SANDIA REPORT

SAND2017-4507
Unlimited Release
April 2017

Systems Engineering Applied to the Development of a Wave Energy Farm

Version 1.01

Diana Bull, Ronan Costello, Aurélien Babarit, Kim Nielsen, Claudio Bittencourt Ferreira, Ben Kennedy, Robert Malins, Kathryn Dykes, Jesse Roberts (co-PI), and Jochem Weber (PI).

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ACKNOWLEDGEMENTS

This work is part of the Wave-SPARC Project. This work was funded by the U.S. Department of Energy’s Wind and Water Power Technologies Office under contract number DE-AC36-08GO28308 with the National Renewable Energy Laboratory and contract number DE-AC04-94-AL85000 with Sandia National Laboratories. The National Renewable Energy Laboratory is a single-mission laboratory and operated by the Alliance for Sustainable Energy. Sandia National Laboratories is a multi-mission laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration.

A special thanks to Mattie Hensley who assisted as a technical writer in the development of this document.

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INTRODUCTION

In order to assist and facilitate better technology development in wave energy the authors undertook a Systems Engineering exercise to formally develop the requirements for a successful wave energy farm. The resulting requirements are expressed as capabilities and functions.

- The capabilities are the goals of a Wave Energy Farm as determined from an analysis of the stakeholder needs.
- The functions are the activities or behaviors which must be performed by the Wave Energy Farm in order to achieve the capabilities (i.e. actions to achieve the goals).

The capabilities and functions are requirements of the wave energy farm rather than the individual sub-systems, such as individual wave energy converters.

A motivation for undertaking this stakeholder requirements analysis and Systems Engineering exercise is to document the requirements for successful wave energy farms to facilitate better design and better design assessments. A difficulty in wave energy technology development is the absence to date of a verifiable minimum viable product against which the merits of new products might be measured. A consequence of this absence is that 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) [1, 2]. 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 stakeholder requirements and particularly economic viability required for market entry.

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 formal process which involves analyzing customer and stakeholder needs through the discipline of Systems Engineering offers a method to develop the requirements that will enable technical solutions that comprehensively address the needs of the stakeholders.

Chapter 2 in this document presents the wave energy farm capabilities. The taxonomy outlines the goals that the wave farm technology must be able to achieve to satisfy stakeholder needs. The capabilities are intended to be independent of the technology or design solution.

Chapter 3 in this document details the development of the wave energy farm functions. The taxonomy outlines the actions a wave farm must be able to perform in order to meet the stakeholder goals. High-level functions are independent of the technology or design used to implement the function. However, detailed functions may begin to border on specific design choices. A strong effort has been made to maintain functions that are design agnostic.

Development of the Technology Performance Level (TPL) [3, 4] as a counterpart to the TRL is complementary to the Systems Engineering reported in this document. The capabilities and functions reported here form the basis for the revised Technology Performance Level (TPL) scale and assessment methodology that are under development by National Renewable Energy Laboratory and Sandia National Laboratories in the Wave-SPARC project [5].

SYSTEMS ENGINEERING

A wave energy farm is a complex system. The WEC, which itself is composed of multiple sub-subsystems like the power conversion, is just one subsystem in the farm. The mooring and anchoring, the point at which power is aggregated, the control center and monitoring equipment, and the delivery of electricity are all additional subsystems. There are competing goals for each of these subsystems and hence determining an optimal solution can only occur through a systems level understanding of the farm. Thus it makes sense to apply Systems Engineering to this problem. Surprisingly, there is no publicly available reported work on the application of Systems Engineering to wave energy farms. The analysis gives the requirements of a wave energy farm when wave energy is at a worldwide maturity of several GW. The requirements for a successful WEC unit will follow from the requirements for a successful wave energy farm.

Systems Engineering is a rigorous application of processes and methods across a system's life cycle in order to ensure the adequacy of a system. The heart of Systems Engineering is a step-wise decomposition and flow down of stakeholder needs to each element of the system. The decomposition, flow down, and tracing of allocations ensures that the requirements and specifications for each subsystem, assembly, and component fully reflect and address stakeholder needs and adequately contribute to overall system performance. Systems Engineering is most influential in the early stages when setting a mission and evaluating the stakeholders' perspectives in the context of the environment in which the system will operate, hence the relevance to the current phase of wave energy technology development. The analysis outcomes are used first to create a functional architecture for the system and to decompose the stakeholder needs while allocating them to the system functions as requirements that are independent of the technology. The Systems Engineering work then continues through the development process to decompose the function-level requirements into specifications for each element of the physical design and to create the technical performance measures used to verify the design and validate the final system. The Systems Engineering process does continue through the rest of the system life cycle to provide the framework against which systems operations and maintenance are measured and candidate upgrades are evaluated. Numerous examples of the success of the Systems Engineering approach can be found in the aerospace, defense, automotive, and oil and gas industries. This program has followed guidance from ISO 15288 [6], as well as IEEE 1233 [7] with some tailoring according to the process described in ISO 15288 Annex A.

