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Technical Submission Form
Technical Specification of a Wave Energy Farm

Version 2.01

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Abstract

The Wave-SPARC project developed the Technology Performance Level (TPL) assessment procedure based on a rigorous Systems Engineering exercise. The TPL assessment allows a whole system evaluation of Wave Energy Conversion Technology by measuring it against the requirements determined through the Systems Engineering exercise. The TPL assessment is intended to be useful in technology evaluation; in technology innovation; in allocation of public or private investment, and; in making equipment purchasing decisions. This Technical Submission Form (TSF) serves the purpose of collecting relevant and complete information, in a technology agnostic way, to allow TPL assessments to be made by third party assessors. The intended usage of this document is that the organization or people that are performing the role of developers or promoters of a particular technology will use this form to provide the information necessary for the organization or people who are performing the assessor role to use the TPL assessment.

ACKNOWLEDGMENTS

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INTRODUCTION TO THE TECHNICAL SUBMISSION FORM CONTENT AND TRL REQUIREMENTS

This document serves as the “Technical Submission” for the assessment of the Technology Performance Level (TPL) of a wave energy conversion technology at Technology Readiness Level (TRL) Ranges TRL1-2, TRL3-4 and TRL5-6.

Given that the wave energy farm system that is being optimized to provide market competitive electricity, each contributing component of the farm is a subsystem which is composed of sub-subsystems and so on.

At the TRL 1-2 range, the information asked for mainly relates to the subsystem level.

At the TRL 3-4 range, the information asked for at TRL 1-2 range should be updated, along with providing any additional information required, including sub-subsystem level information.

At the TRL 5-6 range, the information asked for at TRL 1-2 and TRL 3-4 ranges should be updated, along with providing any additional information required, and should include component level.

The submission form will provide a guide to the type of drawings and details to be submitted and how each physical subsystem, sub-subsystem, or component should be identified in Appendix B.

The TPL assessment is adjusted to TRL 1-2, 3-4, and 5-6 ranges. The higher the TRL range the more detailed questions will be asked in order to evaluate the system. Table 1 indicates the MINIMUM requirements for knowledge bases expected at TRL 1-2, 3-4, and 5-6 as to enable evaluation of the relevant assessment questions and scoring criteria.

Table 1. Expectations for various TRL Ranges.

Key TPL Factors	**TRL 1-2**	**TRL 3-4**	**TRL 5-6**
Farm configuration	Number of devices, packing density	Number of devices, packing density, device arrangement / interaction	Layout considering local bathymetry, number, arrangement
Energy in the deployment environment	5 representative sea states; Sensitivities to tidal, direction, current, etc.	Generic scatter diagram & sea-state definition; No spreading but with mean directions.	Actual deployment scatter diagram and sea conditions known including spreading, tide, current, etc.
Deployment	Target location (near-shore, off-shore, etc.); Sensitivities to seabeds	Targeted distances from shore, seabed types that would work…	Actual farm location known and characterized (distances, seabed, etc.)
WEC Power Production	Freq domain / estimation methods; average only / single efficiency values, etc.	Linear time domain—30min rep’s. Dynamic analysis (i.e. frequency dependent, efficiencies, etc.)	Time domain – 10yr history; Dynamic analysis, nonlinearities included

WEC supporting Structure	Profile of design, CoG, CoB, MoI, dominant material types	~volume of material, large scale loads (bending moments)	Actual structural design—i.e. to withstand all loads
Failure Modes*	Basic understanding of key failure modes; # and types of point loads	Knowledge of the design loads and top 10 FMECA; Characteristic load and catastrophic load known as well as corresponding return period.	Full & complete FMECA
Maintenance and installation.	Weather windows % of time access in a year	Weather windows % of time per month access	# of weather windows in each month and duration
Maintenance	Lifetime, basic failure pathways, location of maintenance (storyboard), MTBF of subsystems, # and type of vessel	Frequency (planned and unplanned), downtime, capacity reduction, permit windows, round trip time, inspection requirements	
Fatigue		Count cycles & point loads for each cycle….	Associate cycles with stress levels & calculate fatigue life.

The Technical Submission Form must be answered in English and all questions relate to the device concept at full scale.

Based on Table 1, please state the TRL range that best matches the submission.

Note: According to this TRL range, when answering questions please describe the techniques (experimental, numerical, etc.) that were used to determine the answers provided in the relevant parts of the submission form. This can be considered as further evidence to support your answers.

The evaluation is included in the report: “Systems Engineering Applied to the Development of a Wave Energy Farm”. SANDIA REPORT   November 2016.

1. DEPLOYMENT LOCATION

Please provide information on the targeted deployment location, resource, and environment suitable for the deployment and operation of the wave energy farm.

1.1. Sea Conditions and Wave Power Resource

TRL 1-2

Provide:

- The target wave resource (kW/m). The resource indicated could be specified with a minimum of FIVE sea states (Hs, Te) combined with each their average total duration over the year. (ref. Annex II OES).

Table 2. Example table of sea states.

Hs [m]	1	2	3	4	5
Tz [sec]					
Te [sec]					
Tp [sec]					
Average duration [% of the year]					

TRL 3-4

Provide:

- A general occurrence scatter diagram (see Appendix D) and mean directions for the resource previously indicated. Typical spectral parameters may be used and should be described.

TRL 5-6

Provide:

- Updated TRL 3-4 information with the actual deployment location scatter diagram, direction rose, and spectral shapes including spreading. Follow IEC PT62600-101 guidelines to provide information at a Class 2 Feasibility level.

Summary Table

Table 3 should be filled in to provide a summary of the information requested in the above section.

Table 2. Summary of Sea Conditions and Wave Power Resource.

Environmental parameter	Unit	Value	Comment
Target water depth	-		Shallow (d< 10m) Medium in-between Deep (d>100m)
Mean annual wave resource	kW/m		
Tidal range	m		At TRL 3-4, 5-6
Max significant wave height at the site	m		
Maximum steepness (Derived from Hs & Te)			TRL 5-6
Max current	m/s		At TRL 3-4, 5-6
Max wind speed	m/s		At TRL 3-4, 5-6
Variation of the incoming direction of the wave resource			Small (%), medium or large TRL 1

1.2. Surrounding Environment for the Wave Energy Farm

The purpose of this section is to describe the surrounding environment suitable for the deployment of the wave energy farm.

TRL 1-2

Provide:

- A description of infrastructures such as ports for production deployment and O&M.
- A description of seabed materials (sand, soft clay, gravel, rock etc.).
- A description of other activities that require consideration in a farm development location such as oil production or fishing.
- A description of any characteristics of the system with an impact on the environment that restricts its application in environmentally sensitive locations (e.g. endangered and threatened species, migratory routes, large shifts in sediments, noise emissions, other emissions, etc.). In addition, describe if the farm will generate any noise, effluent, EMF, etc. that would affect the environment.
- A description of the flexibility of site deployment in addition to the number of different sites that the wave energy farm can be deployed at.
- The expected size of the national and global market share.
- An evaluation of the technology impact if it would be a concern for the local communities surrounding the wave energy farm and if the concern could lead to delays in first power production.

TRL 3-4

Provide:

- Expanded TRL 1-2 information with relevant information on how the wave farm integrates and impacts other activities in the area such as sailing routes, fisheries, etc.
- Details on the probability of marine mammals in the target deployment location.
- Details of biofouling growth types.
- A description of the wave energy farm features that might influence the studies required for environmental permits, such as concerns and controlling regulations related to:
    - Species under special protection (Endangered Species act or other international regulation)
    - Marine mammals (Marine Mammal Protection Act or other relevant international regulation)
    - Migratory Birds (Migratory Bird Threat Act or other relevant international regulation)
    - Important fish and shellfish populations (Magnuson Stevens Fishery Conservation Management Act or other relevant international regulation)
    - Habitats (Magnuson Stevens Fishery Conservation Management Act plus other federal and state regulations or other relevant international regulation)
    - Water Quality (Clean Water Act or other relevant international regulation)
    - Describe what steps have been taken to mitigate delays in first power production (environmental / societal impact from the wave energy farm?) and undertakings in listening to local opinions and receptiveness.

