips per MW **Med:** between high and low **Low:** more than 12 trips per MW • For each subsystem (mechanisms that collect wave power, aggregate power, deliver power, and control position), please answer the following questions: a. What are the weather window requirements for installation? Weather window specifications include the following considerations: maximum significant wave height, maximum steepness (derived from Hs and Te), wave direction, continuous duration, seasonal probability of occurrence, wind speeds, current speeds. **High:** Most months possess 75% or greater access and no months have less than 50% access resulting in limited restriction on access to subsystems. Seasonal dependence on access not anticipated. **Med:** Most months possess 50% or greater access and no months have less than 30% access resulting in some restriction on access to subsystems. Seasonal dependence may be anticipated. **Low:** Most months possess 40% or greater access resulting in severe restriction on access to subsystems. Seasonal dependence anticipated. b. What number of competing installation vessels could complete the installation? **High:** more than 10 **Med:** 3 ≤ # of competing vessels ≤ 10 **Low:** 1 -2 c. How many vessels are needed at once for an assembly procedure?

High: Only one
Med: Two - three
Low: More than three

d. How long will each assembly step take?
High: Sum of all assembly steps is ≤ 20 hours
Med: between high and low
Low: Sum of all assembly steps is ≥ 80 hours

e. Where in the water column will connections between (sub-)subsystems be made? Please identify the (sub-)subsystems being connected.
High: most connections above surface
Med: equal number above and below surface, but few at the ocean floor
Low: most below the surface with many at the ocean floor

f. What are the expected dynamics of the subsystems during connection procedures?
High: The systems to be connected will be calm b/c they can be isolated such that they are not subject to hydrodynamic forcing
Med: Most of the systems to be connected will be calm. If the subsystem that captures power is dynamically moving will automatically move to medium even if the rest are stabilized.
Low: Most of the systems to be connected will be subject to hydrodynamic forcing b/c they are floating

- What percentage of connections / assembly processes is automated vs. manual?
  High: majority automated (≥75%)
  Med: below surface connections / assembly processes are automated and above/near surface connections / assembly processes are manual
  Low: majority manual (≥75%)

- Does the array layout allow for easy access for installation vessels?
  High: Layout of farm (e.g. proximity of devices to vessel) has no bearing on installation windows or permit windows that govern access to farm.
  Med: Layout of farm is one of several considerations in determination of installation windows or permit windows that govern access to farm.
  Low: Layout of farm is principal consideration in determination of installation windows or permit windows that govern access to farm.

- For the subsystem that controls position, please answer the following questions:

a. What level of accuracy must be achieved on foundation positioning?
High: positioning ≥ 100% of the largest length of the foundation (i.e. accuracy on the order of the foundation length)
Med: between high and low
Low: positioning ≤ 10% of the largest length of the foundation (i.e. accuracy much higher than the foundation length)

b. What geophysical conditions are required for the foundations?
High: Soft mud, sand or clay (inexpensive to embed foundations)
Med: Swept rock, cobble reefs, boulder fields, or glacial spill.
Low: Hard rock requiring rock saws. Alternatively passing through 3 or more distinct geophysical properties

c. Is any specialized installation equipment needed for this subsystem?
High: Traditional, high competition vessels and equipment can be used (i.e. tug boats)
Med: Most of the installation can be completed with traditional vessels, but some aspects require specialized equipment
Low: Custom built or highly specialized vessels are needed with specialized equipment (potentially requiring jack-up for drilling for example)

- For the subsystem that delivers power, is any specialized installation equipment needed for this conduit?
  High: Traditional burying methods can be employed
  Med: Pins / concrete mattresses required
  Low: Horizontal drilling required

TRL5-6

- Installation costs = sum over all means of installation (vessels, equipment and infrastructure) of (hours of use* unit cost + hours of stand-by*unit cost + mobilization cost) + sum over all labor types (divers) of (labor hours * unit labor cost + hours of stand-by*unit cost + mobilization cost)

- How many assembly steps and how many connections must be made at the installation point?
  High: ≤5 /MW (e.g. connecting one mooring leg, righting the device to vertical, connecting to aggregate)
  Med: between high and low
  Low: ≥20/MW

- How long will each assembly step and/or connection take during installation?
  High: Sum of all assembly steps / connections is ≤ 20 hours
  Med: between high and low

Low: Sum of all assembly steps / connections is ≥ 80 hours

- What are the expected dynamics of the subsystems during connection procedures?

  High: The systems to be connected will be calm b/c they can be isolated such that they are not subject to hydrodynamic forcing

  Med: Most of the systems to be connected will be calm. If the capture power is dynamically moving will automatically move to medium even if the rest are stabilized.

  Low: Most of the systems to be connected will be subject to hydrodynamic forcing b/c they are floating

- What are the geophysical conditions for the proposed WEC farm? This will influence the cost of both the system that controls position as well as the system that delivers power.

  High: Soft mud, sand or clay allowing the conduit to be ploughed and buried to a deep enough depth that it will be protected (typically 2 meters)

  Med: Swept rock, cobble reefs, boulder fields, or glacial spill.

  Low: Hard rock requiring rock saws and concrete mattresses or rock dumping to maintain the conduits position and offer protection. Alternatively passing through 3 or more distinct geophysical properties.

C.1.2. Have as low an OPEX as possible

OpEx includes **all costs necessary to operate and maintain** the WEC farm over its entire service life. The WEC farm should have as low an OpEx as possible. **Drivers** of OpEx are **reliability** (unplanned maintenance) and **durability** (planned maintenance).

C.1.2.1. Be reliable

The WEC farm should be highly reliable to avoid costly unplanned maintenance. High reliability is achieved with proven high-quality components, by minimizing the number of parts or components subject to well-known failure modes (fatigue, wear, abrasion, corrosion, chemical attack, thermal overload, clogging, and photolysis), and by avoiding impulsive loads (end-stops, shock loading, and snap loads). Cost of repair for subsystems that are likely to require frequent unplanned maintenance should be low. Costs could include replacement parts, transportation to and from the site of repair, fees incurred as a result of wait times for weather windows, and fees for trained workers. Costs do not include lost revenue as a result of downtime.

TRL1-2
In answering these questions consider the likelihood of UNPLANNED maintenance and the implications of this for OPEX. Consider the cost of repair including the cost of access. E.g. cost of use of boats and ships. • What is the technology class for each subsystem in the WEC Farm? **High:** All or predominantly Class 1. **Med:** Predominately Class 1 and 2 with no or few Class 3. **Low:** Any significant number of Class 3 or 4. • For each subsystem that might require an intervention what is the expected number and type of vessels employed? **High:** A single low cost vessel can adequately and safely be utilized for the maintenance intervention for the majority of subsystems. **Med:** A single medium sized work boat is required (e.g. ocean tug with no crane) for at least half of the subsystems **Low:** One or more large/expensive vessels are required (e.g. vessel with large crane or A-frame, large deck area, large crew quarters) for more than 1/3 of the subsystems • What level of access for maintenance of the subsystems is expected given the anticipated weather window criteria and vessel selection? **High:** access ≥ 70% during the year **Med:** 30% < access < 70% during the year **Low:** access ≤ 30% during the year

• What is the size & mass of items being maintained? **High:** No lifting by crane is required at sea AND lifting by crane to be <60t required on land. Envelope dimensions are approximately equivalent to a standard shipping container on at least 1 side of horizontal footprint. **Med:** No lifting by crane is required at sea AND lifting by crane to be <120t required on land. Envelope dimensions are approximately those of a standard shipping container on at least one side of horizontal footprint. **Low:** Lifting by crane is required at sea (any) OR lifting by crane>120t on land. Envelope dimensions are > a standard shipping container. • What are the well-known failure modes (shock, chemical, corrosion, wear, fatigue, thermal, etc.) for each subsystem? **High:** Mainly known failure modes compatible with technology class 1 and/or a minority of subsystems susceptible to failure modes in operational conditions **Med:** Limited level of uncertainties on the failure modes and/or limited number subsystems susceptible to failure modes in operational conditions **Low:** Large uncertainty on the failure modes and/or majority of subsystems susceptible to failure modes in operational conditions • What are the well know failure modes (e.g. fatigue, wear, abrasion, corrosion, chemical attack, thermal overload, clogging, photolysis, other…) for the sub-subsystems (structure, power-take off, etc.) within the subsystem collect wave power? **High:** Failure modes will not occur during operational conditions for a majority of the sub-subsystems (i.e. common failure mode is chemical in nature, however there is no exposure to this chemical or there is but a mitigating action is occurring to minimize exposure) **Med:** Failure modes will occur during operational conditions, however with low probability (i.e. shocks are the common failure mode but these will occur with a low probability) **Low:** Failure modes will occur during operational conditions for a majority of the sub-subsystems (i.e. common failure mode is thermal and no conditioning of ambient environment is being pursued to mitigate this mode)
TRL3-4
Complete in addition to updating TRL1-2 and consider the same areas.

In answering the questions below consider where the maintenance will be performed for each sub-system and sub-subsystem (factory, on-shore, dry-dock, quay-wall, harbor, in-shore, at-sea).

- What is the target annual OPEX cost for the overall WEC farm in terms of CAPEX?

  High: Well justified expectation of approximately 6% of CAPEX.
  Med: Well justified expectation of approximately 10% of CAPEX
  Low: approximately 15% of CAPEX OR insufficient justification of claim.

- What is the maximum array size (MW capacity) that can be serviced by one maintenance vessel (or team of vessels where multiple vessels are needed for a single intervention)?

  High: >100MW
  Med: 10-100MW.
  Low: <10MW.

- What are the anticipated insurance costs?

  High: <2% of CAPEX
  Med: 2-5% of CAPEX
  Low: >5% of CAPEX

- What is the technology class for each sub-subsystem in the WEC Farm?

  High: All or predominantly Class 1.
  Med: Predominately Class 1 and 2 with no or few Class 3.
  Low: Any significant number of Class 3 or 4.

- What level of access for maintenance of the subsystems is expected given the anticipated weather window criteria?

  High: Most months possess 75% or greater access and no months have less than 50% access resulting in limited restriction on access to subsystems. Seasonal dependence on access not anticipated.
  Med: Most months possess 50% or greater access and no months have less than 30% access resulting in some restriction on access to subsystems. Seasonal dependence may be anticipated.
  Low: Most months possess 40% or greater access resulting in severe restriction on access to subsystems. Seasonal dependence anticipated and is concurrent with peak production.

- What is the list of sub-subsystems that are likely to be subject to well-known failure modes and which modes (e.g. fatigue, wear, abrasion, corrosion, chemical attack, thermal overload, clogging, photolysis, other…).

  High: All sub-subsystems are selected/designed to avoid well known failure modes

Med: A majority of sub-subsystems are selected/designed to avoid well known failure modes.
Low: A significant number of sub-subsystems are subject to degradation through well-known failure modes.

- For the top 10 highest impact failures in subsystems and sub-subsystems what are estimates for:
  a. Frequency of failure?
  b. Cost of spare parts?
  c. Location of repair or replacement (on-shore, off-shore, harbor, etc.)?
  d. Cost of vessel required?
  e. Cost of repair and labor
  f. Other costs?

  Note: Refer to initial FMECA in answering these questions.
  High: Total costs (a. multiplied by sum of b., d., e., f.) for high consequence subsystems and sub-subsystems is approximately 6% of CAPEX
  Med: Total costs (a. multiplied by sum of b., d., e., f.) for all subsystems and sub-subsystems is approximately 10% of CAPEX
  Low: Total costs (a. multiplied by sum of b., d., e., f.) for all subsystems and sub-subsystems is approximately 15% of CAPEX

- How many subsystems have unknown failure rates or unverified in this application?
  High: A small number of subsystems
  Med: Approximately 1/3
  Low: A significant number

- What is the total anticipated number of unplanned maintenance events per MW per year and how will this change over the lifetime of the farm?
  High: Well justified expectation of up to 1 trip per 2MW per year. Statistical failure rates will remain constant over the lifetime of the farm.
  Med: Well justified expectation of up to 2 trips per MW per year. Statistical failure rates will increase gradually with age of the farm.
  Low: More than 2 trips per MW per year OR insufficient justification for claims of better performance. Statistical failure rates expected to increase strongly with age of the farm.

- For each sub-subsystem that might require an intervention what is the location of the sub-subsystem within the subsystem and how modular or accessible is it?

High: Sub-subsystem can be readily accessed/removed by the workers that will maintain it.
Med: Sub-subsystem can be readily accessed/removed by other specialist workers besides the ones that will maintain it or specialized equipment is needed in removal.
Low: Sub-subsystem is relatively inaccessible (e.g. divers routinely required to access/remove the sub-subsystem).

- For the chosen vessel type(s) and typical/target installation location and required maintenance tasks what is the round trip travel time plus maintenance time for maintenance interventions?
  High: A round trip including necessary work can be made in one "shift", (e.g. less than 8-12 hours).
  Med: A round trip including necessary work can be made in an extended "shift" (e.g. less than 16-24 hours).
  Low: A round trip takes such time that overnight accommodation is needed for workers on board maintenance vessel(s).

- In addition to the physical conditions at sea, other factors like overtime hours, safety training, etc. will influence the cost of maintenance—these define the permit window. What are these factors for this deployment location and what regulatory mandates supervise the workforce?
  High: Low constraints. Normal health and safety and other legal requirements for work at sea. Not governing the operation.
  Med: Limited constraint. Normal health and safety and other legal requirements for work at sea and additional regulations and environmental constraints. Possible impact in the operation above the metocean conditions. Additional operational costs (~20%)
  Low: High level of constraints. Normal health and safety requirements for work at sea, additional regulations, environmental constraints and operational limits. Governing over metocean conditions. Additional operational costs ≥ 30%

- What is the availability and length of time to access spare parts?
  High: All or most parts available on demand
  Med: Main serviceable parts available on demand
  Low: Numerous parts require ordering and are subject to timelines and availability

- Are the weather window criteria primarily determined by the capabilities of the vessels or the dynamics of the device?
  High: The device dynamic response does not affect the accessibility of the device (e.g. weather windows determined by vessel response/capabilities and not device response)

Med: The dynamics of the system sometimes affect the accessibility of the device (e.g. weather windows determined by both vessel response and also device response)
Low: The dynamics of the system strongly affect the accessibility of the device (e.g. weather windows determined predominantly by device response and not vessel response)

- Is it necessary, for maintenance or other reason, for personnel to transfer to the WEC at sea?
  High: Personnel transfer not expected.
  Med: --- no medium score allowed here ---.
  Low: Personnel transfer expected.

- Where personnel are required enter enclosed spaces in the WEC at sea for maintenance what is the duration required to ventilate the compartment before it is safe to enter?
  High: Adequate ventilation readily achieved.
  Med: Adequate ventilation achieved within 1 hour.
  Low: Adequate ventilation not achieved within 1 hour.

- Does the array layout allow for easy access for maintenance vessels?
  High: Layout of farm (e.g. proximity of devices to vessel) has no bearing on weather windows or permit windows that govern access to farm.
  Med: Layout of farm is one of several considerations in determination of weather windows or permit windows that govern access to farm.
  Low: Layout of farm is principal consideration in determination of weather windows or permit windows that govern access to farm.

- For the WEC farm system, what is the length of intra-array conduit (e.g. length of cable/pressure-pipe within the array) used to deliver transportable power to the aggregators per MW and number of terminations per MW?
  High: Approximately 200m/MW and a total of approximately 2 terminations/MW
  Med: Approximately 1km/MW and a total of approximately 2.5 terminations/MW
  Low: Approximately 5km/MW and a total of approximately 3 terminations/MW

TRL5-6

What is the estimate of annual average cost of unplanned maintenance?
[average cost of unplanned maintenance = sum over all systems of sum over all modes of failure for each system of ((lifetime of system / MTBF -1) * cost of repair for this failure)]

where cost of repair for each failure is a function of (cost of spare parts, cost of vessels and equipment, hours of mobilization of vessels and equipment, hours of labor, unit labor cost)

- What is the total anticipated number of unplanned maintenance events per MW per year and how will this change over the lifetime of the farm?

  High: Well justified expectation of up to 1 trip per 2MW per year. The MTBF far exceeds the lifetime and the expectation is anticipated to remain stable.

  Med: Well justified expectation of up to 2 trips per MW per year. The MTBF is on the order of the lifetime and the expectation is anticipated to increase.

  Low: More than 2 trips per MW per year OR insufficient justification for claims of better performance. The MTBF is less than the lifetime and the expectation is anticipated to increase.

- What access level is expected for each maintenance event for each subsystem given the weather window criteria and maintenance vessel capabilities?

  High: Most months possess approximately 54 weather windows of 10 hour durations and no months possess less than approximately 36 weather windows of 10 hour durations. Seasonal dependence on access not anticipated.

  Med: Most months possess approximately 18 weather windows of 20 hour durations and no months possess less than approximately 10 weather windows of 20 hour durations. Seasonal dependence may be anticipated.

  Low: Most months possess approximately 9 weather windows of 32 hour durations. Seasonal dependence anticipated.

- For all significant failures in subsystems and sub-subsystems what are estimates for:

  a. Frequency of failure?
  b. Cost of spare parts?
  c. Location of repair or replacement (on-shore, off-shore, harbor, etc.)?
  d. Cost of vessel required?
  e. Cost of repair and labor
  f. Other costs?

  Note: Refer to complete FMECA in answering these questions.

  High: Total costs (a. multiplied by sum of b., d., e., f.) for high consequence subsystems and sub-subsystems is approximately 6% of CAPEX

Med: Total costs (a. multiplied by sum of b., d., e., f.) for all subsystems and sub-subsystems is approximately 10% of CAPEX

Low: Total costs (a. multiplied by sum of b., d., e., f.) for all subsystems and sub-subsystems is approximately 15% of CAPEX

C.1.2.2. Be durable over the lifetime of the farm

The WEC farm should be highly durable to avoid costly planned maintenance. The WEC farm is ideally made of high-durability (long lifetime) components. The number of parts and components subject to wear, abrasion, and erosion is small. Ideally, the durability of a farm's components, sub-subsystems, and subsystems are the same as the lifetime of the farm. Cost of servicing for subsystems that require planned maintenance should be low. Costs could include: replacement parts, transportation to and from the site, fees incurred as a result of wait times for weather windows, and fees for trained workers. Costs do not include lost revenue as a result of downtime.

TRL1-2

In answering these questions consider the PLANNED maintenance and the implications of this for OPEX. Consider the cost of repair including the cost of access. E.g. cost of use of boats and ships.

- What is the technology class for each subsystem in the WEC Farm?
  High: All or predominately technology Class 1.
  Med: Predominately Class 1 or 2 with no or few Class 3.
  Low: Any significant number of Class 3 or 4.

- How many subsystems have a MTBF<lifetime of the WEC Farm?
  High: None or few subsystems
  Med: Several subsystems
  Low: Majority subsystems

- For each subsystem that requires an intervention what is the expected number and type of vessels employed?
  High: A single low cost vessel can adequately and safely be utilized for the maintenance
  Med: A single medium sized work boat is required (e.g. ocean tug with no crane)
  Low: One or more large/expensive vessels are required (e.g. vessel with large crane or A-frame, large deck area, large crew quarters)

- What level of access for maintenance of the subsystems is expected given the anticipated weather window criteria and maintenance vessel capabilities?
  High: access $\geq$ 70% during the year
  Med: 30% $<$ access $<$ 70% during the year
  Low: access $\leq$ 30% during the year

- What is the size & mass of items being maintained?
  High: No lifting by crane is required at sea AND lifting by crane to be <60t required on land. Envelope dimensions are approximately

equivalent to a standard shipping container on at least 1 side of horizontal footprint. **Med:** No lifting by crane is required at sea AND lifting by crane to be <120t required on land. Envelope dimensions are approximately those of a standard shipping container on at least one side of horizontal footprint. **Low:** Lifting by crane is required at sea (any) OR lifting by crane>120t on land. Envelope dimensions are > a standard shipping container.
TRL3-4
Complete in addition to updating TRL1-2 and consider the same areas. In answering the questions below consider where the maintenance will be performed for each sub-system and sub-subsystem (factory, on-shore, dry-dock, quay-wall, harbor, in-shore, at-sea). • What is the target annual OPEX cost for the overall WEC farm in terms of CAPEX? **High:** Well justified expectation of approximately 6% of CAPEX. **Med:** Well justified expectation of approximately 10% of CAPEX **Low:** approximately 15% of CAPEX OR insufficient justification of claim. • What is the maximum array size (MW capacity) that can be serviced by one maintenance vessels (or team of vessels where multiple vessels are needed for a single intervention)? **High:** >100MW **Med:** 10-100MW. **Low:** <10MW. • What is the technology class for each sub-subsystem in the WEC Farm? **High:** All or predominantly Class 1. **Med:** Predominately Class 1 and 2 with no or few Class 3. **Low:** Any significant number of Class 3 or 4. • What level of access for maintenance of the subsystems is expected given the anticipated weather window criteria? **High:** Most months possess 75% or greater access and no months have less than 50% access resulting in limited restriction on access to subsystems. Seasonal dependence on access not anticipated. **Med:** Most months possess 50% or greater access and no months have less than 30% access resulting in some restriction on access to subsystems. Seasonal dependence may be anticipated.

Low: Most months possess 40% or greater access resulting in severe restriction on access to subsystems. Seasonal dependence anticipated and is concurrent with peak production.

- How many sub-subsystems have a MTBF<lifetime of the Farm?

  High: None or few sub-subsystems

  Med: Several sub-subsystems

  Low: Majority sub-subsystems

- What is the number of subsystems that have manufacturer recommended services / inspections over the farm lifetime and how many inspections are required?

  High: Minimal services / inspections (~1 per 2-3 years) required for the majority of the subsystems

  Med: Few services / inspections (~1 per year) required with easy access for the majority of the subsystems

  Low: Numerous services / inspections (> 5 per year) required or difficult access required for at least 1/3 of the subsystems

- How many systems and sub-systems have a warranty?

  High: Most components come with a 5+ year warranty

  Med: Most components with any warranty

  Low: Significant number of components without warranty

- What is the total anticipated number of planned maintenance events per MW per year and how will this change over the lifetime of the farm?

  High: Well justified expectation of up to 1 trip per 2MW per year. The MTBF far exceeds the lifetime and the expectation is anticipated to remain stable.

  Med: Well justified expectation of up to 2 trips per MW per year. The MTBF is on the order of the lifetime and the expectation is anticipated to increase.

  Low: More than 2 trips per MW per year OR insufficient justification for claims of better performance. The MTBF is less than the lifetime and the expectation is anticipated to increase.

  Note: The number of planned maintenance events is a choice

- For each sub-subsystem that might require an intervention what is the location of the sub-subsystem within the subsystem and how modular or accessible is it?

  High: Sub-subsystem can be readily accessed/removed by the workers that will maintain it.

  Med: Sub-subsystem can be readily accessed/removed by other specialist workers besides the ones that will maintain it or specialized equipment is needed in removal.

Low: Sub-subsystem is relatively inaccessible (e.g. divers routinely required to access/remove the sub-system).

- For the chosen vessel type(s) and typical/target installation location and required maintenance tasks what is the round trip travel time plus maintenance time for maintenance interventions?

  High: A round trip including maintenance work can be made in one "shift", (e.g. less than 8-12 hours).
  Med: A round trip including maintenance work can be made in an extended "shift" (e.g. less than 16-24 hours).
  Low: A round trip takes such time that overnight accommodation is needed for workers on board maintenance vessel(s).

- In addition to the physical conditions at sea, other factors like overtime hours, safety training, etc. will influence the cost of maintenance—these define the permit window. What are these factors for this deployment location and what regulatory mandates supervise the workforce?

  High: Low constraints. Normal health and safety and other legal requirements for work at sea. Not governing the operation.
  Med: Limited constraint. Normal health and safety and other legal requirements for work at sea and additional regulations and environmental constraints. Possible impact in the operation above the metocean conditions. Additional operational costs (~20%)
  Low: High level of constraints. Normal health and safety requirements for work at sea, additional regulations, environmental constraints and operational limits. Governing over metocean conditions. Additional operational costs $\geq$ 30%

- Are the weather window criteria primarily determined by the capabilities of the vessels or the dynamics of the device?

