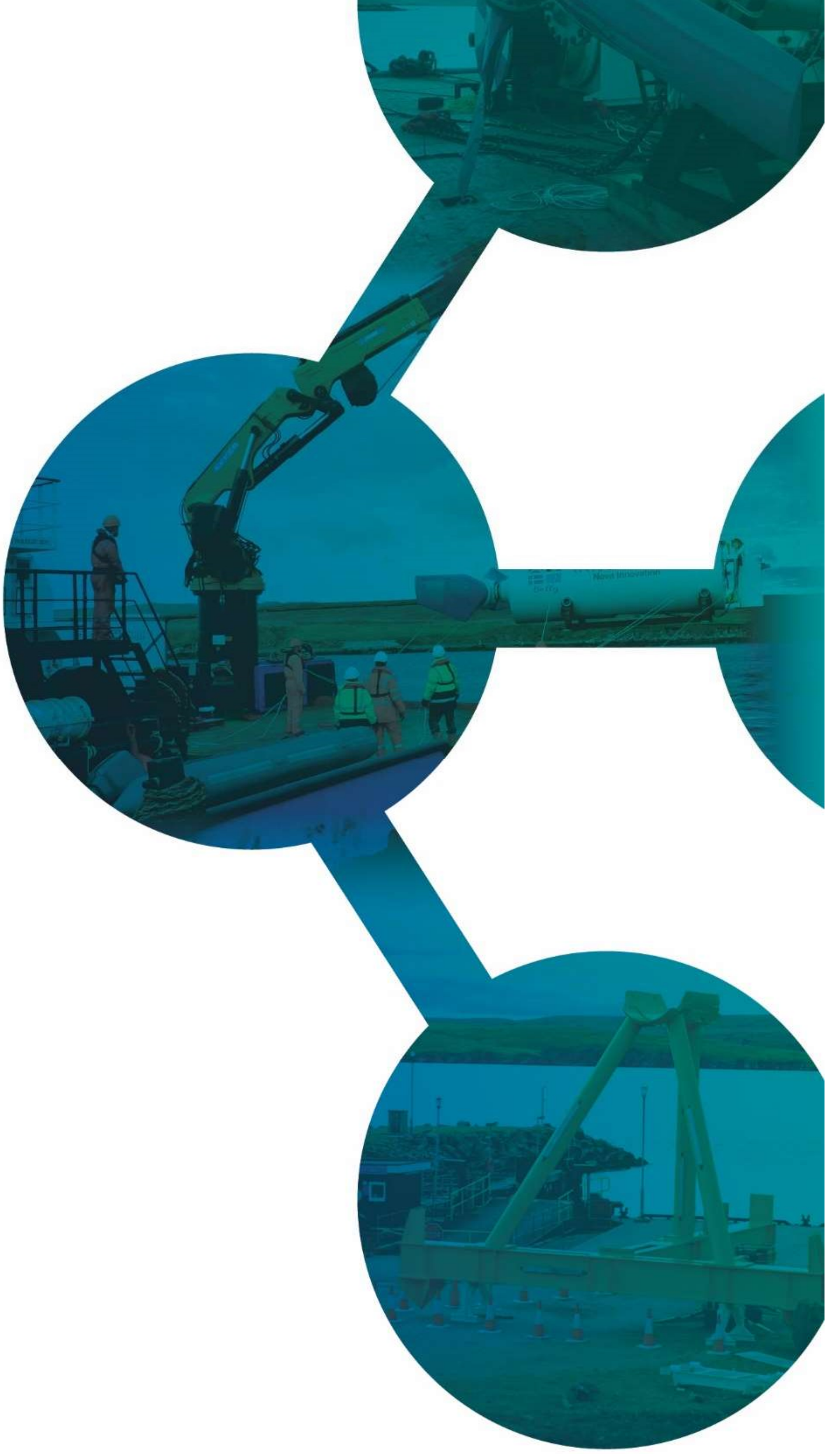

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ENFAIT
ENABLING FUTURE ARRAYS IN TIDAL

T1-6 Final Report:

Performance and Progress of the Shetland Tidal Array

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement number 745862.

