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ENFAIT
ENABLING FUTURE ARRAYS IN TIDAL

T4 Lessons Learned Report

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Contents

1 Introduction

1.1 The Project

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.

WP5 of the EnFAIT project relates to the procurement, assembly, test and construction of the new aspects of the Shetland Tidal Array in Bluemull Sound, including the new turbines, cables, onshore station and subsea hub.

The T4 machine is the first of three M100-D turbines (T4, T5 and T6) to be deployed to the north of the existing three turbines (T1, T2 and T3) on the array – see Figure 1.

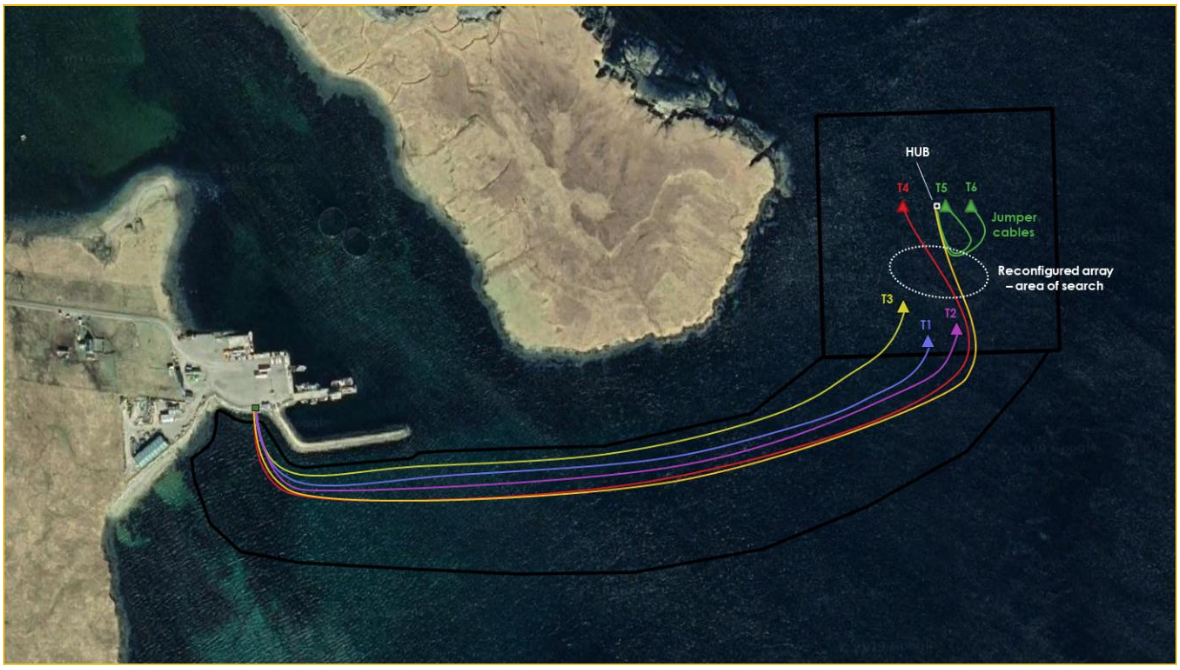

Figure 1: Shetland Tidal Array build-out plan

1.2 Scope of the Lessons Learned Review

The scope of the T4 lessons learned review is to capture learnings from the T4 build that can be integrated into the design and build of the EnFAIT T5/T6 machines and the wider ocean energy industry.

For each of the functional sub-systems defined in Section 1.4, lessons learned were captured across procurement, quality, integration and deployment activities (where relevant). Lessons learned that were captured in more than one subsystem will only feature once within this document.

1.3 Report Content

This report provides lessons captured from the build of T4 which may benefit the wider ocean energy industry. While respecting the need for commercial confidentiality, in sharing these lessons the EnFAIT project aims to enable other projects and developers to obtain knowledge which may enhance their own endeavours to continue to deliver a successful ocean energy industry.