TRL 5-6

Provide:

- Update the answers to previous TRL questions with actual site-specific data.
- A description of how the data have been acquired. If relevant provide a copy of an environmental impact assessment at the site and any surveys concerning seabed materials and water depth can be included.
- A description of the regulatory applications that have been submitted and studies that have been completed to quantify impacts to the following:
    - Impact of farm on coastal wave energy / sedimentation processes
    - Acoustic noise generation
    - Benthic ecosystems and invertebrates
    - Additional monitoring during operation that will be required to ensure environmental acceptability
    - Impact and acceptance of other users

Summary Table

Table 4 should be filled in to provide a summary of the information requested in the above section.

Table 3. Summary Table for the Surrounding Environment Data.

Environmental parameter	Unit	Value	Comment
Seabed materials			
Competing usages of the typical deployment site (fishing, recreational activities, …)	-	[Low/ Medium /High]	
Visual impact of the wave energy farm	-	[Low/ Medium /High]	
Proximity of navigational routes and traffic density	-	[Low/ Medium /High]	
Impact on the environment that restrict its application in environmentally sensitive locations		[Low/ Medium /High]	
Concerns with local opinions and receptiveness		[Low/ Medium /High]	
Global potential		[Low/ Medium /High]	

2. WAVE ENERGY FARM CONFIGURATION

The purpose of this section is to provide an overview and description of the wave energy farm configuration at the system level. The rated power of the wave energy farm is expected to be on the order of 100 -500 MW in order to achieve market competitiveness in the continental US.

Provide an overview description and drawings with information on the layout of the wave energy farm.

Please state the expected wave energy farm lifetime.

Drawings should include:

- Key dimensions of wave energy farm
- Arrangement of WECs in the wave energy farm
- Predominant wave propagation direction and orientation of devices within farm
- Layout and key dimensions of mooring system and/or foundation
- Layout and key dimensions of power export cables or pipelines
- Layout and key dimensions of the power aggregation subsystems
- Point of Connection (PoC) to the mainland grid

At TRL 1-2, the above drawings will be mostly illustrative.
At TRL 3-4, and 5-6 drawings should be to scale and in 3 planes and also with a perspective view.

Using Table 5, identify the subsystems in the wave energy farm. Highlight any redundancies in the power aggregation and delivery subsystems in the overview description of the farm.

Table 4. Subsystem Identification table for Wave Energy Farm.

ID	Subsystem	Function	Number per wave energy farm
01	WEC DEVICE	Convert wave energy into transportable energy	
02	CONTROL POSITION	Mooring system and/or foundations	
03	WAVE POWER AGGREGATION SYSTEM	Aggregate power from the different WEC devices	
04	ELECTRICAL WAVE POWER DELIVERING SYSTEM	Deliver electrical power to the grid at Point of Connection	

3. ID 01 WAVE ENERGY CONVERTER DESCRIPTION

The purpose of this section is to provide a description of the WEC device and the list of identified subsystems with a level of detail reflecting the TRL being assessed.

Provide a short description of sub-subsystems involved in collecting wave power at the WEC level. Table 6 may be adapted and completed to assist with this task.

Table 5. System Identification table for WEC.

ID	Subsystem, sub-subsystem, component	Function	Material	Number per WEC device
01	WEC DEVICE			
0100	Collect Wave Power (Primary Converter)	Collect Wave Energy		
0101	5m OD, 7m long cylindrical tubes	Floating bodies interacting with waves		
0102	Hinge Joints	Reference for relative motion		
0110	Convert Power	Convert Wave Energy		
0111	i.e. Hydraulic rotary motor	i.e. Convert rotational velocity into high pressure fluid flow		
0112	i.e. Flow rectifier			
0113	i.e. High pressure accumulator			
0120	Supporting structure	Provide structure for support		

3.1. ID 0100 Collect Wave Power (Device Primary Absorber)

The purpose of this section is to provide the information required to understand the primary absorber and to obtain estimates of the power absorption by the WEC devices and wave energy farm.

Technical drawings should at a minimum, include views in three orthogonal planes and one three-dimensional perspective view. System ID shall refer to ID numbers in the completed Table 6 with relevant subsystems, sub-subsystems, and components.

Note:
At TRL 1-2, the above drawings will be mostly illustrative.
At TRL 3-4, and 5-6 drawings shall be to scale and in 3 planes along with a perspective view.

3.1.1. Working Principle and Modes of Operation

TRL 1-2

Provide:

- A description of the overall working principle in all relevant configurations and modes of operations. Modes of operations should include power generation at rated power and shut down for maintenance purpose. The description shall refer to relevant information on the targeted environmental parameters from section 1.1 of the Technical Submission Form.

  The description can include illustrations and should include information on:
  - The description of the working principle and modes of operations.
  - A description of distinct physical configurations and envelope dimensions.
  - The sensitivity to environment parameters (wave direction, tidal, current, wind, etc.).
  - Power generation mode at rated power.
  - Power generation mode when below / above rated power.
  - Estimate of wave power absorption.
  - Identification of absolute and/or relative degrees-of-freedom (DOF) and/or modes of deformation and/or modes of operation, if applicable.
  - Any other data relevant to estimating/verifying resting position in calm water.

TRL 3-4

Provide:

- Information on any additional small scale experimental and numerical results that support the descriptions as documentation of operational modes.
- Total device mass and displaced volume.
- Dimensions and mass of each sub-subsystem.
- Ballast details if relevant.
- Total surface area, both wetted and dry, of device profile.
- Mass moment of inertia tensor for all bodies.
- Hydrostatic stiffness matrix for all bodies.
- Any other data relevant to estimating/verifying response to waves.

TRL 5-6

Provide:

- An update to previous TRL levels with additional high fidelity modeling and validation data.

3.1.2. Wave Power Absorption Estimates and Validation

TRL 1-2

Provide:

- An estimate of primary wave absorption of the WEC technology deployed at the location described in Section 1 and consider:
    - Sensitivity to wave power, wave direction, and directional spreading.
    - Sensitivity tidal height, tidal current, wind or influence of mooring systems.
    - Other aspects of the system that could decrease energy production.
    - Present the target capacity factor for the target location.

TRL 3-4

Provide:

- Details on the following using the TRL 3-4 appropriate wave climate and time domain model of performance:
    - The estimated array interaction factors presented in occurrence scatter diagram.
    - Any particular features that make it less likely to be forecastable than a wave energy farm with other technologies in the sub hourly, hourly, and 24-hour time frames.
    - Specify which data have been validated and how the validation of results has been obtained.

TRL 5-6

Provide:

- Details on the following, using the TRL 5-6 appropriate wave climate and a nonlinear time domain model of performance:
    - The array interaction factors presented in occurrence scatter diagram.

Section 13 Power Summary has requests for all power conversion steps in the process. Please fill in relevant information in this section.

Summary Table

Table 7 should be filled in to provide a summary of the information requested in the section above.

Table 6. Summary Table for Wave Power Absorption.

Parameter	Unit	Value	Comment
WEC Device rating	kW		
WEC Device capacity factor for target location	-		TRL3-4, 5-6
Target annual average of capture length	m		Provide note to support claim
Using wave resource provided in section 1 what is the annual average of power absorption	kW		
If applicable, typical relative capture width for WEC devices with similar working principle	%		
If applicable, expected effect of stroke limitation on wave power absorption	-	[Low/ Medium /High]	

If applicable, expected effect of tidal height and/or tidal current on wave power absorption	-	[Low/ Medium /High]	
If applicable, expected effect of wind on wave power absorption	-	[Low/ Medium /High]	
If applicable, expected effect of wave direction and directional spreading on wave power absorption	-	[Low/ Medium /High]	
If applicable, expected effect of mooring systems on wave power absorption	-	[Low/ Medium /High]	

3.2. ID 0110 Power Conversion

The purpose of this section is to present at subsystem level the elements involved in converting the captured power to transportable power.

