EnFAIT

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ENFAIT
ENABLING FUTURE ARRAYS IN TIDAL

Verification Framework

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Contents

Glossary

Abbreviation or Term	Definition
AAT	Assembly Acceptance Test
AIM	Array Interaction Modelling
BoP	Balance of Plant
DFA	Design For Assembly
DFM	Design For Manufacture
DFMtn	Design For Maintenance
Design Team	The team responsible for the design and engineering development of the TiPA generator and sub-systems. Nova Innovation, Siemens, SKF.
DOF	Degrees Of Freedom
DTOCEAN	Design Tools for Ocean Energy Arrays (EU H2020 project)
EnFAIT	Enabling Future Arrays In Tidal
FAT	Factory Acceptance Test
FMECA	Failure Modes and Effects Criticality Analysis
HSEQ	Health, Safety, Environmental, and Quality
KPI	Key Performance Indicator
LCOE	Levelised Cost of Energy
LDs	Liquidated Damages
LOP	List of Open Points
NCR	Non-Conformance Report
ORE Catapult	Offshore Renewable Energy Catapult
QC	Quality Control
RCA	Root Cause Analysis
SCADA	Supervisory Control and Data Acquisition
TEC	Tidal Energy Converter
TiPA	Tidal PTO Accelerator
TQ	Technical Question
TRL	Technology Readiness Level
Validation	Confirmation, through the provision of objective evidence, that the requirements for a specific intended use or application are fulfilled. [ISO 9000:2015]
Verification	Confirmation, through the provision of objective evidence, that specified requirements have been fulfilled. [ISO 9000:2015]
Verification Team	The team responsible for the engineering verification and validation of the EnFAIT turbine and sub-systems. Wood, ORE Catapult and Nova Innovation.

1 The Project

1.1 Introduction

A Funding Grant was awarded from the European Union's Horizon 2020 research and innovation programme in January 2017 to demonstrate a grid-connected tidal energy array at a real-world tidal energy site, propelling tidal energy towards competing on a commercial basis with alternative renewable sources of energy generation – Enabling Future Arrays in Tidal (EnFAIT). This was in response to the call *LCE-15-2016: Scaling up in the ocean energy sector to arrays* to generate significant learning through demonstration of cost-effective tidal arrays.

EnFAIT is cutting edge tidal energy project and is targeting the achievement of a number of industry firsts. The array, which will be deployed in a phased nature, will culminate in the cumulative deployment of a six turbine array. In addition to the development of the Nova Innovation NM100 unit, innovative infrastructure solutions will also be tested within the context of the project.

This document is produced to summarise the framework that will be used to undertake the verification activities of the EnFAIT design, commissioning and operational outputs. It is to be submitted to satisfy deliverable D3.5 of the EnFAIT project and to be also made available for public dissemination.

The Verification Framework outlines the needs and requirements from the EnFAIT project, and sets the expectations that outline the robust and comprehensive review of project performance with respect to target objectives. It also serves as a formal document that outlines the strategic plan for verification of data, from which the formal verification activities within the EnFAIT project shall be based.

1.2 Aims and Objectives

The EnFAIT project has the objective to deliver a cost-effective array and to provide demonstrable pathways to reduce the cost of energy, verified by assessment of project outcomes. The project will demonstrate the full lifecycle of a tidal energy array, from design to decommissioning. It will be operated for a period (anticipated to be in the region of 2-3 years) as a fully commercial array, in order to demonstrate a step change in the lifetime cost of energy from the current state of the art. In addition, the project turbines will be highly instrumented and operated to generate learning into key factors affecting the performance of a tidal array, drawing out the critically required lessons for future cost reductions. The proposed instrumentation and measurement systems to be investigated within the context of the EnFAIT project are discussed in EnFAIT-EU-0004 (D6.1) – Test Plan. In the context of the EnFAIT project, the requirements of the verification process will be defined herein in order to ensure that the project meets its intended objectives as outlined in Appendix 1 of this report.

2 Verification Overview

Verification can be defined as ***confirmation, through the provision of objective evidence, that specified requirements have been fulfilled***.

This framework sets out the means of verification that will be utilised within the EnFAIT project, which will focus on the broader array design and operation as well as the design of the tidal energy converters themselves and associated subsea infrastructure. More specifically, this verification framework will be applied at three specific points in the EnFAIT project, namely detailed design, commissioning, and operations (including maintenance and decommissioning), to produce the defined project verification deliverables.

The outputs of the verification process will help inform the project risk matrix, with learning developed throughout the course of the project used to optimise technology, processes and procedures for future iterations of the technology. Mitigation actions will be developed within the EnFAIT project to address the identified risks, therefore reducing the technical and commercial risk of future array deployments.

2.1 Verification Objectives

Verification within the context of the EnFAIT project is the process of establishing the accuracy or validity of a particular technical, commercial or economic claim. The Verification Team has been established to ensure that the design, commissioning and operation of the project is accountable for producing the evidence that will determine whether project objectives have been met.

The design input requirements outline the design conditions to which the product is designed to withstand. Design requirements can be considered at both device and project level. From a resource perspective, the design input requirements for the EnFAIT project are based on a theoretical site with energetic tidal energy resource. Existing devices have been installed in the Bluemull Sound site in Shetland, UK, however this site is less energetic that the design parameters that have been set for the technology. These design input requirements have been set within the Nova Innovation document (EnFAIT-EU-0003 Project Requirement Definition).

The purpose of the project verification is to confirm that the technology designed and deployed within the EnFAIT project meets the project specific objectives, and that the design complies with the parameters contained within the Design Basis. Additional requirements from a project perspective include the assessment of the array configuration, the electrical connection and cabling, sub-sea infrastructure, and the onshore Balance of Plant (BoP) requirements. In particular, the verification framework will outline the means by which the project design and operation will be interrogated, to ensure that there is robust evidence of the project specific requirements being satisfied.

