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ENFAIT
ENABLING FUTURE ARRAYS IN TIDAL

Series Phase Lessons Learned Report

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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.

T5 and T6 are the second and third M100-D turbines to be deployed in the Shetland Tidal Array; to the north of the existing three turbines (T1, T2 and T3) on the array – see Figure 1. These represent the second phase of the Shetland Tidal Array delivery covered by the EnFAIT project, which became fully operational in January 2023. Unlike the other turbines in the array that had individual cables, T5 and T6 are connected into a subsea hub with a single export cabling coming ashore.

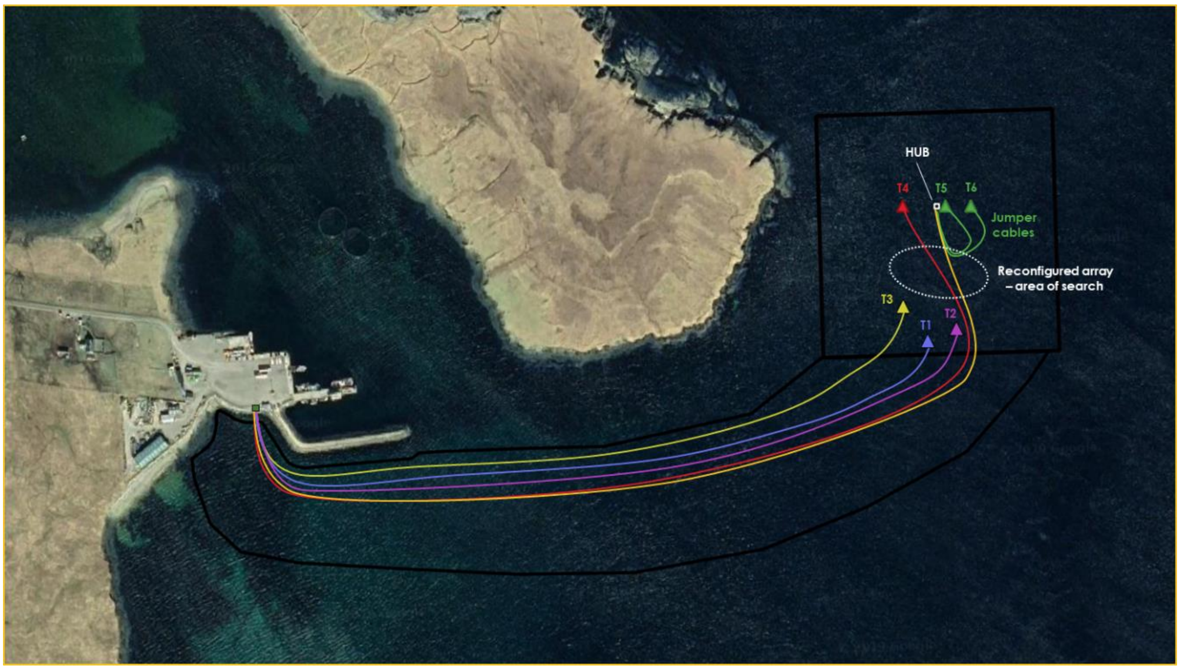

Figure 1: Shetland Tidal Array build-out plan

1.2 Scope of the Lessons Learned Review

This scope of the lessons learned review has focused primarily on the delivery of the T5 and T6 turbines. It differs in scope to the previous T4 lessons learned report as it targets the series phase of turbine delivery, during which multiple turbines and associated infrastructure were produced at the same time. This represented a significant shift towards a more production centric approach with several lessons being learned across the full turbine system. These lessons have been captured throughout the project and reviewed at dedicated lessons learned meetings to capture general themes. 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.

For each of the functional sub-systems, 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.

