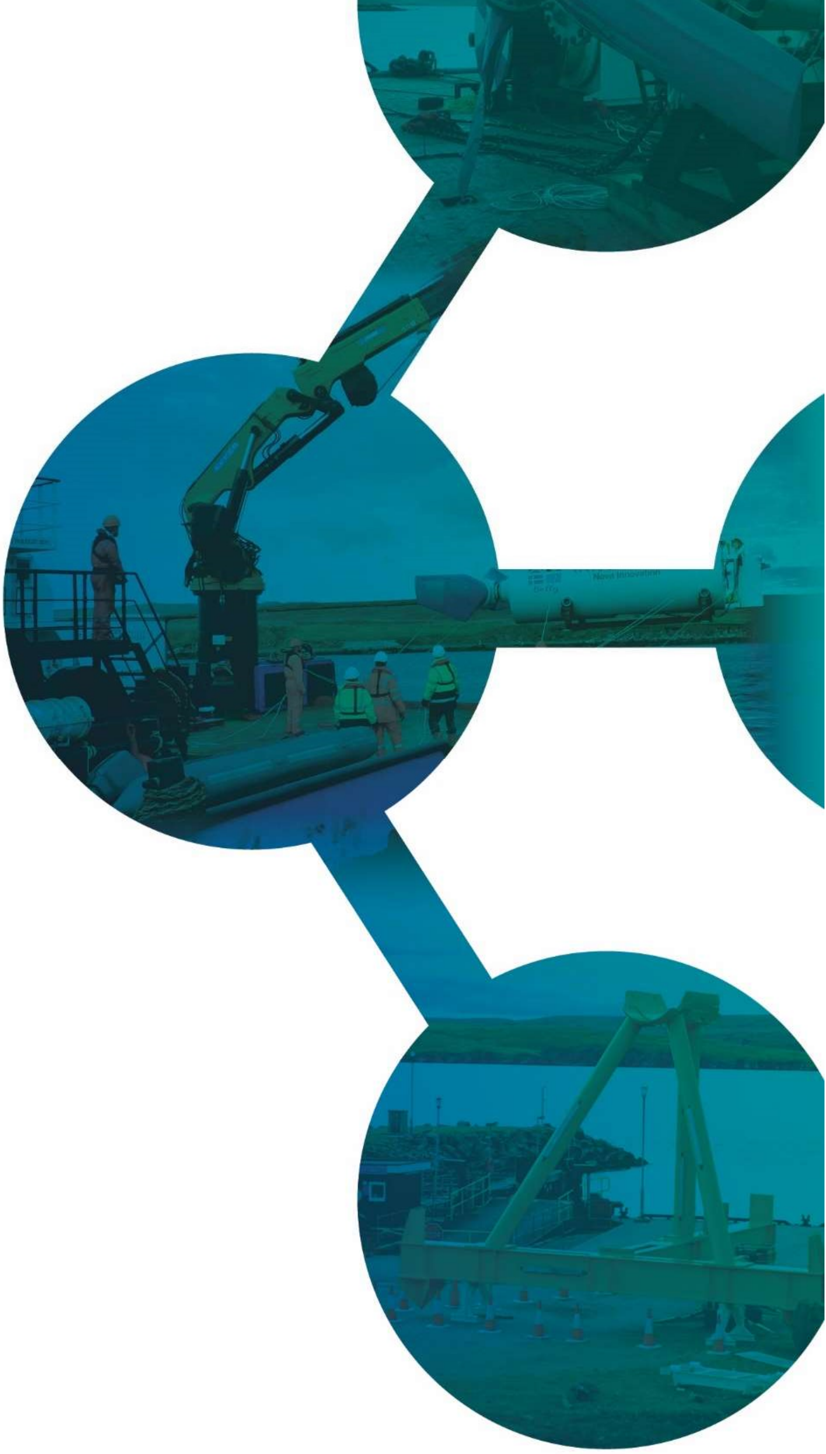

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ENFAIT
ENABLING FUTURE ARRAYS IN TIDAL

Conclusions and Future Recommendations for Tidal Array Optimisation

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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.