The verification framework considers the methods outlined in DNVGL-SE-0163 – Certification of Tidal Turbines and Arrays, which provides general requirements for the certification of technology and projects. Project specific objectives (see Appendix 1) will be assessed using qualitative performance metrics where possible, in order to provide definitive evidence in support of the project objectives. Within the phases of verification, a number of sub-headings will be covered, including: benchmarking, detailed design, manufacturing and assembly, deployment, operation and maintenance (including phases 1 to 6 of the Test Plan, outlined in EnFAIT-EU-0004, D6.1 of the EnFAIT project), and decommissioning.

The objectives of the verification framework are as follows:

1. Explicitly outline the benchmark / baseline from which to make a consistent comparison throughout the course of the EnFAIT project.

2. Provide an overview of the selected approach to conducting the verification at each stage of the project. The main stages include technology and array design, system manufacturing, commissioning, deployment, operations and maintenance, and decommissioning;

3. Provide definition of appropriate measurement, recording, and documenting methods;

4. Identify the necessary tools (e.g. vessels, lifting equipment, sensors, measurement instruments and recording software), and Balance of Plant infrastructure (e.g. maintenance facilities, customer substation, sub-sea hub) that will be required in order to implement the project in a way that meets the requirements of the verification strategy;

5. Provide examples of relevant outputs and supporting documentation (the evidence) necessary to allow the verification process to take place;

6. Provide a framework which can be widely disseminated, presenting the qualification parameters of EnFAIT to the marine energy industry and research sector;

7. Ensure the EnFAIT project deliverables, including the key findings, are delivered to the highest standard;

This Verification Framework should be read in conjunction with the outputs of WPs 4-7 of the EnFAIT project in mind, which will present the technical development and learning throughout the course of the project. In addition, the outputs from the verification framework and associated verification activities (the evidence that is to be produced within these activities) will provide the means by which to make an informed, objective assessment of the overall project performance.

2.2 Verification Methods

Verification consists of assessing the extent to which the design, commissioning and operation of the EnFAIT array fulfils the project requirements, and should be supported by documented evidence and robust measurements. In most cases, verification will involve a combination of methods, with the selection of the applicable method being determined by the degree of novelty and level of risk that a component presents. While the project as a whole is required to undergo verification by a third party, the framework should also include a break-down of the specific systems, sub-systems, features and materials to be considered. An overview of the potential verification methods is presented, in increasing order of complexity:

Similarity: If a design uses products or components that have already demonstrated satisfactory operational performance, meeting or exceeding the requirements within a similar service environment, then evidence to illustrate this similarity may be used to verify a particular requirement. In addition, minor evolution of a product that has an established track record and is designed to appropriate codes and standards, may also use similarity to verify its conformity to requirements.

Design Review: Where parts of the system are considered as novel, and therefore can't be assessed by means of similarity to an existing product, verification of design suitability should be based on a full review of the design. This includes a review of the assumptions that underpin the design, engineering calculations, and use of factors of safety within the engineering calculations against recognised codes and standards, where available.

Analysis: Analysis is the verification of a product or system using models, calculations and specialist software. Analysis allows an engineer to make predictive statements about the expected performance of a product or system, and is particularly relevant in cases where there are no recognised standards, as analysis is based on fundamental principles rather than developed codes. Analysis can reduce technology risk by providing detailed investigation of specific aspects of the design – for example stresses, strains, and load paths within a component or system, thermal performance, or to predict the failure mode. When required, such as for complex systems, Testing (see below) should back up analysis, to confirm the predicted values are observed in practice.

Inspection: Inspection involves the direct measurement of a product's attribute(s). For example, a specification may require that the product is a certain colour, of certain dimensions or within a certain tolerance, or has a certain paint coating thickness. Methods of inspection would be used to confirm that the requirements have been met.

Testing: Testing will involve the manipulation of the product or system under conditions similar to or representative of those that would be experienced within its intended operating environment. Verification through testing allows a product to be assessed under controlled and predefined inputs in a pre-defined test plan to ensure that the product meets the design requirements. The results of the testing can then be assessed to verify whether the system or design has performed as expected. Testing should be carried out in a controlled environment to allow repeatability of test conditions.

Demonstration: Demonstration involves the operation of the selected component within the complete product prototype, in its intended operating environment. Conditions are no longer simulated, but are real-life conditions that would be experienced by subsequent deployments of the technology. Demonstration activities are generally high cost, and can lead to items being damaged in the event of a failure. Therefore demonstration activity should only be carried out after significant de-risking is completed, through the previous verification methods outlined above.

2.3 Verification Process Overview

For the purpose of this framework document, it is necessary to define the difference between two specific project teams – the "Design Team" and the "Verification Team".

The detailed design of the EnFAIT project will be carried out by the Design Team. This team of engineers is responsible for the development of input requirements (such as the Design Basis), the detailed design of the systems and sub-systems, the Balance of Plant, and any environmental data acquisition requirements. They are also required to provide the supporting evidence to assist the verification process. The Design Team is led by Nova Innovation and consists of team members from Nova Innovation, SKF, ORE Catapult, HMK, and Mojo Maritime.

The verification process will be overseen by the Verification Team, consisting of representatives from Wood, Nova Innovation, and the ORE Catapult. Wood will have overall responsibility within the Verification Team, and will lead the verification process. The Verification Team shall review all evidence associated with each verification stage to determine whether acceptance criteria have been met.