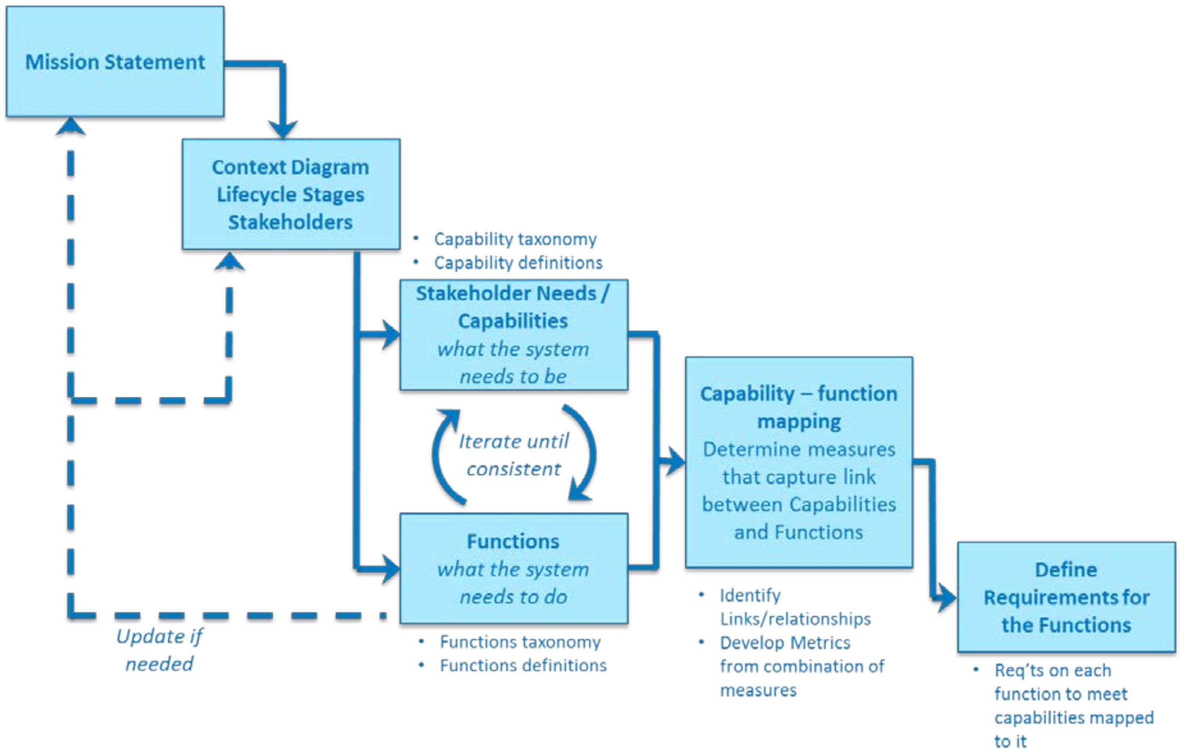

Figure 1: The Systems Engineering process applied to a Wave Energy Farm.

The Systems Engineering process used in this project is illustrated in Figure 1 and is a tailored version of the first steps of ISO 15288 (technical processes 6.4.1 to 6.4.4) [8]. The first activity was to develop a concise mission statement for the system (i.e., the wave energy farm {WEF}). This statement sets the framework for the development of the stakeholder needs and the functions. Capabilities and functions are hierarchical structures (i.e. taxonomies). In the case of capabilities, the taxonomy embodies the list of characteristics that are desired, from the perspective of the stakeholders, for the system to be successful. In terms of the functions, the hierarchy represents the solution agnostic (i.e. independent of specific design embodiments) actions that the farm must be able to perform to meet the stakeholder requirements. As indicated in Figure 1 several iterations between the capabilities and functions were needed to ensure completeness and these iterations also led to some revision of the mission statement and some revisiting of the stakeholder perspectives to ensure they were fully represented.

Fundamentally the capabilities and the functions are intimately tied together. The capabilities capture the stakeholder needs and desires in a distilled manner prior to selecting technologies or design approaches. The functions define the fundamental actions that the system must be able to perform in order to achieve the mission and deliver the capabilities. The functions identify what the system must *do* in order to achieve what the system must *be,* i.e. the capabilities.

The Systems Engineering herein considers the following as the mission of the wave energy farm:

The wave energy farm will convert ocean wave energy to electricity and deliver it to the continental grid market in a competitive and acceptable manner across the lifecycle.

The precise language used in this mission statement allows for changing landscape whilst still specifying the application. Continental grid market means a very large grid market rather than any specialized niche market. The word "competitive" in the mission statement sets a relative levelized cost of energy (LCoE) that will be driven by local market conditions (investors' appetite for risk, offering of feed-in tariffs, etc.) and is considered in relation to the LCoE of other energy types. Competitive encompasses concepts of cost, availability, investor attractiveness, government incentives, and risk. Finally, "acceptability" incorporates the environment, regulation, insurability, safety, socio-economic, and social considerations.

An overview of the full Systems Engineering process can be found in [9]. As the Wave-SPARC project progresses, it is expected that small updates will continue to be made to the taxonomies of the functions and capabilities that will also influence the TPL assessment methodology and scoring criteria. In fact, meaningful updates can already be seen from [10].

1. WEC FARM CAPABILITIES

The requirements of each individual stakeholder have been condensed into a distilled list of properties that ensure the WEC farm will achieve all the needs of each stakeholder. This list of stakeholder needs (or capabilities) is now presented below.

Analysis of stakeholders' needs leads to the specification of seven high-level stakeholder requirements. 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 sublevel. For example, the sub-capability 'C1.1 Have as low a CAPEX as possible' require the satisfaction of the following sub-subcapabilities: 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 2 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 [10].

Tradeoffs in the overall design manifest themselves in the competing capabilities. 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 should be large. Assessments such as the TPL which are built on these capabilities are designed to reflect these tradeoffs to give a balanced system score.

In [3, 4], the original technology performance levels papers, TPL groups and attributes were identified through experience, these are now recognized as being very close to the stakeholder needs that we now refer to as the capabilities. Future refinement of the TPL first presented in [3,4] and used for the Wave Energy Prize [11] will be based on the capabilities as presented here.

The capabilities are customer focused rather than technology focused which is in keeping with the Systems Engineering philosophy.