1.4 Lesson Learned Areas

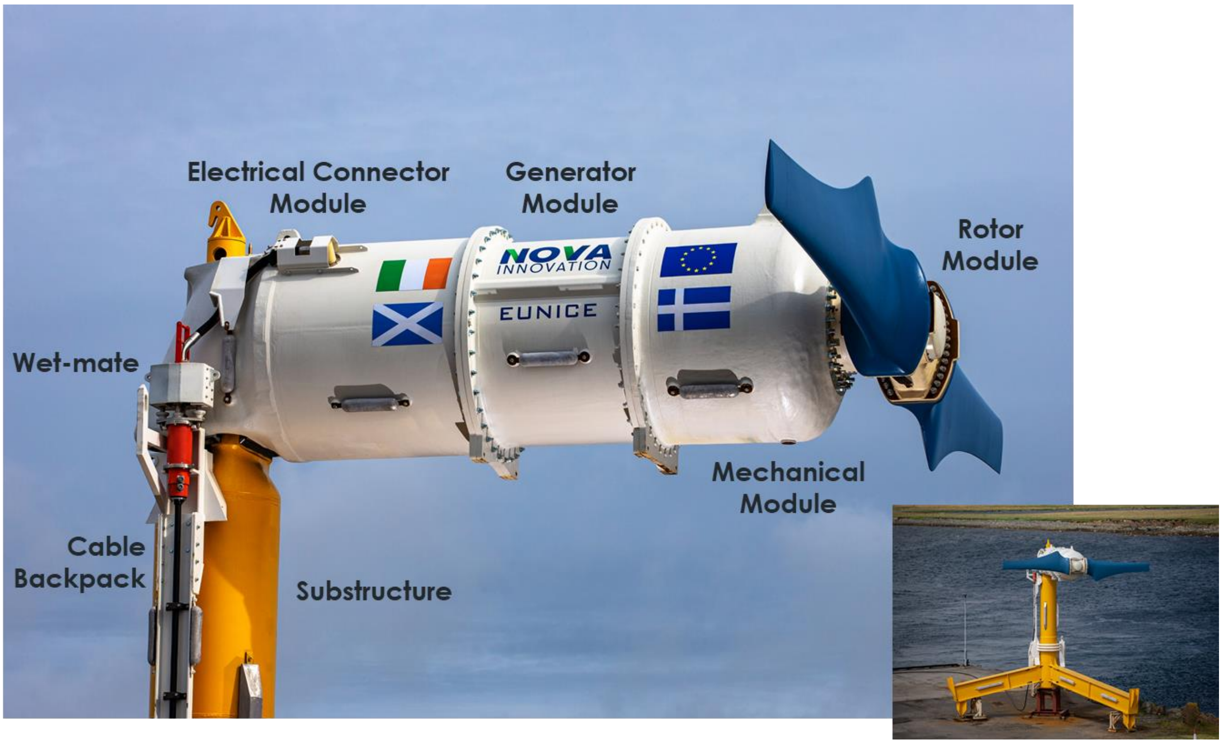

Figure 2: Sub-systems covered by the lessons learned review

The lessons learned from the procurement, assembly, test and construction of the T4 machine are outlined in the following sections:

- Rotor module
- Mechanical module
- Generator module
- Electrical module
- ECM (Electrical Connector Module) comprising:
    - Substructure and connector module
    - Wet-mate system, backpack and subsea cable
- Onshore station
- Offshore deployment equipment and operations
    - Launch and Recovery System
    - Substructure deployment and ballasting
    - Backpack and subsea cable deployment
    - Turbine deployment
- Control system

Note: Nova developed the T4 rotor module, mechanical module and generator module under the D2T2 (Direct Drive Tidal Turbine) project (EU Grant Agreement No 734032), however lessons from these areas are outlined here for completeness. A summary of the outstanding results of the D2T2 project can be found here – https://cordis.europa.eu/article/id/422340-gearless-turbine.

2 Rotor Module

The rotor module converts the kinetic energy of tidal flows to rotational mechanical energy. The T4 rotor module is a novel design which has significantly improved efficiency versus the previous design. As the prime mover within the system, this increased efficiency plays a critical role in reducing the Levelised Cost of Energy (LCOE) of tidal power.

Figure 3: The novel rotor module, seen from below prior to deployment

The following lessons were captured associated with the rotor module.

Lesson 1: In-sea vessel-mounted push-testing was a highly effective way to reduce project risk and validate rotor performance prior to offshore deployments for first-of-a-kind manufacture.