The structure of this Verification Framework will be separated into the following stages, each of which will form a sub-section of this report:

- The Benchmarking Stage – outlined in Section 3;
- The Detailed Design Stage – outlined in Section 4;
- The Commissioning Stage (including manufacturing, assembly, and deployment commissioning activities) – outlined in Section 5;
- The Operations Stage (inclusive of activities within operation, maintenance and decommissioning) outlined in Section 6.

2.3.1 Execution of Verification Activities

A high level overview of the verification activities, the process of recording of results and highlighting of non-conformance is provided below. Detailed discussion on each area will follow in the subsequent report sections:

Benchmarking phase
The benchmarking phase will be primarily a desktop review of performance and cost data to allow the benchmark metrics to be defined. The assessment of the benchmark, and qualification of the calculation methodology is important to ensure consistency throughout the project, and to allow the ability to demonstrate progress throughout the project. The benchmarking phase will include a review of the following areas:

- The documentation and evidence supporting / underpinning the LCOE and Financial Models (and the assumptions in cost and performance therein) for the Project;
- Performance data for the existing Nova NM100 units, including cut in velocity and power curve;

Detailed design phase
The detailed design phase will form a technical review of the design of the turbine, electrical cable layout, subsea hub, balance of plant infrastructure, and the monitoring sensors deployed as part of the EnFAIT project. This phase will be conducted prior to the procurement, fabrication, assembly and deployment of the turbine or sub-sea infrastructure and will broadly include:

- A desktop review of the documentation and evidence supporting the amendments to the design of the turbine. This includes the upgrades to the original NM100 units one to three (contained in EnFAIT D6.2 T1-T3 Upgrade Report), and any new design changes to the new NM100 units four to six, as well as major system components unique to the EnFAIT project (such as the sub-sea hub), and the array layout electrical design and turbine layouts.

- A comparison of the detailed design and the requirements given in the Design Basis, and an assessment as to whether the evidence is sufficient to demonstrate that the requirements have been fully satisfied by the detailed design.

Commissioning phase

The commissioning phase will be spread over a number of months, culminating in the deployment of the six turbine array. It is anticipated that a phased build out of the array will take place, therefore commissioning, installation and operation of the first new unit will be completed prior to the procurement of the second and third units, and a fourth nacelle. Learning from the commissioning of the first unit will feed into the subsequent build and commissioning processes. The commissioning verification will include desktop review and physical inspection of the following:

- Factory Acceptance Test (FAT) procedures and certificates (or equivalent) for major components procured from sub-suppliers;

- Assembly Acceptance Test (AAT) procedures and certificates for both procured assemblies and for Nova Innovation assemblies carried out in-house;

- Commissioning procedures, certificates and supporting documentation for onshore commissioning activities, and any other documents that offer traceability as to the testing carried out on specific components and the full nacelle;

- Visual inspection of relevant subsystems and the full unit to confirm that the build is according to stated manufacturing tolerances and design specifications;

- Mechanical and electrical completion procedures for the NM100 tidal energy converter;

- Commissioning procedures, certificates and supporting documentation for offshore commissioning activities, including documents that offer traceability as to the testing carried out on specific components;

- Reliability run test procedures, test data and error log.

Operations phase

The operational phase of the array will provide the operational data that will allow many of the Key Performance Indicators (KPIs) to be quantitatively assessed against project objectives. The operations phase verification will include a combination of desktop review and analysis of the following items:

- Performance data from the device and array operation in both ebb and flood direction, and the subsequent analysis of Supervisory Control and Data Acquisition (SCADA) data from operation. This analysis should include time series of appropriate performance variables, structural monitoring, component health monitoring systems, and any error logs from the turbine operation requiring resets or intervention;

- Intervention procedures, timescales and costs, based on data and expenditure during the project operations activities, with a particular focus on the areas in which efficiency savings can be made;
- Site visit during one intervention operation to verify project Health, Safety, Environmental and Quality (HSEQ) performance during offshore work.
- Desktop review of resale / scrap value of components, and appropriate disposal / recycling of components once the end of operational life has been reached.

2.3.2 Test plans

Test plans for the EnFAIT project and the associated offshore testing have been prepared within the following document:

- EnFAIT-EU-0004 Test Plan.

Additional testing requirements may be identified throughout the EnFAIT project, particularly as evidence from operation of the early unit upgrades may deliver important lessons for the optimisation of subsequent unit four to six. In addition, it is anticipated that unit four will be constructed and deployed in advance of the build and deployment of units five and six. As such, the test plan should be phased, and may require to be updated in light of any lessons learned from the prior turbine deployments.

The project verification will ensure that testing is carried out in accordance with the defined test plans. Where additional test requirements are identified, these will be recorded and documented within the verification process, to be addressed during the EnFAIT project.

2.3.3 Recording of Results

The format of the data collected will vary depending on the specific variable being recorded. All design reports, test records and project reports should be subject to the quality assurance and authorisation processes of the entity that creates them. Where applicable, review from the wider consortium will also be required.

The design evidence, test results, all applicable records and supplementary data must be stored in a secure virtual data room that can be accessed in the future, as this evidence will provide the basis for future certification (e.g., DNV-GL or Bureau Veritas prototype certificate).

2.3.4 Non-Conformance Process

If a non-conformance (such as a manufacturing anomaly, a deviation from process or procedures, component failure under testing, insufficient evidence to support an objective being met, or a component failing to meet design criteria) is discovered through verification activities, then the root cause must be investigated by the Design Team through Root Cause Analysis (RCA). The non-conformance could be related to the product, processes, test equipment, facilities, or other external factors.

A Non-Conformance Report (NCR) shall be relayed to the responsible party so that corrective actions can be taken. NCRs and associated actions need to be tracked to completion by the Design Team. If an NCR results in a design change, then design verification should be reviewed.