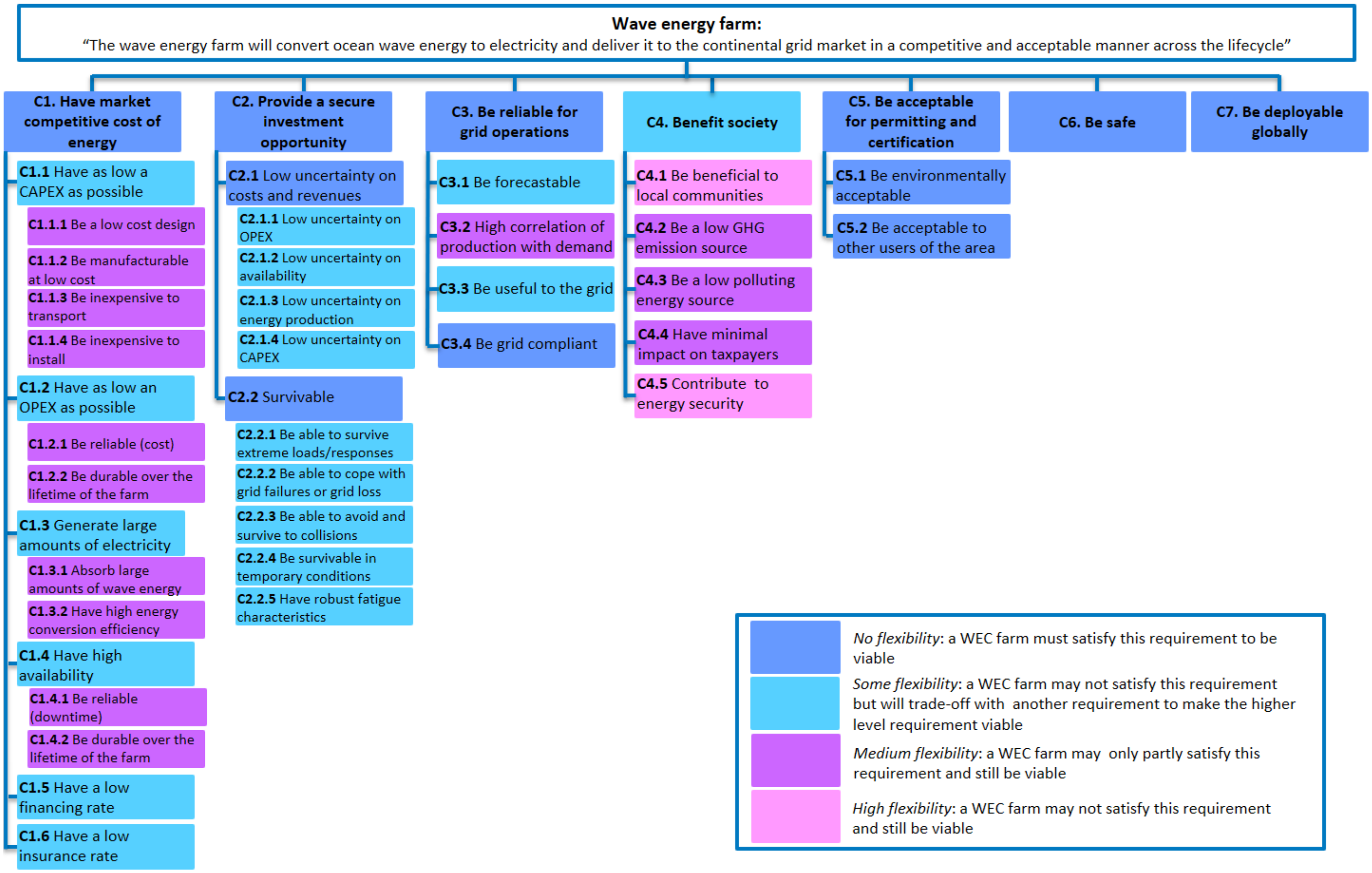

Figure 2. Capabilities taxonomy.

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 2.

Wave Farm Capabilities

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/states. There may be feed-in tariffs, renewable energy certificates, or renewable obligations for wave energy or renewable energy sources. Some countries/states may also require that a certain percentage of the energy portfolio of utility companies is from renewable energy sources. The sub-tier 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.

- 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 [12]:

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

$LCoE$	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”

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.

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.

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.

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.

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.

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.

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.

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.

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.

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.

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.

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**.

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.

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.

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.

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.

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.

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.

C.2.2.2. Be able to survive 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.

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.

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.

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.

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.

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.

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.

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.

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).

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.

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.

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.

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).

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.**

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.

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.

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.

2. WEC FARM FUNCTIONS

This chapter focuses on the development of the functions. The functions define the fundamental actions that the system must be able to perform in order to achieve the mission and deliver the capabilities. They identify the behaviors the farm must possess, i.e. the farm must be able to generate and deliver electricity from wave power. High-level functions are independent of the technology or design used to implement the function. However, detailed functions may begin to border on specific design choices. Hence a strong effort has been made to maintain functions that are design agnostic.

It should be noted that in the case of a Wave Energy Farm, the WEF is the 'system' that is being considered and optimized. The system is further broken down into subsystems and sub-subsystems and so on. These subsystems and sub-subsystems may not be individually optimized, but when combined to form the farm an optimal system can been generated. Examples of the subsystems are the wave energy converters (WECs) or electrical substations while an example of sub-subsystem is the PTO or generator within a WEC.

Figure 3 shows the taxonomy of the functions that were determined as necessary to achieve the capabilities. The functions identify what the system must *do* or a behavior the system must have. The top level functions (5 of them) conceptually identify what the WEF must do to meet its mission. The sub-functions below the top levels further decompose the top level functions. These subfunctions identify the unique aspects that must be achievable to satisfy the higher level function. Further breakdown is given to subfunctions in the form of sub-subfunctions, further focusing in on the details that are needed. In all cases, sub-levels identify all the aspects that must be achieved to fully satisfy the higher level.

Wave Energy Farm Functions detail the definition of each of the functions shown in Figure 3. These definitions should be used to elucidate the intent of each function. Development of these functions has occurred following guidance from: ISO 15288 [6], IEEE 1233 [7], and Systems Engineering handbooks from INCOSE and NASA [13]. Since the functions are presented with generic/abstract terminology the lowest level of each function highlights a specific technical solution as an example of satisfying the functions intent.