TRL 1-2

Provide:

- A list of energy conversion steps at sub-subsystem level within ID 01. Include with reference to Table 6 System Identification table for WEC and provide:
  - Design drawings and descriptions of the conversion steps and systems involved.
  - Estimate of converted absorbed power.
  - The input power for the conversion chain will be the absorbed power described in the previous section. For each sub-subsystem taking absorbed power to transportable power please present the required information in a table similar to the one in the Appendix B. Example Expansion System ID Table.
  - Details if the sub-subsystem that converts absorbed power into transportable power plays a role in withstanding extreme loads and responses.

Section 13 Power Summary has requests for all power conversion steps in the process. Please fill in relevant information in this section. At TRL 1-2, there is only the Rated Power to fill in.

TRL 3-4

Provide:

- The following, just before the point of aggregation, using the TRL 3-4 appropriate wave climate and time domain model of performance:
  - Annual average power production just before point of aggregation (i.e. from the WEC device to the aggregation point).
  - 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.
  - Number of terminations per MW.
- Details on how robust the energy production is to errors in the wave resource (sea conditions) prediction / forecasts.

- Details of the capacity factors for each component within the sub-subsystems that convert absorbed power into transportable power (i.e. generator, variable frequency drive, hydraulic cylinders, etc.) by populating each element of the scatter diagram (see Appendix D. Example Scatter Diagrams).

Section 13 Power Summary has requests for all power conversion steps in the process.

- Details for systems in which power is re-circulated (e.g. reactive control), estimates of the average annual recirculation efficiency, and a scatter diagram of average and peak re-circulated power.

TRL 5-6

Provide:

- An update of previous TRL sections using the TRL 5-6 appropriate wave climate and nonlinear time domain model of performance.

Section 13 Power Summary has requests for all power conversion steps in the process. Please fill in relevant information in this section.

Summary Table

See Section 13 Power Summary.

3.3. ID 0120 Supporting Structure

The purpose of this section is to provide the information required for assessment of the structure of the WEC, including both areas that are intended to collect wave power and those that only provide only a structural element (i.e. structural elements whose main purpose is not to provide surface area for wave power absorption).

TRL 1-2

Provide:

- The mass for structural members that are not intended to collect wave power.
- Specification of quantities and materials types used.
- A description and summary of the overall geometry.
- Details of the connection points of power conversion system to the structure.
- Description of point loads and areas of stress concentrations.
- If applicable describe how strokes are limited (i.e. mechanical).
- Define 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.

TRL 3-4

Provide:

- An engineering report verifying the structural capability of the design and materials involved. Any drawings provided should be to scale and include views in three orthogonal planes and one three-dimensional perspective view.
- The safety class used in all elements of the design (See **Appendix A Definitions).**
- The return period of the sea state that produces the characteristic load.
- The sea state that produces the characteristic load.
- Characteristic loads and annual average median values (P50).
- Load cycles per year of the five most flexed areas as basis for fatigue design.

TRL 5-6

Provide:

- The fatigue lives for the FIVE highest consequence elements.
- Relevant structural design engineering reports and verifications.

Summary Table

Table 8 should be filled in to provide a summary of the information requested in the section above.

Table 7. Summary Table for the Supporting Structure Data.

Parameter	**Unit**	**Value**	**Comment**
Mass of structure	kg		
Number connection points to Collect Wave Power	-		
Number of connection points to Control Position	-		
Number of cycles per year of the most flexed	-		TRL3-4
Average load (P50 load)	kN		TRL3-45-
Characteristic loads	kN		TRL3-4 5-
Return periods for each above	Years		TRL 5-6
Safety factor	-		TRL 5-6
Safety class (see *section safety*)	-		TRL 5-6
Fatigue life	(years)		TRL 5-6

4. ID 02 CONTROL POSITION

The purpose of this section is to provide the information relating to the subsystem used to keep the WEC at its proposed position and how it works in the targeted environment.

TRL 1-2

Provide:

- Design drawings and descriptions of the method of controlling position.
- Specification of the materials used in the control position and their safety class.
- A description of how the Control Position system is connected to the WEC.
- A description of how the Control Position is monitored.
- Overall dimensions of the mooring system layout in relation to one or several WEC (s) (i.e. to illustrate the clearance or shared mooring system).
- Identification of connection points of to the WEC structure and seabed.
- A description or illustration of the point loads.
- Illustration and dimensions of the watch circle and footprint of the WEC.

TRL3-4

Provide:

- A description of the required accuracy of position of the seabed attachments in the array system.
- A description of the design tools and the methodology used to provide the characteristic load and average load of the subsystem design.
- Lists of the sub-subsystems and safety class (Appendix B).
- The characteristic load.
- Information on how many cycles the sub-subsystem must be designed to for the top five most highly flexed areas.
- Specification of the Load/force variations.

TRL 5-6

Provide:

- The load cases, specified return period, safety factor and fatigue life. Reference to separate design reports should be made where possible.
- The return periods corresponding to the characteristic loads.

Summary Table

Table 9 should be filled in to provide a summary of the information requested in the section above.

Table 8. Control Position Summary Information.

Parameter	Unit	Value	Comment
Footprint (distance to anchors)	m		
Watch circle diameter	m		
Excursion limit in the direction of prevailing wave direction of the most flexed connection point	m		
Accuracy of sea bed attachment’s	m		TRL 3-4
Connection points on seabed	No.		
Connection points on a Collect Wave Power	No.		
Number of cycles per year of the most flexed	No.		TRL 3-4
Average load (P50 load)	kN		TRL 3-4, 5-6
Characteristic load	kN		TRL 3-4
Return period for characteristic load	years		TRL 5-6
Safety factor			TRL 5-6
Safety class			TRL 3-4, 5-6
Fatigue life	(years)		TRL 5-6

5. ID 03 WAVE POWER AGGREGATION

The purpose of this section is to provide a description of the wave energy farm aggregation system at the system level. The aggregator integrates the power from a number of WECs in the wave energy farm and connects to the Electrical Wave Power Deliver System.

TRL 1-2

Provide:

- Design drawings and descriptions of the wave power aggregation system, as well as:
    - Drawings illustrating the where in the water column the aggregator is located.
    - How the WEC is connected to the Aggregation System and number of connection points.
    - Array interconnection from WEC to Aggregation system.
    - Aggregation connection to grid connection.
- Description of expected voltage levels.
- Appendix B should be filled where relevant.

TRL 3-4

Provide:

- Details of rated-, peak-, and average power levels according to detail level requested in Section 13 Power Summary.
- Details of power losses according to detail level requested in Section 13 Power Summary.
- Description of the numerical and experimental tools used to derive the power.

TRL 5-6

Provide:

- The annual average capacity factor for the aggregated useable power.
- The fatigue lives for the highest consequence elements.
- The specific capacity factors for the conduit from collect to aggregate and the other sub-subsystems by populating each element of the scatter diagram use same format as Appendix D. Example Scatter Diagrams.

Note: Capacity factor is the average power divided by the rated power. These average capacity factors should be determined through dynamic analysis in which efficiency dependencies are accounted for.

Summary Table

Table 10 should be filled in to provide a summary of the information requested in the section above.

Table 9. Power Aggregation Summary.

Parameter	Unit	Value	Comment
Average distance between WECs	m		
Length of aggregation system	m		
Number of WECs /aggregator	-		
Rated power of the Aggregation system	MW		TRL 3-4, 5-6
Export voltage level	kV		Identify AC or DC, TRL 3-4, 5-6

6. ID 04 ELECTRICAL WAVE POWER DELIVERY

The Electrical Wave Power Delivery system connects the aggregated power to the main grid at the shore. This can be via a DC or an AC connection – it could be an existing offshore hub – it could be anything that brings the power collected in the aggregation system to the shore. Other means of transporting the power to shore can be identified if appropriate.