There is currently some scope within the EnFAIT project for minor component, process, or procedure modifications based on early findings from initial deployments. This does not, however, include any significant re-design of major components within the project scope. For anything other than minor design alterations, the non-conformance should be logged, and the root cause identified. A register of non-conformances, and proposed work required to close out should be maintained by the Design Team. However, it is anticipated that the project would continue with a List of Open Points (LOP) to address in future projects (outside the scope of EnFAIT). Depending on the nature of the fault, the completion of a RCA may not be feasible within the EnFAIT project.

3 Benchmarking Stage

The EnFAIT project shall demonstrate a number of technical and commercial improvements over the current state of the art within tidal energy. The means by which this shall be demonstrated is through the application of the verification framework and recording of the results within the verification reporting, to be carried out at different stages within the project. At each stage, assessment of the relevant KPIs will be used to determine the progress being made towards meeting overall quantitative project objectives.

It is necessary to define the current state of the art within the development of Nova Innovation's tidal energy converters. This should cover the following areas:

- Technology costs;
- Turbine performance;
- Resource data acquisition / monitoring capabilities;
- Environmental / socio-economic impact.

This benchmarking forms a critical element of the verification process, as it will allow the Verification Team to monitor and assess the progress relative to the project specific objectives. This will allow the clear definition of project related performance improvements with regards to net energy export, reliability, availability, and cost. Quantitative values are required in order to accurately demonstrate and reflect the project performance in a meaningful way. Without this benchmark, the ability to demonstrate achievement of project objectives will be significantly hindered. Details of upgrades to sensors and systems will be discussed relative to the defined benchmarks.

3.1 Key Performance Indicators

The benchmark for a number of Key Performance Indicators (KPIs) shall be established. This benchmark is necessary to track performance, relative to project specific targets and objectives, throughout the course of the project. Comparison against a known benchmark is of particular importance where quantitative values are required to provide evidence in objectives being met. Specifically, this shall include:

- Levelised Cost of Energy (LCOE);
- Availability;
- Capacity Factor.

An initial appraisal of the technology within the project, including site specific requirements, will be carried out by Wood to determine whether additional appropriate benchmark metrics should be considered. Evidence of existing operation and maintenance strategies should be reviewed. This may include inspection reports that have been produced from all historic maintenance activities, including photographic records of the work carried out and the results of any oil samples or periodic maintenance activities. Evidence shall be reviewed by Wood to ascertain the general health of the turbines, and whether the operation and maintenance activities to date are in line with initial expectations. Wood will also undertake an assessment of the LCOE, which will be used to compare future performance with the current state of the art.

Critical to the ability to use these metrics throughout the project is the adoption of a standard methodology for their calculation. This is to ensure that changes in the metric over time are reflected in a relative movement of the value compared to the initial value. The calculation methodology for the KPIs will be discussed in D3.9, the LCOE & Financial Models.

3.2 Data requirements

Data required in the benchmarking activity includes (but is not limited to):

- Capital costs of turbines and BoP infrastructure required for a multi-turbine array project;
- Installation and retrieval intervention costs (vessel time, personnel, fuel, etc);
- O&M activities, periodicity, and costs;
- Turbine performance, power curve, reliability and availability statistics;
- Environmental parameters such as flow velocity and turbulence intensity measured and recorded throughout the ebb / flood tidal cycle, and across a full lunar cycle that encapsulates both spring and neap tides.

3.3 LCOE and Financial Model Reports

While the LCOE and Financial Model reporting will be prepared as separate deliverables from the formal project verification reports, it is clear that the LCOE and financial aspects of the project play a significant role in the verification of project objectives. As such, there should be extensive engagement between work package tasks involving LCOE and those involving verification activities.

4 Detailed Design Stage

Design verification is a structured process, typically involving a number of steps carried out sequentially. These steps include:

1. Review of Design Basis / Qualification Basis to ensure that all environmental parameters and expected operating conditions are considered within the design specifications of the technology development. The test procedures which will be applied to the technology will also be reviewed to ensure a robust test plan is implemented.

2. Technology Assessment to identify the design novelty or maturity for components and sub-systems within the turbine, and subsea array components such as cables, and the subsea hub.

3. Technical Question (TQ) Register to record and request clarification on technical items. The TQ register will also allow for responses to be recorded, ensuring traceability.

4. A review of the Failure Modes and Effects Criticality Analysis (FMECA) for project critical components including the turbine and subsea hub.

5. Documentation review and assessment of evidence provided for the Design Verification.

6. Production of a Verification Report to record the outcomes of the verification activity (Acceptance / Non-acceptance / List of Open Points).

The design verification process shall follow a “Claim, Argument, Evidence” approach. A **Claim** is a statement, or a requirement of the design, for which compliance or non-compliance can be assessed. An **Argument** is the reasoning in support of the claim, in which the plausibility of the argument will be reviewed. **Evidence** is the information presented in support of a claim, which combines with the argument to demonstrate that the requirements of the claim are fully satisfied.

For example, in the case of a claim that a structural component would last for the design life of the product: an argument might refer to a recognised design standard, on the basis of which a set of required stress limits and corresponding strain values is calculated. The evidence could be a test report showing that, on the basis of strain gauge data gathered during the test, the specified limits have not been exceeded, or a calculation showing that the stress is not exceeded, if an established design method is being used.

4.1 Design Basis

The design basis for the EnFAIT turbines is similar to the design basis used within the existing Bluemull sound array, as the deployment location is the same as that of the existing units. It should be noted that the turbines are designed for a higher flow velocity than that experienced in the Bluemull sound, but this site represents a good environment for early array deployment and learning. As a result, within the EnFAIT project, the design review will consider existing data from previous projects with regards to the design basis. This includes:

- The environment in which the EnFAIT tidal energy converters and associated array infrastructure are intended to operate;

- The functional requirements of the turbine(s) and the subsea hub, design parameters and design envelope for the turbines and array infrastructure;

- The requirements, such as acceptance criteria for all key systems within the array, and the testing to which these systems will be subject to prior to engaging in full operation.