1.2 Scope

To produce good quality electrical power at a cost-effective LCoE, requires tidal turbines which will operate at a high level of reliability and availability. This requires knowledge of expected failure modes; the effects and other risks which these failures will have on the desired business goals of the tidal array operator; and methods to address these expected risks. Throughout the EnFAIT project Nova and its partners have captured the above information to successfully design and operate tidal turbines.

This deliverable *D9.8 Conclusions and future recommendations for tidal array optimisation* discusses the lessons learned and recommendations which can help move forward tidal energy and tidal arrays as a cost-effective and competitive renewable source of energy. The report focuses on the different tasks which were part of Work Package 9. The objective of EnFAIT Work Package 9 (WP9) *"Optimise array reliability, maintainability & availability"* was to design in reliability and best-practice maintenance regimes to maximise tidal array availability through:

- Delivering a Design Failure Mode Effect & Criticality Analysis (DFMECA) system (EnFAIT Project Report D9.2);
- Validation by Reliability Availability Maintainability (RAM) modelling & simulation (EnFAIT Project Report D9.3);
- Conducting a Maintenance Strategy Review (MSR) to mitigate risk and minimise LCoE (EnFAIT Project Report D9.4);
- Designing, delivering & demonstrating cost-effective state-of-the-art Condition Monitoring System for tidal arrays (EnFAIT Project Report D9.5);
- Architecture and implementation of tidal array condition monitoring (EnFAIT Project Report D9.6)
- Design of tidal turbines array and operational systems (EnFAIT Project Report D9.7)
- Conclusions and future recommendation for tidal array optimisation (EnFAIT Project Report D9.8)

This report presents the more important findings and knowledge of the EnFAIT project partners to further develop the sector. This work package does however need to consider commercial sensitivities and proprietary data. As such, some of the referenced reports are not available to the public. It must also account for the current state of the sector, i.e., the first pre-commercial arrays have been built and operated for some years, and several companies are now planning and developing larger early commercial arrays.

2 Findings from Maintenance and Operations

With the design and operation of tidal turbines and arrays still being a relatively new industry, there is still a lot to be learned about this renewable source of energy and how to make it compete with mature technologies, for example wind turbines.
With little historical information available about tidal array operation the EnFAIT project started off with gathering such information through analysis of component conditions for the most critical components in the turbine design to apply improvements.
Seeing that one of the most important operational modes of a turbine design comprises of rotating equipment, it is of importance that the potential failure modes which are related to the critical rotating equipment are monitored and managed to achieve the desired level of reliability and availability. SKF as a specialist in rotating component design and monitoring has successfully applied existing technologies to the EnFAIT project.
Apart from the design of turbine components and systems, the reliability and availability are also affected through operation of the turbine and array. This includes operating within the known limits of the design and recovering the turbine for maintenance checks and analysis to learn more about the design limitations and potential reliability improvements.

2.1 Component condition analysis

2.1.1 Main bearing and seal analysis

During the EnFAIT project, analysis was performed on the bearings of the main shaft unit (MSU) of a Nova M100 turbine. The lessons from this component analysis were used to further develop the MSU and improve bearings and seals for this unit. Due to commercial sensitivity, only high level points are mentioned here. The lessons learned from the initial component analysis were as follows:

- The main bearings of the MSU performed as expected and would well achieve the 5-year major maintenance interval.

- The seals for the main bearing needed some minor design changes. While the seals did work properly, it was found that some minor changes were needed in order to achieve the 5-year major maintenance interval.

- The MSU housing was redesigned to allow future operators or owners to install different models of seals, giving flexibility to the customer and also decreasing the operational risk associated with a single source or design component.

- Improvements were made on the plugs of the seal housing, and the fit of gaskets in the MSU.

- Further design studies were undertaken to improve cost, maintainability and the assembly process for MSU and hub design.