  High: The device dynamic response does not affect the accessibility of the device (e.g. weather windows determined by vessel response/capabilities and not device response)
  Med: The dynamics of the system sometimes affect the accessibility of the device (e.g. weather windows determined by both vessel response and also device response)
  Low: The dynamics of the system strongly affect the accessibility of the device (e.g. weather windows determined predominantly by device response and not vessel response)

- Is it necessary, for maintenance or other reason, for personnel to transfer to the WEC at sea?

  High: Personnel transfer not expected.
  Med: --- no medium score allowed here ---.
  Low: Personnel transfer expected.

- Where personnel are required enter enclosed spaces in the WEC at sea for maintenance what is the duration required to ventilate the compartment before it is safe to enter?
  - **High**: Adequate ventilation readily achieved.
  - **Med**: Adequate ventilation achieved within 1 hour.
  - **Low**: Adequate ventilation not achieved within 1 hour.

- Does the array layout allow for easy access for maintenance vessels?
  - **High**: Layout of farm (e.g. proximity of devices to vessel) has no bearing on weather windows or permit windows that govern access to farm.
  - **Med**: Layout of farm is one of several considerations in determination of weather windows or permit windows that govern access to farm.
  - **Low**: Layout of farm is principal consideration in determination of weather windows or permit windows that govern access to farm.

- What types of condition based maintenance strategies will be used to ensure maintenance is completed at the correct time?
  - **High**: Automated process both monitoring and processing information for preventative maintenance. Few or no personnel required.
  - **Med:** Automated monitoring process that involves a number of personnel (or full time employed personnel?) to analyze data received.
  - **Low:** No plans to implement condition based maintenance.

TRL5-6

- Average annual of cost of planned maintenance = sum over all systems of sum over all servicing of (lifetime of farm / time between services * servicing cost)

where servicing cost is a function of (cost of spare parts, cost of vessels and equipment, hours of mobilization of vessels and equipment, hours of labor, unit labor cost)

- How many sub-subsystems have a MTBF<lifetime of the Farm?
  - **High:** None or few sub-subsystems
  - **Med:** Several sub-subsystems
  - **Low:** Majority sub-subsystems

- What is the total anticipated number of planned maintenance events per MW per year and how will this change over the lifetime of the farm?

High: Well justified expectation of up to 1 trip per 2MW per year. The MTBF far exceeds the lifetime and the expectation is anticipated to remain stable.

Med: Well justified expectation of up to 2 trips per MW per year. The MTBF is on the order of the lifetime and the expectation is anticipated to increase.

Low: More than 2 trips per MW per year OR insufficient justification for claims of better performance. The MTBF is less than the lifetime and the expectation is anticipated to increase.

Note: The number of planned maintenance events is a choice

- What access level is expected for each maintenance event for each subsystem given the weather window criteria and maintenance vessel capabilities?

  High: Most months possess approximately 54 weather windows of 10 hour durations and no months possess less than approximately 36 weather windows of 10 hour durations. Seasonal dependence on access not anticipated.

  Med: Most months possess approximately 18 weather windows of 20 hour durations and no months possess less than approximately 10 weather windows of 20 hour durations. Seasonal dependence may be anticipated.

  Low: Most months possess approximately 9 weather windows of 32 hour durations. Seasonal dependence anticipated.

C.1.3. Be able to generate large amounts of electricity from wave energy

The amount of **electricity generation** is an essential driver to **the value of the WEC farm** (i.e., the sales price of the WEC farm as a product). Large amounts of electricity generation enable a high energy yield and hence high revenues.

C.1.3.1. Absorb large amounts of wave energy

The WEC farm should absorb a high percentage of the wave energy that passes through the farm. This implies that the farm can absorb energy across a wide range of frequencies, heights, and wave directions. It should be minimally affected by tide, current, and wind. Negative array interference interactions should be minimal. Availability will not be covered here because it is taken into account in requirement C.1.4.

TRL1-2
• What is the target wave resource? **High**: above 30kW **Med**: 20 – 30kW **Low**: below 20kW • How does the target capture length per installed MW of the subsystems that collect wave power compare with existing known technologies? **High**: Higher than average-- higher than 10 meters/MW **Med**: Average-- between 5 to 10 meters/MW **Low**: Below average-- below 5 meters/MW • Is the theoretical limit for energy absorption by the wave power collecting systems units large (# of DoFs and types, orientation, Budal limit)? **High**: power capture in 3+DoFs, dipole radiation pattern (terminator orientation), and large swept volume (Budal limit does not impose significant cuts in power absorption) **Med**: power capture in 2 DoFs, any radiation pattern, and large swept volume (Budal limit imposes some cuts in power absorption) **Low**: power capture in 1 DoFs, any radiation pattern, and limited swept volume (Budal limit imposes significant cuts in power absorption) • If applicable, how is the swept volume of the wave power collecting systems mechanically limited? **High**: no limitation on the kinematic side of absorbed power, mechanical limitations imposed only through the subsystem control position for instance **Med**: through a limitation in a DoF that does not directly contribute to the kinematic side of absorbed power **Low**: through a limitation on the kinematic side of absorbed power

- Is the energy absorption by the wave power collecting systems sensitive to tidal height, tidal current, wind or wave direction?

  High: Minimally sensitive to only current and wind.
  Med: Minimally sensitive to current, wind, and tidal height.
  Low: Sensitivity to all (current, wind, tidal height, and wave direction)

- What is the influence of the subsystem that controls position on energy absorption?

  High: the mooring system does not negatively influence the energy absorption
  Med: limited negative influence
  Low: the mooring system restricts the power absorption

- What aspects of the system that collects wave power are expected to decrease energy production (e.g. end stops, sharp edges producing large viscous losses, power conversion chain that is intended to work at one speed only, long transition times between operational states, etc.)?

  High: There are no aspects that can decrease the ability to collect power
  Med: There are some aspects that could decrease the ability to collect power
  Low: There are many aspects that seriously will decrease the ability to collect power

TRL3-4

Complete the following in addition to updating TRL1-2.

- What is the annual average of the wave energy absorption capability of the WEC plant in capture length per MW installed?

  High: higher than 10 meters/MW
  Med: between 5 to 10 meters/MW
  Low: below 5 meters/MW

- Evaluation of the directional power scatter diagram of the wave power collecting subsystems (taking into account influence of end-stops, mechanical and electrical PTO constraints, external energy/viscous losses) shows the following:

  High: High power production occurs in sea-states that comprise 90% of a typical year in the deployment climate
  Med: Power production is somewhere between high and low
  Low: High power production only occurs in a small area of the scatter diagram (i.e. only at large wavelengths, or only with large waves, or only for a narrow directional band)

• Provide estimated array interaction factor matrix **High**: estimated array interaction factor matrix shows an increase in overall **High**: estimated array interaction factor matrix shows an increase in overall produced power due to interaction between the subsystems collect wave power (i.e. a value of > 1 is found throughout the majority of the matrix) **Med**: there is no significant interaction between the subsystems collect wave power (i.e. a value of 0.9-1.0 is found throughout the majority of the matrix) **Low**: estimated array interaction factor matrix shows a significant decrease in overall produced power due to interaction between the subsystems collect wave power (i.e. a value of < 0.9 is found throughout the majority of the matrix)
TRL5-6
• What is the annual average of the wave energy absorption capability of the WEC plant? • Compare the directional power scatter diagram of the wave power collecting subsystems (taking into account influence of end-stops, mechanical and electrical PTO constraints, external energy/viscous losses) with the energy weighted directional probability scatter diagram for the selected deployment location. **High**: Strong overlap between high power production and high energy weighted sea states **Med**: Some overlap with high power production skewed towards high energy weighted sea states **Low**: High power production does not overlap with the high energy weighted sea states • Provide array interaction factor for sea conditions of the time sequence. **High**: estimated array interaction factor matrix shows an increase in overall produced power due to interaction between the subsystems collect wave power (i.e. a value of > 1 is found throughout the majority of the matrix) **Med**: there is no significant interaction between the subsystems collect wave power (i.e. a value of 0.9-1.0 is found throughout the majority of the matrix) **Low**: estimated array interaction factor matrix shows a significant decrease in overall produced power due to interaction between the subsystems collect wave power (i.e. a value of < 0.9 is found throughout the majority of the matrix)

C.1.3.2. Have high conversion efficiency of extracted energy to electrical energy

The WEC farm device power conversion chain and electrical collection system should have a small number of conversion steps and each conversion step should be highly efficient. Availability will not be covered here because it is taken into account in requirement C1.4.

TRL1-2
• At subsystem level (subsystems that collect wave power, aggregate power, and deliver power): a. How many energy conversion steps are there from the wave power collecting systems to Point of Connection? **High:** 2 or less **Med:** 3 **Low:** more than 3 b. For all energy conversion steps combined from the wave power collecting systems to Point of Connection, what is the target combined efficiency? **High:** above 80% **Med:** above 50% **Low:** below 50% c. For each subsystem, (collect, aggregate, and deliver power) what is the target ratio of peak to mean power?? **High:** last step is 3.0 or lower AND all steps show a decreasing trend OR all steps are below 3.0 **Med**: 3.0 to 5.0 **Low**: higher than 5.0 • For the subsystems that collect wave power: a. At sub-subsystem level, how many energy conversion steps are there to transform absorbed power into transportable power? **High:** 1 **Med:** 2 **Low:** more than 2 b. At sub-subsystem level, what is the target average efficiency to transform absorbed power into transportable power? **High:** high above 80% **Med:** Medium above 50% **Low:** low below 50% c. At each energy conversion step within the subsystem that collects wave power, what is the target ratio of peak to mean power (e.g. output at any or all of: absorbed, mechanical, and electrical power)?

High: last step is 3.0 or lower AND all steps show a decreasing trend OR all steps are below 3.0 **Med**: 3.0 to 5.0 **Low**: higher than 5.0
TRL3-4
• Evaluation of the directional average conversion efficiencies from absorbed power to PoC scatter diagram shows the following (analysis considers all conversion steps at sub-subsystem level, considering the dynamics of the inputs into the sub-subsystems): **High:** High efficiency (above 80%) occurs in sea-states that comprise 90% of a typical year in the deployment climate **Med:** Medium efficiency (above 50%) occurs in sea-states that comprise 90% of a typical year in the deployment climate **Low:** Intermediate efficiency (between 50% and 80%) only occurs in a small area of the scatter diagram (i.e. only at large wavelengths, or only with large waves, or only for a narrow directional band), or low efficiencies (below 50%) in majority of sea-states that comprise 90% of a typical year in the deployment climate • Evaluation of scatter diagrams of peak to mean power ratios at each step in the energy conversion process (absorbed, mechanical, electrical, aggregated, delivered) shows the following: **High:** last step is 3.0 or lower AND all steps show a decreasing trend OR all steps are below 3.0 in sea-states that comprise 90% of a typical year in the deployment climate **Med**: 3.0 to 5.0 in sea-states that comprise 90% of a typical year in the deployment climate **Low**: higher than 5.0 in majority of sea-states that comprise 90% of a typical year in the deployment climate • Evaluation of scatter diagrams of the ratio of peak efficiencies to average efficiencies for each step in the energy conversion process (absorbed, mechanical, electrical, aggregated, delivered) shows the following show the following: **High**: 1.2 or lower in sea-states that comprise 90% of a typical year in the deployment climate **Med**: 1.2 to 1.8 in sea-states that comprise 90% of a typical year in the deployment climate **Low**: higher than 1.8 in majority of sea-states that comprise 90% of a typical year in the deployment climate • If recirculated power (e.g. reactive control) will be utilized, consider the following: a. The average annual recirculation efficiency is: **High:** above 90%

Med: between high and low **Low:** Below 80% b. Evaluation of the WEC farm scatter diagram of average recirculated power against average delivered power at PoC shows the following: **High:** Power draw is 20% or less than average power delivered at PoC or no power draw. Power draw occurs in a small area of the scatter diagram (i.e. only at large wavelengths, or only with large waves, or only for a narrow directional band) OR sufficient energy storage close to front of power transmission chain so that unidirectional power flow preserved at aggregation point. **Med:** Power draw is between high and low **Low:** Power draw is greater than 60% of the average power delivered at PoC. Power draw occurs in majority of sea-states that comprise 90% of a typical year in the deployment climate c. Evaluation of scatter diagrams of of the ratio of peak recirculated power for each collect wave power against device rating shows the following: **High:** Peak power draw is 0.6 or less than the device rating or no power draw. Power draw occurs in a small area of the scatter diagram (i.e. only at large wavelengths, or only with large waves, or only for a narrow directional band) **Med:** Peak power draw is between high and low **Low:** Peak power draw ratio is larger than 0.9 device rating. Power draw occurs in a majority of sea-states that comprise 90% of a typical year in the deployment climate • Evaluation of scatter diagram of average consumed power in ancillary systems against average power at PoC shows the following: **High:** Constant, yet low (~1% of average power delivered at PoC) consumed power **Med:** Irregular and intermediate (~5% of average power delivered at PoC) or high (~10% of average power delivered at PoC) consumed power **Low:** Constant and high consumed power
TRL5-6
• What is the annual average power delivery at PoC including the efficiency losses? • What is the annual average of RMS efficiency (absorbed to POC power, weighted average via the deployment climate) for the WEC farm? **High:** high above 80% **Med:** Medium above 50% **Low:** low below 50%

- Compare the directional average conversion efficiencies from absorbed power to PoC scatter diagram with the energy weighted directional probability scatter diagram for the selected deployment location.
  High: Strong overlap between high conversion efficiencies (above 80%) and high energy weighted sea states
  Med: Some overlap with high conversion efficiencies (above 80%) skewed towards high energy weighted sea states however majority of conversion efficiencies above 50%
  Low: Low conversion efficiencies (below 50%) strongly overlap with the high energy weighted sea states

- What is the largest energy recirculation (maximum time scale of 20sec) in comparison to the device rating?
  High: ratio of less than 0.6
  Med: ratio between high and low
  Low: ratio of 0.9 or higher

- What is the annual average of consumed power in ancillary systems?
  High: the annual average of consumed power less than 1% of the delivered power at PoC
  Med: the annual average of consumed power less than 5% of the delivered power at PoC
  Low: the annual average of consumed power more than 10% of the delivered power at PoC

C.1.4. Have high availability

Availability is the ratio of the average annual power of the farm to the theoretical maximum power capacity. The WEC farm rated power is the maximum power that the farm can deliver to the utility system at the point of connection to the utility grid. Thus, rated power is determined by the power carrying capability of the interconnection cable from the WEC farm and the substation's power handling capacity. A **high availability** will enable a **high energy output** and a dependable output thereby increasing the value of the WEC farms electricity.

C.1.4.1. Be reliable

The WEC farm should be highly reliable to avoid downtime as a result of unplanned maintenance. High reliability is achieved with proven high-quality components, by minimizing the number of parts and components subject to well-known failure modes (fatigue, wear, abrasion, corrosion, chemical attack, thermal overload, clogging, and photolysis), and by avoiding impulsive loads (end-stops, shock loading, and snap loads). Duration of repairs for subsystems that may require unplanned maintenance (including wait time between weather windows) should be short. Reliability with respect to availability accounts for the lost revenue as a result of downtime.

TRL1-2

In answering these questions consider the likelihood of UNPLANNED maintenance and the implications of this for AVAILABILITY. Consider the reduction in power generation capacity and the downtime due to failure, maintenance and waiting/preparing for maintenance.

- What is the technology class for each subsystem in the WEC Farm?
  High: All or predominantly Class 1.
  Med: Predominately Class 1 and 2 with no or few Class 3.
  Low: Any significant number of Class 3 or 4.

- What access level is expected for each maintenance event for each subsystem given the weather window criteria and maintenance vessel capabilities?
  High: access ≥ 70% during the year
  Med: 30% < access < 70% during the year
  Low: access ≤ 30% during the year

- What is the size & mass of items being maintained?
  High: No lifting by crane is required at sea AND lifting by crane to be <60t required on land. Envelope dimensions are approximately

equivalent to a standard shipping container on at least 1 side of horizontal footprint.

Med: No lifting by crane is required at sea AND lifting by crane to be <120t required on land. Envelope dimensions are approximately those of a standard shipping container on at least one side of horizontal footprint.

Low: Lifting by crane is required at sea (any) OR lifting by crane >120t on land. . Envelope dimensions are > a standard shipping container.

- How many subsystems have failure modes with consequent reduction in power production capabilities of >10% of total farm? (e.g. aggregation points, export cables, single points of significant loss of generation/export)

  High: No single points of failure causes loss of >10% of total farm
  Med: 1 single point of failure causes loss of >10% of total farm
  Low: >1 single points of failure causes loss of >10% of total farm

- Does the system have any redundancy in the aggregation points and power delivery system? (e.g. are there any other routes for the power to get to the grid?)

  High: Yes, there are other routes instantly/automatically available.
  Med: Yes but require simple intervention.
  Low: No.

- What are the well-known failure modes (shock, chemical, corrosion, wear, fatigue, thermal, etc.) for each subsystem?

  High: Mainly known failure modes compatible with technology class 1 and/or a minority of subsystems susceptible to failure modes in operational conditions
  Med: Limited level of uncertainties on the failure modes and/or limited number subsystems susceptible to failure modes in operational conditions
  Low: Large uncertainty on the failure modes and/or majority of subsystems susceptible to failure modes in operational conditions

- What are the well know failure modes (e.g. fatigue, wear, abrasion, corrosion, chemical attack, thermal overload, clogging, photolysis, other…) for the sub-subsystems (structure, power-take off, etc.) within the subsystem collect wave power?

  High: Failure modes will not occur during operational conditions for a majority of the sub-subsystems (i.e. common failure mode is chemical in nature, however there is no exposure to this chemical or there is but a mitigating action is occurring to minimize exposure)

Med: Failure modes will occur during operational conditions, however with low probability (i.e. shocks are the common failure mode but these will occur with a low probability)
Low: Failure modes will occur during operational conditions for a majority of the sub-subsystems (i.e. common failure mode is thermal and no conditioning of ambient environment is being pursued to mitigate this mode)

TRL3-4

Complete in addition to updating TRL1-2 and consider the same areas.

Additionally consider where the maintenance will be performed for each subsystem and sub-subsystem (factory, on-shore, dry-dock, quay-wall, harbor, in-shore, at-sea).

- What is the target availability for the overall WEC farm?
  High: Well justified expectation of >90%.
  Med: Well justified expectation of >80%.
  Low: <80% OR insufficient justification for claims of better performance.

- What is the maximum array size (MW capacity) that can be serviced by one maintenance vessels (or team of vessels where multiple vessels are needed for a single intervention)?
  High: >100MW
  Med: 10-100MW.
  Low: <10MW.

- What is the total anticipated number of unplanned maintenance events per MW per year and how will this change over the lifetime of the farm?
  High: Well justified expectation of up to 1 trip per 2MW per year initially. Statistical failure rates will remain constant over the lifetime of the farm.
  Med: Well justified expectation of up to 2 trips per MW per year. Statistical failure rates will increase gradually with age of the farm.
  Low: More than 2 trips per MW per year OR insufficient justification for claims of better performance. Statistical failure rates expected to increase strongly with age of the farm.

- What is the technology class for each sub-subsystem in the WEC Farm?
  High: All or predominantly Class 1.
  Med: Predominately Class 1 and 2 with no or few Class 3.
  Low: Any significant number of Class 3 or 4.

- What access level is expected for each maintenance event for each subsystem given the weather window criteria?

High: Most months possess 75% or greater access and no months have less than 50% access resulting in limited restriction on access to subsystems. Seasonal dependence on access not anticipated.
Med: Most months possess 50% or greater access and no months have less than 30% access resulting in some restriction on access to subsystems. Seasonal dependence may be anticipated however this will not have the potential to influence average annual power production more than 10%.
Low: Most months possess 40% or greater access resulting in severe restriction on access to subsystems. Seasonal dependence anticipated and is concurrent with peak production, thus potentially influencing average annual power production more than 20%.

- What is the list of sub-subsystems that are likely to be subject to well known failure modes and which modes (e.g. fatigue, wear, abrasion, corrosion, chemical attack, thermal overload, clogging, photolysis, other…).
  High: All sub-subsystems are selected/designed to avoid well known failure modes
  Med: A majority of sub-subsystems are selected/designed to avoid well known failure modes.
  Low: A significant number of sub-subsystems are subject to degradation through well-known failure modes.

- For the top 10 highest impact failures in subsystems and sub-subsystems what are estimates for:
  a. Frequency of failure?
  b. The power capacity reduction consequence of each?
  c. The anticipated total downtime?
  d. The waiting time for spare parts?
  e. The time required to repair each? (including access time)

Note: Refer to FMECA in answering these questions.
High: Total power capacity reduction (a. multiplied by b.) < 20% of anticipated power delivery at PoC.
Med: Total power capacity reduction (a. multiplied by b.) > 20% of anticipated power delivery at PoC.
Low: Total power capacity reduction > 50% of anticipated power delivery at PoC.

- How many subsystems have unknown failure rates or unverified in this application?
  High: A small number of subsystems
  Med: Approximately 1/3
  Low: A significant number

- For each sub-subsystem that might require an intervention what is the location of the sub-subsystem within the system and how modular and accessible is it?

  High: Sub-subsystem can be readily accessed/removed by the workers that will maintain it.
  Med: Sub-subsystem can be readily accessed/removed by other specialist workers besides the ones that will maintain it or specialized equipment is needed in removal
  Low: Sub-subsystem is relatively inaccessible (e.g. divers routinely required to access/remove the sub-subsystem).

- For the chosen vessel type(s) and typical/target installation location and required maintenance tasks what is the round trip travel time plus maintenance time for maintenance interventions?

  High: A round trip including necessary work can be made in one "shift", (e.g. less than 8-12 hours).
  Med: A round trip including necessary work can be made in an extended "shift" (e.g. less than 16-24 hours).
  Low: A round trip takes such time that overnight accommodation is needed for workers on board maintenance vessel(s).

- For the WEC farm system, what is the length of intra-array conduit (e.g. length of cable/pressure-pipe within the array) used to deliver transportable power to the aggregators per MW and number of terminations per MW?

  High: Approximately 200m/MW and a total of approximately 2 terminations/MW
  Med: Approximately 1km/MW and a total of approximately 2.5 terminations/MW
  Low: Approximately 5km/MW and a total of approximately 3 terminations/MW

- What is the availability and length of time to access spare parts?

  High: All or most parts available on demand
  Med: Main serviceable parts available on demand
  Low: Numerous parts require ordering and are subject to timelines and availability

- Are the weather window criteria primarily determined by the capabilities of the vessels or the dynamics of the device?

  High: The device dynamic response does not affect the accessibility of the device (e.g. weather windows determined by vessel response/capabilities and not device response)

Med: The dynamics of the system sometimes affect the accessibility of the device (e.g. weather windows determined by both vessel response and also device response)
Low: The dynamics of the system strongly affect the accessibility of the device (e.g. weather windows determined predominantly by device response and not vessel response)

- Is it necessary for maintenance for personnel to transfer to the WEC at sea?
  High: Personnel transfer not expected.
  Med: --- no medium score allowed here ---.
  Low: Personnel transfer expected.

- Where personnel are required enter enclosed spaces in the WEC at sea for maintenance what is the duration required to ventilate the compartment before it is safe to enter?
  High: Adequate ventilation readily achieved.
  Med: Adequate ventilation achieved within 1 hour.
  Low: Adequate ventilation not achieved within 1 hour.

- Does the array layout allow for easy access for maintenance vessels?
  High: Layout of farm (e.g. proximity of devices to vessel) has no bearing on weather windows or permit windows that govern access to farm.
  Med: Layout of farm is one of several considerations in determination of weather windows or permit windows that govern access to farm.
  Low: Layout of farm is principal consideration in determination of weather windows or permit windows that govern access to farm.

TRL5-6

- For each mode of failure:
- Number of failures over lifetime of farm (= component count * lifetime / MTBF)
- Power capacity reduction as a consequence of failure
- Duration of state with reduced capacity = max(mean waiting time between weather windows, procurement time of spare parts) + transportation time (for bringing maintenance team to system or bringing system back to facility) + Duration of repair

- What is the total anticipated number of unplanned maintenance events per MW per year and how will this change over the lifetime of the farm?
  High: Well justified expectation of up to 1 trip per 2MW per year initially, increasing linearly to up to 1 trip per MW per year during the last operational year.