Additional parameters that will be considered within the design review will include the following:

- Definition of additional sensors / systems to be installed on the EnFAIT tidal energy converters, or that will be deployed as additional remote sensors for resource data collection;

- Condition monitoring system for the turbines;

- Identification of testing and risk mitigation activities that have been carried out during the development of novel array infrastructure;

- Details of array layout options to be trialled during the project, and the deployment duration required for each configuration.

4.2 Technology Assessment

A technology assessment of the EnFAIT initial turbine upgrades for units one to three (as outlined in EnFAIT-EU-0079 T1-T3 Upgrade Report), proposed design changes to the turbine for units four to six, and the project electrical and array infrastructure will be undertaken. This task is to ascertain the systems or subsystems in which little or no experience exists, or where proven technology has been applied in a novel manner, as these are likely to be the areas in which the greatest challenges and uncertainties lie.

The first stage of the Technology Assessment process is to assess the currently available information, with a particular focus on identifying key areas of technical risk. It will then be possible to identify areas where the required information to undertake a full technology assessment is not yet available.

Following this initial assessment, the priority areas for further investigation will be defined. Throughout the EnFAIT project, meetings, workshops, TQ exchanges, document reviews and visits / inspections will take place over the course of the project. The areas highlighted within the Technology Assessment could comprise areas where the risk is judged to be high, or where there are many unknowns, or areas where extensive mitigation is in place but additional assurance is needed in order to confirm the effectiveness of the mitigation.

In order to provide an objective assessment of technology risk, a standard set of criteria, which consider a wide range of aspects of design, manufacturing, installation and commissioning is proposed for the Technology Assessment.

The Technology Assessment will be carried out on the turbine itself and on the subsea infrastructure that will be deployed as part of the EnFAIT project. Due to the phased deployment, the assessment criteria will consider the following risk areas:

- Design and prototyping:
  - Design novelty;
  - Designer's track record;
  - Component test programme;
  - Operating environment;
  - Standards / modelling capability;
  - Prototype testing;
  - Vulnerability to scale effects (i.e. will a change in component size impact the integrity of the structure, or the ability to function according to its intended design).
- Manufacturing and supply chain:
  - Process novelty;
  - Supplier capability;
  - Quality Control.
- Installation and commissioning:
  - Process Difficulty.
- Operations and maintenance:
  - Condition monitoring capability;
  - Repair process difficulty.

4.3 Technical Question Register

During the review of documentation, any issue requiring further clarification, evidence, or additional analysis to reduce the risk to an acceptable level, will be recorded in a Technical Question (TQ) register. The Design Team shall address each TQ in a manner that satisfies the Verification Team in order to close the issue. Any items that remain open following the completion of the design verification will be added to a List of Open Points (LOP) to be addressed within the EnFAIT project.

4.4 FMECA

The responsibility for the development of appropriate Failure Modes and Effects Criticality Analysis (FMECA) and acceptance criteria for all systems and sub systems lies with the designer. The scope of the FMECA shall include the tidal energy converters, subsea cables, subsea hub, and data acquisition sensors used within the project. The FMECA process will be reviewed by the verification team, and comments made as to whether risks have been mitigated to an acceptable level. The development of the FMECA was carried out within task T9.2, resulting in the deliverable Design Failure Mode Effect Analysis (FMEA) Report. This document has indicated a proposed “Product Breakdown Structure”, outlining the components that are to be subjected to the FMECA process. Within the verification work package, it will be the responsibility of the verification team to interrogate the FMECA documentation for each of the components identified within the Product Breakdown Structure.

4.5 Documentation Review

The Design Team will provide a list of supporting evidence to show that the design requirements have been fulfilled for each system and sub system that comprise the EnFAIT array. Design documentation should include detailed technical drawings, calculations and analysis demonstrating suitability of design. This will be applied to the following systems:

- NM100 tidal energy converters and associated sub-systems;
- Subsea hub;
- Subsea cables (including cable route surveys and cable protection);
- Data acquisition sensors and support frame.

4.6 Design Verification Report

At the end of the design verification, a design verification report shall be issued. The verification report shall present the overall status of the verification, together with a LOP. It will outline any TQs that have not been satisfactorily addressed as well as any technical or project requirements that have not been fulfilled in the design. This LOP should then be reviewed following the completion of the commissioning and operations phases, to identify where subsequent data collected may have provided additional information that will allow the close out of open points. For any points that remain open at the end of the verification strategy, suitable mitigation shall be implemented by the Design Team to reduce risk to a satisfactory level.

5 Commissioning Stage

Commissioning is the process of assuring that all of the systems and components of the EnFAIT array have been fabricated, installed, and tested according to the design and project operational requirements. This helps to ensure that the project is suitably qualified and ready for array operation for the target project life. The commissioning verification will consider the commissioning process in two stages. The first stage will be the first turbine build, assembly, test, construction and commissioning. The second stage will consist of the series production build, assembly, test, construction and commissioning. Within each stage, a number of different commissioning activities shall be considered, including pre-deployment commissioning of all systems and assemblies undertaken in the production facilities of component suppliers and the assembly workshops of Nova Innovation prior to offshore activity. Additionally, the verification shall also consider all offshore commissioning of the devices and associated array infrastructure following installation of the turbine(s).