TRL 1-2

Provide:

- Design drawings and descriptions of the electrical wave power delivery system.
- Farm grid connection layout.
- Overall dimensions of the Electrical Power Delivering System.
- Illustration of connection to Aggregator(s) and WECs.
- Details of expected voltage levels and frequency.
- Illustration of connection point(s) to Land based Grid.
- A description of materials used and ID numbers (Appendix B).

TRL 3-4

Provide:

- Details of the numerical and experimental tools used.
- Information on what grid type is suited to connect the wave energy farm (i.e. strong or weak grids).
- The "Black-start" capabilities.
- The capabilities to cap power for curtailment purposes.
- The capabilities of the wave energy farm with respect to short-term grid services.
- (such as energy storage or Automatic Generation Control (AGC), voltage and frequency support).
- A description of how power production is monitored.

TRL5-6

Provide:

- A description of the relevant grid compliance regulations to which the wave energy farm must comply. For example, describe how it complies with the requirements to provide reactive power, flicker requirements, ride through capability for specified grid disturbances and dynamic control to continue operating successfully with unbalanced or distorted grid voltages during faults.
- If relevant, a description of the supervisory control and data acquisition (SCADA) of the wave energy farm.
- The Control of real power limit (curtailment), Controlled ramp rate for real power limit, Control of reactive power output OR power factor). If inverters are part of the subsystems describe their ability to command inverter aggregate power factor control (accounting for

site transformers) and automatic voltage control and the characteristic response time of the energy storage capabilities.

- The 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 and the wave energy farm’s ability to comply.

Summary Table

See Section 13 Power Summary.

7. SURVIVABILITY AND RISK

The purpose of this section is to provide the information required for a preliminary assessment of the wave energy farm risk. Some of the areas that should be considered are:

- Survivability under extreme events from waves, wind, and current.
- Risk in the case of grid failure, grid loss, or grid interruption.
- Risk in case of collisions.

TRL 1-2

Provide:

- A description of the most susceptible subsystems (in terms of motions and loads) in the wave energy farm to increasingly energetic conditions and describe how these subsystems react to highly energetic waves or other environmental impacts.
- Details on the number of subsystems that may be significantly damaged by extreme events, grid failure, or interruption or in case of collisions.
- A description on the monitoring and control of wave energy farm operations.
- A description of any subsystem that is able to reroute power from one source to another.
- A description of how the wave energy farm subsystems can easily be detected by other users of the area.

Note: Mechanisms used for signaling to other users of the area as well as the location of the subsystems within the water column should be described with a reference to drawings.

TRL 3-4

Provide:

- Information on extreme loads and/or responses.
- The catastrophic load (the magnitude of the load (stress, force, moment), and area effected, for each subsystem (collect wave power, aggregate power, and deliver power), that causes a failure in the sub-subsystem for which the consequence class is 5) and the corresponding return periods and sea states.
- Information on 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.
- Describe any Cascade failures. Identify if failures of some sub-subsystems lead to failures of other sub-subsystems or subsystems.
- A description of the risk issues imposed to the wave energy farm in terms of circumstance and consequence. Present repair costs, loss of assets and/or loss of production.
- A 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). For this purpose, Appendix C. Example FMEC Table may be completed and adapted.

- If relevant, information on redundancy measures.
- Details on the probability class and consequence class (see Appendix A) with respect to loss of production, repair costs, or loss of assets for each relevant subsystem Appendix C. Example FMEC Table may be completed and adapted.
- A description of the subsystems within the farm that require internal power consumption (i.e. hotel load) and are internally powered and how the wave energy farm provides an un-interruptible power source (UPS) for control and communications to continue operating successfully with unbalanced or distorted grid voltages during faults.
- Details of the time it takes to get back into power generation mode once grid is re-established (assuming grid failure of less than two days).
- Information for each subsystem, if relevant, and explain how power absorption is stopped, how excess power is dumped, how overheating and/or freewheeling is avoided in relation to surviving grid failures.
- Details of the measures in the design to prevent / mitigate collisions.
- Provide a description of the circumstance, probability, and consequence in terms of repair costs, loss of assets, and/or loss of production**.** The information required includes:
    - Collisions with ships
    - Collisions with marine mammals
    - The sub-subsystem that controls position
    - Identify most exposed subsystem

For this purpose, Appendix C can be completed and adapted.

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.

TRL 5-6

Provide:

- A calculation of the financial risk for the farm if weather or operational conditions lead to:
    - Responses that result in asset consequence class 5 event.
    - Responses exceeding FLS.
    - Responses exceeding SLS during temporary conditions.
- A calculation of the financial risk for the farm of grid failures, grid losses, or grid interruption.
- A list of induced damages, if any, cost of repair of induced damages, loss of assets, and loss of production.
- A calculation of the financial risk for the farm of collision with ships, other users of the marine space and marine mammals.
- A list of damages, as a function of increasing environmental conditions, including: cost of repair, loss of assets, and loss of production or delay in first power.

8. RELIABILITY, DURABILITY, AND MAINTENANCE

The purpose of this section is to provide the necessary information required for a preliminary estimate of reliability and durability of the chosen technology involved. The more reliable the less maintenance cost and higher the availability of the wave energy farm.

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

Provide the technology classes used in the wave energy farm:

TRL 1-2: subsystems (highest level of the ID table)
TRL 3-4: subsystems and sub-subsystems (one layer deeper on the ID table)
TRL 5-6: subsystems, sub-subsystems, and components (all three layers deep on the ID table)
For this purpose, Table 11 below may be adapted, expanded, and completed.

Table 10. Identification of Technology Class.

ID	Subsystem, Sub-subsystem, Component	Application		Technology			Technology class
		Known	New	Proven	Limited history	Unproven	
01	WEC DEVICE						
0100	Collect Wave Power (Primary Converter)						
0110	Convert Power						
0111	i.e. Hydraulic rotary motor						
0120	Structure						
02	CONTROL POSITION						
03	WAVE POWER AGGREGATION SYSTEM						
04	ELECTRICAL WAVE POWER DELIVERING SYSTEM						

8.1. Reliability and Durability

The purpose of this section is to describe the reliability of the wave farm. This includes assessment of the likelihood of systems, sub-systems, or sub subsystems that could give reason for UNPLANNED maintenance (reliability), as well as identifying systems, sub-systems, or sub subsystems that will require PLANNED maintenance (durability).

TRL 1-2

Provide:

- Details, for the subsystem and sub-subsystem, of the well-known possible failure modes caused by circumstances such as: shock, chemical attack, corrosion, wear, fatigue, thermal, abrasion, corrosion, thermal overload, clogging, and photolysis, other.
- Estimates of the Mean time between failures (MTBF) for each subsystem.
- Details of the life time of subsystems (here the table below was useful).

ID	**System, Subsystem, Component**	**Failure mode**		**Technology**			**Technology class**
		Known	likely	MTBF	Life time	Fatique	
01	WEC DEVICE				50		
0100	Collect Wave Power (OWC)	X			50	x	1
0110	Convert Power (air turbine / generator)	X	x	x	20		2
0120	Structure	X			100		1
02	CONTROL POSITION						
0200	Pile Anchors	X			100		2
0210	Mooring lines	X	x		20	x	2
03	WAVE POWER AGGREGATION						
0300	Dynamic electrical cables	X	x		20	x	2
0310	Sub-sea hubs	X	x	x	20		2
0320	Intra-array electrical cables	X			20		2
0330	Substation/Platform	X			50		1
0340	Trafo station	X	x	x	50		1
0350	Intra-array electrical cables	X			25		1
04	ELECTRICAL WAVE POWER						
0410	Substation/Platform	X			50		1
0420	HVDC Trafo station	X	x	X	50		1
0430	HVDC cables	X			50		1

TRL 3-4

Provide:

- Details of the service inspection requirements at all levels.
- A FMECA style analysis for the top 10 failures (Appendix C).
- Mean time between failures (MTBF) for the top 10 failures for the subsystems.
- Details of expected warranty provisions at all levels.