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Contents

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Abbreviations

ADCP	Acoustic Doppler Current Profiler
ADV	Acoustic Doppler Velocimeter
AIM	Array Interaction Model
CAPEX	Capital Expenditure
CFD	Computational Fluid Dynamics
CMS	Condition Monitoring System
DTOcean	Design Tools for Ocean Energy Systems
D *x*	Deliverable *x*
ELEMENT	Effective Lifetime Extension in the Marine Environment for Tidal Energy
EnFAIT	Enabling Future Arrays in Tidal
ERP	Enterprise Resource Planning
FBG	Fibre Bragg Grating
IEC	International Electrotechnical Commission
KPI	Key Performance Indicator
LARS	Launch and Recovery System
LCOE	Levelised Cost of Energy
M100	2nd generation Nova turbine with gearbox
M100D	3rd generation direct drive Nova turbine
O&M	Operation and Maintenance
OPEX	Operational Expenditure
PLC	Programmable Logic Controller
R&D	Research and Development
RIDDOR	Reporting of Injuries, Diseases and Dangerous Occurrences Regulations 2013
SCADA	Supervisory Control and Data Acquisition
STA	Shetland Tidal Array
T *x*	Turbine *x*
UV	Ultraviolet
VMADCP	Vessel Mounted Acoustic Doppler Current Profiler
WP	Work Package

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 call *LCE-15-2016: Scaling up in the ocean energy sector to arrays* to generate significant learning through demonstration of cost-effective tidal stream arrays.

Figure 1-1: Shetland Tidal Array (STA) operations

EnFAIT is a €20m project to lower the cost of tidal stream energy through learning and by doubling the capacity of Nova Innovation’s Shetland Tidal Array (STA), from three to six turbines. The project aimed to study wake impacts on generation and cyclic loadings downstream, validating an Array Interaction Model.

This document is a summary report on WP6 Scaling up: Array Operation in Real Conditions – the operation of the Shetland Tidal Array and turbines through the EnFAIT project.

1.2 The Shetland Tidal Array (STA)

The original three Nova M100 tidal turbines (T1-3) each have a horizontal axis two-bladed rotor with a gearbox and medium voltage induction generator (Figure 1-2). The M100D turbines (T4-6) also have horizontal axis two-bladed rotors, but with a Nova-designed direct drive generator (no gearbox). For both turbine designs, the nacelles and rotors are mounted on top of a steel tripod substructure with additional concrete ballast. The whole assembly rests on the seabed under its own weight (no drilling is required). To give an idea of scale, the rotor diameter from tip to tip is 9m, the length of the nacelle is approximately 7m and the nacelle sits approximately 9m above the seabed. Nova Innovation began operating this, the world’s first fully operational and grid connected offshore tidal energy array, in 2016. Since then, the company has gained a wealth of world-leading operational experience through array operations and EnFAIT-related research and development work. With the addition of turbines T5 and T6, the STA became the array with the largest number of turbines (six) anywhere in the world.

Figure 1-2: Nova M100 (left) and M100D (right)

The tidal turbines in the STA are powering local homes, businesses and electric vehicles in Shetland. The array is in Bluemull Sound, which lies between the islands of Yell and Unst in Shetland (Figure 1-3). Bluemull Sound is an excellent location for a tidal energy array, with characteristic maximum current speeds of 2.5m/s, good shelter from the prevailing wave and wind directions and a good quality pier at Cullivoe harbour on Yell, within one kilometre of where the turbines are deployed.