Lesson 2: Fixed costs (e.g. patterns, moulds, tooling) for a one-off manufacture of the new rotor were relatively high, but demonstrate a clear pathway to reducing costs through mass manufacture.

Lesson 3: Significant time is required to achieve a high level of quality inspection, particularly for first-of-a-kind manufacture. High-volume manufacture will rely on efficient automated methods.

3 Mechanical Module

The mechanical module transfers rotational mechanical energy from the rotor module to the generator module. Shaft seals prevent seawater from entering the turbine nacelle and this module also houses the turbine braking system. The key component within the mechanical module is the Main Shaft Unit (MSU) which was developed together with SKF, a global expert in bearing and seal solutions with over 100 years of experience. The design of the MSU is also novel, building on the experiences and lessons learned from Nova's operation of the Shetland Tidal Array and advances made in Nova's TiPA project – https://cordis.europa.eu/article/id/415828-new-generator-design-reduces-the-cost-of-tidal-power. By building upon these, the novel design of the MSU has delivered enhanced performance, reliability and significant decreased operation and maintenance (O&M) requirements – all essential to driving down the costs of the tidal energy industry.

The following lessons were captured associated with the mechanical module.

Lesson 4: Pre-commissioning sub-assemblies prior to full integration and the use of plug connectors significantly increases efficiency during final assembly.

Lesson 5: Strong interface management is essential for good accuracy between components manufactured by different suppliers.

Lesson 6: Efficient supplier management is essential for successful delivery of components, particularly when components are being delivered by a highly diverse pan-European supply chain.

Lesson 7: Space optimisation and full production cycle analysis during the design stage enabled efficiencies to be realised in procurement, build and resource utilisation.

Lesson 8: Specifying stringent quality requirements on the supplier is essential to ensure components do not impact system performance or project delivery.

4 Generator Module

At the heart of the turbine is the generator module, it transforms rotational energy from the mechanical module into electricity. The T4 generator is also a novel design and one which delivers significant improvements, replacing a conventional gearbox drive train with a direct drive generator – where the same shaft that turns with the blades also turns the generator's rotor. This shift in technology draws on experience from the wind industry, where the same transition was made, and significant cost savings were achieved.

The direct drive mechanism leads to higher power output, and lower operations and maintenance costs. It also has fewer moving parts which increases its reliability and lengthens the time between service intervals. All of the above benefits deliver significant improvements towards reducing the cost of tidal energy, enabling this renewable source to compete with other mainstream energy sources.

Figure 4: The generator module at Nova's Manufacturing Facility, Edinburgh, during the final assembly process

The following lessons were captured associated with the generator module.

Lesson 9: Regular progress reporting from the supply chain is essential to capture any quality issues during the manufacturing process in order to avoid impacts to project delivery.

Lesson 10: Testing and validating a generator in a laboratory and controlled vessel-mounted in-sea conditions is an extremely valuable method to fully characterise power production, thermal performance and identify component enhancements.

5 Electrical Connector Module (ECM)

This section outlines the lessons learned from the ECM nacelle manufacture (5.1) and the electrical system it houses (5.2).

5.1 ECM nacelle

The ECM nacelle houses the main electrical module components of the turbine system as well as providing the structural connection to the turbine substructure. The ECM nacelle also provides a mounting location for the subsea cable wet-mate assembly.

This new module provides many benefits to the turbine system, including the fact that it is interchangeable across any substructure and is self-stabilising. This reduces costs of O&M, removing the requirement for divers on site, and will enable the EnFAIT project to cost effectively optimise array layout – one of the main learnings to be gained from the project in order to propel tidal energy arrays to the forefront of the energy transition.

The following lessons were captured associated with the ECM nacelle.

Lesson 11: Controlling dimensional tolerances is essential to the functionality of interconnecting components, the use of 3D scanning instruments allowed this to be accurately validated at appropriate points of the manufacture process to avoid impacts to project delivery.

Lesson 12: Testing novel systems in a testing facility at a reduced scale is an extremely effective method of de-risking first-of-a-kind manufacture.