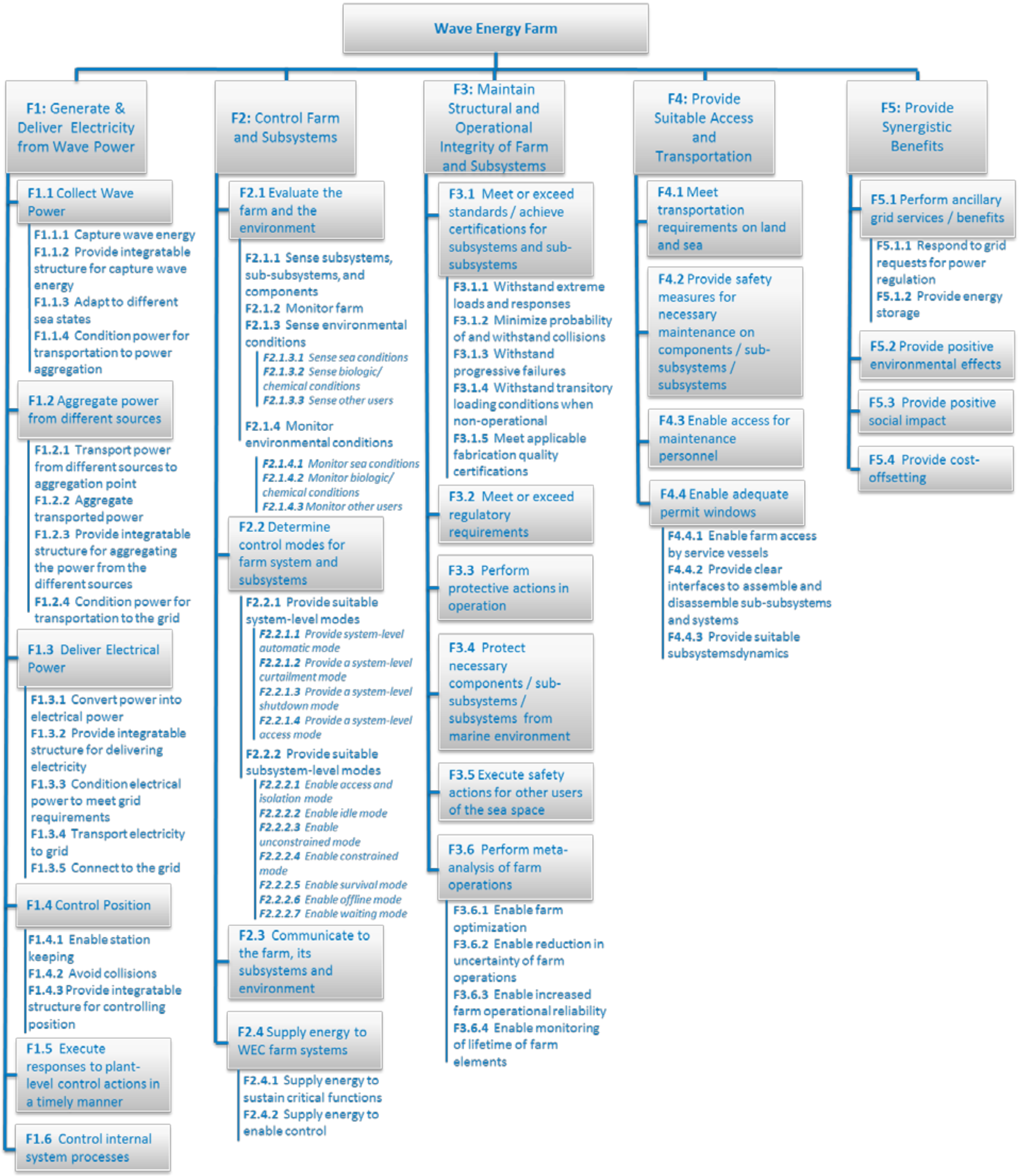

Figure 3: Taxonomy of the functions.

In total 81 functions, subfunctions, sub-subfunctions, and sub-sub-subfunctions have been identified in this taxonomy; however there are only 62 unique functions needed to achieve the WEF mission.

Note: this figure is hyperlinked, press the Control key and click on any function to be directed to the text that fully describes the function. Where pictured, click ▲ *to return to Figure 3.*

Wave Energy Farm Functions

F.1. Generate and deliver electricity from wave power

The farm shall intercept the incoming hydrokinetic power in the ocean and convert it into electricity. The aim of this function is to generate as much power as possible. Within the farm there are four key subsystems that enable the generation and delivery of electricity: the subsystem that collects wave power (typically the WEC), the subsystem that controls position (typically the mooring), the subsystem that aggregates the collected power (typically a substation), and the subsystem that delivers the electricity (typically a seabed export cable, or sometimes a pressure pipeline).

F1.1. Collect wave power

The farm shall intercept the incoming hydrokinetic power in the ocean resulting in kinetic motion and convert this into transportable power.
Ex: a WEC unit

F1.1.1. Capture wave energy

This function is usually implemented by the combined actions of the primary absorber, the supporting structure, and the PTO of the WEC units with the incoming and outgoing waves. The motions of the primary absorber are forced by the incoming and scattered waves and in turn create radiated waves when the primary absorber moves. Broadly categorized, the reference for the primary absorber can be absolute or relative [14]. Absolute reference implies a connection to the seabed. While relative reference can be achieved through multiple bodies or through reaction to an onboard body. Multiple bodies can respond with similar orders of magnitude, mutual reaction, or one body can be inertially dominated (mimicking a “fixed reaction”) while the other is dynamically responding to the waves. The primary absorber, supporting structure and PTO sub-subsystems are usually strongly coupled: the primary absorber drives the PTO by reacting against the supporting structure, and the dynamic response of the primary absorber and supporting structure depends strongly on the characteristics of the PTO.
Ex. The primary absorber + Reference + PTO

F1.1.2. Provide integratable structure for capture wave energy

A physical structure shall be fabricated to enable the capture of wave energy. This physical structure encompasses the 3-D incarnation of the conceptual profile for capturing wave energy. Physical aspects relating to inertia, stiffness, loads, materials, centers of gravity and buoyancy, etc. are all included here. This shall consider interfaces that are intended to be joined once only (ex. grouting a drilled anchor) and interfaces that are intended to be joined and unjoined as required (ex. replacing components in maintenance).

Ex. Pleamis: mutual reaction between the pontoons, pontoons made from rolled steel cylinders, joints capable of withstanding 2000 N-m

F1.1.3. Adapt to different sea states

The environment in which the farm will be deployed will be composed of variable height, frequency, tidal regimes, and incoming directions. The subsystems within the farm may need to adjust operation to these varying conditions or they may need to possess an inherent ability to be suitable for these distinct conditions in order to efficiently capture wave energy.

Ex. Turret mooring to adjust to distinct directions, ability to change wetted surface to alter natural frequency

F1.1.4. Condition power for transportation to the power aggregation subsystem.

The transportable power should be conditioned to its most compact and/or highest consistency form including suitable voltage levels for electrical power and suitable pressure levels for fluid power, each with acceptable levels of power fluctuations.

Ex. Energy storage sub-subsystem and power electronics

F1.2. Aggregate power from the different sources

The farm shall combine the collected wave energy before delivering the transportable power to the electrical delivery subsystem.

F1.2.1. Transport power from the different sources to point of aggregation

The collected wave power from constituent farm subsystems may be conveyed to a number of points of accumulation.

Ex. Dynamic and static cables from the WEC units to the substation

F1.2.2. Aggregate transported power

The collected wave power from constituent farm subsystems may be combined at a number of points of accumulation.

Ex. The substation

F1.2.3. Provide integratable structure for aggregating the power from the different sources

A physical structure shall be provided to enable the aggregation of transportable power from different sources. The physical structure encompasses the 3-D incarnation of the conceptual design. This shall consider interfaces that are intended to be joined once only (ex. grouting a drilled anchor) and interfaces that are intended to be joined and unjoined as required (ex. replacing components in maintenance).

Ex. The design of a floating or seabed mounted substation: the rolled steel cylinder, the entrance for electrical cables, the mooring lug design, etc.

F1.2.4. Condition power for transportation to the grid

The aggregated power should be conditioned to its most compact and/or highest consistency form including suitable voltage levels (or pressure levels) with acceptable levels of power fluctuations.

Ex. Energy storage sub-subsystem and power electronics

F1.3. Deliver electrical power

The farm shall generate electricity and convey the electricity to the continental electrical grid.

F1.3.1. Convert power into electrical power

The subsystem shall convert the collected wave energy into electricity. (The conversion to electricity could occur in the collect wave power subsystem, in an off-shore substation, or on shore.)

Ex. Generator

F1.3.2. Provide integratable structure for delivering electricity

A physical structure shall be provided to enable the delivery of electricity. The physical structure encompasses the 3-D incarnation of the conceptual design. This shall consider interfaces that are intended to be joined once only (ex. grouting a drilled anchor) and interfaces that are intended to be joined and unjoined as required (ex. replacing components in maintenance).