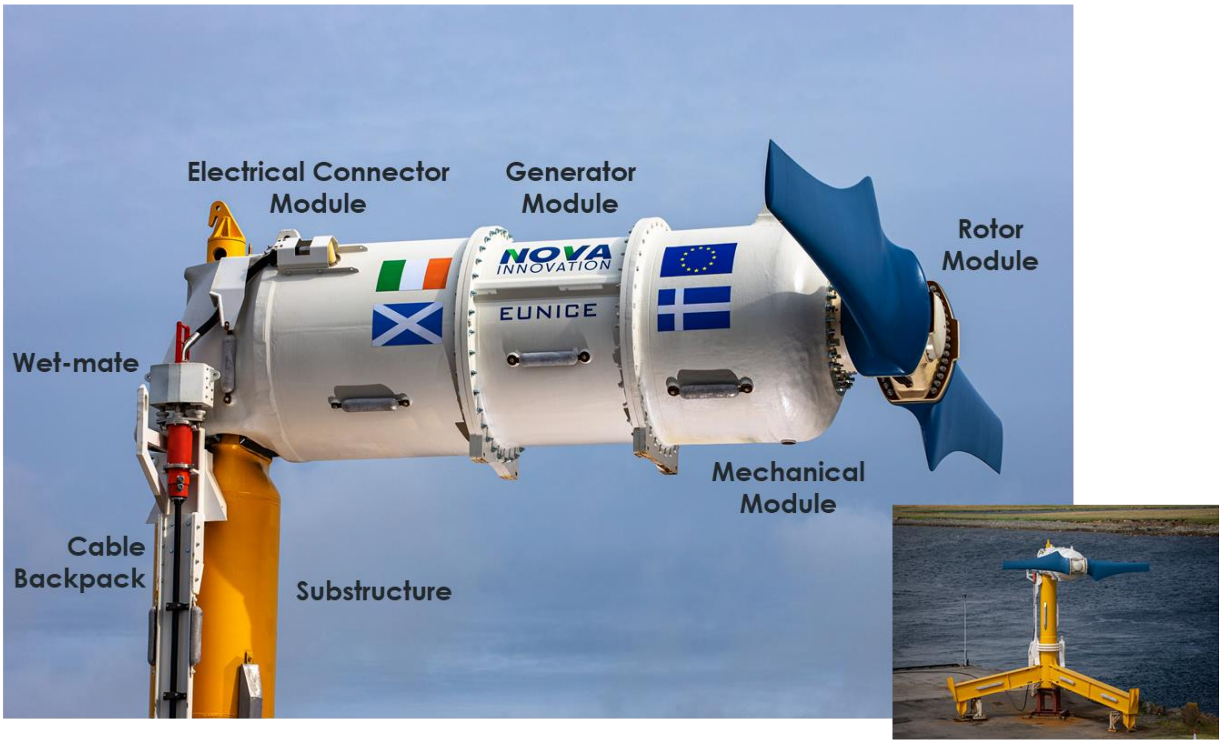

Figure 2: Sub-systems covered by the lessons learned review

The lessons learned from the procurement, assembly, test and construction of the T5 and T6 turbines are outlined in the following sections. These broadly follow the physical architecture of the turbine.

2 Rotor Module

The rotor module converts the kinetic energy of tidal flows to rotational mechanical energy. Through the build and operation of T4, the rotor module was found to operate successfully and not present any significant challenges in the build stage. As such, only minor modifications were made for the T5 and T6 rotor modules, covering the lifting point positions on the hub. Broadly the same procurement decisions were made as for T4, using the same production techniques. However, different suppliers were used for the key castings, demonstrating the flexibility for manufacturing of Nova technology. Efficiencies were gained through placing contracts for the manufacture and assembly at the same time, delivering the increased product volume.

The following lessons were captured associated with parallel production of the rotor module.

Lesson 1: Ensure test methods are appropriate for the kit that is available on site. For example, the use of bubble testing instead of H2 leak testing was as effective for the testing objectives and didn't require specialist equipment. In a similar vein, ensure the tests selected and quality levels are appropriate to only capture genuine issues that risk the performance of the equipment.

Lesson 2: Assembly team interactions and communication is very important on parallel builds where different team members are involved to ensure successful assembly. Ensure systems are developed to easily confirm assembly has been completed to drawings, especially when progressive stages are completed by different people.