Med: Well justified expectation of up to 2 trips per MW per year, increasing linearly to up to 3 trips per MW per year during the last operational year.
Low: More than 2 trips per MW per year, increasing linearly to up to 8 trips per MW per year during the last operational year OR insufficient justification for claims of better performance.

- What access level is expected for each maintenance event for each subsystem given the weather window criteria and maintenance vessel capabilities?
  High: Most months possess approximately 54 weather windows of 10 hour durations and no months possess less than approximately 36 weather windows of 10 hour durations. Seasonal dependence on access not anticipated.
  Med: Most months possess approximately 18 weather windows of 20 hour durations and no months possess less than approximately 10 weather windows of 20 hour durations. Seasonal dependence may be anticipated however this will not have the potential to influence average annual power production more than 10%.
  Low: Most months possess approximately 9 weather windows of 32 hour durations. Seasonal dependence anticipated and is concurrent with peak power production, thus potentially influencing average annual power production more than 20%.

- How many subsystems have failure modes with consequent reduction in power production capabilities of >10% of total farm? (e.g. aggregation points, export cables, single points of significant loss of generation/export)
  High: No single points of failure causes loss of >10% of total farm
  Med: 1 single point of failure causes loss of >10% of total farm
  Low: >1 single points of failure causes loss of >10% of total farm

- Does the system have any redundancy in the aggregation points and power delivery system? (e.g. are there any other routes for the power to get to the grid?)
  High: Yes, there are other routes instantly/automatically available.
  Med: Yes but require simple intervention.
  Low: No.

C.1.4.2. Be durable over the lifetime of the farm

The WEC farm should be highly durable to avoid downtime as a result of planned maintenance. The WEC farm is ideally made of high-durability (long lifetime) components, and the number of parts and components subject to wear, abrasion, and erosion is small. Ideally, the durability of a farm's components, sub-subsystems, and subsystems is the same as the lifetime of the farm. Time of servicing for subsystems that require planned maintenance (including wait time between weather windows) should be short. Durability with respect to availability accounts for the lost revenue as a result of downtime.

TRL1-2
In answering these questions consider **PLANNED** maintenance and the implications of this for **AVAILABILITY**. Consider the reduction in power generation capacity and the downtime due to maintenance and, if relevant, waiting/preparing for maintenance. • What is the technology class for each subsystem in the WEC Farm? **High:** All or predominately technology Class 1. **Med:** Predominately Class 1 or 2 with no or few Class 3. **Low:** Any significant number of Class 3 or 4. • How many subsystems have a MTBF<lifetime of the WEC Farm? **High:** None or few subsystems **Med:** Several subsystems **Low:** Majority subsystems • What level of access for maintenance of the subsystems is expected given the anticipated weather window criteria and maintenance vessel capabilities? **High:** access ≥ 70% during the year **Med:** 30% < access < 70% during the year **Low:** access ≤ 30% during the year • What is the size & mass of items being maintained? **High:** No lifting by crane is required at sea AND lifting by crane to be <60t required on land. Envelope dimensions are approximately equivalent to a standard shipping container on at least 1 side of horizontal footprint. **Med:** No lifting by crane is required at sea AND lifting by crane to be <120t required on land. Envelope dimensions are approximately those of a standard shipping container on at least one side of horizontal footprint. **Low:** Lifting by crane is required at sea (any) OR lifting by crane >120t on land. . Envelope dimensions are > a standard shipping container.

- How many systems have failure modes with consequent reduction in power production capabilities of >10% of total farm? (e.g. aggregation points, export cables, single points of significant loss of generation/export)
  High: 1 or less
  Med: 2 or 3
  Low: > 3

- Does the system have any redundancy in the aggregation points and power delivery system? (e.g. are there any other routes for the power to get to the grid?)
  High: Yes, there are other routes instantly/automatically available.
  Med: Yes but require simple intervention.
  Low: No.

TRL3-4

Complete in addition to TRL1-2 and consider the same areas.

Additionally consider where the maintenance will be performed for each sub-system and sub-subsystem (factory, on-shore, dry-dock, quay-wall, harbor, in-shore, at-sea).

- What is the target availability for the overall WEC farm?
  High: Well justified expectation of >90%.
  Med: Well justified expectation of >80%.
  Low: <80% OR insufficient justification for claims of better performance.

- What is the maximum array size (MW capacity) that can be serviced by one maintenance vessel?
  High: >100MW
  Med: 10-100MW.
  Low: <10MW.

- What is the total anticipated number of planned maintenance events per MW per year and how will this change over the lifetime of the farm?
  High: Well justified expectation of up to 1 trip per 2MW per year. The MTBF far exceeds the lifetime and the expectation is anticipated to remain stable.
  Med: Well justified expectation of up to 2 trips per MW per year. The MTBF is on the order of the lifetime and the expectation is anticipated to increase.

Low: More than 2 trips per MW per year OR insufficient justification for claims of better performance. The MTBF is less than the lifetime and the expectation is anticipated to increase.

Note: The number of planned maintenance events is a choice

- What is the technology class for each sub-subsystem in the WEC Farm?

  High: All or predominantly Class 1.
  Med: Predominately Class 1 and 2 with no or few Class 3.
  Low: Any significant number of Class 3 or 4.

- What access level is expected for each maintenance event for each subsystem given the weather window criteria?

  High: Most months possess 75% or greater access and no months have less than 50% access resulting in limited restriction on access to subsystems. Seasonal dependence on access not anticipated.
  Med: Most months possess 50% or greater access and no months have less than 30% access resulting in some restriction on access to subsystems. Seasonal dependence may be anticipated however this will not have the potential to influence average annual power production more than 10%.
  Low: Most months possess 40% or greater access resulting in severe restriction on access to subsystems. Seasonal dependence anticipated and is concurrent with peak production, thus potentially influencing average annual power production more than 20%.

- How many sub-subsystems have a MTBF < lifetime of the Farm?

  High: None or few sub-subsystems
  Med: Several sub-subsystems
  Low: Majority sub-subsystems

- What is the number of subsystems that have manufacturer recommended services / inspections over the farm lifetime and how many inspections are required?

  High: Minimal services / inspections (~1 per 2-3 years) required
  Med: Few services / inspections (~1 per year) required with easy access
  Low: Numerous services / inspections (> 5 per year) required or difficult access required

- For each sub-subsystem that might require an intervention what is the location of the sub-subsystem within the subsystem and how modular or accessible is it?

  High: Sub-subsystem can be readily accessed/removed by the workers that will maintain it.

Med: Sub-subsystem can be readily accessed/removed by other specialist workers besides the ones that will maintain it or specialized equipment is needed in removal
Low: Sub-subsystem is relatively inaccessible (e.g. divers routinely required to access/remove the sub-system).

- For the chosen vessel type(s) and typical/target installation location and required maintenance tasks what is the round trip travel time plus maintenance time for maintenance interventions?
  High: A round trip including maintenance work can be made in one "shift", (e.g. less than 8-12 hours).
  Med: A round trip including maintenance work can be made in an extended "shift" (e.g. less than 16-24 hours).
  Low: A round trip takes such time that overnight accommodation is needed for workers on board maintenance vessel(s).

- Are the weather window criteria primarily determined by the capabilities of the vessels or the dynamics of the device?
  High: The device dynamic response does not affect the accessibility of the device (e.g. weather windows determined by vessel response/capabilities and not device response)
  Med: The dynamics of the system sometimes affect the accessibility of the device (e.g. weather windows determined by both vessel response and also device response)
  Low: The dynamics of the system strongly affect the accessibility of the device (e.g. weather windows determined predominantly by device response and not vessel response)

- Is it necessary, for maintenance for personnel to transfer to the WEC at sea?
  High: Personnel transfer not expected.
  Med: --- no medium score allowed here ---.
  Low: Personnel transfer expected.

- Where personnel are required enter enclosed spaces in the WEC at sea for maintenance what is the duration required to ventilate the compartment before it is safe to enter?
  High: Adequate ventilation readily achieved.
  Med: Adequate ventilation achieved within 1 hour.
  Low: Adequate ventilation not achieved within 1 hour.

- Does the array layout allow for easy access for maintenance vessels?
  High: Layout of farm (e.g. proximity of devices to vessel) has no bearing on weather windows or permit windows that govern access to farm.

Med: Layout of farm is one of several considerations in determination of weather windows or permit windows that govern access to farm. **Low**: Layout of farm is principal consideration in determination of weather windows or permit windows that govern access to farm.
TRL5-6
For each mode of service: - Number of service over lifetime of farm = number of components * farm lifetime / duration between services - Power capacity reduction - Duration of state with reduced capacity = max(mean waiting time between weather windows, procurement time of spare parts) + transportation time (for bringing maintenance team to system or bringing system back to facility) + Duration of service • What is the total anticipated number of planned maintenance events per MW per year and how will this change over the lifetime of the farm? **High:** Well justified expectation of up to 1 trip per 2MW per year. The MTBF far exceeds the lifetime and the expectation is anticipated to remain stable. **Med:** Well justified expectation of up to 2 trips per MW per year. The MTBF is on the order of the lifetime and the expectation is anticipated to increase. **Low:** More than 2 trips per MW per year OR insufficient justification for claims of better performance. The MTBF is less than the lifetime and the expectation is anticipated to increase. *Note: The number of planned maintenance events is a choice* • What access level is expected for each maintenance event for each subsystem given the weather window criteria and maintenance vessel capabilities? **High:** Most months possess approximately 54 weather windows of 10 hour durations and no months possess less than approximately 36 weather windows of 10 hour durations. Seasonal dependence on access not anticipated. **Med:** Most months possess approximately 18 weather windows of 20 hour durations and no months possess less than approximately 10 weather windows of 20 hour durations. Seasonal dependence may be anticipated however this will not have the potential to influence average annual power production more than 10%. **Low:** Most months possess approximately 9 weather windows of 32 hour durations. Seasonal dependence anticipated and is concurrent with peak power production, thus potentially influencing average annual power production more than 20%.

- How many sub-subsystems have a MTBF < lifetime of the Farm?
    - **High:** None or few sub-subsystems
    - **Med:** Several sub-subsystems
    - **Low:** Majority sub-subsystems

- How many sub-subsystems have a fatigue life < lifetime of the Farm?
    - **High:** None or few sub-subsystems
    - **Med:** Several sub-subsystems
    - **Low:** Majority sub-subsystems

- How many subsystems have failure modes with consequent reduction in power production capabilities of >10% of total farm? (e.g. aggregation points, export cables, single points of significant loss of generation/export)
    - **High:** No single points of failure causes loss of >10% of total farm
    - **Med:** 1 single point of failure causes loss of >10% of total farm
    - **Low:** >1 single points of failure causes loss of >10% of total farm

- Does the system have any redundancy in the aggregation points and power delivery system? (e.g. are there any other routes for the power to get to the grid?)
    - **High:** Yes, there are other routes instantly/automatically available.
    - **Med:** Yes but require simple intervention.
    - **Low:** No.

C.1.5. Have a low financing rate

Financing rate is **the cost of the money borrowed from investors and financiers** to build and operate the WEC farm. Financing rate is **dictated by investors and financiers according to current market climate and reputation of the WEC technology**. The reputation of the WEC technology depends on its track record. The WEC farm project controls the **financial risk** of the technology—the higher the risk, the higher the financing rate.

Note: this capability is not scored for the TPL assessment.

C.1.6. Have a low insurance rate

Financial risk may be mitigated with insurance. Insurance may cover the risks that the investors and financiers are not willing to take. To be insurable, these **risks** shall be well **understood and manageable**. The criticality of these **risks** (i.e., the likelihood of these risks and their financial consequences) **drive the insurance rate**.

Note: this capability is not scored for the TPL assessment.

C.2. Provide a secure investment opportunity

For investors and financiers, it is critical that **WEC farm risks** are **well understood and manageable** so investors and financiers **know** the **financial risk** (i.e., the risk that the farm will **not deliver** the **expected** financial **return**). The financial risk results from the analysis of the probabilities of the risks and of their financial consequences. Uncertainties on costs (CapEx and OpEx), revenues (energy production and availability), and survivability are the drivers.

C.2.1. Low uncertainty on costs and revenues

Uncertainties and external factors may make CapEx, OpEx, energy production, and availability **deviate from expectations** even though the WEC farm is operating in conditions that are below limit states.

TRL1-2

No applicable data expected at TRL1-2.

TRL3-4

No applicable data expected at TRL3-4.

TRL5-6

- By incorporating all of the standard deviations obtained at TRL5-6, what is the variation seen on cost of energy estimates?

High:

	Worst	Average	Best
COE target	0.20$/kWh	0.10$/kWh	0.05 $/kWh

Med:

	Worst	Average	Best
COE target	1.60$/kWh	0.80$/kWh	0.40 $/kWh

Low:

	Worst	Average	Best
COE target	12.80$/kWh	6.40$/kWh	3.20 $/kWh

C.2.1.1. Low uncertainty on OPEX

OpEx may be greater than expected because of uncertainties in the reliability and/or durability of components and sub-subsystems of the WEC farm. The WEC farm shall be made of proven technologies. Standard deviations and uncertainties on the mean time between failures of the WEC farm’s subsystems, sub-subsystems, and technologies may be used to assess the risk on OpEx.

TRL1-2

- What percentage of the overall farm is comprised of technology class 3 or 4 subsystems (mechanisms that collect wave power, aggregate power, deliver power, and control position)?
  - **High:** Less than 10%.
  - **Med:** In between high and low.
  - **Low:** Greater than 40%

- What are the well-known failure modes (shocks, chemical, corrosion, wear, fatigue, thermal, etc.) for each subsystem?
  - **High:** Mainly known failure modes compatible with technology class 1 and/or a minority of subsystems susceptible to failure modes in operational conditions
  - **Med:** Limited level of uncertainties on the failure modes and/or limited number subsystems susceptible to failure modes in operational conditions
  - **Low:** Large uncertainty on the failure modes and/or majority of subsystems susceptible to failure modes in operational conditions

- What are the well know failure modes for the sub-subsystems (structure, power-take off, etc.) within the subsystem collect wave power?
  - **High:** Failure modes will not occur during operational conditions for a majority of the sub-subsystems (i.e. common failure mode is chemical in nature, however there is no exposure to this chemical or there is but a mitigating action is occurring to minimize exposure)
  - **Med:** Failure modes will occur during operational conditions, however with low probability (i.e. shocks are the common failure mode but these will occur with a low probability)
  - **Low:** Failure modes will occur during operational conditions for a majority of the sub-subsystems (i.e. common failure mode is thermal and no conditioning of ambient environment is being pursued to mitigate this mode)

- What level of access for maintenance of the subsystems is expected given the anticipated weather window criteria and maintenance vessel capabilities?
  - **High:** available $\geq$ 70% during the year
  - **Med:** 30% < available < 70% during the year
  - **Low:** available $\leq$ 30% during the year

TRL3-4

Update the answers to TRL1-2 plus answer the following questions:

- Within each subsystem, what are the percentages of Technology Class 3 or 4 sub-subsystems and components?

High: Less than 10%.
Med: In between high and low.
Low: Greater than 40%

- When addressing the failure modes for each subsystem, additionally address for each sub-subsystem within the subsystem. Also, please utilize the following questions to guide more detailed answers (i.e identify the different modes of failure: fatigue, wear, abrasion, corrosion, chemical attack, thermal overload, clogging, photolysis, other).

  a. Have fatigue lives been calculated for the 10 most repeatedly stressed elements of the farm and alterations made to account for repeated cycles over the lifetime of the farm?
  High: Yes and majority of fatigue lives are greater than 1.5 the lifetime of the farm.
  Med: Yes and several of fatigue lives are equivalent to the lifetime of the farm.
  Low: Yes however, a majority of fatigue lives are less than the lifetime of the farm OR fatigue lives have not yet been fully considered.

  b. What type of biofouling (flora and fauna types) is expected and on which sub-subsystems?
  High: Biofouling types are well-known and a minority of sub-subsystems will be susceptible to biofouling and/or have been developed to specifically mitigate influence of biofouling.
  Med: Biofouling types are well-known however either a majority of sub-subsystems will be susceptible to biofouling and/or cannot be developed to specifically mitigate influence of biofouling.
  Low: Biofouling types are not well-known and a majority of sub-subsystems will be susceptible to biofouling

  c. What level of corrosion is expected and what steps were taken to account for corrosion on each relevant sub-subsystem?
     i. If applicable, has the conductance between dissimilar metal types contacting sea water been quantified / mitigated?
  High: A minority of sub-subsystems are susceptible to corrosion, however well-known corrosion protection and/or corrosion allowance (i.e. addition of material) is implemented to mitigate influence
  Med: Well-known corrosion protection implemented, however only a small corrosion allowance is implemented
  Low: A majority of sub-subsystems are susceptible to corrosion and well-known corrosion protection and/or corrosion allowance (i.e. addition of material) is not implemented to mitigate influence

d. Which sub-subsystems are thermally sensitive and what mitigation steps have been taken?
High: Limited number of sub-subsystems with low sensitivity, and effective steps taken to mitigate thermal effects through conditioning of environment surrounding these sub-subsystems
Med: Large number of sub-subsystems with low sensitivity, and effective steps taken to mitigate thermal effects
Low: Any number of sub-subsystems with high sensitivity, and effective steps not taken to mitigate thermal effects

e. Which sub-subsystems have sensitivities to chemical degradation and what steps have been taken to address these sensitivities (batteries, lubricating oil, electrolytic capacitors, etc.)?
High: Limited number of sub-subsystems with low sensitivity, and effective steps taken to mitigate effects
Med: Large number of sub-subsystems with low sensitivity, and effective steps taken to mitigate effects
Low: Any number of sub-subsystems with high sensitivity, and effective steps not taken to mitigate effects

f. Which sub-subsystems are sensitive to acceleration or orientation and what mitigation steps have been taken?
High: Limited number of sub-subsystems with low sensitivity, and effective steps taken to mitigate effects
Med: Large number of sub-subsystems with low sensitivity, and effective steps taken to mitigate effects
Low: Any number of sub-subsystems with high sensitivity, and effective steps not taken to mitigate effects

g. Which sub-subsystems are directly subject to the full distribution of incident energy? Which sub-subsystems are subject to a subset of the distribution (aka peak load is a known value b/c there is some type of filtering in the system that will not allow the translation of load values beyond a certain point)?
High: Limited number of sub-subsystems subject to the full distribution of incident energy (i.e. majority of sub-subsystems have a quantifiable peak load).
Med: Consistent description
Low: Majority of sub-subsystems subject to the full distribution of incident energy resulting in high uncertainty with respect to the peak load that the sub-subsystems are subject to.

- Within each subsystem, what are the mean time between failures (MTBF) and the standard deviations on the MTBFs for each sub-subsystem and component?

High: only a few sub-subsystems or components have large standard deviations and MTBFs<lifetime of the farm (i.e. the majority of items have MTBFs>>lifetime of the farm, if MTBF is much longer than the lifetime of the farm then the probability of early replacement is low)
Med: a high number of sub-subsystems or components have large standard deviations on MTBF and MTBFs>lifetime of the farm
Low: a high number of sub-subsystems or components have unknown MTBF's or unknown standard deviations on MTBF; a high number of sub-subsystems or components have MTBFs<lifetime of the farm

- For the chosen vessel type(s) and typical/target installation location and required maintenance tasks what is the round trip travel time plus maintenance time for maintenance interventions?
  High: A round trip including necessary work can be made in one "shift", (e.g. less than 8-12 hours).
  Med: A round trip including necessary work can be made in an extended "shift" (e.g. less than 16-24 hours).
  Low: A round trip takes such time that overnight accommodation is needed for workers on board maintenance vessel(s).

- What is the risk ranking for each sub-subsystem within each subsystem? The risk ranking is a quantitative procedure which ranks failure modes according to their probability and consequences (i.e. the resulting effect of the failure mode on safety, environment, operation and asset). The probability classes, consequence classes, and risk ranking are detailed in the definitions.
  High: Risk ranking performed and complete. Number of high risk is limited (less than 10% of the overall risks). Recommended actions are consistent with the mechanism of failure and feasible.
  Med: Risk ranking performed with limited detail in some areas. Number of high risk is less limited (less than 25% of the overall risks). Recommended actions may not be consistent with the mechanism of failure and/or may not be feasible.
  Low: Risk ranking performed with minimal level of detail. Number of high risk is high (around 30% of the overall risks). Recommended actions are not entirely consistent with the mechanism of failure and / or more difficult to implement and be successful.

- What access level is expected for each maintenance event for each subsystem given the weather window criteria and maintenance vessel capabilities?

High: Most months possess 75% or greater access and no months have less than 50% access resulting in limited restriction on access to subsystems. Seasonal dependence on access not anticipated.
Med: Most months possess 50% or greater access and no months have less than 30% access resulting in some restriction on access to subsystems. Seasonal dependence may be anticipated.
Low: Most months possess 40% or greater access resulting in severe restriction on access to subsystems. Seasonal dependence anticipated and is concurrent with peak production.

- Have the maintenance thresholds taken into account the ensuing dynamics of the subsystems? If yes, please explain how they have been accounted for.

  High: The dynamics of the subsystem does not affect the accessibility / maintenance activities needed for the subsystems (e.g. weather windows determined by vessel response/capabilities and not device response)
  Med: The dynamics of the subsystem sometimes affect the accessibility / maintenance activities needed for the subsystems (e.g. weather windows determined by both vessel response and also device response). Both the threshold significant wave height and steepness have been altered to accommodate the subsystem dynamics
  Low: The dynamics of the subsystem strongly affect the accessibility / maintainability of the subsystem. The subsystem must be serviced in a sheltered location or on shore.

- When determining the durations required for each maintenance activity, were the dynamics of the subsystem or sub-subsystem taken into account? Do the durations appropriately account for multi-stepped activities?

  High: The dynamics of the subsystem does not affect the accessibility / maintenance activities needed for the subsystems. The duration is simply based on time needed to complete task under normal circumstances with a small additional factor added.
  Med: The dynamics of the subsystem sometimes affect the accessibility / maintenance activities needed for the subsystems. Hence the duration of the required weather window increased to allow for maintenance on a dynamic device and an additional factor is added to allow for multi-stepped activities in dynamic conditions.
  Low: The dynamics of the subsystem strongly affect the accessibility / maintainability of the subsystem. The subsystem must be serviced in a sheltered location or on shore, thus the

increase in duration is based on transit time to servicing location.

- What is the criticality if a maintenance task must be stopped before completed?

  High: Installation tasks can be stopped at any time safely, and continued later on.
  Med: Any task that is not complete that must be stopped can be reverted to a safe state in a timely and safe manner until the task can be resumed.
  Low: Any task that is not complete that must be stopped cannot be reverted to a safe state. Ex. Installation window is exceeded, requiring finishing the work in increasing unsafe conditions.

- If applicable, when sub-systems are disconnected in water (at sea or in sheltered water) e.g. joining/un-joining hinged barge, what are the stability characteristics of the disconnected systems?

  High: Disconnected subsystems have similar stability to connected subsystems. Weather window criteria for operations on disconnected subsystem is the same as for the connected subsystem.
  Med: Disconnected subsystems have reduced stability compared to connected subsystems. Weather window criteria for operations on disconnected subsystem is higher than for the connected subsystem.
  Low: Disconnected subsystems have significantly reduced stability compared to connected subsystems. Systems can only be disconnected in sheltered calm water.

- In addition to the physical conditions at sea, other factors like overtime hours, safety training, etc. will influence the cost of maintenance—these define the permit window. What are these factors for this deployment location and what regulatory mandates supervise the workforce?

  High: Low constraints. Normal health and safety and other legal requirements for work at sea. Not governing the operation.
  Med: Limited constraint. Normal health and safety and other legal requirements for work at sea and additional regulations and environmental constraints. Possible impact in the operation above the metocean conditions. Additional operational costs (~20%)
  Low: High level of constraints. Normal HSE requirements for work at sea, additional regulations, environmental constraints and operational limits. Governing over metocean conditions. Additional operational costs ≥ 30%

- What is the sensitivity of the maintenance vessel(s) cost to external factors (e.g. activity in oil & gas exploration)? How many competing suppliers of maintenance vessel(s) are there?