Ex. Cable protections on seabed; a mat that is placed over the electrical delivery cable on the ocean floor to limit changes in the cable position

F1.3.3. Condition electrical power to meet grid requirements

Quality control of the electricity shall be ensured to interface appropriately with the grid.

Ex. Following XX guidelines. Voltage in correct range, frequency in correct range, and acceptable flicker etc.

F1.3.4. Transport electricity to grid

A mechanism shall be provided to convey the aggregated electricity to the continental electrical grid.

Ex. Electrical Cable.

F1.3.5. Connect to the grid

The physical hardware shall interface appropriately with the grid.

Ex. Electrical cable voltage matching Transformer station voltage.

F1.4. Control Position

The farm shall control the position and orientation of its' constituent subsystems.

F1.4.1. Enable station keeping

A mechanism shall be provided for station keeping that will be capable of controlling the position and orientation of subsystems within the farm (i.e. potentially the subsystems used to capture wave power or to aggregate this power). The combined actions of the dynamics of the subsystems being kept on station with the desired force characteristics of the mechanism implementing the station keeping determine the conceptual form of the mechanism.

Ex. 3-point slack-moored WEC

F1.4.2. Avoid collisions

The station keeping mechanism should be designed to avoid collisions that are due to subsystem actions (i.e. prevent a WEC drifting off station and causing 3rd party damage). This mechanism will be designed to avoid both internal (between WECs) and external (WEC not running into another user of sea space) collisions.

Ex. 3-point slack-moored WEC

F1.4.3. Provide integratable structure for controlling position

A set of physical structures shall be provided to enable position control. The physical structure encompasses the 3-D incarnation of the conceptual design. Physical aspects relating to inertia, stiffness, loads, materials, wet weight, etc. are all included here. This shall consider interfaces that are intended to be joined once only (ex. grouting a drilled anchor) and interfaces that are intended to be joined and unjoined as required (ex. replacing components in maintenance).

Ex. Selection of correctly sized drag embedment anchor to withstand load for the deployment geophysical conditions

F1.5. Execute responses to farm-level control modes in a timely manner

The farm shall possess the means to respond to the communicated control modes either by the farm operation control center or farm operator. These responses should be quick in order to maximize the time spent in the operational mode and minimize the time spent in any mode other than the desired/intended mode for the current system state.

Ex. Transitioning from survival mode to below-rated mode occurring within minutes

F1.6. Control internal subsystem processes

The subsystems shall be able to accept internal communications / commands and execute upon them

Ex. Change control set-point

F.2. Control farm and subsystems

The farm should be capable of continued knowledge and support of its subsystems' and their critical states'. The farm operator shall be able to determine the appropriate control decisions for the farm and its constituent subsystems. The farm and its constituent subsystems shall employ internal and external mechanisms and measures that achieve safe surroundings during all control modes. The necessary instrumentation, telemetry, processing, synthesis, and communication shall be present to inform the control mode and confirm successful implementation of control mode. The meta-analysis performed on the farm can be used in control decisions (see F4.6). In normal operations, the control may be implemented through an automated arrangement. The overarching objective is to contribute to lowering cost of energy by generating energy when possible while entering modes necessary for preservation of the system and compliance with external factors when needed.

F2.1. Evaluate the farm and environment

The farm shall both sense the key environment and key subsystems, sub-subsystems, and components as well as systematically review and compile this data, i.e. monitor, in order to determine potential control modes and meet other regulatory requirements. Both sets of information pertaining to the environment and the farm elements shall be used together.

F2.1.1. Sense subsystems, sub-subsystems, and components

Key elements of the farm shall be instrumented and the appropriate telemetry present to identify physical properties of the elements. These instrumented subsystems will form the foundation of the farm control.

Ex. Vibrations in the structure, Delivered electricity to the grid, Primary power absorption, Location of WEC

F2.1.2. Monitor farm

Processing and compilation of the sensed elements shall occur to continually review farm and subsystems states' in order to determine control modes for the farm and subsystems. Further, the same processing and compilation should be used to confirm correct implementation of control modes within farm and subsystems.

Ex. Multiple WECs all connected to the same anchor begin moving outside of designated watch circles thus indicating their anchor may have dislodged. The primary power absorption is not resulting in expected electricity generation thus indicating the generator is not functioning to expectation.

F2.1.3. Sense environmental conditions

Key aspects of the environment shall be sensed to fulfill permit requirements and should be sensed to assist in determination of control modes.

F2.1.3.1. Sense Sea Conditions

The directional energy spectrum of the incoming wave environment should be measured close to the farm as well as the tidal, current and wind conditions.
Ex. Install a wave measurement buoy in front of the wave farm, infer wave field from acceleration or other sensors on in the WEC.

F2.1.3.2. Sense Biologic / Chemical Conditions

Sensing of the marine environment shall meet permit requirements such that appropriate knowledge can be obtained.
Ex. Install hydrophones to listen for sensitive species

F2.1.3.3. Sense Other Users

Sensing of the other users of the area shall meet permit requirements such that the appropriate knowledge can be obtained.
Ex. Monitor Automatic Identification System (AIS) signals for ship monitoring, Install a radar/sonar to look for moving objects

F2.1.4. Monitor environmental conditions

Processing and compilation of the sensed environment shall occur to continually track the incoming environmental conditions allowing for determination of control modes.

F2.1.4.1. Monitor Sea Conditions

Using collected data from installed sensors, meteorological forecasts, and/or statistical theories make short term predictions of incoming sea conditions.
Ex. A sea state of 5.8m Hs, 12sec Tp, with mean heading of -20 deg is approaching.

F2.1.4.2. Monitor Biologic / Chemical Conditions

Using the sensed data determine the biologic and chemical factors required by the permit.
Ex. An endangered whale is approaching the leased area

F2.1.4.3. Monitor Other Users

Using the sensed data and/or publically available tracking mechanisms determine the other users of the sea space within the leased area as required by the permit.
Ex. A submarine is detected via sonar within the leased area

F2.2. Determine control modes for farm system and subsystems

Control modes for the farm and subsystems shall be determined based on synthesis of the information provided by evaluation of the farm and environment. Longer term trends, found through the meta-analysis (F4.6) can also be employed in these control decisions. The modes detailed below contribute to achieving multiple goals: power production, maintenance, safety, and compliance with permit driven requirements. Some modes are essential while other modes may or may not be necessary depending on the nature of the system and subsystems under consideration. In practice, where the design allows, some modes may be combined.