Lesson 3: If space and time constraints allow, align equipment orders with dips in the commodity market. The use of cast components in the rotor module make it particularly susceptible to variations in metal and electricity costs. This also impacted other components, for example glass fibre, resin and anti-foul paint.

Lesson 4: With parallel builds, the pressure will be on to clear assembly facilities for the build of subsequent units. Ensure appropriate solutions are implemented to minimise the risk of damage to key details whilst in storage (e.g. machined sealing faces, sensitive anti-foul coatings, etc).

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. 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 sealing solutions with over 100 years of experience.

The T5 mechanical module has the same main sealing technology as T4, whereas T6 trialled a new technology that extends the service life considerably. This required additional systems and changes to the build and test procedures. In addition, both T5 and T6 used a different material specification for the main seal housing, further increasing the service life. The internal systems in the mechanical module remained broadly the same in both turbines, with Nova's high torque, fast acting braking system and flexible coupling included on the drivetrain.

Figure 3: The new main shaft sealing solution implemented on T6

The following lessons were captured associated with the mechanical module.

Lesson 5: Full interchangeability between modules was demonstrated successfully, proving the modular design improves serviceability. This is particularly critical to increase high turbine production availability in the field.

Lesson 6: The implementation of new technologies to an established production ready system must be well managed to maintain delivery timelines. Sufficient design assurance must be completed far enough in advance that any issues have been overcome before timescales become critical during assembly.

Lesson 7: Appropriate naming and complete specification of parts and build instructions is required to ensure accurate ordering and consistency of supply. This is particularly necessary where access to the original designers could be restricted.

Lesson 8: Successes with the development and implementation of procurement and quality management systems for this phase of the EnFAIT project have provided much improved communication within the business. These systems will become even more valuable with increased product volume where the quantity of data will increase significantly, and the developed computer systems will be required to maintain an accurate understanding of project delivery.

4 Generator Module

At the heart of the turbine is the generator module, which transforms rotational energy from the mechanical module into electricity. The T5 and T6 generators were very similar in design to T4. Only modest modifications to improve the buildability were implemented, along with a modification to how the encoders are integrated with the drivetrain. Following the success of the T4 type testing, the piece tests for the T5 and T6 generators focused on FATs by the manufacturer slimming and focussing the operations required. This produced continued high-quality components more quickly at reduced cost.

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: Ensure critical build steps are reversible. Use of adhesives and other sealants on critical components can improve reliability but significantly reduce the maintainability. Carefully consider the trade-offs between these.

Lesson 10: Complete product documentation packs enable speedy production by reducing interactions between suppliers and designers during the production process.

5 Electrical Connector Module (ECM)

This section outlines the lessons learned from the ECM mechanical system (5.1) and the ECM electrical system (5.2).

5.1 ECM Mechanical System

The ECM mechanical system comprises of the nacelle, drive skid and external equipment. Changes to the T5 and T6 design included the removal of the secondary substructure engagement method and changes to assembly methods for the drive skid cooling system. Both changes reduced assembly time and in the case of the secondary substructure engagement method removal, reduced associated CAPEX as well.

Figure 5 - Fully assembled ECM, prior to full turbine assembly

The following lessons were captured associated with the ECM mechanical system.

Lesson 11: The increased modularity of the drive skid enables earlier stand-alone testing of the subsystem, reducing the final assembly and commissioning time once the module is fully assembled.

5.2 ECM Electrical System

The ECM electrical system includes the offshore power electronics, control panel, transformer and wiring held within the ECM nacelle. There were no significant design changes associated with the T5 and T6 electrical system. However, recent post-COVID global supply chain issues did mean that certain parts could not be sourced within the project timeline and alternatives needed to be selected instead. Changes in the way the electrical system was built did occur. The T4 ECM electrical system was completed with significant involvement and supervision by the electrical design team. For T5 and T6, detailed build instruction documentation was created and shared with the production team. This enabled manufacture to be run independently, significantly speeding up the build process and demonstrating scalable manufacture.

The following lessons were captured associated with the ECM electrical system.