High: Low sensitivity. More than 10 competing vessel suppliers that are multi-purpose (i.e. the vessels could be used by more than one industry) **Med:** Medium sensitivity. Somewhere between 3 ≤ # of competing vessels ≤ 10 that are multi-purpose **Low:** High sensitivity. Only 1-2 competing vessel suppliers that are multi-purpose (i.e. the vessels could be used by more than one industry) • Has the speed that the maintenance vessel operates at been optimized? **High:** Optimised for several combinations of target/typical port/farm location and resource. **Med:** Optimised for a single combination of target/typical port/farm location and resource. **Low:** Not optimised e.g. assumptions based on other industries. • What are the anticipated insurance costs? **High:** <2% of CAPEX **Med:** 2-5% of CAPEX **Low:** >5% of CAPEX
TRL5-6
• Standard deviation of average annual cost of maintenance resulting from a Monte Carlo analysis (standard deviation of MTBF, distribution of weather windows, number of Technology class 1 components/sub-systems/systems, number of failures*criticality of failures) **High:** Standard deviation ($) ≤ 10%(maintenance ($)) **Med:** 10%(planned maintenance ($)) < Standard deviation ($) < 40%(maintenance ($)) **Low:** Standard deviation ($) ≥ 40%(maintenance ($)) • Within each subsystem, what are the mean time between failures (MTBF) and the standard deviations on the MTBFs for each sub-subsystem and component? **High:** only a few sub-subsystems or components have large standard deviations and MTBFs<lifetime of the farm (i.e. the majority of items have MTBFs>>lifetime of the farm, if MTBF is much longer than the lifetime of the farm then the probability of early replacement is low) **Med:** a high number of sub-subsystems or components have large standard deviations on MTBF and MTBFs>lifetime of the farm **Low:** a high number of sub-subsystems or components have unknown MTBF's or unknown standard deviations on MTBF; a high number of sub-subsystems or components have MTBFs<lifetime of the farm

- What access level is expected for each maintenance event for each subsystem given the weather window criteria?

  High: Most months possess approximately 54 weather windows of 10 hour durations and no months possess less than approximately 36 weather windows of 10 hour durations. Seasonal dependence on access not anticipated.

  Med: Most months possess approximately 18 weather windows of 20 hour durations and no months possess less than approximately 10 weather windows of 20 hour durations. Seasonal dependence may be anticipated.

  Low: Most months possess approximately 9 weather windows of 32 hour durations. Seasonal dependence anticipated.

- What are the fatigue lives for the highest consequence elements of the farm?

  High: Majority of fatigue lives are greater than 1.5 the lifetime of the farm.

  Med: Several of fatigue lives are equivalent to the lifetime of the farm.

  Low: Majority of fatigue lives are less than the lifetime of the farm OR fatigue lives have not yet been fully considered.

- How have the characteristic loads been validated (experimentally) or otherwise verified as applicable?

  High: Statistically significant and broad experimental validation. Nonlinear numerical modelling capable of resolving high nonlinearities (impact events).

  Med: Experimental validation, however not statistically significant or ignoring major contributing factors (wind, current, etc.). Nonlinear numerical modelling incapable of high nonlinearities (impact events).

  Low: No experimental validation. Linear numerical modelling.

- What is the risk ranking for each sub-subsystem within each subsystem? The risk ranking is a quantitative procedure which ranks failure modes according to their probability and consequences (i.e. the resulting effect of the failure mode on safety, environment, operation and asset). The probability classes, consequence classes, and risk ranking are detailed in the definitions.

  High: Risk ranking performed and complete. Number of high risk is limited (less than 10% of the overall risks). Recommended actions are consistent with the mechanism of failure and feasible.

Med: Risk ranking performed with limited detail in some areas. Number of high risk is less limited (less than 25% of the overall risks). Recommended actions may not be consistent with the mechanism of failure and/or may not be feasible. **Low:** Risk ranking performed with minimal level of detail. Number of high risk is high (around 30% of the overall risks). Recommended actions are not entirely consistent with the mechanism of failure and/or more difficult to implement and be successful.

C.2.1.2. Low uncertainty on availability

Availability may be smaller than expected because of uncertainties in the reliability and/or the durability of components and sub-subsystems. If unplanned maintenance activities are more frequent than expected, the farm availability is less than expected. Availability may also be diminished because waiting time between weather windows for planned and unplanned maintenance is longer than expected.

TRL1-2
• What percentage of the overall farm is comprised of Technology Class 3 or 4 subsystems (mechanisms that collect wave power, aggregate power, deliver power, and control position)? **High:** Less than 10%. **Med:** In between high and low. **Low:** Greater than 40% • What are the well-known failure modes (shock, chemical, corrosion, wear, fatigue, thermal, etc.) for each subsystem? **High:** Mainly known failure modes compatible with technology class 1 and/or a minority of subsystems susceptible to failure modes in operational conditions **Med:** Limited level of uncertainties on the failure modes and/or limited number subsystems susceptible to failure modes in operational conditions **Low:** Large uncertainty on the failure modes and/or majority of subsystems susceptible to failure modes in operational conditions • What are the well know failure modes for the sub-subsystems (structure, power-take off, etc.) within the subsystem collect wave power? **High:** Failure modes will not occur during operational conditions for a majority of the sub-subsystems (i.e. common failure mode is chemical in nature, however there is no exposure to this chemical or there is but a mitigating action is occurring to minimize exposure) **Med:** Failure modes will occur during operational conditions, however with low probability (i.e. shocks are the common failure mode but these will occur with a low probability) **Low:** Failure modes will occur during operational conditions for a majority of the sub-subsystems (i.e. common failure mode is thermal and no conditioning of ambient environment is being pursued to mitigate this mode) • What level of access for maintenance of the subsystems is expected given the anticipated weather window criteria and maintenance vessel capabilities? **High:** available $\geq$ 70% during the year **Med:** 30% < available < 70% during the year **Low:** available $\leq$ 30% during the year

TRL3-4

Update the answers to TRL1-2 plus answer the following questions:

- Within each system, what are the percentages of Technology Class 3 or 4 sub-systems and components?
  High: Less than 10%.
  Med: In between high and low.
  Low: Greater than 40%

- When addressing the failure modes for each subsystem, additionally address for each sub-subsystem within the subsystem. Also, please utilize the following questions to guide more detailed answers (i.e identify the different modes of failure: fatigue, wear, abrasion, corrosion, chemical attack, thermal overload, clogging, photolysis, other).
  a. Have fatigue lives been calculated for the 10 most repeatedly stressed elements of the farm and alterations made to account for repeated cycles over the lifetime of the farm?
     High: Yes and majority of fatigue lives are greater than 1.5 the lifetime of the farm.
     Med: Yes and several of fatigue lives are equivalent to the lifetime of the farm.
     Low: Yes however, a majority of fatigue lives are less than the lifetime of the farm OR fatigue lives have not yet been fully considered.

  b. What type of biofouling (flora and fauna types) is expected and on which sub-subsystems?
     High: Biofouling types are well-known and a minority of sub-subsystems will be susceptible to biofouling and/or have been developed to specifically mitigate influence of biofouling.
     Med: Biofouling types are well-known however either a majority of sub-subsystems will be susceptible to biofouling and/or cannot be developed to specifically mitigate influence of biofouling.
     Low: Biofouling types are not well-known and a majority of sub-subsystems will be susceptible to biofouling

  c. What level of corrosion is expected and what steps were taken to account for corrosion on each relevant sub-subsystem?
     i. If applicable, has the conductance between dissimilar metal types contacting sea water been quantified / mitigated?
     High: A minority of sub-subsystems are susceptible to corrosion, however well-known corrosion protection and/or corrosion allowance (i.e. addition of material) is implemented to mitigate influence

Med: Well-known corrosion protection implemented, however only a small corrosion allowance is implemented
Low: A majority of sub-subsystems are susceptible to corrosion and well-known corrosion protection and/or corrosion allowance (i.e. addition of material) is not implemented to mitigate influence

d. Which sub-subsystems are thermally sensitive and what mitigation steps have been taken?
High: Limited number of sub-subsystems with low sensitivity, and effective steps taken to mitigate thermal effects through conditioning of environment surrounding these sub-subsystems
Med: Large number of sub-subsystems with low sensitivity, and effective steps taken to mitigate thermal effects
Low: Any number of sub-subsystems with high sensitivity, and effective steps not taken to mitigate thermal effects

e. Which sub-subsystems have sensitivities to chemical degradation and what steps have been taken to address these sensitivities (batteries, lubricating oil, electrolytic capacitors, etc.)?
High: Limited number of sub-subsystems with low sensitivity, and effective steps taken to mitigate effects
Med: Large number of sub-subsystems with low sensitivity, and effective steps taken to mitigate effects
Low: Any number of sub-subsystems with high sensitivity, and effective steps not taken to mitigate effects

f. Which sub-subsystems are sensitive to acceleration or orientation and what mitigation steps have been taken?
High: Limited number of sub-subsystems with low sensitivity, and effective steps taken to mitigate effects
Med: Large number of sub-subsystems with low sensitivity, and effective steps taken to mitigate effects
Low: Any number of sub-subsystems with high sensitivity, and effective steps not taken to mitigate effects

g. Which sub-subsystems are directly subject to the full distribution of incident energy? Which sub-subsystems are subject to a subset of the distribution (aka peak load is a known value b/c there is some type of filtering in the system that will not allow the translation of load values beyond a certain point)?
High: Limited number of sub-subsystems subject to the full distribution of incident energy (i.e. majority of sub-subsystems have a quantifiable peak load).
Med: Consistent description

Low: Majority of sub-subsystems subject to the full distribution of incident energy resulting in high uncertainty with respect to the peak load that the sub-subsystems are subject to.

- Within each subsystem, what are the mean time between failures (MTBF) and the standard deviations on the MTBFs for each sub-subsystem and component?

  High: only a few sub-subsystems or components have large standard deviations and MTBFs<lifetime of the farm (i.e. the majority of items have MTBFs>>lifetime of the farm, if MTBF is much longer than the lifetime of the farm then the probability of early replacement is low)
  Med: a high number of sub-subsystems or components have large standard deviations on MTBF and MTBFs>lifetime of the farm
  Low: a high number of sub-subsystems or components have unknown MTBF's or unknown standard deviations on MTBF; a high number of sub-subsystems or components have MTBFs<lifetime of the farm

- What is the risk ranking for each sub-subsystem within each subsystem? The risk ranking is a quantitative procedure which ranks failure modes according to their probability and consequences (i.e. the resulting effect of the failure mode on safety, environment, operation and asset). The probability classes, consequence classes, and risk ranking are detailed in the definitions.

  High: Risk ranking performed and complete. Number of high risk is limited (less than 10% of the overall risks). Recommended actions are consistent with the mechanism of failure and feasible.
  Med: Risk ranking performed with limited detail in some areas. Number of high risk is less limited (less than 25% of the overall risks). Recommended actions may not be consistent with the mechanism of failure and/or may not be feasible.
  Low: Risk ranking performed with minimal level of detail. Number of high risk is high (around 30% of the overall risks). Recommended actions are not entirely consistent with the mechanism of failure and / or more difficult to implement and be successful.

- Has any redundancy been added to alter the risk ranking? If so, please identify the subsystem, sub-subsystem, component that was made redundant.

  High: Irrespective of original risk, introduction of redundant elements reduce risk to low OR no redundant elements found to be needed
  Med: Original risk found to be high, introduction of redundant sub-subsystems

Low: Introduction of redundant elements…OR no introduction of redundant elements Original risk found to be high, introduction of redundant sub-subsystems

- For the chosen vessel type(s) and typical/target installation location and required maintenance tasks what is the round trip travel time plus maintenance time for maintenance interventions?

  High: A round trip including necessary work can be made in one "shift", (e.g. less than 8-12 hours).
  Med: A round trip including necessary work can be made in an extended "shift" (e.g. less than 16-24 hours).
  Low: A round trip takes such time that overnight accommodation is needed for workers on board maintenance vessel(s).

- What access level is expected for each maintenance event for each subsystem given the weather window criteria?

  High: Most months possess 75% or greater access and no months have less than 50% access resulting in limited restriction on access to subsystems. Seasonal dependence on access not anticipated.
  Med: Most months possess 50% or greater access and no months have less than 30% access resulting in some restriction on access to subsystems. Seasonal dependence may be anticipated.
  Low: Most months possess 40% or greater access resulting in severe restriction on access to subsystems. Seasonal dependence anticipated and is concurrent with peak production.

- Have the maintenance thresholds taken into account the ensuing dynamics of the subsystems? If yes, please explain how they have been accounted for.

  High: The dynamics of the subsystem does not affect the accessibility / maintenance activities needed for the subsystems (e.g. weather windows determined by vessel response/capabilities and not device response)
  Med: The dynamics of the subsystem sometimes affect the accessibility / maintenance activities needed for the subsystems (e.g. weather windows determined by both vessel response and also device response). Both the threshold significant wave height and steepness have been altered to accommodate the subsystem dynamics
  Low: The dynamics of the subsystem strongly affect the accessibility / maintainability of the subsystem. The subsystem must be serviced in a sheltered location or on shore.

- When determining the durations required for each maintenance activity, were the dynamics of the subsystem or sub-subsystem taken into account? Do the durations appropriately account for multi-stepped activities?

High: The dynamics of the subsystem does not affect the accessibility / maintenance activities needed for the subsystems. The duration is simply based on time needed to complete task under normal circumstances with a small additional factor added.
Med: The dynamics of the subsystem sometimes affect the accessibility / maintenance activities needed for the subsystems. Hence the duration of the required weather window increased to allow for maintenance on a dynamic device and an additional factor is added to allow for multi-stepped activities in dynamic conditions.
Low: The dynamics of the subsystem strongly affect the accessibility / maintainability of the subsystem. The subsystem must be serviced in a sheltered location or on shore, thus the increase in duration is based on transit time to servicing location.

- What is the criticality if a maintenance task must be stopped before completed (use risk ranking identified above)?
  High: Installation tasks can be stopped at any time safely, and continued later on.
  Med: Any task that is not complete that must be stopped can be reverted to a safe state in a timely and safe manner until the task can be resumed.
  Low: Any task that is not complete that must be stopped cannot be reverted to a safe state. Ex. Installation window is exceeded, requiring finishing the work in increasing unsafe conditions.

- If applicable, when sub-systems are disconnected in water (at sea or in sheltered water) e.g. joining/un-joining hinged barge, what are the stability characteristics of the disconnected systems?
  High: Disconnected subsystems have similar stability to connected subsystems. Weather window criteria for operations on disconnected subsystem is the same as for the connected subsystem.
  Med: Disconnected subsystems have reduced stability compared to connected subsystems. Weather window criteria for operations on disconnected subsystem is higher than for the connected subsystem.
  Low: Disconnected subsystems have significantly reduced stability compared to connected subsystems. Systems can only be disconnected in sheltered calm water.

- In addition to the physical conditions at sea, other factors like overtime hours, safety training, etc. will influence the cost of maintenance—these define the permit window. What are these factors for this deployment location and what regulatory mandates supervise the workforce?
  High: Low constraints. Normal health and safety and other legal requirements for work at sea. Not governing the operation.
  Med: Limited constraint. Normal health and safety and other legal requirements for work at sea and additional regulations and

environmental constraints. Possible impact in the operation above the metocean conditions. Additional operational costs (~20%) **Low:** High level of constraints. Normal HSE requirements for work at sea, additional regulations, environmental constraints and operational limits. Governing over metocean conditions. Additional operational costs $\geq$ 30% • What is the sensitivity of the maintenance vessel(s) cost to external factors (e.g. activity in oil & gas exploration)? How many competing suppliers of maintenance vessel(s) are there? **High:** Low sensitivity. More than 10 competing vessel suppliers that are multi-purpose (i.e. the vessels could be used by more than one industry) **Med:** Medium sensitivity. Somewhere between 3 $\leq$ # of competing vessels $\leq$ 10 that are multi-purpose **Low:** High sensitivity. Only 1-2 competing vessel suppliers that are multi-purpose (i.e. the vessels could be used by more than one industry) • Has the speed that the maintenance vessel operates at been optimized? **High:** Optimized for several combinations of target/typical port/farm location and resource. **Med:** Optimized for a single combination of target/typical port/farm location and resource. **Low:** Not optimized e.g. assumptions based on other industries.
TRL5-6
• What is the standard deviation on the on power capacity reduction? (Monte Carlo analysis should be performed using 10 years of sea state data to determine this value.) **High:** Standard Deviation (kW) $\leq$ 10%(Power Capacity Reduction (kW)) **Med:** 10%(Power Capacity Reduction (kW)) < Standard Deviation (kW) < 40%(Power Capacity Reduction (kW)) **Low:** Standard Deviation (kW) $\geq$ 40%(Power Capacity Reduction (kW)) • What is the standard deviation on the duration of state with reduced capacity? (Monte Carlo analysis should be performed using 10 years of sea state data to determine this value.) **High:** Standard Deviation (days) $\leq$ 2%(Duration of reduced capacity (days)) **Med:** 2%(Duration of reduced capacity (days)) < Standard Deviation (days) < 10%(Duration of reduced capacity (days)) **Low:** Standard Deviation (days) $\geq$ 10%(Duration of reduced capacity (days))

- Within each subsystem, what are the mean time between failures (MTBF) and the standard deviations on the MTBFs for each sub-subsystem and component?

  High: only a few sub-subsystems or components have large standard deviations and MTBFs<lifetime of the farm (i.e. the majority of items have MTBFs>>lifetime of the farm, if MTBF is much longer than the lifetime of the farm then the probability of early replacement is low)
  Med: a high number of sub-subsystems or components have large standard deviations on MTBF and MTBFs>lifetime of the farm
  Low: a high number of sub-subsystems or components have unknown MTBF's or unknown standard deviations on MTBF; a high number of sub-subsystems or components have MTBFs<lifetime of the farm

- What are the fatigue lives for the highest consequence element of the farm?

  High: Majority of fatigue lives are greater than 1.5 the lifetime of the farm.
  Med: Several of fatigue lives are equivalent to the lifetime of the farm.
  Low: Majority of fatigue lives are less than the lifetime of the farm OR fatigue lives have not yet been fully considered.

- What access level is expected for each maintenance event for each subsystem given the weather window criteria and maintenance vessel capabilities?

  High: Most months possess approximately 54 weather windows of 10 hour durations and no months possess less than approximately 36 weather windows of 10 hour durations. Seasonal dependence on access not anticipated.
  Med: Most months possess approximately 18 weather windows of 20 hour durations and no months possess less than approximately 10 weather windows of 20 hour durations. Seasonal dependence may be anticipated however this will not have the potential to influence average annual power production more than 10%.
  Low: Most months possess approximately 9 weather windows of 32 hour durations. Seasonal dependence anticipated and is concurrent with peak power production, thus potentially influencing average annual power production more than 20%.

C.2.1.3. Low uncertainty on energy production

Energy production may be smaller than expected because the resource may be smaller than expected. Energy production estimates are normally made based on the statistically worst year. First power delivery may be delayed because of acceptability issues or delays in construction. This type of uncertainty may be mitigated through insurance or penalties in contracts with suppliers.

TRL1-2

- How sensitive are subsystem power conversions to variable incoming power?
  - **High:** The subsystems operate with a high constant efficiency over a wide range of variable inputs (energy, frequency, etc.).
  - **Med:** The subsystems operate with a high efficiency, but only over a limited range of variable inputs (energy, frequency, etc.).
  - **Low:** The subsystems are very sensitive to variable input and will only achieve high efficiency over a small range of inputs (energy, frequency, etc.).

- May the technology be a concern for the local communities that could cause delays in first power production?
  - **High:** The technology has been demonstrated and is accepted by the local community upfront
  - **Med:** The technology may result in unwanted consequences to a few local groups
  - **Low:** The technology poses unknown consequences to area (species of interest, coastline, recreational use, etc.)

TRL3-4

Update the answers to TRL1-2 plus answer the following questions:

- What are the validation results for the numerical model? Specify the aspects that have been validated (direction, array interaction, control, etc.).
  - **High:** Numerical model, inclusive of nonlinearities, validated against:

Validation Aspect	*Description*	*Min Scale*
Incoming Seas	Short-crested irregular seas for various spectral shapes	1:30
Additional Environmental Aspects	Considerations of tide (height and current), current and wind accounted for	1:30
Control Strategies	Tested expected control strategies for those to be used at full scale	1:30
Array	Configuration tested in regular and long-crested irregular waves for head and off-head directions	1:70

	Validation Aspect	Description	Min Scale
	Configuration changes (physical)	If applicable tested in all incoming seas identified above.	1:30
	Power Conversion Efficiencies	Variable inputs matching expected seas	1:1
	Med: Numerical model, inclusive of nonlinearities, validated against:		
	Validation Aspect	*Description*	*Min Scale*
	Incoming Seas	Short-crested irregular seas for one spectral shape	1:50
	Additional Environmental Aspects	Not tested	N/A
	Control Strategies	Tested representative control strategies but still have fundamental issues to work through (slew-rates for instance)	1:50
	Array	Configuration tested in regular and long-crested irregular waves for head directions only	1:100
	Configuration changes (physical)	Not tested	N/A
	Power Conversion Efficiencies	Variable inputs matching expected seas	1:25
	Low: Linear numerical model validated against:		
	Validation Aspect	*Description*	*Min Scale*
	Incoming Seas	Long-crested irregular seas (in both head an off-head directions) for one spectral shape	1:50
	Additional Environmental Aspects	Not tested	N/A
	Control Strategies	Tested representative control strategies but still have fundamental issues to work through (slew-rates for instance)	1:50
	Array	Not tested	N/A
	Configuration changes (physical)	Not tested.	N/A

	Power Conversion Efficiencies	Not tested	N/A

- What steps have been taken to mitigate delays in first power production (environmental / societal impact from the WEC Farm?)
  - **High:** The installation procedure/plan has been prepared to minimize delays
  - **Med:** The installation procedure/plan gives some concerns of delays
  - **Low:** There is no description of the installation procedure/plan

TRL5-6

Update the answers to TRL1-2 & TRL3-4 plus answer the following questions:

- What is the standard deviation of average annual power production at PoC over the 10 year period (as requested in Design Class of IEC TS 62600-101 for instance)? What is the worst (10^{th} quantile) average annual power production at PoC? What is the best (90^{th} quantile) average annual power production at PoC?
  - **High:** The standard deviation of APP over 10 years less than 10% and the difference between the best (90^{th} quantile) and worst (10^{th} quantile) year is less than 30%
  - **Med:** between high and low
  - **Low:** The standard deviation of APP over 10 years greater than 15% and the difference between the best (90^{th} quantile) and worst year (10^{th} quantile) is greater than 40%

- How much contingency has been built into the construction and installation schedules?
  - **High:** A contingency of at least 10% has been built into the construction and installation schedules
  - **Med:** A contingency less than 10% has been built into the construction and installation schedules
  - **Low:** No contingency has been built into the construction and installation schedules

C.2.1.4. Low uncertainty on CAPEX

CapEx may be greater than expected. It may happen because of an increase in materials and/or component prices; and/or increased manufacturing costs/durations; and/or increased transportation and installation costs. The supply chain should be low risk.

TRL1-2
• What percentage of the WEC farm will be comprised of Technology Class 3 or 4 subsystems (subsystems that collect wave power, aggregate power, deliver power, and control position)? **High:** Less than 10%. **Med:** In between high and low. **Low:** Greater than 40% • What material types in the WEC farm, if any, are rare or located only in particular parts of the world; i.e. what material types are vulnerable to price fluctuations? **High:** traditional inexpensive material types comprise the majority of the subsystems. **Med:** a few of the subsystems are comprised of expensive material types (subjected to price fluctuations e.g. rare earth magnetic material) **Low:** a few of the subsystems are comprised of novel material types (rare or subjected to price fluctuations) • Are new manufacturing facilities / workforce expertise needed to construct systems within the WEC farm? **High:** No **Med:** Either new facilities or new expertise are needed but not both **Low:** Yes
TRL3-4
Update the answers to TRL1-2 plus answer the following questions: • What percentage of the WEC farm will be comprised of Technology Class 3 or 4 sub-subsystems? **High:** Less than 10%. **Med:** In between high and low. **Low:** Greater than 40% • For the identified installation weather window thresholds, please answer the following questions: a. What are the expected weather window criteria for each installation event for each subsystem?