- Finally throughout the project Nova and SKF achieved efficiency in the mounting, dismounting and rework process of the MSU and hub unit, which directly results in better more efficient maintainability.

2.1.2 Planned replacement components

Inspection of components within the turbine showed extremely good condition, with the scope for extending the service interval from that often quoted by manufacturers. The following key points are noted:

- Rubber components such as hoses showed no evidence of ageing after 5 years
- The cleanliness and condition of electrical components remained high throughout the EnFAIT project. Due to the sealed, very stable and controlled environment within the turbine, there is no expected need to clean systems (which is often stated in instruction manuals).
- Sampling of lubricants within the system showed very stable conditions, which allowed extension of the planned maintenance interval of the M100 turbines during the EnFAIT project. Inspection of the later 100D design showed no evidence of degradation in any of the lubricants or fluid systems over its 1st maintenance interval (18 months).

2.1.3 External components

Inspection of external components, on retrieval and during decommissioning showed very good conditions.

- Anode consumption was lower than expected, providing scope for reduction of anode mass or extension of life.
- Structural condition of the decommissioned substructures was extremely good, in terms of corrosion, surface coating and bolted joint condition. Structures in this condition after 8 years would be expected to easily achieve well beyond a 25-year target life.
- Biofouling management through the targeted application of coatings has shown to be highly effective over long-term operation. This use of environmentally friendly coatings where necessary to ensure long term performance of the turbine has to date proven very effective.

Figure 1: Negligible blade biofouling after 18 months of operation

Figure 2: Inspection of 8-year-old substructure showed no notable deterioration

2.2 Tidal Array Condition Monitoring

Condition-based vibration monitoring systems are a common use in many other industries where capital intensive assets are used; for example in conventional turbines or wind-turbines. The decision to use condition monitoring depends on the expected potential failure-modes and the effect this will have on the availability of the tidal turbine, energy production, and business objectives. Eventually the goal is to be in full control of the reliability and availability of the turbines and arrays, and with that to achieve the targeted LCoE.

In rotating equipment, the expected failure modes are loss of function due to imbalance, misalignment, mechanical looseness, lubricant degradation or rotating component jamming. Each of these failure modes can be pro-actively monitored through a vibration monitoring system which collects its data from sensors on the most critical roller bearings.

2.2.1 Condition monitoring setup for tidal arrays

The SKF condition-based monitoring system was implemented using an on-line system utilising specialised condition monitoring data devices and sensors. The sensors are accelerometers with the primary objective of determining the condition of the rolling element bearings in the major components of the tidal turbine drive train with a view to detecting early failure of these components. In report *D9.6 Condition Monitoring for Tidal Array*, a more detailed explanation is given about the architecture of the condition monitoring system implemented on the EnFAIT tidal turbines.

An additional objective was to monitor the overall vibration of the machine to compare with ISO standards for acceptable machinery vibration and to provide an insight into potential failure modes of the rotating components such as imbalance, misalignment, and mechanical looseness. As with similar technologies such as wind, both manufacturing tolerance and environmental loading induced imbalance will be present to some degree.

SKF installed an additional speed sensor to permit data gathering and more advanced diagnostics to be performed on the data. The data was directly transmitted from the subsea turbine to a remote data centre for analysis by SKF specialists. This set up is similar to that used in the wind turbine industry where condition monitoring of the major rotating components has been in use for over twenty years.

2.2.2 Implementing condition monitoring into the Operations Management system

Many other industries routinely pass other types of data between systems. Examples include process data related to systems or operational status parameters. Communication protocols such as Modbus or OPC are used for this purpose. Although not specifically part of the EnFAIT project related to condition monitoring systems to receive data from other sources, this is a feature that could be utilised to embed the condition monitoring system more fully into the other existing control and monitoring systems. This embedding can lead to more advance alarming and decision-making processes.

The capability of data acquisition devices and software to enable this type of data transfer often exists but is often under-utilised either due to interface issues between devices and systems or that the use of these additional signals is recognised only after a period of operation of the turbine and reviews of the data to identify some parameters that could enhance to the monitoring system.