F2.2.1. Provide suitable system level control modes

Farm level control modes command the system as a whole given internal and external circumstances to facilitate a desired holistic performance. Through F2.5& F2.6 farm level control modes allow information and control inputs to be inherited by all subsystems when needed.

F2.2.1.1. Provide system level automatic mode

No special farm level considerations are active, individual subsystems operate according to their prevailing individual modes. This mode will aim to maximize power delivery from the farm.

Reasons to enter mode: no overall farm control—subsystem control adequate

F2.2.1.2. Provide a system level curtailment mode

The farm dynamics or power production must be limited below rated conditions in order to achieve a system level outcome. The subsystems shall be controlled to meet the systems level outcome which could require suboptimal performance on a subsystem by subsystem basis through curtailment of sub-subsystems and components.

Reasons to enter mode: regulate power delivery (e.g. due to grid requests), a permit driven obligation relating to the larger environmental conditions

F2.2.1.3. Provide a system level shutdown mode

This mode applies where no power can be exported even when waves are present. Shutdown may be enforced or voluntary, due to internal or external faults (loss of grid connection), operational or legal reasons. Some or all subsystems may still be capable of generating power but are not allowed to. The farm must be shut down in a manner in which it will not endanger itself or its surroundings, can be safely accessed, and will maintain the structural and operational integrity of the farm. Self-endangerment given loss of power supply to the communications as well as monitoring and control shall be thoroughly considered. Special consideration should be given to the following two questions: can the system deal with confluence of loss of grid and periods of calm water, can the wave farm safely power its own auxiliaries while disconnected from grid or safely hibernate until systems can power on again. Lastly, the ensuing dynamics of the subsystems shall be designed considering the impact on permit and weather windows (see F5.4.3).

Reasons to enter mode: loss of grid connection (e.g. the cable connecting the sub-station to the grid transformer has failed), loss of communication, grid failure, significant damage to a majority of the subsystems a permit driven obligation relating to the larger environmental conditions, legal

F2.2.1.4. Provide a system level access mode

Where necessary the system may provide a global access mode. Where a subsystem is to be accessed for maintenance/installation/uninstallation this mode enforces constraints on some or all subsystems other than the one that is to be accessed.

Reasons to enter mode: subsystems are tightly coupled requiring other subsystems to alter performance for access

F2.2.2. Provide suitable subsystem level control modes

Subsystem control modes command individual subsystems given internal and external circumstances to facilitate a desired performance and safely manage the different stages encountered throughout their deployment. Each subsystem control mode is fundamental to achieving the system level goals; however, they may operate without an overarching system level goal.

F2.2.2.1. Enable Access & Isolation mode

The aim of this mode is to provide safe access and allow installation, uninstallation, repair or maintenance. Critical subsystems should be de-energized to allow safe access or joining/unjoining interfaces as required. An objective is to maintain structural and operational integrity of the subsystems during access. Further, the ensuing dynamics of the subsystems shall be designed considering the impact on permit and weather windows (see F5.4.3). For the rest of the farm, the aim is to operate as close as possible to normal operations. This mode allows that some of the subsystems are operational while others are being installed, uninstalled, or maintained.

Reasons to enter mode: New subsystem to be installed and commissioned, Unplanned maintenance is needed due to a reliability issue with a component/sub-subsystem/subsystem (e.g. the malfunction of a generator requires one subsystem to enter idle mode), planned maintenance is needed due to the durability of a component/sub-subsystem/subsystem, a mid-life retro-fit of a component/sub-subsystem/subsystem is needed, or a subsystem has failed that needs to be recovered, destructed and replaced.

F2.2.2.2. Enable Idle Mode

The subsystem is not producing power but is ready to start as soon as possible. Reasons to enter mode: the sea conditions are too low to start the farm (the power consumed by the operating farm would be larger than the produced power, cost of wear caused by small, high frequency, waves would be greater than revenue from generation),

F2.2.2.3. Enable Unconstrained Mode

No element within the subsystem has reached a rated condition hence the subsystem is operating below rated conditions. Curtailment actions may be employed to keep the elements within the subsystem below rated conditions due to external factors. The aim is to maximize power for the subsystem given potential curtailments and/or sea conditions.

Reasons to enter mode: the sea conditions are moderate to large however no aspect has reached a rated limit (e.g. the WEC is not producing power at the generator rating), a permit driven obligation relating to the larger environmental conditions, other users in the sea space, grid ancillary requests superseding the sea conditions, and/or fatigue concerns.

F2.2.2.4. Enable Constrained Mode

At least one element within the subsystem has reached a rated condition hence the subsystem is operating at full capacity. The aim is to maximize power for the subsystem while controlling that operational limits are not exceeded for components and sub-subsystems within the subsystem.

Reasons to enter mode: the sea conditions are moderate to large and there are no complicating external factors, however one aspect is at its limit (e.g. the large amplitudes of motions are resulting in the full use of the available stroke length)

F2.2.2.5. Enable Survival Mode

The subsystem may or may not be producing power, but maximization is not the aim. The aim is to maintain structural and operational integrity until optimized production can be recommenced. The sea conditions are such that it is not possible to make sure that operational limits will not be exceeded for at least one of the components, sub-subsystems and subsystems. Designing the subsystem response is central to this mode (see F4.1.1).

Reasons to enter mode: the sea conditions are too large or are expected to result in a breach of operational limits, and/or other users in the sea space

F2.2.2.6. Enable Offline Mode

The subsystem is not producing power and may be employing curtailment actions to ensure the safety of the external environment or preservation of the subsystem. The subsystem can switch to other modes as required by operational decision/policy.

Reasons to enter mode: a permit driven obligation relating to the larger environmental conditions, other users in the sea space, grid ancillary requests superseding the sea conditions, fatigue concern.

F2.2.2.7. Enable Waiting Mode

A subsystem, or element of a subsystem, is in need of maintenance for either preventative reasons or a failure. The subsystem is not producing power and self-preservation actions are being pursued to deter cascade failures while awaiting a maintenance team. For the rest of the farm, the aim is to operate as close as possible to normal operations.

Reasons to enter mode: access and isolation mode will not ensure the sustainment of structural and operational integrity; the maintenance team cannot access the subsystem for a long period of time.

F2.3. Communicate to farm, its subsystems, and the environment

Mechanisms to communicate to the farm, its constituent elements, and the environment shall be present and redundant mechanisms should be present.

Ex. Fiber-optic cable running from control operations center to farm with backup radio or satellite communications.

F2.4. Supply energy to farm subsystems

Subsystems in the farm may need to accept external energy for monitoring, sensor operation, and potentially to execute control over the sub-subsystems. Energy may need to be supplied for any of the control modes (see F3.2). This energy could be supplied from the power production from the farm subsystems, energy storage sub-subsystems such as batteries, or from the grid.