High: Most months possess 75% or greater access and no months have less than 50% access resulting in limited restriction on access to subsystems. Seasonal dependence on access not anticipated.
Med: Most months possess 50% or greater access and no months have less than 30% access resulting in some restriction on access to subsystems. Seasonal dependence may be anticipated.
Low: Most months possess 40% or greater access resulting in severe restriction on access to subsystems. Seasonal dependence anticipated.

b. Have the installation thresholds taken into account the ensuing dynamics of the subsystems? If yes, please explain how they have been accounted for.
High: The dynamics of the subsystem does not affect the accessibility / installation activities needed for the subsystems (e.g. weather windows determined by vessel response/capabilities and not device response)
Med: The dynamics of the subsystem sometimes affect the accessibility / installation activities needed for the subsystems (e.g. weather windows determined by both vessel response and also device response). Both the threshold significant wave height and steepness have been altered to accommodate the subsystem dynamics
Low: The dynamics of the subsystem strongly affect the accessibility / maintainability of the subsystem. The subsystem must be serviced in a sheltered location or on shore.

c. When determining the durations required for each installation activity, were the dynamics of the subsystem or sub-subsystem taken into account? Do the durations appropriately account for multi-stepped activities?
High: The dynamics of the subsystem does not affect the accessibility / installation activities needed for the subsystems. The duration is simply based on time needed to complete task under normal circumstances with a small additional factor added.
Med: The dynamics of the subsystem sometimes affect the accessibility / installation activities needed for the subsystems. Hence the duration of the required weather window increased to allow for installation on a dynamic device and an additional factor is added to allow for multi-stepped activities in dynamic conditions.
Low: The dynamics of the subsystem strongly affect the accessibility / maintainability of the subsystem. The subsystem must be serviced in a sheltered location or on shore, thus the increase in duration is based on transit time to servicing location.

d. What is the criticality if an installation task must be stopped before completed?

High: Installation tasks can be stopped at any time safely, and continued later on.
Med: Any task that is not complete that must be stopped can be reverted to a safe state in a timely and safe manner until the task can be resumed.
Low: Any task that is not complete that must be stopped cannot be reverted to a safe state. Ex. Installation window is exceeded, requiring finishing the work in increasing unsafe conditions.

e. If applicable, when sub-systems are disconnected in water (at sea or in sheltered water) e.g. joining/un-joining hinged barge, what are the stability characteristics of the disconnected systems?
High: Disconnected sub-systems have similar stability to connected sub-system. Weather window criteria for operations on disconnected sub-system is the same as for the connected sub-system.
Med: Disconnected sub-systems have reduced stability compared to connected sub-system. Weather window criteria for operations on disconnected sub-system is higher than for the connected sub-system.
Low: Disconnected sub-systems have significantly reduced stability compared to connected sub-system. Systems can only be disconnected in sheltered calm water.

- Will any non-standard transportation be required (e.g. escort for oversized load, construction of new infrastructure, etc.)? Identify the type and the effect this is expected to have.
  High: by non-specialized boat, railway and or road requiring no upgrade to existing infrastructure (such as widening roads) and no special permissions or precautions e.g. permission from local authorities or police, special speed limit, special escort.
  Med: by specialized boat, railway and or road requiring no upgrade to existing infrastructure (such as widening roads) but requiring special permission or precautions e.g. permission from local authorities or police, special speed limit, special escort.
  Low: any option that requires an upgrade to existing infrastructure

- Will components be sourced from large reputable companies with long standing histories?
  High: Large reputable companies often support the migration of legacy components to newer versions and have a decreased risk of closing.
  Med: In between high and low.
  Low: New and or small companies have an increased risk of closing potentially leaving key systems with parts that cannot be replaced causing redesign efforts.

- What steps will be taken to ensure that the integration of manufactured subsystems, sub-subsystems, and components will achieve the quality required?
  High: Testing occurs early and continuously throughout the manufacturing process (expects a triangle of manufacturing)
  Med: Some crucial tests are performed late in the manufacturing process (by late we mean difficult to go back and fix/identify true cause of problem)
  Low: no testing is indicated or occurs late in the manufacturing process

TRL5-6

Update the answers to TRL1-2 & TRL3-4 plus answer the following questions:

- What are the standard deviations on the following projections: expected manufacturing rate in day / MW and MW's of installed power per year.
  High: Standard Deviation (day/MW) ≤ 10%(Manufacturing Rate (day/MW), and Standard Deviation (MW/year) ≤ 10%(Installed Power (MW/year))
  Med: between high and low
  Low: Standard Deviation (day/MW) ≥ 20%(Manufacturing Rate (day/MW), and Standard Deviation (MW/year) ≥ 20%(Installed Power (MW/year))

- What techniques (experimental, numerical, etc.) were used to determine the characteristic loads for the sub-subsystems asked about above (structure of collect wave energy, absorbed to useful power, and control position)?

High:

Experimental Technique	*Modeling Technique*
Statistically significant testing in appropriate return period confirming characteristic load to within 10% of expectation	Dynamic modeling including predominant nonlinearities and capable of resolving impact events

Med:

Experimental Technique	*Modeling Technique*
Statistically significant testing in appropriate return period confirming characteristic load to within 20% of expectation	Dynamic modeling based on nonlinear assumptions

Low:

Experimental Technique	*Modeling Technique*
Statistically significant testing in appropriate return period	Dynamic modeling based on linear assumptions

confirming characteristic load to within 50% of expectation	

- What percentage of contingency has been added to the CAPEX projections?
  High: A contingency of at least 15%
  Med: 5% < contingency < 15%
  Low: A contingency of less than 5%

C.2.2. Survivable

Because of the stochastic nature of the farm environment (including other users of the area and grid), and uncertainties in the understanding of the response of the farm, **conditions resulting in consequence classes 4 and higher** may happen. These events cause significant damage. The financial consequences (loss of revenues because of downtime, loss of assets, cost of repairs) shall be well understood and as low as possible.

C.2.2.1. Be able to survive extreme loads and responses

Because of the stochastic nature of the marine environment, weather conditions or operational conditions may lead to extreme loads and responses that result in consequence classes 4 and higher. The probabilities of such events and their financial consequences (repair costs, loss of assets, or loss of production) shall be understood. If relevant, possible cascade failures shall be taken into account.

TRL1-2
• Identify how susceptible subsystems in the farm are to increasingly energetic conditions by identifying how the subsystems of the farm react (in terms of motions and loads) to highly energetic environments (i.e. large return period environments). **High:** Subsystems with surface expression that are subject to the large energy in the forcing environment are designed to decouple (i.e. load shedding, submergence, etc.) OR no subsystems have surface expression **Med:** Subsystems possess only minimal surface expression OR possess a limited scope decoupling mechanism **Low:** Subsystems with surface expression are subject to the large energy in the forcing environment because they have no special coping mechanisms • How many sets of point loads (heave plate, mooring lugs, PTO, end stops) affect the subsystem that collects wave power? Note: Point loads occur when two bodies connect for which the forcing profiles are distinct (general hull withstands hydrostatic pressure combining with the PTO attachment at which thrust forces must be mitigated); special structural solutions may be employed to distribute the point loads across a wider area. Identify the type, number, and accessibility. **High:** Only one set of point loads (for instance mooring attachment points or PTO attachment points) and accessible to inspection and repair **Med:** Three sets of point loads (for instance mooring attachment points, end stops, and heave plate) and limited access to inspection **Low:** More than three sets of point loads an limited or no access to inspection and repair

• For the subsystem that aggregates the collected power, what are the dynamics at the connection points? **High**: Both wave power collecting subsystem and aggregator are fixed. **Med**: One or both of them are floating but dynamics are low (e.g very large non resonant platform, floating subsurface body with little or no wave forces) **Low**: Both wave power collecting subsystem and aggregator are floating • What is the target safety level for each subsystem in terms of annual probability of failure for the survival conditions? **High:** high safety class < 10^{-5} failures per annum **Med:** medium safety class <10^{-4} failures per annum **Low:** low safety class <10^{-3} failures per annum • Does the sub-subsystem that converts absorbed power into transportable power play a role in withstanding extreme loads and responses? **High:** This sub-subsystem does not play a role in withstanding extreme loads and responses. **Med:** This sub-subsystem may play a role, however it has been shown that if this role fails the WEC's structural integrity is not at an elevated risk. **Low:** This sub-subsystem is integral to the survival strategy and must be fully operational to withstand extreme loads and responses (e.g. the PTO is needed to avoid hitting end-stops and too hard of an impact can result in a catastrophic failure in which the structural integrity of the WEC is at risk).
TRL3-4
• Identify how susceptible subsystems in the farm are to increasingly energetic conditions by identifying how the subsystems of the farm react (in terms of motions and loads) to highly energetic environments (i.e. large return period environments). **High:** Subsystems with surface expression that are subject to the large energy in the forcing environment are designed to decouple (i.e. load shedding, submergence, etc.) OR no subsystems have surface expression **Med:** Subsystems possess only minimal surface expression OR possess a limited scope decoupling mechanism **Low:** Subsystems with surface expression are subject to the large energy in the forcing environment because they have no special coping mechanisms

- For the structure that collects wave power, identify the catastrophic load (the magnitude of the load (stress, force, moment) that causes a failure in the structure for which the consequence class is 5). The Catastrophic Factor is (Catastrophic Load / Characteristic load).

  High: Catastrophic Factor > 5
  Med: 2< Catastrophic Factor < 5
  Low: Catastrophic Factor <2

- Considering the structure that collects wave power what safety class will it be designed to and what is the return period of the sea state that produces the characteristic load?

  High: high safety class $<10^{-5}$ per annum resulting in a larger factory of safety being applied to the structural design & return period $\geq$ 60 years
  Med: medium safety class $<10^{-4}$ per annum & 40 < return period < 60 years
  Low: low safety class $<10^{-3}$ per annum resulting in the smallest factory of safety being applied to the structural design & return period < 40 years

- For the sub-subsystem that converts absorbed power into useable power, identify the catastrophic load (the magnitude of the load (stress, force, moment) that causes a failure in the sub-subsystem for which the consequence class is 5). The Catastrophic Factor is (Catastrophic Load / Characteristic load).

  High: Catastrophic Factor > 5
  Med: 2< Catastrophic Factor < 5
  Low: Catastrophic Factor <2

- Considering the sub-subsystem that converts absorbed power into useable power what safety class will be designed to and what is the return period of the sea state that produces the characteristic load?

  High: high safety class $<10^{-5}$ per annum resulting in a larger factory of safety being applied to the structural design & return period $\geq$ 60 years
  Med: medium safety class $<10^{-4}$ per annum & 40 < return period < 60 years
  Low: low safety class $<10^{-3}$ per annum resulting in the smallest factory of safety being applied to the structural design & return period < 40 years

- For the sub-subsystem that controls position, identify the catastrophic load (the magnitude of the load (stress, force, moment) that causes a failure in the sub-subsystem for which the consequence class is 5). The Catastrophic Factor is (Catastrophic Load / Characteristic load).

  High: Catastrophic Factor > 5

Med: 2< Catastrophic Factor < 5
Low: Catastrophic Factor <2

- Considering the sub-subsystem that controls position what safety class will be designed to and what is the return period of the sea state that produces the characteristic load?
  High: high safety class <10^{-5} per annum resulting in a larger factory of safety being applied to the structural design & return period ≥ 60 years
  Med: medium safety class <10^{-4} per annum & 40 < return period < 60 years
  Low: low safety class <10^{-3} per annum resulting in the smallest factory of safety being applied to the structural design & return period < 40 years

- Could failures of some sub-subsystems lead to failures of other sub-subsystems or subsystems (cascade failure)?
  High: No
  Med: Yes but limited cascade failure not leading to catastrophic failure (less than asset consequence class 4)
  Low: Yes with possibility to lead to failure higher than asset consequence class 4

- What is the number of sub-subsystems where loads are directly related to full distribution of incident energy vs. the number where loads are related to a truncated distribution i.e. are protected from the extreme tails of the distribution (e.g. force is clipped to a known max value due to action of hydraulic relief valve)? Note: Consider all point loads, bearings, PTO, moorings, end stops, etc.
  High: All point loads (PTO, bearing, end-stop, mooring attachment, etc.) have predefined maximum loads and are protected by relief mechanisms so these maximum are never exceeded.
  Med: One or more point loads are not protected from extremes but are designed with appropriate design factors.
  Low: One or more point loads are not protected from extremes and cannot achieve appropriate design factors.

TRL5-6

- What is the financial risk for the farm if weather or operational conditions lead to loads and/or responses that result in asset consequence class 5 events?
  High: capital assets loss <10% AND AEP loss < 10%
  Med: capital assets loss <20% AND AEP loss > 10%
  Low: capital assets loss >50% OR AEP loss > 20%

- Considering the structure that collects wave power what are the following: the catastrophic factor and the smallest return period of the sea-state(s) that corresponds to the production of the catastrophic structural load? The Catastrophic Factor is (Catastrophic Load / Characteristic load). The catastrophic load identifies the magnitude of the stress / force / moment that causes a failure in the structure for which the consequence class is 5.

  High: Catastrophic Factor > 5 & (catastrophic return period / characteristic return period) ≥ 10
  Med: 2< Catastrophic Factor < 5 & 2< (catastrophic return period / characteristic return period) < 10
  Low: Catastrophic Factor <2 & (catastrophic return period / characteristic return period) < 2

- Considering the structure that collects wave power what safety class will it be designed to and what is the return period of the sea state that produces the characteristic load?

  High: high safety class $<10^{-5}$ per annum & return period ≥ 60 years
  Med: medium safety class $<10^{-4}$ per annum & 40 < return period < 60 years
  Low: low safety class $<10^{-3}$ per annum & return period < 40 years

- Considering the sub-subsystem that converts absorbed power into useable power what are the following: the catastrophic factor and the smallest return period of the sea-state(s) that corresponds to the production of the catastrophic structural load? Catastrophic Factor is (Catastrophic Load / Characteristic load). The catastrophic load identifies the magnitude of the stress / force / moment that causes a failure in the sub-subsystem for which the consequence class is 5.

  High: Catastrophic Factor > 5 & (catastrophic return period / characteristic return period) ≥ 10
  Med: 2< Catastrophic Factor < 5 & 2< (catastrophic return period / characteristic return period) < 10
  Low: Catastrophic Factor <2 & (catastrophic return period / characteristic return period) < 2

- Considering the sub-subsystem that converts absorbed power into useable power what safety class will be designed to and what is the return period of the sea state that produces the characteristic load?

  High: high safety class $<10^{-5}$ per annum & return period ≥ 60 years

Med: medium safety class $<10^{-4}$ per annum & 40 < return period < 60 years
Low: low safety class $<10^{-3}$ per annum & return period < 40 years

- Considering the sub-subsystem that controls position what are the following: the catastrophic factor and the smallest return period of the sea-state(s) that corresponds to the production of the catastrophic load? Catastrophic Factor is (Catastrophic Load / Characteristic load). The catastrophic load identifies the magnitude of the stress / force / moment that causes a failure in the sub-subsystem for which the consequence class is 5.
  High: Catastrophic Factor > 5 & (catastrophic return period / characteristic return period) ≥ 10
  Med: 2< Catastrophic Factor < 5 & 2< (catastrophic return period / characteristic return period) < 10
  Low: Catastrophic Factor <2 & (catastrophic return period / characteristic return period) < 2

- Considering the sub-subsystem that controls position what safety class will be designed to and what is the return period of the sea state that produces the characteristic load?
  High: high safety class $<10^{-5}$ per annum & return period ≥ 60 years
  Med: medium safety class $<10^{-4}$ per annum & 40 < return period < 60 years
  Low: low safety class $<10^{-3}$ per annum & return period < 40 years

- How have the characteristic loads been validated (experimentally) or otherwise verified as applicable?
  High: Statistically significant and broad experimental validation according to international standards. Nonlinear numerical modelling capable of resolving high nonlinearities (impact events).
  Med: Experimental validation, however not statistically significant or ignoring major contributing factors (wind, current, etc.). Nonlinear numerical modelling incapable of high nonlinearities (impact events).
  Low: No experimental validation. Linear numerical modelling.

C.2.2.2. Be able to cope with grid failures, grid loss, or grid interruption

The grid is an external system to the WEC farm. Grid failure is a critical ultimate limit state. As such, the WEC farm design shall be able to cope with it. However, characteristics of grid failure (particularly downtime) may exceed the specifications in the corresponding ultimate limit state. Often loss of the grid is highly correlated with extreme weather events and for that reason WEC ultimate limit states may need to be considered simultaneously with loss of grid events. Technical consequences of such events shall be harmless for the WEC farm and the financial consequences should be minimal.

TRL1-2
• At farm level, how many subsystems may be significantly damaged by grid failure, grid loss or grid interruption? **High:** None **Med:** Few (less than 2) not leading to catastrophic failure **Low:** Several (2 or more) or any number that leads to catastrophic failure • For the systems that collect wave power, how many sub-subsystems may be significantly damaged by grid failure or grid interruption? (Note: Mechanisms for addressing grid failure within this subsystem (how power absorption is stopped, how excess power is dumped, how overheating and/or freewheeling is avoided) should be considered when scoring this question.) **High:** None **Med:** Few (less than 2) not leading to consequence class greater than 3 (system) **Low:** Several (2 or more) or any number that leads to catastrophic failure • For the subsystems that aggregate the collected power, are they able to reroute power from one source to other sources? **High:** Yes (e.g. one subsystem can power instrumentation & auxiliaries on other subsystems) **Med:** Yes, but limited in some way **Low:** No
TRL3-4
Update the answers to TRL1-2 plus answer the following questions: • For each identified damage to each subsystem due to grid failure, loss or interruption, what are the probability class and consequence class with respect to loss of production, repair costs or loss of assets? (See "Probability Class" & "Consequence Class" in glossary)

High: Probability Class 1 or 2 and most damages limited to Consequence Class 2 and few Consequence Class 3
Med: Probability Class 2 or 3 and most damages limited to Consequence Class 3 and few Consequence Class 4
Low: Probability Class 3 or 4 and most damages above Consequence Class 4

- For each identified damage to each sub-subsystem or component in the wave power collecting subsystems due to grid failure, loss or interruption, what are the probability class and consequence class with respect to loss of production, repair costs or loss of assets? (See "Probability Class" & "Consequence Class" in glossary)
  High: Probability Class 1 or 2 and most damages limited to Consequence Class 2 and few Consequence Class 3
  Med: Probability Class 2 or 3 and most damages limited to Consequence Class 3 and few Consequence Class 4
  Low: Probability Class 3 or 4 and most damages above Consequence Class 4

- How many subsystems within the farm that require internal power consumption (i.e. hotel load) are internally powered?
  High: Majority of subsystems with internal power consumption can be internally powered for > 3 hours
  Med: Majority of subsystems with internal power consumption can be internally powered for < 3 hours
  Low: No internal power

- Does the WEC farm provide un-interruptible power source (UPS) for control and communications to continue operating successfully with unbalanced or distorted grid voltages during faults?
  High: Yes fully (at least 3 hours)
  Med: Yes partly
  Low: No

- How long does it take to get back into power generation mode once grid is re-established? (assuming grid failure of less than two days)
  High: Less than 20 minutes
  Med: Less than one hour
  Low: More than one hour

TRL5-6

- What is the financial risk for the farm of grid failures, grid losses or grid interruption?
  High: capital assets loss <10% AND AEP loss < 10%
  Med: capital assets loss <20% AND AEP loss > 10%
  Low: capital assets loss >50% OR AEP loss > 20%

C.2.2.3. Be able to avoid and survive collisions

Other marine users, ships, and marine mammals are external systems to the WEC farm. They may collide with one or several subsystems of the farm, resulting in an accidental limit state. It may result in cascade failures. Technical and financial consequences of such events should be low.

TRL1-2

- Can the WEC farm subsystems be easily detected by other users of the area? (Note: Mechanisms for used for signalling to other users of the area as well as the location of the subsystems within the water column should be considered when scoring this question.)
  High: Majority of subsystems are either on the ocean floor or they are visible to the eye (both day and night via the use of signalling lights) or radar.
  Med: Subsystem not on ocean floor are not visible by eye (day or night), they are only visible by radar.
  Low: Majority of subsystems are not visible by eye (day or night) and are not located on the ocean floor.

- Are there many other human activities in the target deployment location?
  High: No
  Med: Limited (Seasonal)
  Low: Yes (year-round)

- How many WEC farm subsystems may be significantly damaged by collision with a ship?
  High: None or 1
  Med: between 1 and 3
  Low: 3 or more

- Are there many marine mammals in the target deployment location?
  High: No
  Med: Limited (Seasonal)
  Low: Yes (year-round)

- The sub-subsystem that controls position can affect both the probability of and the consequence of collisions. Please answer the following questions:
  a. What role does the sub-subsystem that controls position play in the probability of a collision?
     High: tight/small watch circles with sufficient spacing between elements of the farm
     Med: large watch circles

Low: compact spacing between elements of the farm

b. What role does the sub-subsystem that controls position play in the consequence of a collision?
High: compliant control position designs allow for the elements of the farm to move during a collision
Med: a stiff but compliant control position design
Low: rigid control position designs resulting in a direct transference of impact forces to the elements of the farm

TRL3-4

Update the answers to TRL1-2 plus answer the following questions:

- Does the array layout allow for other users of the area to easily maneuver?
  High: Vessel sizes of other users are of the same size as installation and maintenance vessels, and these vessels have no bearing on installation windows or permit windows that govern access to the farm OR there is an exclusion zone in which other vessels will not be allowed access.
  Med: Vessel sizes of other users are larger than the installation and maintenance vessels, however passages of appropriate size are planned to allow other users to safely pass through.
  Low: Vessel sizes of other users are larger than the installation and maintenance vessels, and no special passages have been designed for these other users.

- For each identified damage resulting from a collision with a ship, what is the probability class and consequence class with respect to loss of production, repair costs or loss of assets? (See "Probability Class" & "Consequence Class" in glossary)
  High: Probability Class 1 or 2 and most damages limited to Consequence Class 3 and few Consequence Class 4
  Med: Probability Class 2 or 3 and most damages limited to Consequence Class 4 and few Consequence Class 5
  Low: Probability Class 3 or 4 and most damages at Consequence Class 5

- How many WEC farm sub-systems may be significantly damaged by collision with a marine mammal?
  High: None
  Med: 1 or 2
  Low: 3 or more

- For each identified damage with a marine mammal, what is the probability class and consequence class with respect to loss of

production, repair costs or loss of assets? (See “Probability Class” & “Consequence Class” in glossary) **High:** Probability Class 1 or 2 and most damages limited to Consequence Class 3 and few Consequence Class 4 **Med:** Probability Class 2 or 3 and most damages limited to Consequence Class 4 and few Consequence Class 5 **Low:** Probability Class 3 or 4 and most damages at Consequence Class 5 • What are the measures in the design to prevent / mitigate collisions? *Note: Consider ships colliding with system in normal state e.g. at the farm location, subsystem in failed state colliding with ships e.g. outside the farm location. Ships colliding with each other, e.g. during installations or O&M, should also be considered.* **High**: Marking according to rules (E.g. navigational aids, lights, radar beacons etc.) OR active avoidance mechanisms **Med:** Some measures taken but the farm has systems that in some cases can be difficult to recognize e.g. part of the system is invisible just under surface. **Low**: No measures taken or inadequate combination of visibility, radar signature, marking, lighting.
TRL5-6
• What is the financial risk for the farm of collision with ships, other users of the marine space and marine mammals? Note: in scoring this question consider possible collision scenarios, probabilities of collisions, induced damages, costs of repair, loss of assets, loss of production. **High:** largest capital assets loss <10% AND largest AEP loss < 10% **Med:** largest capital assets loss <20% AND largest AEP loss > 10% **Low:** largest capital assets loss >50% OR largest AEP loss > 20%

C.2.2.4. *Be survivable in temporary conditions including installation (tow-out, if applicable) and maintenance*

Because of the stochastic nature of the marine environment, weather or operational conditions may lead to extreme loads and responses that exceed serviceability limit states during temporary conditions. The probabilities of such events and their financial consequences should be understood.