Lesson 12: For serial production ensure robust stand-alone build and test documentation are generated and that they are communicated to production in an effective format. Clear bi-direction communication paths for the 'transfer of knowledge' between engineers and production staff are key to the delivery of a good quality product prior to and during build.

Lesson 13: Functional testing of subsystems should be completed progressively during the build process. Testing completed solely at the end risks identifying issues triggering re-work activities that are time consuming and expensive to rectify.

Lesson 14: Ensure sufficient assembly and test equipment is available to meet the production build plan projections. Early planning stages must identify potential over-utilisations and seek to smooth these out.

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 T5 and T6 substructures are very similar in design to T4. The only changes were a reduction in the height of the book ends to enable container loading and intermediate ballast stops added to the legs to enable lifting in a partially ballasted state. As with T4, the T5 and T6 substructures were manufactured in road transportable sections and welded together on site. The cable backpacks were manufactured at the same supplier, enabling trial fits to be completed before delivery to site.

Figure 6: T5 and T6 substructures assembled on the quayside and awaiting deployment

The following lessons were captured associated with the substructure.

Lesson 15: With increased production quantities, decisions taken for the delivery of a smaller number of units must be considered. Spatial constraints on build locations worked for the delivery of 2

substructures but parallel working on remote construction locations may not be cost effective for a larger number of units as the infrastructure is likely limited.

Lesson 16: The substructure is fully welded with limited but important geometrical interfaces. Consider adding features that enable adjustability in the event that the interfacing structures do not meet the tolerances required.

Lesson 17: Placing contracts for the substructure and cable backpack (the main interfacing components) with the same supplier worked well. This allowed integration testing to be completed in the fabricator's facility rather than on site, increasing quality and in turn reducing costs.

Lesson 18: Ensure that sufficient spares are provided and that a clear list of acceptable alternatives is created for site build activities to ensure speedy delivery is maintained.

7 Wet-mate System, Backpack, Subsea Cables and Subsea Hub

When operating multiple assets in an array, issues with cost, consenting and practicalities restrict the number of cables that can come ashore. To overcome this, the T5 and T6 turbines are connected to a subsea hub – a first for the tidal energy industry. A single export cable runs from the onshore station to the subsea hub, with shorter turbine cables running to T5 and T6 turbines. The turbine wet-mate system, backpack and subsea cables were generally unchanged. However, the turbine subsea cables were terminated at both ends to enable connection and disconnection at both the turbines and subsea hub.

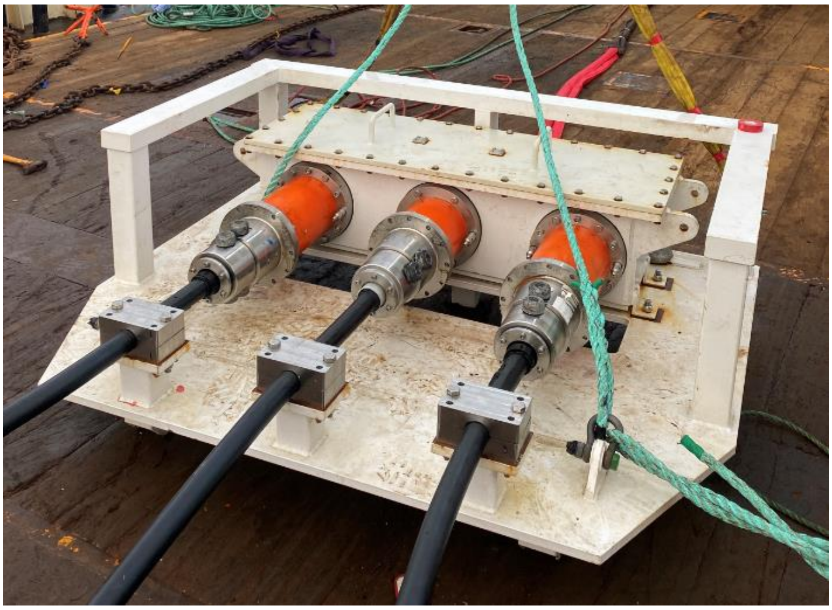

Figure 7: The EnFAIT Subsea Hub ready for deployment, with 2 turbine cables and 1 export cable

Lesson 19: Subsea hubs and the export cables connected to these can be the most important single points of failure in the entire array. Implementation of a rigorous pre-deployment testing regime is critical to the success of these systems.