Additionally, integration of communication protocols provides the benefit that the data acquisition infrastructure can be designed more cost-effectively. For example, understanding early in the design phase what operational and condition monitoring data needs to be collected to make use of a minimal number of sensors. This takes away the necessity to install too many sensors from different vendors or system providers.

2.2.3 Recommendations for use of condition monitoring in tidal

Looking at the operational context of tidal turbines and arrays, all conditions are there which could trigger those potential failure-modes affecting critical rotating components and equipment in tidal turbine and array operation. The remote nature of tidal turbine operation with its offshore logistical complexities means that it is important to have a system and processes in place to acquire potential failure data in a remote manner to pro-actively manage the reliability and availability of the turbines and arrays. Not having such a system or processes in place would mean that potential failure of critical rotating components will go unnoticed or will be noticed too late. This will lead to unplanned energy production stops, unplanned corrective maintenance, and potentially secondary failures to other components.

It is up to each operator and owner to gain an understanding how potential failures - which can be monitored through a condition monitoring system - will affect the availability of energy production, energy distribution, logistics, overall business objectives and ultimately the LCoE. The cost of monitoring for those failures must be weighed up against the cost saving that the monitoring can bring, whether by early warning or prevention of secondary failures.

The effects of failures need to be considered within a given operational context: for example, the failure of a single turbine in an array comprising of 2 large turbines is already a 50% loss of energy production and can therefore be considered very critical. The failure of a single turbine in an array comprising of 20 smaller turbines is a 5% loss of energy production and might be considered less critical. This lost revenue should be assessed relative to the cost of mitigating that risk (i.e. increased maintenance, dual redundancy).
It is unlikely that a single turbine failure will affect a whole array, therefore the economic sense to implement condition monitoring and the justification from an acceptable or un-acceptable risk point of view will lie with the operator or owner of the tidal array. The use of methodologies such as FMEA, FMECA, RCM and RBM combined with KPI's and risk-matrixes aid such decision-making. Report *D9.4* Maintenance Strategy Review (MSR) Specification provides a more thorough explanation of such a process. It is up to the manufacturers of tidal turbines and arrays to aid and support future customers in making these decisions.

During the EnFAIT project SKF has found that within the given operational context, the turbine design has proved to withstand the kind of operation that was intended. There were no significant exceedances of vibration thresholds. Regardless of the low RPM of the turbines, there were no problems to properly carry out condition monitoring. This can be considered a success and a compliment to those who helped in the design and operation of the EnFAIT project turbines. Report *D9.6 Condition Monitoring for Tidal Array* provides details on measured vibrations.

Apart from the effects on production and business goals, the remote nature, logistical complexity and pro-active maintenance approach of tidal turbine operation is reason for SKF to recommend that condition monitoring be a standard implementation in tidal arrays. There are different levels and complexities of condition monitoring systems, each with their own limitations and advantages. Additionally, condition monitoring technology could be enhanced by fully integrating the condition monitoring system into any existing control system via communications protocols such as Modbus or OPC. These signals either passed to the condition monitoring data acquisition devices enable more advance diagnostic tools to be deployed or alternatively to pass the condition monitoring output conditions to dashboards or other data monitoring systems.
With the continued advancement in technologies, the condition monitoring data could ALSO be used as an input to machine learning or AI applications to optimise turbine operations.

2.3 Tidal array operations

2.3.1 Tidal array operation

As reported in D6.1-6.6, the performance of the array has improved substantially over time, due to an increase in reliability, improved maintenance timescales, confidence in extended maintenance intervals, and also the introduction of the next generation of machine, which has improved performance, including self-checking and fault ride-through, allowing automated restart in a much broader range of conditions than the older machines. T4 performance (below) demonstrates that even on the 1st of series unit of the M100D design, availabilities are typically over 95%.