F2.4.1. Supply energy to sustain critical functions

At times when the farm is not producing power, external power may be required to maintain components that enable sensing of farm state or powering of auxiliary systems.

Ex. Powering the data acquisition system

F2.4.2. Supply energy to enable control

The farm may employ a strategy that requires the input of energy into the capture of wave power through the control of the physical profile or the PTO (e.g. for reactive control), energizing elements of the power conversion chain (e.g. magnetizing switched reluctance generator, pressurizing closed circuit pneumatic or hydraulic circuits) or energy to assist in another control action such as changing control modes.

Ex. Supply energy for reactive control

F.3. Maintain structural and operational integrity of farm and subsystems

The structural and operational integrity of the farm and its' subsystems shall be maintained throughout all environmental conditions. Achieving this durability and reliability in both the structure and other operational elements requires conforming with standards and regulatory requirements specifically developed to ensure the quality of the farm elements. Compliance with structural standards will focus on events that have the potential of causing a failure and the steps required to avert that potential. Taking actions to avoid destructive responses, protect against the marine environment, and to employ meta-analyses to investigate the performance of the farm are all needed to ensure the farm remains durable and reliable.

F3.1. Meet or exceed standards / achieve certifications for subsystems and sub-subsystems

The integratable structural supports for the subsystems and sub-subsystems shall be certified to have met applicable standards. These standards are generated by certification bodies (DNV GL, Lloyds Register, ABS, etc.) and each has its own set of criteria that must be satisfied to ensure that expected loads have been determined accurately and that the structural design can withstand these loads. Additionally, these standards may relate to fabrication techniques as specified in work authorizations.

F3.1.1. Withstand extreme loads and responses

The farm and subsystems shall be survivable, i.e. they will be constructed to withstand extreme loads and responses. The magnitude of the survival condition is dependent upon the devices response (motions and loads) to environmental forcing. Hence there are two aspects to achieving survivability: designing the devices response to the forcing and structural engineering solutions capable of withstanding the loads and responses. In addition to understanding the extreme loads and needed structural designs, the stochastic nature of the marine environment will naturally determine the occurrence of these loading events. Hence, the target safety level for the subsystems identifies the probability of failure within a year. Higher levels of safety may be required for critical subsystems and sub-subsystems depending on their consequences of failure.

Ex. Pelamis diving through waves thus experiencing smaller responses and then structurally designing to a high target safety level (a probability of failure less than 0.001% in a year)

F3.1.2. Minimize probability of and withstand collisions

The farm and subsystems shall be designed to minimize probability of collisions with external environmental factors (sea life, boats, etc.) and internal subsystems (other WECs or sub-stations). This analysis will consider the type of collision, location of collision, and the environmental conditions occurring during the collision in order to determine the failure points.

Ex. collision with the selected maintenance vessel at the surface in the largest weather window only results in a failure if there is a current above 0.25m/s

F3.1.3. Withstand progressive failures

The farm and subsystems shall be designed to withstand progressive failures in which one of the subsystems or sub-subsystems is in a damaged condition. This analysis shall consider both the type of progressive failure as well as the environmental condition in order to determine the failure point.

Ex. one mooring line in a 3-line system has broken, identified that a 20-yr return storm will cause complete failure (accidental limit state)

F3.1.4. Withstand transitory loading conditions when non-operational

Subsystems within the farm shall be designed to withstand temporary loading conditions that are unique from operational regimes either because the subsystem is in a unique orientation or because it is subject to abnormal loading.

Ex. Towing out a device on its side during installation (serviceability limit state)

F3.1.5. Meet applicable fabrication quality certifications

Subsystems shall be designed utilizing well-known fabrication techniques that are able to achieve certifications of quality.

Ex. Employing the correct the weld bead size

F3.2. Meet or exceed regulatory requirements

Elements of the farm shall meet all regulatory requirements relating to environmental concerns as identified in permits and work authorizations.

Ex. Using a double walled vessel to contain corrosive liquid material, monitoring of local sea-life

F3.3. Perform protective actions in operation

The systems shall execute actions, which may be active or passive, that are required to avoid damages to subsystems or their elements in any of the control modes. End stops and snap loads are typical challenges. The influence of the sea conditions on these control modes must be considered with respect to the operational limits.

Ex. Opening of a relief valve in hydraulic accumulator to release pressure, damping of kinetic energy when primary absorber is reaching an end-stop, considering the kinetic results of locking-up WEC in an idle state, providing protection form vibrations/dynamic shock environment for components.

F3.4. Protect necessary components/sub-subsystems/subsystems from marine environment

The farm shall provide fortification against the marine environment for components, sub-subsystems, and or subsystems that requires safeguarding.

Ex. Encapsulating the PTO inside of a pressurized vessel, cathodic protection on steel structural elements

F3.5. Execute safety actions for other users of the sea space

The subsystems shall alert and notify other users of the sea of their presence and operational hazards according to the local jurisdiction controlling the deployment

Ex. Use of navigational lights around leased area

F3.6. Perform meta-analysis of farm operations

Using the longer term records obtained from monitoring the farm as well as analyzing the time spent in particular control modes and the procedures used to carry-out control actions, a meta-analysis should be pursued that will identify information that can enable optimization, increased reliability, reduced uncertainty, and remaining lifetime.

F3.6.1. Enable farm optimization

As procedures are implemented, "real-world" experience can inform the farm operator on potential efficiency gains and alterations that would result in improvements. These experiences and ideas should be catalogued for future use by the operator or for planned control mode upgrades.

Ex. It is found that the use of an underwater robot greatly decreases the time to reconnect the electrical umbilical.

F3.6.2. Enable reduction in uncertainty of farm operation

Through operation of the farm data may be obtained that will result in reduced uncertainty either in terms of the environmental characteristics, the farm power performance, the procedures used for installation/maintenance, or the appropriate safety factors that should be applied during construction.

Ex. Power performance.

F3.6.3. Enable increased farm operational reliability

Through experience of the farm operation, data will be available on unplanned maintenance events thus allowing reliability issues to transfer into durability issues. Further, data may indicate that particular components /sub-subsystems/ subsystems need redesign or minimally rethinking.

Ex. An accelerometer continually breaks and a more expensive but robust design is chosen.

F3.6.4. Enable monitoring of lifetime of farm elements

Throughout the lifetime of the farm data shall be available related to the remaining lifetime of the farm, subsystem and sub-subsystems. These data can be analyzed to allow for early identification of element lifetimes, therefore allowing event planning to be more easily predicted and managed.

Ex. Fatigue Limit State monitoring, Wear life monitoring, cycles on elements, working fluid contamination levels etc.