Lesson 20: To optimise the subsea electrical cabling package for array deployments requires careful consideration of where and when to use subsea hubs. Whilst single cables to shore may be easier to deploy, subsea hubs could offer a reduced LCOE. For the first time, the EnFAIT project has demonstrated that subsea hubs can be implemented successfully in tidal arrays. Future projects will look at developments of this technology to optimise the number of turbines that connect into these hubs.

8 Offshore Deployment

8.1 Cable and Subsea Hub Deployment

The inclusion of a subsea hub for T5 and T6 meant that deployment activities differed to those of T4. A single export cable was efficiently run ashore using Nova's tried and tested cable laying techniques. This was connected to the turbine cables using drymate connections (cabling connections that can operate subsea, but need to be connected and disconnected out of the water) on the deck of the boat, before lowering these to the seabed.

8.2 Turbine Deployment

As with T4, turbines T5 and T6 were deployed using a Launch and Recovery System (LARS) – effectively a reusable frame that can remotely mate to and become the turbine lifting interface during deployment or recovery from the substructure subsea. The slight modification of LARS camera positions provided improved visibility of the turbine relative to the substructure during the installation process. Furthermore, operations were completed during spring tides, demonstrating the capability to successfully install in fast tidal flows and a very wide range of tidal windows.

Figure 8: View of turbine deployment. LARS is yellow frame on top of turbine

Lesson 21: With increasing numbers of turbines on site, appropriate storage spaces are required. Wet storage of the turbines was an effective means of optimising quayside space.

Lesson 22: The drymate subsea hub solution worked well, reducing array CAPEX over wetmate type solutions for electrical and communication connections that do not require regular mating / unmating.

Lesson 23: Turbine deployment in spring tides and sizeable waves (the conditions which T5 and 6 were successfully installed during) greatly increases the window for deployment reducing time between deployment and recovery for maintenance and thus overall array availability for power generation.

9 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.

For T4 the software associated with the control system was new and required significant "type" testing to ensure this was fit for purpose. Commissioning of T5 and T6 differed as the software had already been tested in a systematic manner enabling a much more condensed period to be achieved. Furthermore, whilst T4 was commissioned on its own, T5 and T6 were commissioned in parallel. An overall reduction in commissioning duration of 75% was achieved along with a doubling of efficiency. These types of savings pave the way for commissioning of larger arrays with limited supervision, reducing the cost of this part of the operation

Lesson 24: Automate as much of the commissioning process as possible and carefully set the alarm trip points to enable expedited commissioning. This reduces the level of human supervision, enabling the turbines to be tested for longer over a shorter duration.

Lesson 25: Synchronisation of the commissioning process with the tidal cycle enabled progressive commissioning to be achieved, with lower power conditions occurring earlier in the commissioning programme.

10 Lessons Learned Conclusion

The series production phase of the EnFAIT project has delivered numerous lessons in how to deliver multiple turbines successfully and efficiently at the same time. These are detailed in the previous report sections. Moving from prototype builds to the first production units presents challenges, but also opportunities. Step changes in speed of build, installation and commissioning have been experienced as a result. This has been broadly supported by a shift towards a more production centric manufacturing model, with fully documented build steps enabling scaled production.

Significant advances in procurement and quality systems have also been tried and tested, leading to cost reductions, improved communication, and efficient planning across the business. Looking forwards, this project has built systems to achieve the next major step for the tidal industry sector: the delivery of large arrays with commercial quantities of turbines, deployed rapidly, safely and to budget. The EnFAIT project has therefore been a key steppingstone, with the lessons learned from it being pivotal to the success of the scaling up required to meet future LCOE objectives.

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