TRL1-2
• What typical distance must the installation and maintenance vessel(s) travel? At TRL1-2 simply identifying the general range (on-shore, near-shore, off-shore) is sufficient. **High:** on-shore: implies short distance **Med:** near shore: implies an intermediate distance **Low:** off-shore: implies a long distance • How different is the system orientation in temporary conditions vs in operations? **High:** same orientation **Med:** different orientation, but safely and easily re-oriented **Low:** different orientation that requires complex operation to be re-oriented
TRL3-4
• Are the weather window criteria primarily determined by the capabilities of the vessels or the dynamics of the device? **High:** The device dynamic response does not affect the accessibility of the device (e.g. weather windows determined by vessel response/capabilities and not device response) **Med:** The dynamics of the system sometimes affect the accessibility of the device (e.g. weather windows determined by both vessel response and also device response) **Low:** The dynamics of the system strongly affect the accessibility of the device (e.g. weather windows determined predominantly by device response and not vessel response) • What are the expected dynamics of the subsystems during connection procedures? **High:** The systems to be connected will be calm b/c they can be isolated such that they are not subject to hydrodynamic forcing **Med:** Most of the systems to be connected will be calm. If the subsystem that captures power is dynamically moving will automatically move to medium even if the rest are stabilized. **Low:** Most of the systems to be connected will be subject to hydrodynamic forcing b/c they are floating • How long does it take to install each subsystem?

High: Sum of all assembly steps is $\leq$ 20 hours
Med: between high and low
Low: Sum of all assembly steps is $\geq$ 80 hours

- How long is a typical maintenance intervention for the subsystem?
  High: A round trip including necessary work can be made in one "shift", (e.g. less than 8-12 hours).
  Med: A round trip including necessary work can be made in an extended "shift" (e.g. less than 16-24 hours).
  Low: A round trip takes such time that overnight accommodation is needed for workers on board maintenance vessel(s).

- How different is the subsystems orientation in temporary conditions vs in operations?
  High: same orientation
  Med: different orientation, but safely and easily re-oriented
  Low: different orientation, but require complex operation to be re-oriented

- Can operations carried out in temporary conditions be easily interrupted?
  High: Installation tasks can be stopped at any time safely, and continued later on.
  Med: Any task that is not complete that must be stopped can be reverted to a safe state in a timely and safe manner until the task can be resumed.
  Low: Any task that is not complete that must be stopped cannot be reverted to a safe state. Ex. Installation window is exceeded, requiring finishing the work in increasing unsafe conditions.

- If applicable, when sub-systems are disconnected in water (at sea or in sheltered water) e.g. joining/un-joining hinged barge, what are the stability characteristics of the disconnected systems?
  High: Disconnected subsystems have similar stability to connected subsystems. Weather window criteria for operations on disconnected subsystem is the same as for the connected subsystem.
  Med: Disconnected subsystems have reduced stability compared to connected subsystems. Weather window criteria for operations on disconnected subsystem is higher than for the connected subsystem.
  Low: Disconnected subsystems have significantly reduced stability compared to connected subsystems. Systems can only be disconnected in sheltered calm water

- What possible accidental states during maintenance activities have been identified? What measures are in the design to prevent / mitigate the increased probability of injury during accidental states? Note: injury to 3rd parties should be considered as well as injury to personnel.

High: Accidental states have been identified and risk mitigated by implementing redundant measures

Med: Accidental states have been identified and no measures have been implementing to mitigate the risk of personnel accidents

Low: Accidental states have not been identified

- What possible temporary states during maintenance, installation, etc. have been identified? What are the measures in the design to prevent / mitigate the increased probability of injury during temporary states? Note: injury to 3rd parties should be considered as well as injury to personnel.

  High: Temporary states have been identified and measures described to prevent mitigate risk of injury to personnel

  Med: Temporary states have been identified and no measures described to prevent mitigate risk of injury to personnel

  Low: Temporary states have not been identified

TRL5-6

- What is the financial risk for the farm if weather or operational conditions lead to loads and/or responses exceeding SLS during temporary conditions? Note: in scoring this question consider increasing environmental conditions, list damages, cost of repair, loss of assets, loss of production or delay in first power.

  High: largest capital assets loss <10% AND largest AEP loss < 10%

  Med: largest capital assets loss <20% AND largest AEP loss > 10%

  Low: largest capital assets loss >50% OR largest AEP loss > 20%

- How long does it take to tow-out the subsystems to installation site?

  High: less than 6 hours towing at the lower of the maximum safe speed and the economic optimum speed.

  Med: between 6 and 12 hours towing at the lower of the maximum safe speed and the economic optimum speed.

  Low: more than 12 hours towing at the lower of the maximum safe speed and the economic optimum speed.

- How have the characteristic loads been validated (experimentally) or otherwise verified as applicable?

  High: Statistically significant and broad experimental validation considering relevant orientation of subsystems and accelerations. Nonlinear numerical modelling capable of resolving high nonlinearities (impact events).

Med: Experimental validation, however not statistically significant or ignoring major contributing factors (orientation, wind, current, etc.). Nonlinear numerical modelling incapable of high nonlinearities (impact events).
Low: No experimental validation. Linear numerical modelling.

C.2.2.5. Have robust fatigue characteristics

Because of the stochastic nature of the marine environment, loads and responses may exceed fatigue limit states. The probabilities of such events and their financial consequences should be understood.

TRL1-2
• What is the technology class for each subsystem in the WEC Farm? **High:** All or predominantly Class 1. **Med:** Predominately Class 1 and 2 with no or few Class 3. **Low:** Any significant number of Class 3 or 4. • Is fatigue expected to be one of the top 3 failure routes for subsystems in the WEC Farm? **High:** Only one subsystem. **Med:** 2 to 3 subsystems. **Low:** More than 3 subsystems.
TRL3-4
• What types of condition based maintenance strategies will be used to ensure maintenance is completed at the correct time? **High**: Automated process both monitoring and processing information for preventative maintenance. Few or no personnel required. **Med:** Automated monitoring process that involves a number of personnel (or full time employed personnel?) to analyze data received. **Low:** No plans to implement condition based maintenance. • For power producing forces (i.e. forces translated to the structure due to power production, like at the PTO attachments) what are the magnitudes of the point loads identified previously in TRL1-2? What modeling technique was used to identify these magnitudes? (Use highest values where multiple power producing point loads exist) **High:** Non-linear dynamic modeling applied and the ratio of the average annual P95 point loads to the average annual P50 power producing force is < 6 in a typical deployment climate **Med:** Linear dynamic modeling applied and the ratio of the average annual P95 point loads to the average annual RMS power producing force is < 10 in a typical deployment climate **Low:** Static modeling only and the ratio of the average annual P95 point loads to the average annual RMS power producing force is > 12 in a typical deployment climate • Considering the structure that collects wave power identify how many cycles the structure must be designed to for the top five most highly flexed areas.

High: flexion cycles < (number of waves in a year * lifetime of structure) **Med:** flexion cycles ≈ (number of waves in a year * lifetime of structure) **Low:** flexion cycles > (number of waves in a year * lifetime of structure) • Considering the sub-subsystem that converts absorbed power into useable power identify how many cycles the sub-subsystem must be designed to for the top five most highly flexed areas. **High:** flexion cycles < (number of waves in a year * lifetime of structure) **Med:** flexion cycles ≈ (number of waves in a year * lifetime of structure) **Low:** flexion cycles > (number of waves in a year * lifetime of structure) • Considering the structure that sub-subsystem that controls position identify how many cycles the sub-subsystem must be designed to for the top three most highly flexed areas. **High:** flexion cycles < (number of waves in a year * lifetime of structure) **Med:** flexion cycles ≈ (number of waves in a year * lifetime of structure) **Low:** flexion cycles > (number of waves in a year * lifetime of structure)
TRL5-6
• What is the financial risk for the farm if weather or operational conditions lead to loads and/or responses exceeding FLS? **High:** largest capital assets loss <10% AND largest AEP loss < 10% **Med:** largest capital assets loss <20% AND largest AEP loss > 10% **Low:** largest capital assets loss >50% OR largest AEP loss > 20% • What are the fatigue lives for the highest consequence elements of the farm? **High:** Majority of fatigue lives are greater than 1.5 the lifetime of the farm. **Med:** Several of fatigue lives are equivalent to the lifetime of the farm. **Low:** Majority of fatigue lives are less than the lifetime of the farm OR fatigue lives have not yet been fully considered.

- What types of condition based maintenance strategies will be used to ensure maintenance is completed at the correct time?

  High: Automated process both monitoring and processing information for preventative maintenance. Few or no personnel required.

  Med: Automated monitoring process that involves a number of personnel (or full time employed personnel?) to analyze data received.

  Low: No plans to implement condition based maintenance.

- How have the characteristic loads been validated (experimentally) or otherwise verified as applicable?

  High: Statistically significant and broad experimental validation. Nonlinear numerical modelling capable of resolving predominate nonlinearities and high nonlinearities (impact events).

  Med: Experimental validation, however not statistically significant or ignoring major contributing factors (wind, current, etc.). Nonlinear numerical modelling incapable of high nonlinearities (impact events).

  Low: No experimental validation. Linear numerical modelling.

C.3. *Be reliable for grid operations*

Reliability for grid operations covers several aspects. **Energy production** from the WEC farm **shall be forecastable to enter the day-ahead wholesale electricity market**. Moreover, the increase of the share of **intermittent renewable energy sources** in the energy mix **is challenging for grid operators** with respect to grid stability and load balancing. This could limit the development of the wave energy industry. Thus, the WEC farm should have a **high-capacity factor** and produce electricity during periods of higher electricity demand. Moreover, a WEC farm may provide useful **ancillary services to the grid**. These include energy storage, automatic generation control, and voltage and frequency control.

C.3.1. Be forecastable

The **electricity market requires prediction of energy production in advance** to enable optimal dispatch within electricity markets and to contribute to power system operations such as maintaining equilibrium with generation and load; thus, the energy production from the WEC farm should be forecastable. Typical prediction horizons are in the range of 20 minutes to season-ahead. Further, a farm with a **high-capacity factor**, defined as the ratio of the farm output over a year to its potential output if it were operating continuously at full nameplate capacity, characterizes low long-term variability thus contributing to forecastability. Long term forecastability assists the grid operator in **planning future energy capacities** and reserves.

TRL1-2
• What is the target capacity factor? **High:** Target capacity factor is greater than 40% **Med:** Target capacity factor is between 20 and 40% **Low:** Target capacity factor is smaller than 20%
TRL3-4
• How robust is energy production to errors in the wave resource (sea conditions) prediction? **High:** Elements of the power directional matrix of the WEC farm show less variation between sea conditions then the incident wave power flux shows. Hence, errors in energy production estimates will be significantly less than errors in sea condition estimates. **Med:** Elements of the power directional matrix of the WEC farm show the same variation between sea conditions as the incident wave power flux shows. Hence, errors in energy production estimates will be on the order of errors in sea condition estimates. **Low:** Elements of the directional power matrix of the WEC farm shows large variability (~30% or more) to either mean

directional estimates or spectral profiles and given the difficulties in estimating these well with forecasting techniques do not result in robust estimates.

- Does the WEC farm have particular features that make it less likely to be forecastable than a WEC farm with other technologies in the subhourly, hourly, and 24-hour time frames?
  High: The WEC farm power production accurately predicted from statistical description of the resource.
  Med: The WEC farm power production shows some sensitivity to 1-hour to daily forecasts of the resource.
  Low: The WEC farm power production sensitive both short term and long-term energy forecasts (i.e. time resolved) resulting in large forecast errors in the 20min to day-ahead time periods.

- What is the net capacity factor of the WEC farm? Use: **a.** the annual average for the power production at point of connection to the grid according to C1.3, **b**. the WEC farm rated power at point of connection to the grid, and **c.** the availability according to C1.4
  High: Using information requested above (points a. – c.), the capacity factor is calculated via ((a.*c.)/b.)*100 and is > 40%
  Med: Using information requested above (points a. – c.), the capacity factor is calculated via ((a.*c.)/b.)*100 and is between 20% and 40%
  Low: Using information requested above (points a. – c.), the capacity factor is calculated via ((a.*c.)/b.)*100 and is < 20%

TRL5-6

Update the answers to TRL3-4 plus answer the following question:

- What is the inter-annual variability in net capacity factor for the WEC farm?
  High: Net capacity factor varies less than 15%
  Med: Net capacity factor varies on the order of 30%
  Low: Net capacity factor varies on the order of 50%

C.3.2. Have high correlation of power production to demand

As the mix of generation capabilities for the grid continues to diversify, **ensuring that energy generation from intermittent renewables is matched to periods of demand by the public** becomes more important. The WEC farm should be able to produce power during periods of high demand in order to reduce the need for traditional generation capabilities. If the WEC farm only produces power during periods of low demand, it may require the grid to upgrade storage capabilities or may make the integration of this generation source difficult.

TRL1-2
No applicable data expected at TRL1-2.
TRL3-4
No applicable data expected at TRL3-4.
TRL5-6
• For the given deployment location please answer the following questions: a. Statistically, is there a diurnal cycle to power production? **High:** Higher power production by the farm is correlated with the time of day when there is higher demand (i.e. power production is largest during the grids morning ramp up). **Med:** There is little daily dependence on power production. **Low:** The daily dependence is inverted between production and demand (i.e. peak power production during the night when demand is largest during the day). b. Statistically, is there a seasonal cycle to power production? **High:** Higher power production by the farm is correlated with the seasons when there is higher demand (i.e. winter on the Northwest coast of USA). **Med:** There is little seasonal dependence on power production. **Low:** The seasonal dependence is inverted between production and demand (i.e. peak power production in the summer when demand is largest in the winter).

C.3.3. Be useful to the grid

The integration of **intermittent renewable energy sources is challenging for grid operators** with respect to grid stability and load balancing. However, WEC farms may **provide useful ancillary services** to the grid. These include energy, automatic generation control, voltage and frequency control, and operational reserves. An energy storage capability by the WEC farm facilitates these services.

TRL1-2
No applicable data expected at TRL1-2.
TRL3-4
• Is the WEC able to participate in short-term grid services such as AGC **High:** Yes **Med:** N/A **Low:** No • Can the WEC provide voltage and frequency support to the grid? **High:** WEC farm capable of voltage and frequency support **Med:** WEC farm capable of some voltage and frequency support **Low:** WEC farm incapable of providing voltage and frequency support • How much and for how long can the WEC farm act as an energy storage system for the grid? **High:** WEC farm capable of storing rated power for 15 min **Med:** WEC farm capable of storing rated power for 5 min **Low:** WEC farm incapable of storing power • Is the farm capable of a blackstart? **High:** Yes **Med:** N/A **Low:** No • Can the output power be capped for curtailment purposes? **High:** Yes fully **Med:** Yes partly **Low:** No
TRL5-6
Update the answers to TRL3-4 plus answer the following questions: • Does the WEC farm include SCADA (Supervisory control and data acquisition) based communications with multi-unit control including •

Control of *real power limit* (curtailment) • Controlled *ramp rate for real power limit* • Control of *reactive power output OR power factor?*

High: Yes fully
Med: Yes partly
Low: No

- If the WEC farm uses inverters does it provide the ability to command inverter aggregate power factor control (accounting for site transformers) and automatic voltage control?

  High: Yes fully
  Med: Yes partly
  Low: No

- What is the characteristic response time of the energy storage?

  High: Response times are very short, on the order of a millisecond.
  Med: Response times are on the order of 10's of seconds.
  Low: Response times are longer than 1 minutes.

C.3.4. Be grid compliant

The WEC farm shall deliver electrical power that **meets grid operator requirements for power quality**, including voltage, frequency, and flicker.

TRL1-2

No applicable data expected at TRL1-2.

TRL3-4

- Weak grids, which have unstable voltage and/or frequency, are sometimes present in coastal areas. Is the farm suitable for connection to weak grids?
  - **High**: The choice of equipment is such that weak grids are strengthened by connection of the farm and power export will pose no problems
  - **Med:** The choice of equipment is such that the farm can connect and export to weak grids
  - **Low**: The choice of equipment is such that the farm will not be able to export power or will make weak grids less stable

- For the Wave farm determine the average annual peak to average electrical power production and the standard deviation of this value by populating a scatter diagram of the ratio. What is the standard deviation and the average annual value?
  - **High:** A small average annual ratio indicates that the power from the WEC Farm will be relatively stable and thus have little impact on power quality of the grid. A small standard deviation, <50% of the average annual value, indicating homogeneous production in power over the year.
  - **Med:** A ratio value in between High and Low.
  - **Low:** A large ratio indicates that the power quality of the grid will be susceptible to large swings in WEC Farm production. If additional there is a large standard deviation, >150%, then very heterogeneous production is occurring which will be difficult for the grid.

TRL5-6

- What is the size, MW rating, of the grid that the WEC farm will be connected to?
  - **High**: The rating of the grid is several times stronger than the rated power of the farm
  - **Med:** The rating of the grid is similar to the rated power of the farm but the farm has a small average annual ratio of peak to average electrical power production
  - **Low**: The rating of the grid is smaller than the rated power of the farm OR the farm has a large average annual ratio of peak to average electrical power production.

Answer the following questions regarding the WEC farm that would be connected to a standard US power system grid assuming NERC and FERC compliance:

- If the farm uses non-synchronous generators can it comply with the requirement to provide reactive power at the high-side of the generator substation as a condition of interconnection?
  High: The farm can comply.
  Med: The farm might require a derogation.
  Low: The farm cannot comply.

- NERC and FERC requirements for interconnection include that the sustained reactive power capability shall meet or exceed +0.9 (producing) to - 0.95 (absorbing) power factor based on the aggregated plant MW level . Can the wave farm comply?
  High: The farm can comply.
  Med: The farm might require a derogation.
  Low: The farm cannot comply.

- Can the WEC farm meet all other NERC and FERC requirements for interconnection?
  High: The farm can comply.
  Med: The farm might require a derogation.
  Low: The farm cannot comply.

- Does the WEC farm comply with flicker requirements?
  High: Flicker has been addressed and complies with requirements.
  Med: Flicker has been addressed but a derogation is required
  Low: Flicker bas not been addressed OR cannot comply with requirements

- Does the farm have ride through capability for specified grid disturbances.
  High: The farm can comply.
  Med: The farm might require a derogation.
  Low: The farm cannot comply.

- Does the farm have enhanced dynamic control to continue operating successfully with unbalanced or distorted grid voltages during faults
  High: The farm can comply.
  Med: The farm might require a derogation.
  Low: The farm cannot comply.

C.4. Benefit society

A **WEC farm needs** to obtain **buy-in and support** from the local communities and the general public. Like any industrial project, a **WEC farm** is likely to **cause some negative impacts** (higher cost of energy, disruption to other activities) that **shall be** largely **overcome by benefits for society** (low-carbon-emission energy source, local job creation, or coastal protection). Otherwise, public concerns and actions against the project can seriously delay the project or cause it to fail (even if permits are granted).

C.4.1. Be beneficial to local communities

The WEC farm shall be beneficial to local communities to obtain buy-in and support from them. Local benefits may include **local job creation, increase of local gross domestic product, protection from coastal erosion, increases in the local tax base, or improvement of infrastructure**. Local benefits shall largely overcome possible negative impacts (e.g. visual obstruction in the seascape).

TRL1-2
• How many jobs will the farm contribute to the local community in units of FTE/GW (the full time equivalent jobs per GW installed capacity)? **High:** The farm will generate long-term jobs (more than 50 FTE/GW) lasting the lifetime of the farm in the local community **Med:** The farm will generate some jobs (between 10 and 50 FTE/GW) in the local community but they will not exist over the lifetime of the farm **Low:** Development of the farm will generate few jobs (< 10 FTE/GW) in the local community but they will not exist over the lifetime of the farm
TRL3-4
Update the answers to TRL1-2 plus answer the following questions: • Will components of the farm be manufactured near the deployment location? **High:** Majority of subsystems / components **Med:** ~Half of subsystems / components **Low:** Minority of subsystems / components • Will installation and maintenance activities employ local ship owners? **High:** Majority of activities **Med:** ~Half of activities **Low:** Minority of activities • What other local jobs will result due to the farms development?

High: Other jobs (tourism, marketing, hotels, etc.) that will last the lifetime of the farm **Med:** Other jobs (tourism, marketing, hotels, etc.) that will only occur during the construction of the farm **Low:** No other jobs • Will local infrastructure be improved by the development of the farm; e.g., infrastructural upgrade of roads, harbors, communications, grid, etc.? **High:** Most likely yes **Med:** All will remain the same **Low:** Overuse of local infrastructure by the development of the farm • What ancillary benefits for the local community will the farm perform (such as coastal erosion protection, tourist draw, fish nursery, etc.)? **High:** The farm will offer more than one ancillary benefit for the local community **Med:** The farm will offer only one ancillary benefit for the local community **Low:** the project does not provide any ancillary benefit for the local community
TRL5-6
• What number of local jobs, in FTE/GW, will be created in the following areas as a result of the farm's deployment in an area: • Construction (manufacturing and assembly of portions of the farm)? **High:** jobs ≥ 150 FTE/GW **Med:** 30 < jobs < 150 FTE/GW **Low:** jobs ≤ 30 FTE/GW • Installation and maintenance? **High:** jobs ≥ 30 FTE/GW **Med:** 10 < jobs < 40 FTE/GW **Low:** jobs ≤ 10 FTE/GW • Control center operation? **High:** jobs ≥ 10 FTE/GW **Med:** 2 < jobs < 10 FTE/GW **Low:** jobs ≤ 2 FTE/GW • Outreach and marketing? **High:** jobs ≥ 5 FTE/GW **Med:** 1 < jobs < 5 FTE/GW **Low:** jobs ≤ 1 FTE/GW

- Legal?
  High: jobs ≥ 5 FTE/GW
  Med: 1 < jobs < 5 FTE/GW
  Low: jobs ≤ 1 FTE/GW

- What is the estimated tax revenue for the local community that this farm will produce?
  High: The farm will generate substantial tax revenue (~$500k/GW) for the local community
  Med: The farm will generate some tax revenue (~$50k/GW) for the local community
  Low: The project does not generate tax revenue for the local community

- What is the cost-savings or revenue generation that results from the identified ancillary benefits?
  High: The cost-savings or revenue generation offset more than ~$1M/GW
  Med: The cost-savings or revenue generation offset somewhere between $100k to $1M/GW
  Low: The cost-savings or revenue generation offset up to $100k/GW

C.4.2. Be a low greenhouse gas (GHG) emission energy source

The WEC farm needs to be a **low-greenhouse-gas-emission energy source** over the entire lifecycle. A measure of lifecycle greenhouse-gas emissions is the global warming potential per unit of electrical energy generated. The **global warming potential** is the ability of a greenhouse **gas to trap heat in the atmosphere relative to an equal amount of carbon dioxide**, and is dependent upon a full lifecycle assessment.

TRL1-2

- For each lifecycle stage, when will GHGs beyond those resulting from typical office work be released?

  High:

Engineering	Procurement	Construction	Installation	Operations	Disposal
0	0	GHG	GHG	GHG	0

  Med:

Engineering	Procurement	Construction	Installation	Operations	Disposal
0	0	GHG	GHG	GHG	GHG

  Low:

Engineering	Procurement	Construction	Installation	Operations	Disposal
GHG	GHG	GHG	GHG	GHG	GHG

TRL3-4

- What system boundaries will be used to determine the global warming potential?

  High: Consider the entirety of the system: mining of raw materials, manufacture, tool fabrication (computers, mills, etc.), installation, operations, maintenance, decommissioning, office space HVAC, etc.

  Med: Consider core areas of manufacturing and operations but neglect one or more of mining of raw materials, decommissioning, office space HVAC etc.

  Low: Neglects one or more of core areas of manufacturing and operations or inadequate documentation of claims for High or Med.

- What are the upstream (raw materials, construction, and installation) GHG emissions in grams of carbon dioxide equivalent per kilowatt hour (gCO_2eq/kWh)?

  High: ~50 gCO_2eq/kWh

  Med: ~110 gCO_2eq/kWh

  Low: ~270 gCO_2eq/kWh

- What are the operations (including maintenance) GHG emissions in grams of carbon dioxide equivalent per kilowatt hour (gCO_2eq/kWh)?