F.4. Provide suitable access & transportation

The concepts of transportation and access are relevant to the logistics of initial installation, ongoing operations and maintenance and final recovery. Recovery may involve similar steps to installation but in a different (reversed) sequence. Where a system employs an onshore maintenance location then maintenance involves a combination of the recovery and installation steps. Where a system employs offshore maintenance then the maintenance activities will likely require different transportation than the installation and recovery. The farm may use different approaches for large scale installation and recovery (10's or 100's of subsystems) and for small scale installation and recovery (1 by 1). Transport encompasses transportation of farm elements (subsystems/sub-subsystems/components) to and from the farm location, movement of service vessels with and without the elements, and movement of crew transfer vessels. Access encompasses the weather and permit window thresholds that result from design choices such as vessel selection as well as interface design for ease of assembly and disassembly. Inherent to suitable access is the concept that any of the control modes identified in F3.2.1.4, F3.2.2.1, and F3.2.2.7 can be achieved. These modes are specifically designed to enable access and transportation.

F4.1. Meet transportation requirements on land and at sea

Each transported element of the farm shall adhere to the local road and sea transportation requirements. Selected transportation mechanisms shall possess characteristics that will not endanger the integrity of the transported element.

Ex. A standard shipping size should not exceed: (depth, width, height) on US national highways. Equipment to be towed should not exceed maximum draft for local harbor conditions.

F4.2. Provide safety measures for necessary maintenance on components/ sub-subsystems/ subsystems

The components/sub-subsystems/subsystems shall adhere to safety standards to enable the maintenance of components, sub-subsystems, and or subsystems. Interfaces designed for assembly and disassembly by a human shall thoroughly consider the health and safety of the person doing the work. A novel or higher cost solution may be required to ensure the health and safety of the person. In the event that maintenance is occurring in the ocean (and not on a dock), particular attention should be paid to additional safety measures that ensure the health of the maintenance personnel due to the sea conditions. Time periods under which maintenance personnel should be utilized in the ocean should be considered.

Ex. Building in a small crane capable of lifting the generator inside of the pressurized vessel.

F4.3. Enable access for maintenance personnel

Physical admittance to components, sub-subsystems, subsystems that are in need of repair shall be provided. Access may require removal of the farm element from its operational location or it may require appropriate design considerations. Space, orientation, air quality, and lighting are often important factors to consider for maintenance personnel access.

Ex. Provide 7ft of working height so maintenance personnel can stand, enough room to rotate a wrench, removing PTO from hull.

F4.4. Enable adequate permit windows

Permit window criteria are the key factor in determining the amount of time access is available for elements within the farm. Permit window criteria result from a combination of design *choices* and environmental conditions at the *chosen* location. The overarching objective is to contribute to lowering cost of energy by increasing access to the farm through sufficient permit windows.

F4.4.1. Enable farm access by service vessels

The system layout shall be designed so that it is not a significant factor in determining the permit window criteria for the chosen vessels and tasks. The dynamics of the service vessels due to environmental conditions shall not unreasonably impose additional criteria on the permit windows, i.e. the service vessels shall possess adequate capabilities that do not impact permit windows.

Ex. the WEC equipment should not be so close together that a service vessel must enforce additional permitting constraints to ensure safe movement and work between rows of WEC's, vessel dynamics impose no further requirements on the permit windows.

F4.4.2. Provide clear interfaces to assemble and disassemble sub-subsystems and subsystems

Assembly of interfaces to be joined and unjoined as required (maintenance operations, installation, etc.) shall occur through identification of well-defined boundaries. Interfaces that will need to be assembled and disassembled while in the ocean need particular attention to ensure ease of assembly and disassembly due to the uncontrollability of the sea conditions. The permit window criteria are strongly influenced by the assembly / disassembly requirements at sea.

Ex. A PTO sub-subsystem within a WEC subsystem that has well designed interfaces so that it can be easily removed/replaced, moorings are designed to be connected or disconnected in broad weather conditions, crane hooks can be attached without additional permitting constraints.

F4.4.3. Provide suitable subsystem dynamics

Adequate permit windows are additionally defined by the dynamics of the subsystem being accessed. The dynamics of the subsystems shall not unreasonably impose additional criteria on the permit windows.

Ex. The control mode may act to cancel or reduce motion and allow access in higher wave heights or wind speeds than would otherwise be possible.

F.5. Provide synergetic benefits

The farm should provide positive environmental, social, or grid services.

F5.1. Provide ancillary grid services/benefits

The farm can offer secondary grid services that are becoming more important to grid operation.

F5.1.1. Respond to grid requests for power regulation

The farm may be dynamic enough to assist the grid in fast (minutes) regulation of power.

Ex. Integrate into Automatic Grid Control (AGC) strategies

F5.1.2. Provide energy storage

The farm may be able to act as a dynamic energy storage location for the grid.

Ex. A substation has 1min x Farm's Rated Power of storage available as part of its power conditioning procedure that can be made available to the grid when not in use.

F5.2. Provide positive environmental impacts

The farm should act to benefit the environment. Overall, the farm shall act as a low greenhouse gas (GHG) emission energy source. Additionally, some environmental benefits may be found that are not the primary purpose of the farm.

Ex. Protecting the shore-line from erosion, emitting less GHG than oil

F5.3. Provide positive social impact

The farm should provide benefits to society potentially in the form of jobs, or infrastructure improvement. These benefits could extend from the local to the international level.

Ex. Create an underwater habitat for local species of flora and fauna which increase the fish population for fishers, provide employment, provide local employment.

F5.4. Provide cost-offsetting

The farm will result in reduced CO_2 production which could be recognized in the form of a carbon credit or payment. Alternatively, the development of the farm may serve two purposes at once, thus saving cost for those purposes.

Ex. OWC's acting as a breakwater—the structure of the OWC is needed to enable capture wave energy, but this structure is also acting as a breakwater thus protecting infrastructure behind it. Thus, matching funds could be provided to the OWC farm from the city for this dual-purpose development.

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4. 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 (in meters) of mechanical power absorbed by a wave power collecting system to the incident wave energy flux per meter wave crest.

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 component's life. Durability is concerned with scheduled maintenance and planned maintenance activities especially where sub-systems and components have a shorter life than the farm as 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 referring 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 during which access is possible due to environmental variables, and any other variables, being below relevant thresholds. E.g. working hour 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.

Subsystems: Systems within the System. For wave energy purposes subsystems are the building blocks of the wave farm e.g. WEC units, sub-stations, mooring systems etc..

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

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

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.

5. DISTRIBUTION

1	MS0899	Technical Library	9536 (electronic copy)

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