It is recognised that the EnFAIT array build out will follow a sequential and structured approach, and the first turbine will be assembled, installed, commissioned and operated in advance of the manufacture and commissioning of the following three serial production units (two remaining turbines and one hot-swappable nacelle – a spare unit that can be used to replace any of the turbines being removed for maintenance, thus preventing large amounts of downtime). Therefore, lessons learned from the onshore and offshore commissioning of the first unit will allow efficiency improvements to be made in the commissioning of latter devices. The final commissioning verification report will not be produced until the full array has been commissioned and installed, thus will summarise the lessons learned throughout the commissioning process.

The commissioning phase of the EnFAIT project is also an opportunity to develop a commissioning plan, commissioning procedures, and commissioning documentation that would be expected by a client as part of any future commercial project. Where possible an estimation of the installation costs will be made during this phase.

5.1 First Turbine Build, Assembly, Test Onshore Commissioning

Verification at the manufacturing and assembly stage will ensure that the technology manufactured for use within the EnFAIT array meets the design specifications. It will also offer an opportunity to verify the success of Design For Manufacture (DFM) and Design For Assembly (DFA) activities, with success determined by quantitative assessment against benchmark cost values. This commissioning verification stage will form a final product check prior to deployment of the devices within the array. The intention is to carry out commissioning at a modular level prior to full unit assembly. Build, assembly and test verification will include desktop review of:

- Quality certification from major component manufacturers, and demonstrated implementation of quality control procedures within the manufacture of major components. This quality control documentation may include a production log following the fabrication and assembly of a component from raw material to finished component (e.g. blades, gearbox or generator), with a traceable record of any rework carried out in the production process;
- Factory Acceptance Test certification for all major components, and Assembly Acceptance Test certificates for all major systems.

- Commissioning test results / certificates for any commissioning carried out at a modular or system level whilst onshore.

As a result of the phased deployment of the array, lessons learned from manufacture and assembly of earlier devices will feed into optimisation of the procedures for later devices.

5.2 First Turbine Deployment Commissioning and Reliability Run

Following the deployment of the turbine(s), the offshore commissioning process shall be verified. This includes a review of mechanical and electrical completion of the turbine, and a reliability run of the unit to confirm that operation of the device meets with performance expectations. The verification process will include a desktop review of documentation and data including:

- Installation procedures, and procedure for mechanical and electrical connection completion. Certificates of completion will also provide documented confirmation that all mechanical and electrical connections have been established and secured;
- Commissioning procedure, checklist, and commissioning completion certificate;
- Reliability run procedure, including test requirements / criteria, and pass criteria.
- Reliability run test data, and associated reliability run completion certificate.

As a result of the phased deployment of the array, lessons learned from offshore commissioning of earlier devices will feed into optimisation of the procedures for later devices.

5.2.1 Grid Code Compliance

As the purpose of the Nova NM100 turbines is to function as power generation equipment, the turbines will be required to produce power that is compatible with the requirements of the local grid code. The UK grid code is available from Ofgem, and can be accessed online[1].

The purpose of grid compliance testing is to ensure safe, secure and economic operation of the power system when new (and, in the case of the EnFAIT array, novel) units are connected to the transmission or distribution system of the Power System. The new system will be required to demonstrate compliance with the Grid Code and an ability to operate under the criteria defined therein. The compliance test determines the true capabilities of the generator unit at the commissioning stage, and would be applicable throughout the lifetime of the unit. Where grid compliance testing identifies any non-compliance, it will be necessary to address this via remedial actions. The grid tests will also assess the level of impact on other users of the local grid infrastructure and the general performance of the power system.

In order to undertake appropriate grid testing, the system operator will require certain data. Some of the required data will be produced during the commissioning process, and will be reviewed as part of the verification process. This may include:

[1] The Grid Code, Ofgem, available online: https://www.ofgem.gov.uk/ofgem-publications/55007/7885-gridcodebetta04b.pdf, accessed 16/03/1986.

- Turbine data sheets & models;
- Turbine commissioning programme (both pre- and post-deployment);
- Completion certificates (wiring / pre & post energisation signals and control check);
- Completion certificates and reliability run test certificates;
- Raw data for completed tests.

5.3 Serial Production Turbine Build, Assembly, Test Onshore Commissioning

This commissioning process will follow the processes outlined in Section 5.1, with the additional inclusion of lessons learned from the commissioning of the initial unit to ensure improvements in process efficiency.

5.4 Serial Turbine Deployment Commissioning and Reliability Run

This commissioning process will follow the processes outlined in Section 5.2, with the additional inclusion of lessons learned from the commissioning of the initial unit to ensure improvements in process efficiency. Grid code compliance testing will be carried out for the serial production turbines and the sub-sea hub. With the inclusion of the novel sub-sea hub (which will represent technology at an earlier TRL than the turbine itself), there may be additional grid compliance testing that will need to be carried out in order to satisfy the requirements of the System Operator.

5.5 Technical Question Register

An update to the TQ register will take place based on observations and queries regarding the commissioning process, and will follow the same procedure as that identified during the design verification phase.

5.6 Cost Reduction Scenarios

During the manufacturing and assembly stage, it will be possible to review the economies of volume and learning gained from progression from the historic manufacturing of initial units to the manufacture of the new devices. The serial manufacture of the NM100 will includes the two remaining turbines to be deployed, and one “hot-swappable” spare. Once this has been completed, the cost differences between the different generations of the device will be quantifiable, and predictions as to the cost further NM100 units beyond EnFAIT can be made with reduced uncertainty. While quantitative evaluation of the independent impact of each factor may not be possible, a number of cost reduction opportunities have been identified. The relative contribution of each of these cost reduction pathways can be assessed when comparing multiple units and multiple iterations of the NM100 device. For the purposes of the EnFAIT project, the cost reduction is to be proven empirically and shall be subject to the verification process. The cost reduction focus will be on the following items:

- Cost reduction by Design - Design for manufacture, assembly, maintenance.