5.2 Electrical Module

The electrical module houses the turbine electrical and control system. The novel design of the ECM has enabled the power electronics to be subsea within the turbine – building on lessons from the TiPA project. This in turn enables the turbine to be controlled better, which in turn improves the performance of the turbine. Further development of the control system is underway as part of Nova's ELEMENT project, where a new control system will developed and tested, with a target of delivering an LCOE reduction of 17% - https://cordis.europa.eu/project/id/815180.

The following lessons were captured associated with the electrical module.

Lesson 13: Improved access to relevant parts of the module and electrical system streamlines the assembly process.

Lesson 14: Standardisation of components (e.g. bolts, connectors) is essential to reduce number of parts/accessories required, improving assembly efficiency and project delivery performance.

6 Substructure

The steel substructure (and the concrete ballast which is added to it) provide the gravity foundation for the turbine. The structural connection to the turbine is made when the substructure spigot is fully engaged with the inside of the connector module at the back of the turbine.

The design of the substructure is a novel one which has provided significant improvements to the previous design utilised for turbines T1-3. The innovative design is significantly stronger than the previous generation of substructure yet weighs in 30% lighter and is more easily deployed. This innovation has delivered a reduction in LCOE through reduced material costs, O&M requirements and improved performance.

Figure 5: T4 mounted on the substructure prior to deployment in Bluemull Sound, Shetland

The following lessons were captured associated with the substructure.

Lesson 15: Undertaking complete onshore trial fits of interconnecting subsystems is an extremely efficient way to de-risk project delivery.

Lesson 16: Gaining an understanding of supplier project management resources for delivery of components prior to contract award is essential to ensure levels of communications will be as required so as to not impact project delivery.

Lesson 17: Completing risk assessments of the supply chain during procurement activities may help de-risk project delivery.

Lesson 18: Local supply chain opportunities can provide excellent quality cost-effective solutions.

7 Wet-mate System, Backpack and Subsea Cable

The wet-mate system is the method which electrically connects the subsea cable to the turbine. This is an external connection which is built into the substructure backpack which also secures the subsea cable from the turbine to the seabed. This system was designed as part of the EnFAIT project, working in harmony with the new substructure, ECM and Launch and Recovery System (LARS). The system delivers a number of benefits and when combined with the LARS, covered in Section 9.1, it means the turbines can be deployed more efficiently and without the use of a dive team, providing significant cost reductions.

Figure 6: The wet-mate system, backpack and subsea cable (white structure), mounted to the substructure tower.

The following lessons were captured associated with the wet-mate system, backpack and subsea cable.

Lesson 19: Completing on-shore trial fits for first-of-a-kind components is an extremely efficient way to de-risk project delivery.

8 Onshore Station

The onshore station is where the subsea cable comes ashore and is connected to the electrical control and distribution equipment before being delivered to the local electricity grid – allowing the predictable, renewable energy generated by the turbines to be distributed to the local community.

The following lessons were captured associated with the onshore station.

Lesson 20: The use of modular assemblies creates efficiencies by enabling assembly and testing prior to shipping components to site.

Lesson 21: The ability to replicate subsea connection of turbines at the quayside prior to deploying the turbine is an excellent way of de-risking project delivery.

9 Offshore Deployment (Equipment and Operations)

9.1 Launch and Recovery System (LARS)

The LARS is a recoverable turbine lift frame fitted with cameras and powered systems to engage/release the turbine and substructure and wet-mate electrical connections. This system will be used across all M100-D turbines on the array and will play a crucial role in reducing O&M costs.

9.2 Substructure Deployment

The steel substructure was first installed offshore using the work boat and then the concrete ballast blocks were added. This is a technique which Nova have perfected through the development and operation of the Shetland Tidal Array.

Figure 7: Deployment of the substructure and concrete ballast blocks

9.3 Cable Deployment

Nova's experience of multiple cable lay operations meant that the T4 cable lay went very smoothly with the new T4 backpack providing a secure path for the cable from the turbine to seabed – increasing longevity and decreasing O&M costs.