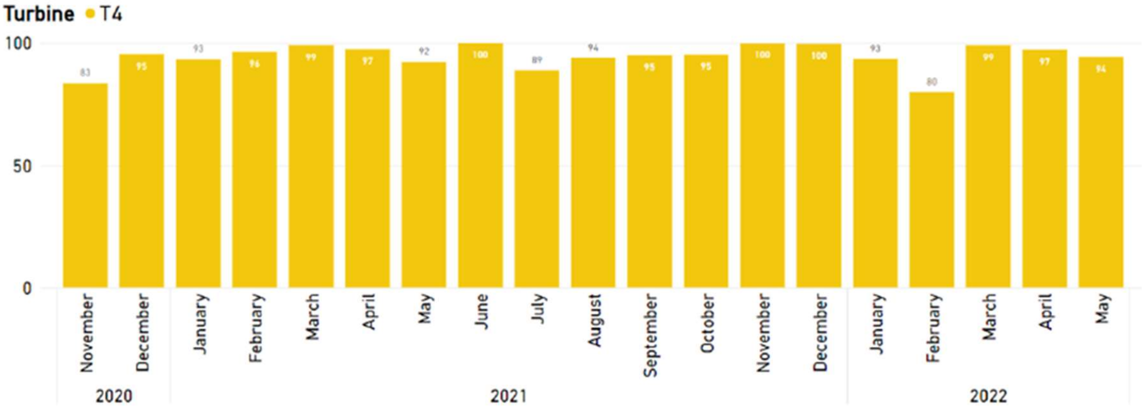

Figure 3: T4 running data showing high availability (Note planned tidal array maintenance event Nov 2020 and Feb 2022)

2.3.2 Findings and recommendations from tidal array operations

To date, the planned maintenance intervals of components has generally proven to be conservative, with these periods being extended as more operational experience is gained. This provides scope to reduce the cost of tidal energy. Initial operating experience of T4-6, and initial maintenance of T4 suggest that further improvements will be made with this series of machines, and that the theoretical maintenance interval of the system components of 5 years is a realistic target for mature operation of these turbines.

To ensure cost-effective and suitable components are selected, strong guidance is required to suppliers to ensure the supplier/designer has a realistic understanding of the environmental conditions in which parts need to operate.

- The internal turbine environment is very benign, and it is important for cost reasons not to over-specify maintenance, material or coating requirements. Due to the relative novelty of the technology strong guidance must come from the turbine developer, as suppliers will otherwise take experience from marine or offshore wind environments which are far harsher than Nova's turbine environment and therefore lead to over-specification of components.

- For external components, the environment is less challenging than offshore or near-surface operations with regards to pressure and corrosion respectively, however the design must allow for greater water flow and biofouling than many other existing design applications.

The EnFAIT array has demonstrated step by step improvements in both technology and operations. Maintaining the high availability of turbines is key to ensure a good LCOE, and to do that, as well as the planned maintenance interval extension, high system reliability is required to minimise unplanned maintenance, as well as good turbine automation to prevent unnecessary downtime. The M100D turbines (T4-6) have shown extremely good performance with regards to automation of operation, for example riding through or restarting after external grid disturbances. Initial performance and condition inspection suggests good system reliability, however more running-years of data are required to provide an increasingly meaningful quantified value for this.

3 Reliability, Availability and Maintainability

An important measure is the levelized cost of energy (LCoE), which is affected by the reliability and availability of individual tidal turbines and the array. Reliability of individual components affects the reliability of the turbine which again affects the availability of an array. Therefore, the design phase becomes the most important phase to have influence on the total reliability and availability of turbine arrays.

Depending on the design, chosen components and materials the tidal turbine will have a certain inherent reliability which needs to be maintained throughout its entire life cycle. This will also affect the expected major maintenance intervals.

This in turn will require each different tidal turbine design to implement a different maintenance concept or operational mode to make sure that the inherent reliability is maintained at an optimum level or is even improved through (re)design.