- Information on the subsystems for which fatigue expected to be one of the top 3 routes for failure.

Note: 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 detail:

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?
b. What type of biofouling (flora and fauna types) is expected and on which sub-subsystems?
c. What level of corrosion is expected and what steps were taken to account for corrosion on each relevant sub-subsystem?
    a. If applicable, has the conductance between dissimilar metal types contacting sea water been quantified / mitigated?
d. Which sub-subsystems are thermally sensitive and what mitigation steps have been taken?
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.)?
f. Which sub-subsystems are sensitive to acceleration or orientation and what mitigation steps have been taken?
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)?

TRL 5-6

Provide:
- The fatigue lives for the highest consequence elements of the farm and the number of sub-subsystems that have a fatigue<lifetime of the farm.
- The number of failures over lifetime of farm (= component count * lifetime / MTBF).
- The mean time between failures (MTBF) and the standard deviations on the MTBFs for each subsystem and sub-subsystem and component within each subsystem (use ID table).

8.2. Maintenance Process and Requirements

The purpose of this section is to present a story-board description of planned and unplanned maintenance activities for the wave energy farm. This information is required for a preliminary estimate of the wave energy farm maintenance cost.

TRL 1-2

Provide:
- A description of maintenance strategies, processes, limitations, and timelines.

- A description of key systems and subsystems that require maintenance.
- Details of required equipment and infrastructure (ships).
- The quantities, size, and masses of items being maintained.
- Identification of temporary positions.
- The weather window criteria for each key maintenance process and limiting factors.
- Access time for maintenance.
- An illustration of the relationship between the maintenance operation vessel and WEC and the accessibility to the targeted objects.

TRL 3-4

Provide:

- The target annual OPEX cost for the overall wave energy farm in terms of CAPEX and details of how much of this is included for insurance.
- Details of subsystems with manufacturer recommended services / inspections.
- Details of spare part accessibility.
- Information on the maximum array size (MW capacity) that can be serviced by one maintenance vessel.
- Information on the number of PLANNED and UNPLANED maintenance events per MW per year and how will this change over the lifetime of the farm.
- Details of the duration of the round trip travel time plus maintenance time for each intervention.
- The weather window criteria for each subsystem (include vessels and device dynamics).
- Information relating to access for maintenance vessels within the array layout and personnel transferred to the WEC.
- A description of the modularity and the location of the sub-subsystem within the subsystem (enclosed spaces in the WEC at sea and the duration required to ventilate).
- The number of assembly steps and connections that need to be made for a maintenance event (including time taken), where in the water column and expected subsystem dynamics.
- Details on the vessels required including the sensitivity to external factors and information on the number of competing vessels available.
- A description of the condition based maintenance strategies (i.e. information on tasks that cannot be stopped before completion and stability characteristics in case of the disconnected systems or sub-systems that are disconnected in water).
- The criticality of tasks being stopped before completion.
- Legal factors like overtime hours, regulatory mandates to supervise the workforce, safety training, etc. will influence the cost of maintenance.
- A completed version of Table 12. It should be completed and adapted providing estimates of relevant capacity reduction of the farm as consequence of each activity.

Table 11. Maintenance Planning.

ID		System, Subsystem, Component	Target lifetime	Planned maintenance			Unplanned maintenance		
				Target frequency	Expected downtime	Farm capacity reduction	Target frequency	Expected downtime	Farm capacity reduction
01		WEC DEVICE	20						
	0110	Primary absorber	20	1/5y	2w	1%	1/40y	6m	15%
	0120	Power Conversion							
		…							
02		WAVE POWER AGGREGATION SYSTEM							
03		ELECTRICAL WAVE POWER DELIVERING SYSTEM							
04		…							

- The identified top 10 highest impact failures in subsystems and sub-subsystems. Table 13 below may be used and adapted.

Table 12. Maintenance Summery for 10 Highest Impact Failures.

Issue	Unit	Highest impact failure in systems and sub-system					
		1	2	3	4	5	…
Frequency of failure (Unknown if unverified)							
Standard deviation of failure							
The power capacity reduction consequence of each							
The anticipated total downtime							
Cost of spare parts							
The anticipated total downtime							
The waiting time for spare parts?							
The time required to repair each (including access time)							

Location of repair or replacement (on-shore, off-shore, harbor, etc.)							
Distance to maintenance location							
Cost of vessel required							
Cost of repair and labor							
Other costs							

Note: Refer to initial FMEC in answering these questions

TRL 5-6

Provide:

- An updated version of Table 13 to include all significant failures in subsystems and sub-subsystems.
- 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.
- Number of services over lifetime of farm
- (= number of components * farm lifetime / duration between services).
- Calculate the financial risk for the farm if weather or operational conditions lead to loads and/or responses exceeding SLS during temporary conditions.

Note: consider increasing environmental conditions, list damages, cost of repair, loss of assets, loss of production or delay in first power.

9. AVAILABILITY

The purpose of this section is to provide information on the availability of the wave energy farm. Availability factor expresses on an average annual basis how much power is lost due to planned and unplanned maintenance.

TRL 1-2

Provide:

- Details of the target availability for the overall wave energy farm.
- Details of subsystems with failure modes with consequent reduction in power production.
- Information on power capacity reduction as a consequence of failures on an annual basis.
- A description of any redundancy in the subsystem.

TRL 3-4

Provide:

- Details of the subsystems that 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).
- Identify redundancy in the aggregation points and power delivery system (e.g. other routes for the power to get to the grid).

TRL 5-6

Provide:

- The 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))

10. MANUFACTURING AND TRANSPORTATION

The purpose of this section is to provide a story-board description of the key stages of the manufacturing and production and transportation processes involved in building the wave energy farm.

TRL 1-2

Provide:

- A description of the production processes and facilities, key activities at factory, at harbor or in the ocean (final assembly).
- Details of subsystems of technology class 3 & 4 that need to be custom-manufactured and the quantity.
- A description of the transportation process.
- Key dimensions and masses of subsystems being manufactured.
- Envelope dimension of parts that needs to be transported to the installation staging point.
- A description of the workforce expertise level needed to construct subsystems within the wave energy farm.

TRL 3-4

Provide:

- An estimate of the cost to manufacture all complete subsystems, using a single production facility.
- Details of unit costs of material type and volume.
- Details of identified companies to supply and manufacture subsystems and sub-subsystems.
- Information on the number of transportation trips and distance per WEC unit, of custom manufactured subsystems, sub-subsystems, and components.
- Details of the number of available competing means of transport.
- A description of the mechanisms employed to achieve and maintain necessary alignment.
- Details of the key transportation and storage activities including the supply chain.
- An estimation of time spent in each key stage of the production.
- A description of different manufacturing techniques used and which can be automated and which for each subsystem and sub-subsystems (i.e. rolling steel, welding steel, winding fiberglass, etc.).
- Information on the adaptability of the manufacturing techniques/infrastructure to other locations.
- A description of the key interfaces between parts that need to be assembled and the Quality Control measures.

TRL 5-6

Provide:

- The expected manufacturing rate in day/MW for all complete subsystems.

- Describe, at all manufacturing levels, what level the manufacturing techniques can be automated.

Summary Table

Table 14 should be filled in to provide a summary of the information requested in the above section.

Table 13. Fabrication Summary.