- Lean production cost reduction - Just in time production. Ensuring ordering of specific quantities of raw materials, consumables and sub-components to prevent excess in supply, and prevention of excessive delays involving components in storage or on the production line awaiting assembly.

- Overhead cost reduction - electricity cost, rent and rates for manufacturing facilities, fixed costs and expenses.

- Standardisation cost reduction – ensuring component commonality between devices, progressing towards a commercial unit suitable for mass production and type certification.

- Product-line rationalisation cost reduction – focusing on a limited number of product types being offered by Nova Innovation to target investment in the most profitable products. This will involve the consolidation of the product line into select turbine types.

- Supply-chain management cost reduction – controlling the supply of essential components within the supply chain, ensuring competitive prices are achieved for all procured components and sub-assemblies.

- Quality cost reduction – reducing the amount of re-work or repair necessary following the production of a component. Getting the product right first time will save manufacturing time and cost.

- Total cost measurement to support all cost-reduction activities – determining in detail the total cost of the product, and the cost centres that constitute the largest component of the lifecycle costs. By developing a more robust understanding of the life cycle costs, the potential for further cost reduction can be clearly identified.

5.7 Commissioning Verification Report

At the end of commissioning verification, a commissioning verification report shall be issued. The verification report shall present the overall status of the verification, together with a LOP, such as TQs that have not been satisfactorily addressed (if any), or any technical or project requirements that have not been fulfilled in the commissioning. This LOP should then be reviewed following the completion of the operation phase to see where subsequent data collected may have provided additional information that will allow the close out of open points. For any points that remain open at the end of the verification strategy, suitable mitigation shall be implemented by the Design Team to reduce risk to a satisfactory level.

6 Operations Stage

The operations stage will be an important stage of the project, where empirical data will become available to support many of the project objectives. The outputs from this stage will provide the evidence to determine the success of the project. The operational phase will also be a test of the longer term performance of the array and continuation of the KPI assessment process throughout the operational phase. In addition to the performance assessment across the full life-cycle of the project, the operations stage will be a useful period to assess the contractual aspects of turbine supply, with a view to developing the contractual documentation that will support future array deployments. While not an exhaustive list, this could include formal documentation outlining the contracting strategy, power performance and component warranties, benchmarking for contractual performance incentives and / or Liquidated Damages (LDs), preparation for future commercial contracts to improve Nova's positioning within the nascent stages of industry development and operation monitoring requirements such as remote monitoring from a serviced control centre.

Hazard identification, near miss and incident reporting will also be required in detail throughout the operational life of the project. The target throughout the EnFAIT project is zero accidents resulting in harm or environmental damage, however, document preparation and adequate data recording through the project must take place in order to robustly demonstrate that suitable procedures are in place should an incident occur. Lessons learned and efficiency improvements should also be recorded in order to improve future array operations.

6.1 Operational Stage Data Requirements

In order to evaluate KPIs and project objectives, quantitative and accurate data is required for a number of project critical parameters. This includes:

- Exported energy – meter readings to validate the energy exported over discrete time periods;
- SCADA data for instantaneous power generation, available as 10 minute averaged dataset;
- Metocean conditions that allow permissible device installation or recovery;
- Intervention time – start timer when vessel departs from port, stop timer when vessel has returned to port (separate measurement for deployment and for retrieval)
- Device downtime – start timer when device is stopped automatically or remotely. Stop timer when turbine is restarted (either with original unit, or hot-swapped unit;)
- Intervention costs (for deployment and for retrieval interventions)
- Maintenance procedures to be carried out on the device during scheduled maintenance (including periodicity);
- Maintenance costs, including cost of all components and consumables replaced during the maintenance procedure.

6.2 Array Layout Change

One feature that is unique to the tidal energy sector is the ability to reposition the NM100 devices in a cost effective way using low cost vessels. This offers an opportunity to investigate the effects of the array layout on operational performance of the devices themselves, and also the maintainability and operability of the project. The array layout optimisation provides an opportunity to quantify the impact on the performance of the turbines when positioned in certain configurations and proximity to other devices. This will allow array optimisation to be undertaken according to measured and validated results from the ADCP deployments. The measured data will also feed into the validation of the numerical modelling tools being used within the EnFAIT project, namely tools from the DTOCEAN and Array Interaction Modelling (AIM) projects.

The data collected within the EnFAIT project must be of sufficient quality to analyse array performance, load predictions and wake effects, which will be measured and compared with predictions. The verification activity will document the reliability of the modelling and predictions when compared to the physical performance and environmental data collected from the devices during the array operation.

6.3 Decommissioning

Upon successful completion of the decommissioning, the demonstration of array lifecycle will be complete, albeit for a shortened lifecycle than is anticipated for later production turbines. In future projects, decommissioning would not be expected until the project has achieved 20 years of operation. The decommissioning stage will require Nova Innovation to:

1. Demonstrate the disassembly of the device and infrastructure;
2. Determine the components or materials that can be recycled;
3. Identify any non-reusable / recyclable components or materials, and to define a sustainable disposal methodology for non-recoverable / recyclable items.

The Oil and Gas Authority are preparing an outline of the building blocks required to draft a decommissioning roadmap[2], for which much of the information could be of benefit to other industries within the marine space. This stage will also allow for the estimation of decommissioning costs of the turbine array.

6.4 Review Status of the Demonstration of Project Objectives

Following the decommissioning of the EnFAIT array, a final review will be undertaken of all project objectives (as defined in Appendix 1). This will determine the overall extent to which objectives were met.