3.1 Effect of the environment on reliability

The analysis done at the component level consists of an FMEA/FMECA analysis. The FMEA/FMECA methodically assess each component; how the component can fail, the expected component life (mean time between failure), the effect of failure on the turbine and electricity generation and how the failure can be prevented or mitigated. The tidal environment should be considered when assessing the reliability of components or systems, and when looking at manufacturers or data book reliability data.

- External components are subject to energetic water flow, biofouling and corrosion. This is often very different to other marine environments e.g.
    - The sector has previously seen reliability issues with connectors which were originally designed for the deep, dark and still water found in offshore subsea environments.
    - Submersed turbines are not in challenging corrosion conditions such as the near-surface or splash zone, and therefore corrosion is far less challenging than for many marine and O&G applications.

- Internal components are protected in a well-sealed and cooled atmosphere, often leading to very benign conditions, and therefore have a longer life than experienced by most other marine or offshore industries.

As seen in chapter 2.1 the marine environment has posed less of a risk than could have been expected. Part of that is specifically due to Nova and partners being able to control biofouling through use of special environment friendly coatings. Given the experience with these coatings, the expected major maintenance intervals of 5 years can well be achieved. Due to the internal components being in an enclosed atmosphere, no further issues were found with regards to reliability or availability. In the design of the turbines, it has been considered that the atmospheric circumstances in the turbine housing are properly monitored and controlled.

3.2 Maintainability in a marine energy environment

Operating in a marine energy environment brings with it the challenge of maintainability: how easily the operator can gain access to systems or components in case of failure and how the downtime of the turbines is managed in a way that is considered acceptable for the availability of the turbines and the array.

For most varieties of tidal technology, in-situ physical access to the device is limited to diver or ROV intervention during slack-tide, and therefore bringing the turbine to shore is the normal maintenance method. This affects the cost versus reliability (or maintenance interval) balance, especially for lower cost components. This is similar to the trend in offshore wind, where tasks which are carried out manually in many industries (e.g., regreasing) are automated, or a higher specification part is selected as it has a lower through-life cost once the cost of O&M is included. This includes the addition of sensors and their associated communication systems, which are used instead of a physical inspection. See Chapter 2.2 .

These considerations may also affect the system architecture design, as choice of array layout must consider the accessibility of inherently shorter-lifetime or lower-reliability components. This also makes quality control and pre-deployment commissioning checks vital as post-deployment intervention should be limited.

Within the EnFAIT project methods were demonstrated and lessons were learned with regards to deployment and recovery:

- Marine operations at a scale suitable for use of Multicat vessels can provide fast and cost-effective deployments in a range of conditions. Their compatibility with locally available facilities vastly reduces costs related to transit to and from the deployment site and increases operational weather windows thus turbine availability.
- Scaling up of arrays will improve cost efficiency of options, as costs can be shared. The use of higher capability Multicat vessels has also been demonstrated, which permit a faster work rate in return for their higher day-rate cost.
- In-water deployment and recovery of the newer M100D design is vastly superior to the older turbines. The system is tolerant of adverse metocean conditions, of operating during spring tide periods and requires only a short window of suitable conditions at the tidal site to install or recover.
- Efficient multi-turbine maintenance has been demonstrated, with 3 turbines maintained over a short period in a low-cost facility. Local maintenance of the newer M100D turbine was also demonstrated over a single neap period at a non-specialist facility local to the array. This demonstrates the practicality of low-cost intervention for arrays in the future.
- Fast, environmentally friendly and cost-efficient decommissioning methods have been fully demonstrated very successfully. This should help reduce the perceived risk of decommissioning for the industry.

Due to the environment in which Nova’s turbines operate, the maintenance strategy is different from other marine technologies. Regular maintenance tasks are not acceptable; however, it has been demonstrated during the project that typical regular maintenance tasks are not required or easily designed out for a robust design of turbine such as the M100D.
The aim was to design the turbines in such a way that a maintenance interval of 5 years could be achieved. From the available data and after some slight design improvements, Nova and its partners are confident that the goal of a 5-year planned maintenance interval will be achieved.