Description	**Unit**		**Comment**
Manufacturing rate, and standard deviation	in days / MW		TRL 3-4, 5-6
Transportation cost	$/MW		TRL 3-4, 5-6
Transportation distance	km		
Manufactured capacity rate, and standard deviation	MW/Year		TRL 3-4, 5-6
Workforce	Man hours/day		

11. INSTALLATION

This section describes how the subsystems of the wave energy farm will be installed. The installation process must consider the weather conditions, the required time to complete each part of the installation, maximize the use of readily available vessels, and minimize the need for skilled workers.

TRL 1-2

Provide:

- A story-board and description of the key stages and activities, including time lines, of the installation process of the wave farm. Identify critical operations carried out in temporary conditions that cannot be interrupted.
- A description of assembly points and connections.
- Details on the required equipment and infrastructure (types of installation vessels & ships).
- An estimation of continuous duration of weather windows required in each key stage of the deployment and installation process and any limiting factors, including access time required.
- The masses and envelope sizes of subsystems being transported to and maneuvered within the installation area.
- Mechanisms that collect wave power, aggregate power, deliver power, and control position.
- Details and drawings if appropriate, of the main systems being transported to their deployment location.
- Drawings of the subsystems orientation in temporary conditions versus in deployed operational conditions.
- A drawing of the array layout of WECs with an indication of access for installation vessels.

TRL 3-4

Provide:

- The MW of rated power (at point of grid connection) can be installed per year.
- Details on the number of trips required per installed MW. (Note: exclude the possibility of multiple installation teams working in parallel to assess rate of installation.)
- Weather window specifications and considerations to the capabilities of the vessels and the dynamics of the device and specific task.
- The number of assembly steps and connections that need to be made at the installation point (including time taken), where in the water column and expected subsystem dynamics.
- The number of vessels required for assembly procedures.
- Information on the number of competing vessels that can be used.

TRL 5-6

Provide:

- The time it takes to tow the subsystems to installation site.
- Details of the planned duration of each assembly step and/or connection during installation.

Summary Table

Table 15 should be filled in to provide a summary of the information requested in the above section.

Table 14. Installation Summary.

Description	**unit**		**comment**
Trips / MW			
Number of assembly steps / connections			
Time to complete each assembly step	hours		
Tow out time to installation point	hours		
Installation rate	MW/Year		TRL 3-4, 5-6
Weather window criteria	X % for each month		TRL 3-4, 5-6
Average length of weather window / year	hour		TRL 3-4, 5-6
Workforce	Man hours/day		TRL 3-4, 5-6
Transportation cost	$/MW		TRL 3-4, 5-6
Vessel costs (total fleet)	$/day		TRL 3-4, 5-6

12. WAVE ENERGY SAFETY (FOR PERSONNEL)

This section addresses the safety requirements to activities with humans involved, particularly at sea. The wave energy farm shall be safe for personnel and third parties at each stage of its lifecycle.

TRL 1-2

Provide:

- A story board and description of the safety philosophy and how it is implemented.
- Describe if there is a threat to human health and safety during any of the life cycle stages of the wave energy farms lifecycle: construction, deployment, operation & maintenance and disposal stage.
- The target maximum safe sea state for safe maintenance.
- Details if personnel are required to transfer from a ship to the device at sea, if personnel are to enter enclosed spaces at sea and if personnel are required to work in or under the sea (e.g. divers).
- Details on 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).

TRL 3-4

Provide:

- Information on any challenging features with respect to safety legislation (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").
- Using a systematic risk assessment methodology identify potential hazards in the work 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.) For this purpose Table 16 may be used or adapted**.**
- Details on the level of specialist training of personnel required to access the device at sea.
- Information on the duration periods of skilled maintenance (e.g. impact of workers' fatigue).
- A description of possible accidental and temporary states during maintenance, installation activities.
- Design considerations made to prevent injury during accidental states, to personnel, and 3rd parties, including measures in the design to prevent / mitigate the increased probability of injury during accidental states (injury to 3rd parties should be considered as well as injury to personnel).
- Details on the number of connections that involve hands on human work at sea (e.g. connecting moorings or connecting crane hooks).
- Information on the use of remotely controlled operations versus onsite operations.
- Details on the number of remotely monitored sensors versus onsite inspection.
- Information on arrangements for escape from the device at sea.

- A description of the risk of fire while people are onboard, risk of contact with dangerous chemicals or liquids and the need for a detection and suppression system.

Table 15. Risk Matrix Concerning Safety.

Risk Register										
ID	**Risk Level category**	**Description of risk**	**Risk ownership**	**Risk status**	**Probability Class**	**Consequence Class**	**Risk ranking**	**Mitigation**	**Contingency**	**Impact**

TRL 5-6

Provide:

- The projected number of serious accidents over the lifetime of the farm that can be attributed to the wave energy farm during maintenance, installation, etc.
- Details of the relevant Health and Safety documentation that should be submitted as required at deployment site.
- A list of regulatory applications submitted.
- A description of how the safety level will change as a function of the percentage of global wave energy capacity exploited.

13. POWER SUMMARY

The purpose of this section is to summarize information related to power throughout the entire wave energy farm.

TRL 1-2

Provide:

- The expected wave farm rated power.
- A description of any aspects of the system that could decrease power production.
- Any data relevant to estimating/verifying power absorption or transfer.
- Details of each stage of Power Conversion: Absorbed Power, transportable power, (re-circulated power), power aggregation, electrical power delivery and PoC. Aspects that should be considered are:
    - Target peak power values.
    - Estimated average power values.
    - Expected power losses (efficiencies).

TRL 3-4

Provide:

- Details of each stage of Power Conversion: Absorbed Power, transportable power, (re-circulated power), power aggregation, electrical power delivery and PoC. Aspects that should be considered are:
    - Peak power values.
    - Average Power values.
    - Power losses (efficiencies).
    - Rated Power values.
    - Variability in power—diurnal, seasonal, and over the year.
    - The annual average of consumed power in ancillary systems.
    - Scatter diagram.

TRL 5-6

Provide:

- The worst (10^{th} quantile) average annual power production at PoC.
- The best (90^{th} quantile) average annual power production at PoC.
- Details of any power production cycles i.e. diurnal / seasonal.
- Standard deviation of average annual power production at PoC over a 10-year period.
- The theoretical global wave energy capacity that is suitable for capture by the wave energy farm (estimated global size of the resource that can be exploited by the wave energy farm taking into account physical site conditions, manufacture and installation logistics and port infrastructure).
- Details on any particular features that makes the wave energy farm less likely to be forecastable than a wave energy farm with other technologies; in the sub-hourly, hourly, or 24-hour time frames.

- The directionally spread average and peak absorbed power values presented in the occurrence scatter diagram (see Appendix D. Example Scatter Diagrams).
- For each step in the conversion process (absorbed, transportable, electrical, aggregated, and delivered) please indicate:
  - Pr (rated power)
  - P_{avei} (average power production in the i^{th} bin of the scatter diagram (power matrix))
  - P_{maxi} (peak power in the i^{th} bin of the scatter diagram (power matrix)
  - ζi (percent occurrence in the i^{th} bin per year)
  - $Eff_{a\ I}$ (average efficiency of the i^{th} bin)
  - $Eff_{max\ i}$ (maximum efficiency of the i^{th} bin)
- Details of the modeling techniques used to calculate the given values.

Note: An Appendix D style diagram can be used to detail relevant information and the Summary Table below should be completed and may be adapted.

Summary Table

Table 17 should be filled in to provide a summary of the information requested in the section above.

Table 16. Summary Table for the Power Conversion Data.