  High: ~80 gCO_2eq/kWh

Med: ~160 gCO_2eq/kWh **Low:** ~400 gCO_2eq/kWh • What are the downstream (decommissioning, disposal, and recycling) GHG emissions in grams of carbon dioxide equivalent per kilowatt hour (gCO_2eq/kWh)? **High:** ~30 gCO_2eq/kWh **Med:** ~50 gCO_2eq/kWh **Low:** ~140 gCO_2eq/kWh
TRL5-6
• What is the life-cycle global warming potential of this farm in grams of carbon dioxide equivalent per kilowatt hour (gCO_2eq/kWh)? [13] **High:** GHG emissions ≤ 150 gCO_2eq/kWh (better than coal / gas with scrubbing technologies) **Med:** 150 gCO_2eq/kW <GHG emissions < 500 gCO_2eq/kWh (less than combined cycle gas turbine (CCGT) plants) **Low:** GHG emissions ~ 800 gCO_2eq/kWh (equivalent to coal)

C.4.3. Be a low polluting energy source

The **WEC farm should not pollute the environment** during construction, operation, or disposal. The use of readily available and environmentally inert materials is desired. The entire lifecycle shall be considered.

TRL1-2

- Are the WEC farm subsystems easily recyclable?
  High: yes
  Med: most of it
  Low: no

- What is the lifetime of the WEC farm?
  High: >30 years
  Med: approximately 20 years
  Low: approximately 10 years or less

TRL3-4

- Do the WEC farm manufacturing process and operation involve significant amount of pollutants (solids, liquids)?
  High: Significantly less than manufacture and operation of a combined cycle gas turbine (CCGT) plants of same capacity
  Med: Comparable to manufacture and operation of a CCGT plant of same capacity
  Low: Significantly more than manufacture and operation of a CCGT plant of same capacity.

- Are the WEC farm subsystems and sub-subsystems easily recyclable?
  High: 80% of the subsystems and sub-subsystems can be recycled
  Med: 50% of the subsystems and sub-subsystems can be recycled
  Low: 20% of the subsystems and sub-subsystems can be recycled

- How many times will the subsystems and sub-subsystems of the WEC farm need to be replaced to achieve the lifetime of the farm?
  High: Major subsystems & sub-subsystems will last for the lifetime of the plant and some require replacement every 10 years
  Med: Most sub-subsystems will be replacement once every 10 years
  Low: Many sub-subsystems will be replaced on a yearly basis, some will be replaced every 5 years

TRL5-6

- What are the pollutants involved in making and operating the WEC farm and in what amounts?

High: Pollutants are known to the industry, can be safely disposed of or have a short lifetime, and are produced in quantities of significantly less magnitude than combined cycle gas turbine (CCGT) plants of same capacity
Med: Pollutants are known to the industry, cannot be safely disposed of or have a long lifetime, and are produced in quantities comparable to CCGT plants of same capacity
Low: Pollutants are not known to the industry, are viewed as highly toxic and difficult to dispose of, or produced in quantities that are of significantly higher magnitude than CCGT plants of same capacity

- What percentage of the sub-subsystems and components of the WEC farm cannot be recycled?
  High: 20% of the sub-subsystems and components cannot be recycled
  Med: 50% of the sub-subsystems and components cannot be recycled
  Low: 80% of the sub-subsystems and components cannot be recycled

- What percentage of waste does the WEC farm produce over its lifetime from replacement parts? The percentage should be given according to: $\sum$(replacement part weight) / $\sum$(originally installed weight).
  High: < 1%
  Med: ~5%
  Low: >10%

C.4.4. Have minimal impact on taxpayers

Electricity consumers are the final users of the generated electricity. They want **market-competitive electricity** in the long term.

TRL1-2
• Will the development of the WEC Farm require subsidies or credits to match the market competitive electricity costs? **High:** No subsidies or credits will be needed **Med:** Subsidies or credits will be needed, but only for a limited duration less than the lifetime of the plant **Low:** Subsidies or credits will be needed over the entire lifetime operation of the farm
TRL3-4
Update the answer to TRL1-2 plus answer the following question: • What is the target learning rate expressed in a progress ratio? o Provide justifications and explanations for how the target learning rate will be achieved with increasing installed capacity. **High:** A progress ratio of 80% or lower is adequately justified(lower progress ratios are better they imply a faster rate of cost reduction) **Med:** A progress ratio of 90% or lower is adequately justified **Low:** A progress ratio approximately 95% OR inadequate justification for claims of faster progress.
TRL5-6
Update the answers to TRL1-2 and TRL3-4.

C.4.5. Contribute significantly to energy security

Like other renewable energy sources, a WEC farm contributes to energy security. It does **not rely on foreign countries** for supplying necessary fuel. The contribution to energy security should be significant (i.e., the WEC farm should be a significant share of the energy mix).

Note: this capability is not scored for the TPL assessment.

C.5. *Be acceptable for permitting and certification*

Permits for occupying the sea space and connecting to the grid **shall be obtained by the WEC farm developer before starting construction of the WEC farm**. Consequently, the WEC farm shall **fulfil all regulatory and permitting requirements**. The requirements usually consist of assessing and addressing environmental impacts, impacts to other users of the area, and impacts to the electrical grid.

C.5.1. Be environmentally acceptable

The WEC farm technology and design shall enable the construction of a power farm that meets all environmental regulations. Thus, it shall cause **no unacceptable impacts on the seafloor, no unacceptable impacts on local currents or sedimentation, no unacceptable impacts on local or global wildlife, and no unacceptable impacts on local or global marine life.**

TRL1-2
• Are there any characteristics of the system and its impact on the environment that restrict its application in environmentally sensitive locations? (e.g. endangered and threatened species, migratory routes, large shifts in sediments, noise emissions, other emissions etc.)? **High:** The system is benign and can be deployed without restriction. **Med:** The system is not completely benign and <20% of otherwise suitable sites are possibly restricted. **Low:** The system is not completely benign and >20% of otherwise suitable sites are possibly restricted. • Will the farm generate any output besides motions (noise, effluent, EMF, etc.) that would affect the environment? **High:** The generated farm output is not expected to affect the environment **Med:** The farm will generate output that will acceptably affect the environment **Low:** The farm output will unacceptably affect the environment.
TRL3-4
• Features of the technology will influence the studies required for environmental permits. Listed below are a series of potential environmental concerns and controlling regulations; rate the technology based on how its features may influence the required studies for environmental permits. • Species under special protection (Endangered Species act or other relevant international regulation)? **High:** Pre-installation literature review of species, abundance, distribution, and behavior is sufficient in concert

with paper studies to show no environmental concern. No actions during operation are required.
Med: Pre-installation in situ baseline study (1 year or less) to determine species, abundance, distribution, and behavior in concert with paper studies to show no environmental concern. Seasonal monitoring for species of concern over the lifetime of the farm required to ensure validity of paper studies.
Low: Pre-installation in situ baseline study (1 + years) to determine species, abundance, distribution, and behavior in concert with additional experimental studies to evaluate environmental concern. Continual monitoring for species of concern over the lifetime of the farm required. .

- Marine mammals (Marine Mammal Protection Act or other relevant international regulation)?
  High: Pre-installation literature review of species, abundance, distribution, and behavior is sufficient in concert with paper studies to show no environmental concern. No actions during operation are required.
  Med: Pre-installation in situ baseline study (1 year or less) to determine species, abundance, distribution, and behavior in concert with paper studies to show no environmental concern. Seasonal monitoring for species of concern over the lifetime of the farm required to ensure validity of paper studies.
  Low: Pre-installation in situ baseline study (1 + years) to determine species, abundance, distribution, and behavior in concert with additional experimental studies to evaluate environmental concern. Continual monitoring for species of concern over the lifetime of the farm required.

- Migratory Birds (Migratory Bird Threat Act (international treaty) or other relevant international regulation)?
  High: Pre-installation literature review of species, abundance, distribution, and behavior is sufficient in concert with paper studies to show no environmental concern. No actions during operation are required.
  Med: Pre-installation in situ baseline study (1 year or less) to determine species, abundance, distribution, and behavior in concert with paper studies to show no environmental concern. No actions during operation are required.
  Low: Pre-installation in situ baseline study (1 + years) to determine species, abundance, distribution, and behavior in concert with additional experimental studies to evaluate environmental concern. Monitoring for species of concern over the lifetime of the farm required.

- Important fish and shellfish populations (Magnuson Stevens Fishery Conservation Management Act or other relevant international regulation)?
  High: Pre-installation in situ baseline study (1+ years) to determine species, abundance, distribution, and behavior in concert with paper studies. No actions during operation are required.
  Med: Pre-installation in situ baseline study (2+ years) to determine species, abundance, distribution, and behavior along with paper studies. Seasonal monitoring for species of concern over the lifetime of the farm required to ensure validity of paper studies
  Low: Pre-installation in situ baseline study (3+ years) to determine species, abundance, distribution, and behavior. Continual monitoring for species of concern over the lifetime of the farm required.

- Habitats (Magnuson Stevens Fishery Conservation Management Act plus other federal and state regulations or other relevant international regulation)?
  High: Pre-installation in situ baseline study (1+ years) to determine species, abundance, distribution, and behavior in concert with paper studies. No actions during operation are required.
  Med: Pre-installation in situ baseline study (2+ years) to determine species, abundance, distribution, and behavior along with paper studies. Seasonal monitoring for species of concern over the lifetime of the farm required to ensure validity of paper studies
  Low: Pre-installation in situ baseline study (3+ years) to determine species, abundance, distribution, and behavior. Continual monitoring for species of concern over the lifetime of the farm required.

- Water Quality (Clean Water Act or other relevant international regulation)?
  High: Pre-installation review and paper studies to indicate insensitivity.
  Med: Pre-installation sampling and paper studies to indicate insensitivity.
  Low: Pre-installation sampling and experimental studies to indicate insensitivity.

TRL5-6

- What regulatory applications have been submitted?
  High: Complete relevant list submitted
  Med: Partial relevant list submitted
  Low: No applications have been submitted

- What studies have been completed to quantify impacts to the following:
  - Impact of farm on coastal wave energy / sedimentation processes?
    High: Estimation of effect on coastal processes through a coupled WEC-wave-circulation model capable of evaluating the effect of the removal of energy from the ocean on sediment transport
    Med: Baseline model to understand the coastal processes at the selected location without including impact of wave energy farm.
    Low: This aspect has not yet been considered

  - Acoustic noise generation?
    High: Experimental quantification of subsystem of concern over multiple frequencies and power levels.
    Med: Estimation of acoustic signature from subsystem using numerical or empirical models.
    Low: This aspect has not yet been considered

  - Benthic ecosystems and invertebrates?
    High: Complete relevant list of studies completed
    Med: Literature review to obtain baseline understanding of species, abundance, and distribution.
    Low: This aspect has not yet been considered

- What additional monitoring during operation will be required to ensure environmental acceptability?
  High: minimal additional monitoring utilizing well-known autonomous instrumentation and data analysis techniques
  Med: significant seasonal monitoring utilizing autonomous instrumentation that is not well known or requires new data analysis
  Low: additional monitoring that is not autonomous OR significant continual monitoring utilizing autonomous instrumentation that is not well known or requires new data analysis

C.5.2. Be acceptable to other users of the area

The WEC farm technology and design must **integrate smoothly with other users of the area**. Other users of the area are local and global fishing industries, other industries using the local area, recreational users of the local area, tourists and entertainment users of the local area, and local communities.

TRL1-2

- Can the technology form a farm that could co-exist with other potential users of the area? (e.g. fishing fleet, surfers, shipping, sailing area, etc.)

  High: The farm can be developed to co-exist with the majority of potential users of the area.

  Med: The farm will restrict multiple users; however the area of restriction will not coincide with areas of interest for other users (e.g. sailing and fishing will be restricted however not co-located with nurseries or sailing routes)

  Low: The farm will restrict multiple users and the area of restriction may coincide with areas of interest for the other users (e.g. coastal devices and prime surfing areas)

- Given the desired farm rated power along with the expected footprint distance (distance from device to anchors, L) of the WECs within the farm, what is the proposed area the farm will occupy per rated farm power?

  High: $1X10^4$ m^2/MW

  Med: $9X10^4$ m^2/MW

  Low: $36X10^4$ m^2/MW

TRL3-4

Update the answers to TRL1-2 plus answer the following questions:

- For the aspects of the WEC technology or farm layout that will restrict access for potential other users of the area, is there flexibility for alteration?

  High: The aspects of concern could be altered if necessary.

  Med: Although the layout and technology cannot change, there is large flexibility in the proposed deployment location.

  Low: No. The aspects of concern along with specific restrictions on deployment locations are fundamental to the success of the project and alteration will result in loss of energy production. (e.g. cannot change that the device is a coastal design).

TRL5-6

- Have the other users of the area and their principal concerns been identified for target deployment locations? (e.g. fishing fleet, surfers, shipping, sailing area, etc.)

High: Formal and thorough study completed
Med: Informal but useful understanding has been gained
Low: No meaningful understanding has been gained

- What steps have been taken to ensure acceptability to these other users? Social science research should be undertaken to gauge opinions and receptiveness.
  High: The wave farm project has been publicized to the local users of the area, informational meetings are planned, and key stakeholders for continued conversation have been identified.
  Med: The wave farm project has been publicized to the local users of the area
  Low: The wave farm project has not been publicized.

- What portions of the farm boundaries intersect with or will change the way other users interact with the sea space?
  High: The wave farm is established with adequate bypass zones or boundaries for other users
  Med: The wave farm is flexible with regards to restricted zones or boundaries for other users
  Low: The wave farm will result in a large restricted zone or boundaries for other user

C.6. Be safe

Safety is a key requirement as soon as **human activities** are involved, particularly at sea. The **WEC power farm shall be safe** at each stage of its lifecycle. The focus shall be on the construction, operations, and disposal stages.

TRL1-2
• Has a safety philosophy been incorporated into the design process? (E.g. Adopt best practice and appropriate formal standards at design stage. Appoint a responsible person to take charge of safety. Review design for safety early, design out risks early. Design in mitigation for risks that cannot be eliminated. Ensure designers are suitably qualified and trained. Keep appropriate records...) **High**: Safety philosophy is incorporated and adequate. **Med:** Some safety aspects have been considered and are adequate but some areas need improvement. **Low**: Safety philosophy is not incorporated or is generally inadequate. • Is there a threat to human health and safety during any of the life cycle stages? (Consider all life stages from design, manufacturing, assembly, lifting, transport, installation, operation, maintenance, removal, decommissioning etc.) **High**: All activities are well understood and carried out by companies with adequate safety systems and good track-records, no access to 3rd parties, the risk to human health and safety is low. **Med:** All activities are carried out by companies with adequate safety systems and good track-records but one or more activities are novel and not yet well understood, or access by 3rd parties can't be prevented, there is a medium threat to human health and safety **Low**: Threat to human health and safety is not considered or one or more companies involved do not have adequate safety systems. The risk is high. • What is the target maximum safe sea state for maintenance? **High**: Maintenance methodologies are such that adequate safety is provided in most sea states **Med:** Maintenance methodologies are such that adequate safety is provided when using commonly available vessels and equipment within their standard weather windows. **Low**: Maintenance methodologies are such that adequate safety is only provided when using commonly available vessels and equipment with more stringent weather window criteria. Or proposed methodologies are fundamentally unsafe.

- Does the design require personnel to transfer from a ship to the device at sea?
  - **High**: No
  - **Med:** For a few exceptional operations (less than 1 per 100MW*year)
  - **Low**: Many times during the year
- Does the design require personnel to enter enclosed spaces at sea?
  - **High**: No
  - **Med:** For a few exceptional operations (less than 1 per 100MW*year)
  - **Low**: Many times during the year
- Does the design require personnel to work in or under the sea? (e.g. divers)
  - **High**: No
  - **Med:** For a few exceptional operations (i.e. not every installation, not routine maintenance but maybe for an infrequent type of maintenance intervention)
  - **Low**: Many times during the year
- Is any lifting by crane done at sea? (e.g. from a vessel/platform through the water surface, or from a vessel/platform onto/off the seabed)
  - **High**: Requirements for lifting have been designed out
  - **Med:** For a few exceptional operations (i.e. not every installation , not routine maintenance but maybe for an infrequent type of maintenance intervention)
  - **Low**: Many times during the year

TRL3-4

Update the answers to TRL1-2 plus answer the following questions:

- Does the WEC technology have features that could be challenging with respect to safety compliance with relevant legislation in the applicable jurisdiction(s)? (e.g. Occupational Safety and Health Administration (OSHA), European directives on safety and health at work, UK "health and safety at work act", UK "Construction Design Management regulations")
  - **High**: System complies to local regulations
  - **Med:** System can be adapted to local regulations
  - **Low**: System cannot be adapted to local regulations
- Has a risk assessment systematically identifying potential hazards in the work place been implemented in compliance with OSHA

or foreign equivalent for key activities in each life cycle stage? (Please provide the risk assessments for all the key activities in manufacture, installation, transport and maintenance.)

High: Hazard identification and risk assessment has been implemented for all activities and the risk is low in each.
Med: The main activities have been identified and assessed, and the risk is low in each.
Low: Hazard identification and risk assessment has not been implemented for all activities or one or more activities have been assessed to have high risk.

- What possible accidental states during maintenance activities have been identified? What measures are in the design to prevent / mitigate the increased probability of injury during accidental states? Note: injury to 3rd parties should be considered as well as injury to personnel.
  High: Accidental states have been identified and risk mitigated by implementing redundant measures
  Med: Accidental states have been identified and no measures have been implementing to mitigate the risk of personnel accidents
  Low: Accidental states have not been identified

- What possible temporary states during maintenance, installation, etc. have been identified? What are the measures in the design to prevent / mitigate the increased probability of injury during temporary states? Note: injury to 3rd parties should be considered as well as injury to personnel.
  High: Temporary states have been identified and measures described to prevent mitigate risk of injury to personnel
  Med: Temporary states have been identified and no measures described to prevent mitigate risk of injury to personnel
  Low: Temporary states have not been identified

- What is the number of vessels required simultaneously for each maintenance activity?
  High: only one vessel at a time
  Med: two vessels at the same time
  Low: several vessels required at the same time

- What are the measures in the design to prevent / mitigate collisions?
  Note: Consider ships colliding with system in normal state e.g. at the farm location, subsystem in failed state colliding with ships e.g. outside the farm location. Ships colliding with

each other, e.g. during installations or O&M, should also be considered.

High: Marking according to rules E.g. navigational aids, lights, radar beacons etc.

Med: Some measures taken but the farm has systems that in some cases can be difficult to recognize e.g. part of the system is invisible just under surface.

Low: No measures taken or inadequate combination of visibility, radar signature, marking, lighting.

- Is the WEC farm and system(s) easily identifiable for vessels and sea users? E.g. navigational aids, lights, radar beacons etc.

  High: Easily identifiable in all sea states, day and night, by eye and radar (or other electronic means).

  Med: Not easily identifiable in some combinations of conditions.

  Low: Not easily identifiable in many conditions

- What is the number of remotely controlled operations vs onsite operations?

  High: All operations can be carried out remotely

  Med: Almost all operations can be carried out remotely

  Low: All operations controlled onsite

- What is the number of remotely monitored sensors vs onsite inspections?

  High: All monitoring is achieved remotely

  Med: Most monitoring is achieved remotely but some will also require onsite inspections

  Low: Many components require onsite inspections

- What are the arrangements for escape from the device at sea?

  High: Safe gangway to exit in all sea states (or no personnel on device)

  Med: Escape from the device only possible in 80% of all sea states.

  Low: It's only possible to escape the device in calm weather.

- What level of specialist training of personnel is required to access the device at sea? (if required)

  High: No more specialized than offshore wind farm maintenance.

  Med: More specialized than offshore wind farm.

  Low: Only very highly specialized and trained personnel can work on the farm.

- Is there a risk of fire while people are onboard? Is there need for a detection and suppression system?
  High: No risk of fire (no combustible material, or no sources of ignition)
  Med: Low risk of fire (small volumes of combustible material and low probability of ignition)
  Low: high risk of explosions and/or fire (some significant combustible material, any probability of ignition)

- Does the design require long periods of skilled maintenance? E.g. is the impact of workers' fatigue a consideration?
  High: All maintenance can be carried out in one "shift", (e.g. less than 8-12 hours) without leading to worker fatigue
  Med: Trained personnel can in most cases complete the tasks with reasonable effort in an extended "shift" (e.g. less than 16-24 hours)
  Low: Only very specialized and trained personnel can work on the farm or maintenance tasks may take considerable time e.g. maintenance requires extensive use of divers or overnight accommodation is needed for workers to complete tasks

- Is there a risk of contact with dangerous chemicals or liquids?
  High: No risk - no dangerous chemicals present
  Med: A very limited risk – dangerous chemicals present but adequate mitigation.
  Low: Some risk - dangerous chemicals present and mitigation not adequately described or mitigation inadequate.

- What is the number of connections that involve hands on human work at sea? E.g. connecting moorings or connecting crane hooks.
  High: No connections that involve hands on operation at sea
  Med: Only in a few exceptional operation (i.e. not every installation, not routine maintenance but maybe for an infrequent type of maintenance intervention)
  Low: Many connections that involve hands on operation at sea

TRL5-6

Update the answers to TRL1-2 & TRL3-4 plus answer the following question:

- What are the projected numbers of serious accidents over the lifetime of the farm that can be attributed to the WEC farm during maintenance, installation, etc.?
  High: $<10^{-4}$ serious accidents per MW*year
  Med: $<10^{-2}$ serious accidents per MW*year

Low: $>10^{-2}$ serious accidents per MW*year

C.7. Be deployable globally

The ability to provide steady sales is another **key requirement for sustainable business for the WEC farm developer, the WEC farm construction company, and for the suppliers of the supply chain**. It may also be an **important requirement for the local, regional, and national development agencies, policymakers, and general society** with respect to the overall benefits from the WEC farm. Thus, the WEC farm shall be deployable at many different sites that represent a large national and global market share. It shall be able to adapt to variable site characteristics, including wave resource, geophysical conditions, distance to shore, and local infrastructure.

TRL1-2
• What is the water depth requirement to deploy the WEC farm? **High:** Anywhere with water depth greater than 20 meters. The WEC farm can be installed near-shore and deep offshore. **Med:** The device requires very specific water depth; smaller than 20 meters, or greater than 100 meters or a specific narrow range of depth between 20 and 100 meters. **Low:** Onshore. • What geophysical conditions are required to deploy this concept? **High:** sand and soft clay **Med:** aggregated substance, i.e. gravel **Low:** solid rock • What is the feasible wave resource for attractive LCOE? **High:** 20kW/m **Med:** 20 - 30 kW/m **Low:** larger than 40 kW/m • What is the sensitivity tidal range? **High:** System is insensitive to tidal range. **Med:** Tidal range of 2m or more has significant impact on energy yield, costs or survivability. **Low:** Tidal range of 1m or more has significant impact on energy yield, costs or survivability. • Are there any characteristics of the system and its impact on the environment that restrict its application in environmentally sensitive locations? (e.g. endangered and threatened species, migratory routes, large shifts in sediments, noise emissions, other emissions etc.)? **High:** The system is benign and can be deployed without restriction. **Med:** The system is not completely benign and <20% of otherwise suitable sites are possibly restricted.

Low: The system is not completely benign and >20% of otherwise suitable sites are possibly restricted.
TRL3-4
Update the answers to TRL1-2 plus answer the following questions: • What is the sensitivity to current? **High:** The system is unaffected by current **Med:** Currents less than 0.5m/s have no adverse impact **Low:** Currents less than 0.2m/s have no adverse impact • Are the manufacturing and construction techniques / infrastructure able to be developed easily at many locations? **High:** yes the methodologies can be applied in all locations **Med:** there some restrictions that will impose additional costs **Low:** there are restrictions in that will impose significant additional costs • What is the theoretical global wave energy capacity that is suitable for capture by the WEC farm (estimated global size of the resource that can be exploited by the WEC farm taking into account physical site conditions, manufacture and installation logistics and port infrastructure)? **High:** Greater than 500GW **Med:** Between 100GW and 500GW **Low:** Less than 100GW • Of the theoretical global wave energy capacity identified above, how will the safety level change as a function of the percentage of global wave energy capacity? **High:** Maintain safety level in more than 60% of the global wave energy capacity. **Med:** Safety level of medium is obtained in more than 60% of the global wave energy capacity. **Low:** Safety level drops to low in more than 40% of the global wave energy capacity.
TRL5-6
Update the answers to TRL1-2 & TRL3-4

4 CALCULATION OF TPL VALUE

This chapter describes how the final TPL system score is determined from the individual scores based on the TPL assessment guidance and scoring criteria. The lowest level of each capability has a series of questions that must be answered and scored on a scale of 1 to 9 according to the scoring criteria that is given following each guidance question (as shown in Chapter 2). The next level (or group score) is then calculated from a mathematical calculation of the underlying levels. Finally, a calculation is performed on the seven highest level capabilities to determine the final TPL system score.