3.3 Maintenance management for tidal turbines

As mentioned in public report D9.5 which focused on the implementation and use of a computerized maintenance management system (CMMS), the choice to use such a system in the tidal energy sector will greatly depend on the size of the tidal array and the complexity of the turbines. Under some circumstances the use of a CMMS system might not yield sufficient business benefits to justify the cost associated with the purchase and implementation of such a system.

While Nova did invest in a relatively simple CMMS system, it was found that at this stage there was no major benefit for such a system. This is in line with expectations that a CMMS system is not efficient when the number or complexity of the assets is low. In this case Nova was able to easily manage the turbines bill of materials, maintenance history and other aspects via non-dedicated software. It is expected that with the growing number of assets in the future, the need to use the CMMS system will grow and become more evident.

One area that brings a large risk to relatively small companies using specialist parts in a new industry is that of stock holding for unplanned component replacement. There have been multiple instances of a faulty component having a very long replacement lead-time, resulting in delays to either new-build or maintenance, and therefore to turbine availability. Even though the majority of instances have been as a result of supplier quality issues, any liability never covers the total cost impact to the company. This makes it difficult to directly demonstrate the achievable performance feasible for larger turbine volumes. As the industry grows and turbine numbers increase, using a suitable CMMS alongside more mature supplier agreements and stock-holding strategies will become commercially feasible, reducing avoidable delays and downtime.

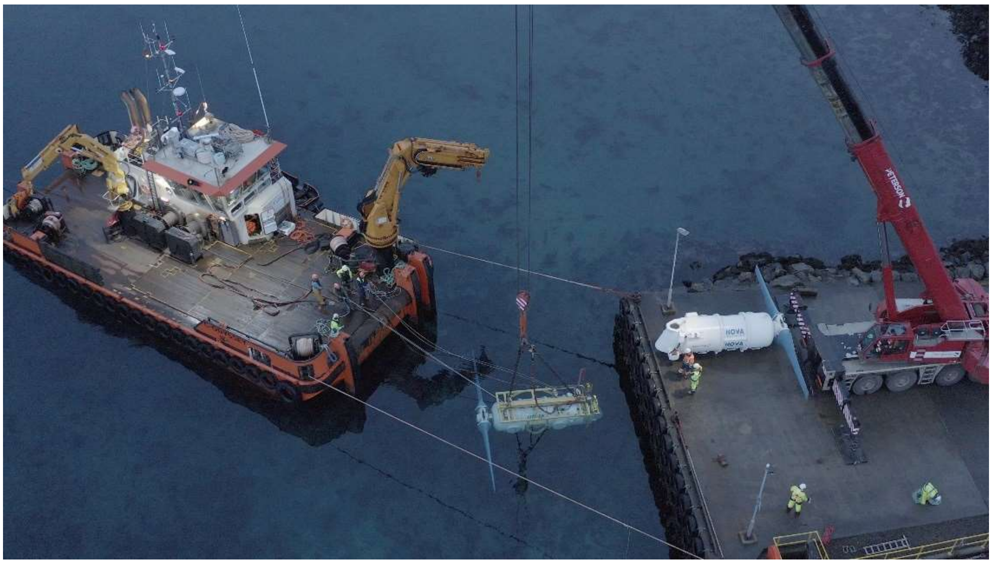

Figure 4: Multicat Vessel and M100-D turbines T5 and T6 during EnFAIT deployment activities

4 Conclusion and Recommendations

Throughout the EnFAIT project the deliverables of Work Package 9 aimed to achieve a high level of reliability and availability through different stages of the design and operation of the turbines, with the goals to achieve a major maintenance interval of 5 years.

The lessons learned have allowed Nova and their partners to achieve an ever-increasing and very successful level of reliability and availability which is visible in both the maintenance and operations strategy.

To further develop and help move further the industry, future developers and operators of tidal turbines and arrays can further focus on some of the areas where Nova and EnFAIT partners have started to explore.