Parameter	**Unit**	**Value**	**Comment**
Rated Power of wave energy farm	MW		
Average power values	MW		TRL 3-4, 5-6 Incl. efficiency losses
Variability in annual power	MW		TRL 3-4, 5-6 inter-annual
Annual average of RMS efficiency	%		TRL 3-4, 5-6
Largest energy recirculation per WEC rating	MW		TRL 3-4, 5-6 time scale of 20sec
The annual average of consumed power in ancillary systems	MW		TRL 3-4, 5-6
What is the largest energy recirculation (maximum time scale of 20sec) in comparison to the device rating?			TRL 3-4, 5-6
MW rating of the grid the wave energy farm is connected to	MW		
Capacity Factor of Average annual Power delivered			TRL 3-4, 5-6
Average power at POC	MW		TRL 3-4, 5-6
Fatigue life	Years		TRL 3-4, 5-6

14. COST SUMMARY

The purpose of this section is to summarize information related to cost of energy which can be used to calculate an estimate of LCOE estimate and the variation on cost of energy.

$$LCOE = \frac{ICC \times FCR + AOC}{AEP}$$

$LCOE$	Levelized cost of energy (\$/MWh)
ICC	Initial capital cost per installed capacity (\$/MW)
AOC	Annual operating expenses per installed capacity (\$/MW/year) $$AOC = O\&M(1-T)$$
AEP	Annual energy production per installed capacity (MWh/MW/year = hours/year) $$AEP = CF_{net} \times 365 \times 24$$
FCR	Fixed charge rate calculated to be $10.8\frac{\%}{year}$
$O\&M$	Annual operations and maintenance cost per installed capacity (\$/MW/year)
CF_{net}	Net Capacity Factor, averaged over typical year (%). Note: Must be derived using the installed capacity to determine the potential output.

TRL 5-6

Net Annual Energy Production (AEP)

Provide:

- The wave farm rated power.
- The expected Annual Energy Production.
- The power capacity reduction as a consequence of failures on an annual basis.
- The annual average of the wave energy absorption capability of the WEC plant.

CAPEX

Provide:

$$materials\ and\ component\ costs = \sum COM - RR$$

COM Cost of materials and components
RR Recycling revenues of the sea-state(s) that correspond to the characteristic structural load

$$manufacturing\ costs = \sum(LH * LC + TEH * TEC + SH * SC) - CO$$

LH Labour hours LC Unit cost of labour TEH Hours of use of tools and equipment TEC Unit cost of tools and equipment	SH Hours of storage SC Unit cost per hour of storage CO Cost offsetting

$$transportation\ costs = \sum_{\substack{All\ means\\ of\ transport}} (hours\ or\ distance\ of\ trasportation * unit\ cost\ of\ transportation)$$

$$installation\ costs = \sum_{\substack{All\ means\\ of\ installation}} (EHOU * EUC + EHOS * SEUC + EMC) + \sum_{\substack{All\ labor\\ types}} (LH * LC + LHOS * LSC + LMC$$

EHOU Equipment hours of use EUC Equipment unit cost EHOS Equipment hours of standby SEUC Standby equipment unit cost EMC Equipment mobilization cost	LMC Labour mobilization cost LH Labour hours LC Unit cost of labour LHOS Labour hours of standby LSC Labour standby cost

The contingency for the construction and installation schedules.

OPEX

Provide:

$$Average\ annual\ cost\ of\ planned\ maintence = lifetime\ of\ farm * \sum_{\substack{All\ servicing\ types\\ All\ systems}} \left(\frac{servicing\ cost}{time\ between\ services}\right)$$

$$Average\ annual\ cost\ of\ unplanned\ maintence = \sum_{\substack{All\ systems\\ All\ modes\ of\ failure}} \left(\frac{Lifetime\ of\ system}{MTBF} - 1\right) * Cost\ of\ repair\ for\ failure$$

- 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)
- Cost for monitoring the farm over the lifecycle including the monitoring cost to ensure environmental acceptability.

Uncertainties

Provide:

- Details on the uncertainties and external factors that may make CapEx, OpEx, energy production, and availability deviate from expectations and calculate the standard deviations on cost of energy estimates incorporating all of the uncertainties.
- The inter-annual variability in net capacity factor for the wave energy farm.
- The magnitude of energy production to errors in the wave resource (sea conditions) prediction.
- 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).
- 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).
- 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).

15. BENEFIT SOCIETY

The purpose of this section is to summarize information related to the impacts of a wave energy farm on society.

TRL 1-2

Provide:

- The estimated number of jobs the farm will contribute to the local community in units of FTE/GW (the full time equivalent jobs per GW installed capacity).
- Details for each lifecycle stage, describing the Green House Gasses (GHG) beyond those resulting from typical office work that are released.
- A description of the parts of the wave energy farm subsystems that cannot be recycle.
- Information on the subsidies or credits to match the market competitive electricity costs required for the development of the wave energy farm.

TRL 3-4

Provide:

- The number of components of the farm to be manufactured near the deployment location.
- Details relating to installation and maintenance activities that can employ local ship owners.
- Information relating to other local jobs as a result of the wave energy farm development.
- A description of how local infrastructure will be improved by the development of the wave energy farm (e.g., infrastructural upgrade of roads, harbors, communications, grid, etc.).
- Information on any ancillary benefits for the local community that can be contributed to the wave energy farm (such as coastal erosion protection, tourist draw, fish nursery, etc.)
- A description of system boundaries used to determine the global warming potential.
- The upstream (raw materials, construction, and installation) GHG emissions in grams of carbon dioxide equivalent per kilowatt hour (gCO2eq/kWh).
- The operations (including maintenance) GHG emissions in grams of carbon dioxide equivalent per kilowatt hour (gCO2eq/kWh).
- The downstream (decommissioning, disposal, and recycling) GHG emissions in grams of carbon dioxide equivalent per kilowatt hour (gCO2eq/kWh).
- A description of the amount of pollutants (solids, liquids) in the manufacturing and operation process.
- Details of the sub-subsystems that cannot be recycled and why.
- Details on how many times will the subsystems and sub-subsystems of the wave energy farm need to be replaced to achieve the lifetime of the farm.
- The target learning rate expressed in a progress ratio.

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Provide:

- The number of local jobs, in FTE/GW, that will be created in the following areas as a result of the farm's deployment in an area due to:
    - construction (manufacturing and assembly of portions of the farm)
    - Installation and maintenance
    - control center operation
    - outreach and marketing
    - legal
    - estimated tax revenue for the local community that this farm will produce
    - cost-savings or revenue generation that results from the identified ancillary benefits
- The life-cycle global warming potential of this farm in grams of carbon dioxide equivalent per kilowatt hour (gCO2eq/kWh).
- The percentage of waste that the wave energy farm will produce over its lifetime from replacement parts.
- The percentage should be given according to: Σ(replacement part weight) / Σ(originally installed weight).

16. REFERENCES

1. D. Bull, R. Costello, A. Babarit, K. Nielson, C. Bittencourt Ferreira, B. Kennedy, R. Malins, K. Dykes, J. Roberts, J. Weber, "Technology Level Performance Assessment Methodology." SAND2017-4471. Sandia National Laboratories, Albuquerque, NM, April, 2017.

APPENDIX A. DEFINITIONS

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 fulfill 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.

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

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

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.

APPENDIX B. EXAMPLE EXPANSION SYSTEM ID TABLE

The table below shows as an example how additional rows of information can be inserted at each item. Further rows could be added such as type of material and unit costs.

ID	Subsystem(i.e. 01), Sub-subsystem(i.e. 0100), Component(i.e. 0101)	Function	Target Average Efficiency (%)	Target Rated Power (MW)	Target Average Power (MW)	Target time scale	Safety class	Number per WEC device or farm
01	WEC DEVICE							
0100	Collect Wave Power (Primary Converter)	Collect Wave Energy						
0101	5m OD, 7m long cylindrical tubes	Floating bodies interacting with waves						
0110	Power conversion	Convert Wave Energy						
0111	Hydraulic Cylinder							
0120	Supporting structure	Provide structure for support						
02	CONTROL POSITION							
0201	Anchors	Maintain average position of WEC						
0202	Mooring lines	Maintain average position of WEC						
03	WAVE POWER AGGREGATION SYSTEM							
04	ELECTRICAL WAVE POWER DELIVERING SYSTEM							

APPENDIX C. EXAMPLE FMEC TABLE

The table below shows as an example of a FMEC analysis.