One of the principal aims of EnFAIT is to demonstrate a minimum cost reduction of 40% in the LCOE for early tidal arrays to a maximum of €240/MWh. The EnFAIT project is expected to demonstrate all phases in a tidal array's lifecycle from design and manufacture, through operation and maintenance to decommissioning within 5 years. However, requirements such as the design life of the turbines will be

[2] The Oil and Gas Authority, Decommissioning Roadmap, Available Online, accessed 19/03/2018. https://www.ogauthority.co.uk/decommissioning/decommissioning-roadmap/

aligned to the expected design life for commercial projects (e.g. 20 years) so that the cost of energy target can be adequately demonstrated.

6.5 Operational Verification Report

At the end of operational verification, an operational verification report shall be issued. The verification report shall present the overall status of the verification, together with a LOP, such as TQs that have not been satisfactorily addressed (if any), or any technical or project requirements that have not been fulfilled in the operational stages of the project. For any points that remain open at the end of the verification strategy, suitable mitigation shall be implemented by the Design Team to reduce risk to a satisfactory level for any subsequent projects or deployments.

7 Conclusion of Verification Activities

Once each of the verification activities (design, commissioning and operation verification) has been completed, a separate report will be issued for each stage. This will ensure traceability of the technical assessment and reporting at each stage of the process. In addition, the TQ register and LOP will remain live documents that will be used by the Design Team to develop, optimise and enhance the array operation throughout the remainder of the EnFAIT project.

It is the aim of the consortium to ensure that the EnFAIT array successfully achieves significant de-risking, and that the project generates evidence in support of performance and operational improvements that demonstrate a path towards sustained cost reduction. The activities carried out under the Verification Framework, and the evidence presented to support each of the verification stages, will provide a measure of technologies' technical and commercial performance. In addition, the results of the verification process will determine the level of confidence that the technology can meet longer term cost reductions through subsequent iterations of the device.

Appendix I Overall EnFAIT Project Objectives

Project Objective	Detail	How demonstrated within the project	Work packages
Demonstrate the full lifecycle of a tidal array	Demonstrate the full lifecycle of a tidal array of six turbines, from design to decommissioning through successful completion of array design, build, operation and decommissioning activities.	Successful completion of array design, build, operation and decommissioning.	WP4,5,6,7
Demonstrate the cost-effectiveness of tidal arrays	From results achieved within the project, demonstrate a minimum cost reduction of 40% in LCOE for early tidal arrays to a maximum of €240/MWh, through the delivery of Array LCOE model, informed by project results, demonstrating reduced LCOE.	Delivery of Array LCOE model, informed by project results, demonstrating reduced LCOE.	WP3,4,5,6,7, 10
Demonstrate safe operation and mastery of array project risks	Demonstrate the ability to minimize and master the risks of ocean energy arrays by operating the array safely. Zero accidents leading to harm or environmental damage over the 5-year project duration.	Zero accidents leading to harm or environmental damage over the 5-year project duration.	WP1,5,6,7
Increase the commercial attractiveness of ocean energy arrays	Engage with potential clients and investors to educate them on the potential of the ocean energy sector and drive demand for future projects. Delivery and issue of a Commercialisation Strategy for tidal energy and a Business Plan template for potential project developers	Delivery and issue of a Commercialisation Strategy for tidal energy and a Business Plan template for potential project developers	WP2,3
Evaluate modelling tools for ocean energy arrays	Evaluate modelling tools for ocean energy arrays, including the DTOcean suite of array design tools and hydrodynamic tools for modelling array loading to develop sector knowledge and data sets. Delivery of reports and data sets on the results of evaluation of array modelling tools.	Delivery of reports and data sets on the results of evaluation of array modelling tools.	WP10
Demonstrate the effects of array layout on turbine loading and performance	Measure the impact of array wake effects on downstream turbine loads by changing the layout of the turbines to assess the sensitivity of array spacing on fatigue and reliability and compare the results with predictions of state of the art tidal array modelling tools. Delivery of a report on the results of the array layout reconfiguration experiments.	Delivery of a report on the results of the array layout reconfiguration experiments.	WP6,10

Project Objective	Detail	How demonstrated within the project	Work packages
Engage stakeholders to disseminate results	Map and engage actively with stakeholders to ensure that the objectives and outcomes of the project maximise the benefits to the wider industry by adopting a collaborative, open approach to maximise transparency. Delivery of the Communication and Training Plan; engage with a target of 1000 individuals in training events during the course of the project	Delivery of the Communication and Training Plan; engage with a target of 1000 individuals in training events during the course of the project	WP2
Maximise the benefits of ocean energy for local communities	Demonstrate a significant, positive impact on maritime communities within this project, and develop a strategy to maximise the impact of future ocean energy projects on maritime communities. Delivery of the Local Community Engagement Strategy; demonstrate a target of 25% of array expenditure in the local community.	Deliver of the Local Community Engagement Strategy; demonstrate a target of 25% of array expenditure in the local community	WP5,6,8
Evaluate the environmental and socioeconomic impacts of ocean energy	Map and engage stakeholders to understand the inter-relationships, benefits and conflicts and maximize learning. Appraise the environmental and socio-economic impacts of this tidal array project, and the potential impacts of the wider ocean energy sector. Deliver an environmental and socioeconomic appraisal for the EnFAIT project, and for the wider sector.	Deliver an environmental and socioeconomic appraisal for the EnFAIT project, and for the wider sector	WP8
Demonstrate a state-of-the-art reliability, availability and maintenance system	Develop and demonstrate an industry leading condition monitoring system for tidal arrays, based on industry leading, risk-based design and operational analysis tools used in the oil and gas and wind power sectors. Delivery of reports on reliability, availability and maintenance analysis.	Delivery of reports on reliability, availability and maintenance analysis.	WP6,9

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