4.1 Effect on the maintenance and operations strategy

- As demonstrated in the EnFAIT project, substantial efficiencies can be made carrying out maintenance on multiple turbines in quick succession, and interventions can be carried out without specialist facilities. This method suits the tidal cycle and sub-MW scales of turbine very well, as local, quick-turnaround maintenance is feasible, and local launch locations keep the deployment vessel transit times to a minimum, maximising productivity during a single neap period.
- Cost-balance decisions for tidal technology will be different to many other industries, as any non-automated internal maintenance requires turbine retrieval. The project has shown however that the benign internal environment allows for long maintenance intervals, and automated systems (e.g. regreasers) can be used where necessary to reach the target intervention intervals. As such, planned maintenance events for minor tasks (e.g. regreasing, cleaning, inspecting, adjusting/replacing short-life components) are not anticipated to be required, and should not be permitted when defining future designs.
- Condition monitoring is critical to enabling a ‘no operational inspection’ strategy. The project has demonstrated the benefits of automated remote monitoring. Automated monitoring is essential for practical array operation due to the quantity of data. With further tidal array running data, the optimum level of monitoring for the most economic and practical operation at array scale will be refined.
- Short deployment or recovery durations (in the tidal area) which are practical in a range of metocean conditions are required for economic and low risk operation. The latest turbine design provided great improvements in this area, demonstrating that marine operations were feasible both in non-ideal metocean conditions and also in spring tides. Workability, and therefore cost efficiency of operations is however obviously best in summer (as in the offshore wind industry), and for tidal in neap tides, and therefore large planned interventions should target these optimum periods.

4.2 Implications for tidal marine energy

The tidal marine energy sector is still developing. However, many of the proven technologies from other industries can be implemented to accelerate the success of tidal turbine design and operation. The most important aspect to consider is the context within which tidal turbines are operated. As mentioned earlier in this report, the marine environment, the remote operation of the array and the enclosed and benign conditions in which many of the components operate requires special attention in the design phase. Performing thorough FMECA and RAMS analysis helps in this regard.

To help move the tidal industry forward, focus should be given to:

- Designing ‘deploy and recover’, reliability and maintainability in from the start. As with offshore wind, commercial success is reliant on high availability and minimised OPEX cost.

- Integrated condition monitoring and operation. For example, integrating condition monitoring and operational software to maximise the level of monitoring that can be carried out without operator input. This helps reduce the number of sensors that need to be installed on the turbines, whilst maximising the benefit of the data gathered.

- Environmentally friendly materials which can handle the marine environment of tidal turbines. This goes especially for the materials used on the outside of the turbine structure. This project has demonstrated the use of materials which can handle biofouling very well. Any further improvements in their long-term effectiveness can help extend the routine maintenance intervals even beyond 5 years.

- Develop and demonstrate O&M strategies that are optimum for a commercial array scale, including commercial arrangements, marine operations, tools and facilities, and critical spares management.

- Learn from other industries. For example one of the greatest challenges in the wind industry at present is that turbine blades cannot be recycled. Nova’s turbines currently have very good recyclability; however they and the broader tidal industry need to take the learnings from similar industries into account as the industry develops.

- The use of other innovative operations methods, materials and production processes which will allow optimization between cost and reliability. This will have a direct effect on lowering the cost of production of tidal turbines and a direct result on the LCoE.

4.3 Conclusion

The EnFAIT project has successfully demonstrated the major aspects required to achieve the highest levels of reliability and availability of tidal turbines in arrays, and therein for the sector to progress to commercial maturity. Some metrics, such as very long-term reliability and availability, will be demonstrated with further turbine operating hours and increasing numbers of deployed turbines.

To complete this pathway to industry maturity, more commercial projects at a larger scale are required. These will further demonstrate the methods and cost savings that this project has developed, and that larger arrays would increasingly benefit from.

The findings from this work package show extremely positive tidal array demonstrations and improvements over the course of the EnFAIT project, pointing towards a reliable tidal technology with long maintenance periods suitable for the next stage of the industry’s development.

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