Calculations

Three different ways of combining scores are used in the revised formulation. These are **arithmetic mean, geometric mean** and **multiplication with normalization**.

Arithmetic mean is used when combining scores that measure similar attributes e.g. used for combining costs. The arithmetic mean has the property that it is similar to a logical OR e.g. when combining costs it does not matter what the individual costs are only what the combined cost is.

Geometric mean and **Multiplication** are used when combining scores that measure disparate attributes.

Multiplication is similar to a logical AND, it is used to combine 'must haves'. As a result this method is more punitive than the geometric mean; to get a good score in the combined result it is necessary to have a good score in ALL of the inputs. e.g. the different types of survivability are 'must haves'.

Lastly, threshold TPL values have been associated with the lowest levels of the capabilities. In the calculation tool these thresholds do not alter the score, however a tally of the breached thresholds are kept. This should help identify areas that are of great concern for the technology.

On balance the revised TPL is probably less punitive than the previous spreadsheet, multiplication is used sparingly as a method of combining scores. This is in line with the feedback of the Wave Energy Prize judges.

The weights and threshold TPL values associated with each of the sub and sub-subcapabilities are subject to revision.

An example calculation is shown in Figure 2. The calculator is an excel sheet delivered separately with this document.

Summary:

		Technology Performance Level:	4.0	9 Thresholds Breached
C1	Have market competitive cost of energy		4.8	
C1.1		Have as low CAPEX as possible	1.6	All Thresholds OK
C1.2		Have as low an OPEX as possible	5.3	All Thresholds OK
C1.3		Be able to generate large amount of electricity from wave energy	6.4	All Thresholds OK
C1.4		Have high availability	8.5	All Thresholds OK
C2	Provide a secure investment opportunity		1.8	
C2.1		Be survivable	2.0	3 Thresholds Breached
C2.2		Be low risk under design conditions	1.6	4 Thresholds Breached
C3	Be reliable for grid operations		4.0	All Thresholds OK
C4	Be beneficial to society		7.5	All Thresholds OK
C5	Be acceptable for permitting and certification		7.0	1 Threshold Breached
C6	Be acceptable w.r.t safety		5.0	1 Threshold Breached
C7	Be deployable globally		4.0	All Thresholds OK

Note 1: Preliminary version - 30 June 2016.

Note 2: The weights are subject to revision. This is not the final version.

	Capability			Input Score	threshold	weight	relative weight	contrib.'	Group Score	Threshold	Notes:
C1	Have market competitive cost of energy								4.8		Note: C1 is scored as the geometric mean of: 1/total cost, generation, availability. With equal weighting to each. CAPEX:OPEX weighting within 'total cost' is 70:30.
C1.1		Have as low CAPEX as possible			threshold	weight	relative weight		1.6		Note: C1.1 is scored as a weighted sum of the "value for money" scores. Weights are shown.
C1.1.1			Be a low cost design	1	0	20	36%			Threshold OK	
C1.1.2			Be manufacturable at low cost	2	0	20	36%			Threshold OK	
C1.1.3			Be inexpensive to transport	3	0	5	9%			Threshold OK	
C1.1.4			Be inexpensive to install	4	0	10	18%			Threshold OK	
C1.2		Have as low an OPEX as possible			threshold	weight	relative weight		5.3		Note: C1.2 is scored as a weighted sum of the "value for money" scores. Weights are shown.
C1.2.1			Be reliable (cost of maintenance)	5	4	7	70%			Threshold OK	
C1.2.2			Be durable over the lifetime of the plant	6	4	3	30%			Threshold OK	
C1.3		Be able to generate large amount of electricity from wave energy			threshold				6.4		Note: C1.3 is scored as the product of the inputs. Each input is equally important.
C1.3.1			Absorb large amounts of wave energy	7	4					Threshold OK	
C1.3.2			Have high energy conversion efficiency of extracted energy to electrical energy	8	4					Threshold OK	
C1.4		Have high availability			threshold	weight	relative weight	contrib'	8.5		Note: C1.4 is scored as the weighted average (arithmetic mean) of its inputs. Weights are shown.
C1.4.1			Be reliable (lost revenue w.r.t time taken)	9	4	5	50%	4.50		Threshold OK	
C1.4.2			Be durable over the lifetime of the plant	8	4	5	50%	4.00		Threshold OK	
C2	Provide a secure investment opportunity								1.8		Note: C2 is scored as the geometric mean of its inputs. Each input is equally important.
C2.1		Be survivable			threshold				2.0		Note: C2.1 is scored as the product of its inputs. Each input is equally important.
C2.1.1			Be able to survive extreme loads/responses (can be caused by extreme weather conditions or high power operational conditions)	7	7					Threshold OK	
C2.1.2			Be able to cope with grid failures, grid loss or grid interruption (black start capability); coupling grid loss with a communication loss	6	7					Threshold Breached	
C2.1.3			Be able to avoid and survive to collisions (ships, other marine users, mammals)	5	7					Threshold Breached	
C2.1.4			Be survivable in installation (& tow-out)	4	7					Threshold Breached	
C2.2		Be low risk under design conditions			threshold				1.6		Note: C2.2 is calculated to reflect the impact of the inputs on cost of energy. CAPEX:OPEX weighting is 70:30
C2.2.1			Be low uncertainty on OPEX	3	4					Threshold Breached	
C2.2.2			Be low uncertainty on availability	2	4					Threshold Breached	
C2.2.3			Be low uncertainty on energy production	1	4					Threshold Breached	
C2.2.4			Be low uncertainty on CAPEX	2	4					Threshold Breached	
C3	Be reliable for grid operations				threshold	weight	relative weight	contrib.'	4.0		Note: C3 is scored as a weighted average (arithmetic mean) of its inputs. Weights are shown.
C3.1		Be forecastable		3	1	1	33%	1.00		Threshold OK	
C3.2		Have stable annual power production		4	1	1	33%	1.33		Threshold OK	
C3.3		Be useful to the grid		5	1	1	33%	1.67		Threshold OK	
C4	Be beneficial to society				threshold	weight	relative weight	contrib.'	7.5		Note: C4 is scored as a weighted average (arithmetic mean) of its inputs. Weights are shown.
C4.1		Be beneficial to local communities		6	1	1	25%	1.50		Threshold OK	
C4.2		Be low carbon emission energy source		7	4	1	25%	1.75		Threshold OK	
C4.3		Be a low polluting energy source		8	4	1	25%	2.00		Threshold OK	
C4.4		Minimize impact on taxpayers		9	4	1	25%	2.25		Threshold OK	
C5	Be acceptable for permitting and certification				threshold				7.0		Note: C5 is scored as a geometric mean. Each input is equally important.
C5.1		Be environmentally acceptable		8	7					Threshold OK	
C5.2		Be acceptable to other users of the area		7	7					Threshold OK	
C5.3		Be grid compliant		6	7					Threshold Breached	
C6	Be acceptable w.r.t safety			5	7				5.0	Threshold Breached	
C7	Be deployable globally			4	4				4.0	Threshold OK	

Figure 2. An example calculation in the calculator tool.

Overall Structure

The overall TPL score is calculated from scores for the seven high level capabilities arranged in in three categories as follows.

Capability	**Category**
C1: Have market competitive cost of energy.	Economics
C2: Provide a secure investment opportunity.	Economics
C3: Be reliable for grid operations.	Benefits
C4: Benefit society.	Benefits
C5: Be acceptable to permitting & certification.	Acceptability
C6: Be safe.	Acceptability
C7: Be deployable globally.	Economics

The overall TPL is calculated as a weighted average (arithmetic mean) of the scores for these three categorizations. The weightings for the categories are 0.7:0.2:0.1 for economics, acceptability and benefits, respectively. The equation is:

$$TPL = 0.7 \cdot TPL_{eco} + 0.2 \cdot TPL_{acc} + 0.1 \cdot TPL_{ben} \tag{1}$$

The combined scores for each of the categories that are passed as inputs to equation 1 are calculated as a geometric mean of their respective inputs. The equations used are:

$$TPL_{eco} = (TPL_{C1} \cdot TPL_{C2} \cdot TPL_{C7})^{1/3} \tag{2}$$

$$TPL_{acc} = (TPL_{C5} \cdot TPL_{C6})^{1/2} \tag{3}$$

$$TPL_{ben} = (TPL_{C3} \cdot TPL_{C4})^{1/2} \tag{4}$$

Capabilities Scoring

C.1. Have market competitive cost of energy

The TPL_{C1} value is calculated from two levels of nested sub-capabilities that have been identified through a systems engineering process. The sub-capabilities within C1 are:

C1	**Have market competitive cost of energy**		
C1.1		Have as low CAPEX as possible	
C1.1.1			Be a low cost design
C1.1.2			Be manufacturable at low cost
C1.1.3			Be inexpensive to transport
C1.1.4			Be inexpensive to install
C1.2		Have as low an OPEX as possible	
C1.2.1			Be reliable (cost of maintenance)
C1.2.2			Be durable over the lifetime of the plant
C1.3		Be able to generate large amount of electricity from wave energy	
C1.3.1			Absorb large amounts of wave energy
C1.3.2			Have high energy conversion efficiency of extracted energy to electrical energy
C1.4		Have high availability	
C1.4.1			Be reliable (lost revenue w.r.t time taken)
C1.4.2			Be durable over the lifetime of the plant

C1 is scored as the geometric mean of the TPL scores for total cost, generation, availability, with equal weighting of each.

$$TPL_{C1} = (TPL_{COST} \cdot TPL_{C1.3} \cdot TPL_{C1.4})^{1/3} \tag{1}$$

The score for total cost is a combination of the CAPEX and OPEX scores and relies on a CAPEX: OPEX weighting of 70:30.

$$TPL_{COST} = \frac{1}{\frac{0.7}{TPL_{C1.1}} + \frac{0.3}{TPL_{C1.2}}} \tag{2}$$

C1.1 is scored as a weighted sum of the individual cost TPL scores in CAPEX.

$$TPL_{C1.1} = \frac{1}{\frac{0.36}{TPL_{C1.1.1}} + \frac{0.36}{TPL_{C1.1.2}} + \frac{0.09}{TPL_{C1.1.3}} + \frac{0.18}{TPL_{C1.1.4}}} \tag{3}$$

C1.2 is scored as a weighted sum of the individual cost TPL scores in OPEX.

$$TPL_{C1.2} = \frac{1}{\frac{0.7}{TPL_{C1.2.1}} + \frac{0.3}{TPL_{C1.2.2}}} \tag{4}$$

C1.3 is scored as the product of the inputs and then scaled to a range of 1-9. Each input is equally important.

$$TPL_{C1.3} = (TPL_{C1.3.1} \cdot TPL_{C1.3.2} - 1)\left(\frac{8}{9^2 - 1}\right) + 1 \tag{5}$$

C1.4 is scored as the weighted average (arithmetic mean) of its inputs. Weights are 50:50.

$$TPL_{C1.4} = 0.5 \cdot TPL_{C1.4.1} + 0.5 \cdot TPL_{C1.4.2} \tag{6}$$

C.2. Provide a secure investment opportunity

The TPL_{C2} value is calculated from two levels of nested sub-capabilities that have been identified through a systems engineering process. The sub-capabilities within C2 are:

C2	**Provide a secure investment opportunity**		
C2.1		Low uncertainty on costs and revenues	
C2.1.1			Be low uncertainty on OPEX
C2.1.2			Be low uncertainty on availability
C2.1.3			Be low uncertainty on energy production
C2.1.4			Be low uncertainty on CAPEX
C2.2		Survivable	
C2.2.1			Be able to survive extreme loads/responses

C2.2.2		Be able to survive grid failures, grid loss, or grid interruption
C2.2.3		Be able to avoid and survive collisions
C2.2.4		Be survivable in temporary conditions including installation and maintenance
C2.2.5		Have robust fatigue characteristics

C2 is scored as the geometric mean of its inputs. Each input is equally important.

$$TPL_{C2} = (TPL_{C2.1} \cdot TPL_{C2.2})^{1/2} \tag{7}$$

C2.1 is calculated to reflect the impact of the inputs on cost of energy. It is the geometric mean of 1/combined cost, availability and energy production. Within the total cost the CAPEX:OPEX weighting is 70:30.

$$TPL_{C2.1} = \left(\frac{1}{\frac{0.3}{TPL_{C2.1.1}} + \frac{0.7}{TPL_{C2.1.4}}} \cdot TPL_{C2.1.2} \cdot TPL_{C2.1.3} \right)^{1/3} \tag{8}$$

C2.2 is scored as the product of its inputs scaled to a range of 1-9. Each input is equally important.

$$TPL_{C2.2} = (TPL_{C2.2.1} \cdot TPL_{C2.2.2} \cdot TPL_{C2.2.3} \cdot TPL_{C2.2.4} \cdot TPL_{C2.2.5} - 1)\left(\frac{8}{9^5 - 1}\right) + 1 \tag{9}$$

C.3. Be reliable for grid operations

The TPL_{C3} value is calculated from a single level of sub-capabilities that have been identified through a systems engineering process. The sub-capabilities within C3 are:

C3	**Be reliable for grid operations**

C3.1		Be forecastable
C3.2		Have a high correlation of power production with demand
C3.3		Be useful to the grid
C3.4		Be grid compliant

C3 is scored as a geometric mean of “be grid compliant” and the weighted average (arithmetic mean) of the other three inputs. Weights are shown.

$$TPL_{C3} = ((0.33 \cdot TPL_{C3.1} + 0.33 \cdot TPL_{C3.2} + 0.33 \cdot TPL_{C3.3}) \cdot TPL_{C3.4})^{1/2} \quad (10)$$

C.4. Benefit society

The TPL_{C4} value is calculated from a single level of sub-capabilities that have been identified through a systems engineering process. The sub-capabilities within C4 are:

C4	**Be beneficial to society**	
C4.1		Be beneficial to local communities
C4.2		Be low carbon emission energy source
C4.3		Be a low polluting energy source
C4.4		Minimize impact on taxpayers

C4 is scored as a weighted average (arithmetic mean) of its inputs.

$$TPL_{C4} = 0.25 \cdot TPL_{C4.1} + 0.25 \cdot TPL_{C4.2} + 0.25 \cdot TPL_{C4.3} + 0.25 \cdot TPL_{C4.4} \quad (11)$$

C.5. Be acceptable for permitting and certification

The TPL_{C5} value is calculated from a single level of sub-capabilities that have been identified through a systems engineering process. The sub-capabilities within C5 are:

C5	**Be acceptable for permitting and certification**	
C5.1		Be environmentally acceptable
C5.2		Be acceptable to other users of the area

C5 is scored as a geometric mean. Each input is equally important.

$$TPL_{C5} = (TPL_{C5.1} \cdot TPL_{C5.2})^{1/2} \tag{12}$$

C.6. Be safe

The TPL_{C6} value has no sub-capabilities its value is determined by the assessor in consideration of the questions under this capability.

C.7. Be deployable globally

The TPL_{C7} value has no sub-capabilities its value is determined by the assessor in consideration of the questions under this capability.

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6 GLOSSARY

Availability: The real capacity available to generate as a percentage of the rated or installed capacity (usually averaged over a year)

Black Start: Can start generating even if the grid isn't present (could also be a grid ancillary benefit)

Capacity Factor: The average value divided by the rated value

Capture Width: Ratio of mechanical power absorbed by a wave power collecting system to the incident wave energy flux. In meters

Components: The constituent entities that make the sub-systems; PTO: hydraulic rams, hydraulic motor, etc.

Consequence Classes: Defines the different consequence levels that can occur following a failure. The consequence can be related to one or several of the following categories: safety, environmental impact, asset and production / generation. The consequence is normally classified from no impact to catastrophic.

Class	Description of consequences (impact on) One System / Technology				
	Safety	Environment	Operation	Assets	Cost (GBP)
1	Negligible injury or health effects	Negligible pollution or no effect on environment	Negligible effect on production (hours)	Negligible	1k
2	Minor injuries or health effects	Minor pollution / slight effect on environment (minimum disruption on marine life)	Partial loss of performance (retrieval not required outside maintenance interval)	Repairable within maintenance interval	10k
3	Moderate injuries and/or health effects	Limited levels of pollution, manageable / moderate effect on environment	Loss of performance requiring retrieval outside maintenance interval	Repairable outside maintenance interval	100k
4	Significant injuries	Moderate pollution, with some clean-up costs / Serious effect on environment	Total loss of production up to 1 m (GBP)	Significant but repairable outside maintenance interval	1m
5	A fatality	Major pollution event, with significant clean-up costs / disastrous effects on the environment	Total loss of production greater than 1 m (GBP)	Loss of device, major repair needed by removal of device and exchange of major components	10m

Class	Description of consequences (impact on) Farm				
	Safety	Environment	Operation	Assets	Cost (GBP)
1	Minor injuries or health effects	Negligible pollution or no effect on environment	Negligible effect on production (hours)	Negligible	10k
2	Moderate injuries and/or health effects	Minor pollution / slight effect on environment (minimum disruption on marine life)	Loss of array performance (remedial activity takes place within scheduled maintenance)	Repairable within maintenance interval	100k
3	Significant injuries	Limited levels of pollution, manageable / moderate effect on environment	Loss of array performance requiring retrieval outside maintenance interval	Repairable outside maintenance interval	1m
4	A fatality	Moderate pollution, with some clean-up costs / Serious effect on environment	Total loss of array production up	Loss of one device or associated array infrastructure	10m
5	Few fatalities	Major pollution event, with significant clean-up costs / disastrous effects on the environment	Total loss of production greater than 10 m (GBP)	Loss of multiple devices and/or array infrastructure	100m

Durability: The length of a system, sub-system or components life. Durability is concerned with scheduled maintenance and planned maintenance activities especially where sub-systems and components have a shorter life than the farm at a whole.

Elements of the Farm: This can refer to any sub level below the farm: subsystem, sub-subsystem, or components.

Environment: Includes the entirety of the ocean; sea conditions, other users, biologic and chemical factors, etc.

Equipment: When refer to maintenance components, the crane needed to achieve the maintenance—more like tools.

FMECA: Failures mode, effects and criticality analysis. FMECA methodology is further described in BS 5760, Part 5, Guide to failure modes, effects and criticality analysis and IEC-60300-9, Part 3: Application guide - Section 9: Risk analysis of technological systems.

Incoming Waves: Waves generated by wind that come to the system from a distance away.

Limit State: A limit state is a condition beyond which a structure or structural component or system will no longer satisfy the design requirements. The following limit states are considered in order to satisfy, to a certain probability, that structure or system will fulfil its function:

- Ultimate limit states (ULS): corresponding to the maximum load-carrying resistance

- Fatigue limit states (FLS): corresponding to failure due to the effect of cyclic loading
- Accidental limit states (ALS) (including progressive collapse limit state - PLS): corresponding to survival conditions in a damaged condition or in the presence of nonlinear environmental conditions
- Serviceability limit states (SLS): corresponding to tolerance criteria applicable to intended use.

  Accidental limit states with a probability of occurrence of less than 10^{-3} per year and involving only one system or unit may be considered as an SLS depending on the level of risk. In the case that the risk is not acceptable due to safety, environmental, economic or reputational viewpoint, the structural integrity should be improved. Accidental limit states involving progressive failure or failure with high economical or societal impact shall always be considered.

MTBF: Mean time between failures.

Net Capacity Factor: Gross capacity factor x availability

Permit Windows: Periods of time where access is possible due to environmental variables, and any other variables, being below relevant thresholds. E.g. working hours limitations (legal or technical)

Probability Classes: Defines the different probability levels that can be expected for an event to occur. It is normally associated to a failure mechanism that it is trigged by an event. The probability is classified from the very frequent to the remote / accidental event.

Class	Name	Description	Indicative annual failure rate (up to)	Reference
1	Very Low	Negligible event frequency	1.0E-04	Accidental (event not failure)
2	Low	Event unlikely to occur	1.0E-03	Strength / ULS
3	Medium	Event rarely expected to occur	1.0E-02	Fatigue / FLS
4	High	One or several events expected to occur during the lifetime	1.0E-01	Operation low frequency
5	Very high	One or several events expected to occur each year	1.0E+00	Operation high frequency

Progress Ratio: Cost(t) = Cost(0)(1-a)^d . progress ratio = (1-a). for some commodity, if Cost(t) is cost at time, t, d(t) is the number of doublings of cumulative output of the commodity in time, t, and a is the percent reduction in cost for each doubling of cumulative output.

Radiated Waves: Waves created by the motion of subsystems in the system, e.g. circular outgoing waves created by motion of an axis-symmetric buoy, waves made by a wavemaker.

Reliability: The likelihood that a system, sub-system or component will not fail within a given time period. Reliability is concerned with unplanned maintenance and random failures.

Risk: The qualitative or quantitative likelihood of an accident or unplanned event occurring, considered in conjunction with the potential consequences of such a failure. In quantitative terms, risk is the quantified probability of a defined failure mode multiplied by its quantified consequences.

Risk Matrix: Defines the risk level (low, medium and high for example) for each combination of the different probability and consequence classes.

	Consequence				
Probability	**1**	**2**	**3**	**4**	**5**
5	Low	Med	High	High	High
4	Low	Med	Med	High	High
3	Low	Low	Med	Med	High
2	Low	Low	Low	Med	Med
1	Low	Low	Low	Low	Med

Notes:

Low	Tolerable, no action required
Medium	Mitigation and improvement required to reduce risk to Low
High	Not acceptable: mitigation and improvement required to reduce risk to Low (ALARP)

Safety Classes: Three safety classes (low, normal and high) are normally identified. Low safety class is defined where failure implies negligible risk to human life, low risk for personal injuries and pollution and low risk for economic consequences. Normal safety class defined where failure implies some risk for personal injuries, significant pollution or high economic or political consequences. High safety class defined where failure implies large possibilities for personal injuries or fatalities, significant pollution or very large economic or political consequences.

From experience with representative industries and activities the nominal annual probability of failure for the safety classes defined below:

- low safety class $<10^{-3}$ per annum
- normal safety class $<10^{-4}$ per annum
- high safety class $< 10^{-5}$ per annum.

Safety classes may be considered while defining redundancy or safety features for the equipment and systems. Higher levels of safety may be required for critical sub-systems and components depending on their consequences of failure. As an example, due to access difficulties for unplanned maintenance (plus costs related to offshore intervention, and any additional "downtime" penalties when not generating to the grid), a higher level of reliability may be required.

Hence, safety aspect impacts all service and operational requirements resulting from the use of the device and the environmental conditions that can affect the design.

The normal safety level is aimed at for structures / systems, whose failures are ductile, and which have some reserve capacity.

The target safety levels for the different systems and components should be identified in the risk assessment stage taking into account the present constraints regarding access and aimed reliability. The normal safety level is aimed and it is reflected in the use of existing standards from other industries and adjusted requirements to address novelty and risks.

Scattered Waves: Waves generated by the interaction between the unmoving system and the incoming waves e.g. reflections, diffractions.

Sea Conditions: includes the 3-D spectral properties of the waves (frequency, direction, energy) as well as the tidal, current, and wind conditions.

Specific Capacity Factor: populated scatter diagram of capacity factors.

Sub-subsystems: systems within the subsystem. E.g. PTO, power electronics, auxiliary systems within WEC or sub-station.

System: In Systems Engineering (SE) the system is the thing that is designed or optimized. Therefore, in wave energy the system is the wave farm.

Target Safety Level: target safety level is a nominal acceptable probability of structural / system failure. The target safety level is described considering the definition of safety classes.

Technology Class: Proven technology is considered a technology classified as '1 - No new technical uncertainties'. All other classes reflect varying levels of technology novelty.

Application Area	Technology Status		
	Proven	**Limited Field History**	**Unproven**
Known	1	2	3
New	2	3	4

Technology Class	Definition
1	No new technical uncertainties
2	New technical uncertainties
3	New technical challenges
4	Demanding new technical challenges

WEC: The system that collects wave power.

WEC Farm Rated Power: Maximum 15' average power exportable to the grid as agreed between the farm operator and the farm operator.

Weather Windows: Periods of time where access is possible due to environmental variables being below relevant thresholds. E.g. waves, wind, current and tide.

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