Figure 1-3: Bluemull Sound location

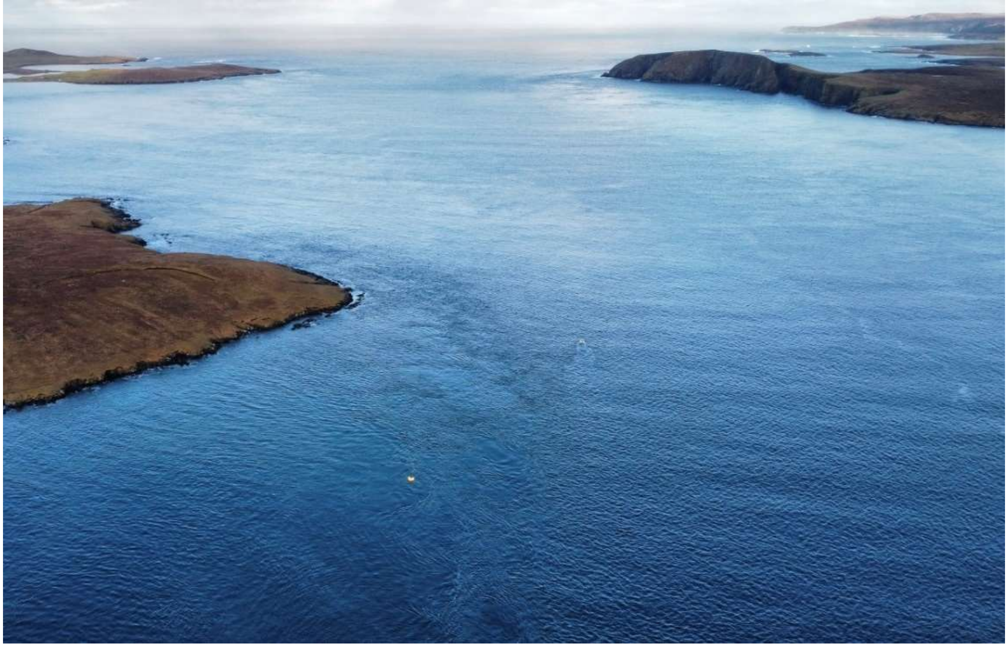


Figure 1-4: Shetland Tidal Array – the most turbines in a single tidal array … but hard to spot!

1.3 Scope of this report

The purpose of this document is to provide a final report covering the lifetime of the Shetland Tidal Array turbine operations for Tasks 6.1 to 6.11 of the EnFAIT project:

- **T6.1 Define test plan and performance metrics**
- **T6.2 Operate two of the original M100 turbines**
- **T6.3 Define T1-3 M100 turbine upgrade requirements**
- **T6.4 Procure and implement T1-3 M100 turbine upgrades**
- **T6.5 Operate the upgraded turbines**
- **T6.6 Analyse turbine data**
- **T6.7 Operate expanded array including M100D T4**
- **T6.8 Operate full array including new turbines T5 & T6**
- **T6.9 Modify array layout**
- **T6.10 Modify array operating strategy**
- **T6.11 Prepare data for verification of array operations**

1.4 Operations objectives

This report summarises Shetland Tidal Array operations during the Enabling Future Arrays in Tidal (EnFAIT) project from July 2017 to June 2023 with particular focus on meeting the specific objectives set for WP6:

- Safely operate an array of tidal turbines for several years as part of a structured test programme
- Demonstrate operational strategies that deliver the availability necessary for commercial arrays
- Deliver load and performance data to validate tidal array design tools at full scale in the real world
- Generate the results required to achieve third party verification of the operational results
- Capture and disseminate lessons learned for the industry on optimised operation of tidal arrays

2 Test plan and performance metrics

2.1 Phase 1: Operation of the existing turbines

This initial phase focused on the operation, monitoring and analysis of the original three pre-EnFAIT Nova M100 turbines (T1–T3) with the aim of identifying suitable upgrades and additional instrumentation possibilities to maximise learning.

Activities were undertaken to collect operational data and report Key Performance Indicators (KPIs) to provide a baseline for comparison with the improvements later delivered in the project. The activities were co-ordinated with the modelling tasks in work package 10 to ensure quality data was provided for resource assessment and turbine wake measurement purposes.