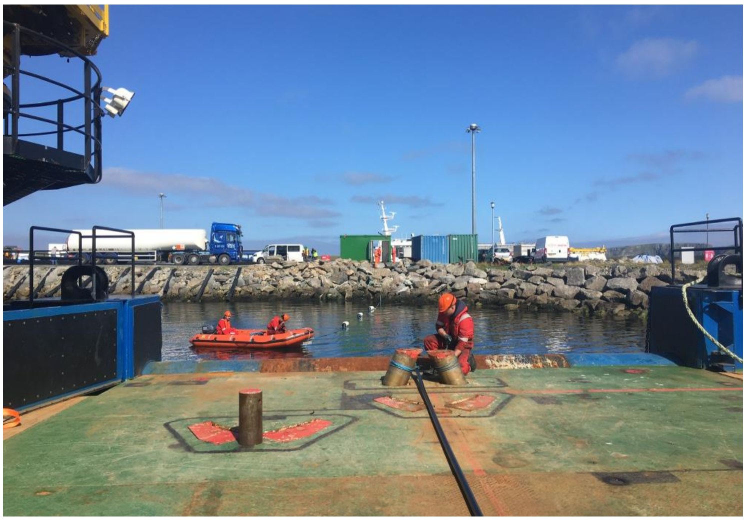

Figure 8: Cable laying operations at Cullivoe pier

9.4 Turbine Deployment

The use of the novel deployment systems for the turbine brought significant advantages and positives which drive down costs, as covered by previous sections of this report. Despite several novel subsystems coming together for the first time in an operational environment, deployment of the turbine was extremely successful, with the turbine operational within 20 minutes of deployment.

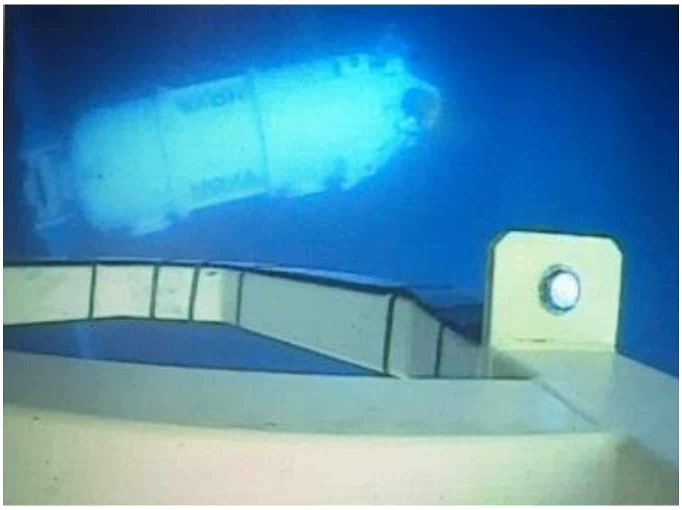

Figure 9: View of the deployed T4 turbine from the LARS camera systems

Lesson 22: Having variety of control options on deployment equipment as well as a comprehensive suite of adjustable cameras is beneficial for a well-controlled deployment.

10 Control System

The control system, a combination of software and electrical hardware, is the brains of the turbine. The system is used to determine how the turbine operates in order to maximise performance.

As mentioned previously, work is currently underway as part of EnFAIT's sister project, ELEMENT, where LCOE will be reduced by 17% through development of a novel turbine control system. As part of the project, the new ELEMENT control system will be tested in multiple environments before finally being tested on the new EnFAIT turbines deployed at the Shetland Tidal Array. This will combine benefits from two European projects and deliver significant reductions in LCOE, powering Nova's technology to delivering "bankable" tidal energy.

Lesson 23: Use of a standardised control system enables learnings from previous projects to be captured and improvements easily made.

Lesson 24: Operational efficiencies can be realised through the utilisation of cloud-based data and video management systems.

Lesson 25: Extensive software testing from an early stage of development, on subassemblies, and once assembly has been completed (but before subsea deployment) is greatly beneficial for de-risking project delivery.

11 Overview of All Lessons Learned

This section provides a summary of all the lessons learned which have been detailed in the above sections of the report.

Lesson 1: In-sea vessel-mounted push-testing was a highly effective way to reduce project risk and validate rotor performance prior to offshore deployments for first-of-a-kind manufacture.

Lesson 2: Fixed costs (e.g. patterns, moulds, tooling) for a one-off manufacture of the new rotor were relatively high, but demonstrate a clear pathway to reducing costs through mass manufacture.

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