ID	System, Subsystem, Component	Issue 1			Issue 2
		Circumstance	Consequence	Probability	
01	WEC DEVICE				
0100	Collect Wave Power (Primary Converter)				
0110	Convert Power				
0120	Supporting structure				
02	CONTROL POSITION				
03	WAVE POWER AGGREGATION SYSTEM				
04	ELECTRICAL WAVE POWER DELIVERING SYSTEM				

APPENDIX D. EXAMPLE SCATTER DIAGRAMS

The scatter diagrams below show examples of inserting data of interest from the device operation or the wave environment (efficiencies, power values, occurrences, etc.) in the scatter diagram with the shading representing either the sea state occurrence or the energy occurrence of the sea state.

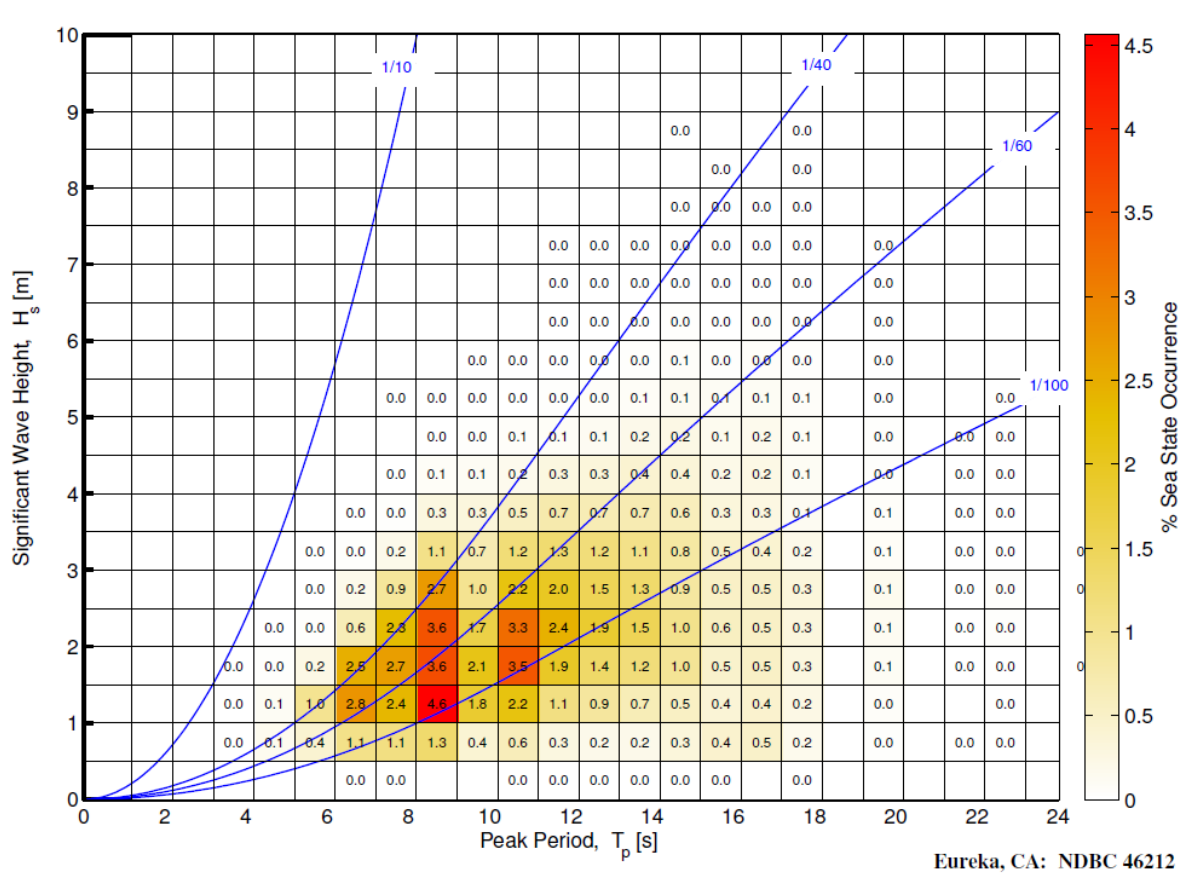

Figure 1. Sea State Occurrence in % per year per bin.

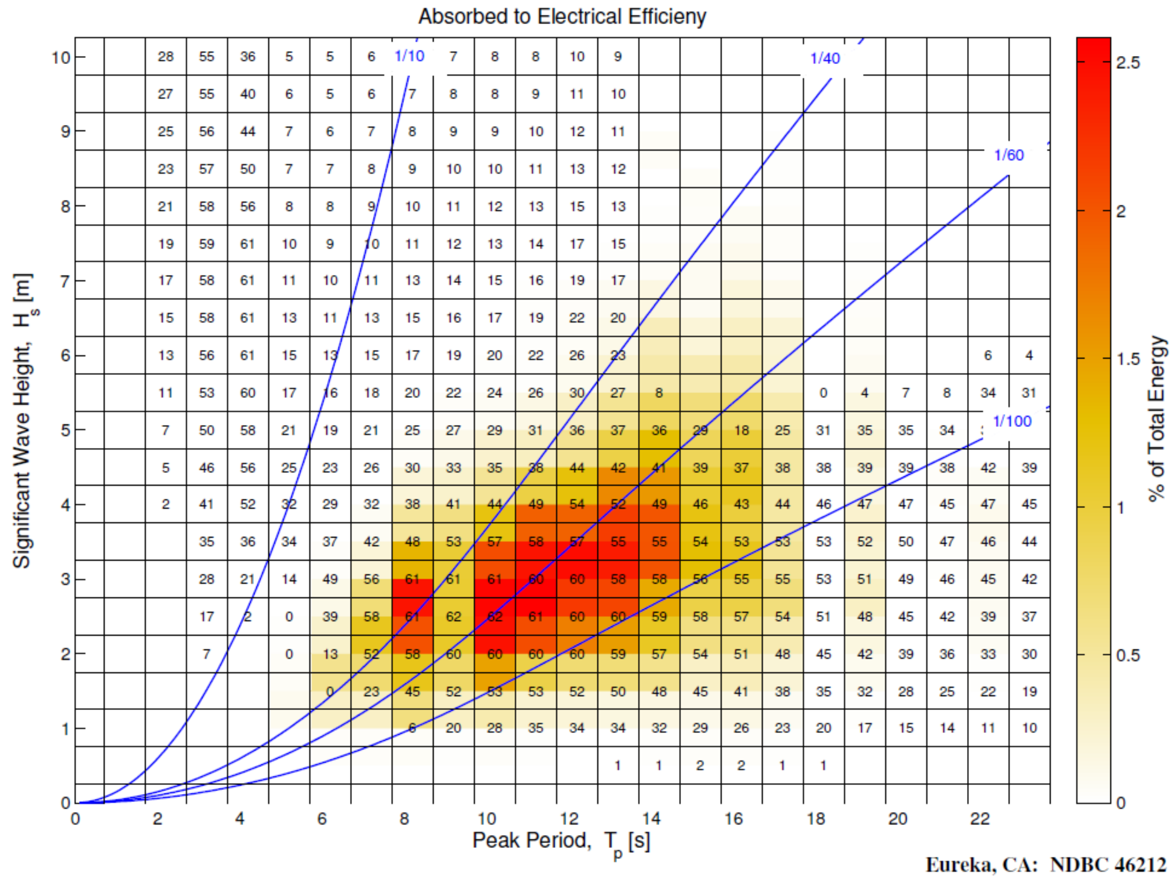

Figure 2. Conversion Efficiency Form Absorbed Pneumatic Power to Electricity in % Each Bin of the Scatter Diagram.

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