The aspects of measurement to be included:

- Operations and maintenance requirements, with maintenance needs (planned and unplanned);
- Detailed review of all consumed components;
- Measurement of the full power curve for both ebb and flood operation;
- Measurement of fluctuations from theoretical turbine power curve;
- As installed data: heading, verticality, positional tolerance for the substructure and turbines;
- Cable movement along length;
- Strain gauges on blades to compare design loads to actual loads and improve fatigue design;
- Testing of different anti-fouling coatings to assess efficiency of different manufacturers' products;
- Monitoring of anodes to confirm actuals against expected depletion to identify the requirement for intervention;
- Measurement of vibration on the nacelle for input into component design life calculations, and for analysis of common causes and cascading failures;
- Logbook of actual failures and comparison against original failure rates provided by suppliers;
- Cost, procurement time and repair / replacement time of failed components;
- Detailed velocity field around the turbine;
- Detailed current profiles in the lease area;
- Costs of O&M to demonstrate the baseline and reductions in LCOE over the project.

2.2 Phase 2: Operation of the three upgraded turbines

Following on from the upgrade of the original three turbines in Q2 2018, this phase oversaw the operation of the three upgraded turbines (T1–T3) through to Q1 2019, with the purpose of capturing learning to inform the design, build and installation of a new turbine in the array (T4).

The key activities included the installation and operation of the upgraded turbines T1-T3 at Bluemull Sound and the collection of data from the new instrumentation to aid Phase 1 of D6.1. This included continued recording and reporting of KPIs for the turbines and the array, and co-ordination with the modelling work package to ensure quality data was provided for wake modelling and performance assessment purposes, including the installation of any stand-alone instrument packages on the seabed.

2.3 Phase 3: Operation of the expanded array of four turbines

Following on from the build and commissioning of turbine T4, this phase oversaw the operation of the expanded array of four turbines (T1–T4) from Q2 2019 to Q4 2020, with the key objective of beginning to evaluate upstream and downstream turbine interactions.

The learnings captured from T1 - T4 were used to inform further improvements for the design, build and operation of T5 and T6. Again, this was co-ordinated with the modelling work package to ensure quality data was provided for load and performance assessment purposes.

2.4 Phase 4: Operation of the full array of six turbines

Following on from the build, deployment and commissioning of turbines T5 and T6 in Q4 2022 and January 2023, this phase focused on the operation of all six turbines (T1–T6), with a detailed evaluation of the interaction and wake effects within the array. In particular, the optimal inter-turbine spacing of arrays was investigated (WP10), in line with appropriate lease and consents arrangements.

The KPIs for the turbines and the array were used in the modelling work package to better understand and demonstrate the effect of operating upstream turbines on the loads and performance of those downstream.

2.5 Phase 5: Optimisation of the full array and model validation

The full array (T1–T6) was operated and optimised from Q1 to Q2 2023, with options to turn turbines on and off in order to monitor and investigate inter-turbine wake effects. This phase also considered further instrumentation and modified operating regimes, with validation of assumptions made in the tidal array techno-economic modelling.

The array performance, load predictions and wake effects were measured and used in the modelling work package (WP10) to enable predictions to be compared with real world data, with any change in KPIs monitored.

This phase of work aimed to demonstrate improved turbine reliability and array availability through planned condition-based maintenance, rather than unplanned reactive maintenance interventions and demonstrate rapid local nacelle maintenance to validate availability assumptions.

The additional aspects of measurement that were to be considered included:

- New velocity and turbulence measurements at new turbine locations;
- Re-measurement of previous parameters;
- Concerted effort to align the resource work with array modelling and optimisation, so that a software tool can be developed for future projects which takes resource data and then uses modelling to establish the fully optimum layout for any given site at a sufficiently early stage in the development process;
- Subsea Hub deployment for energy export from the T5 and T6 turbines using wetmate and jumper cables for easy array manipulation, connection and disconnection;
- Intelligent tooling to simplify installation and retrieval;

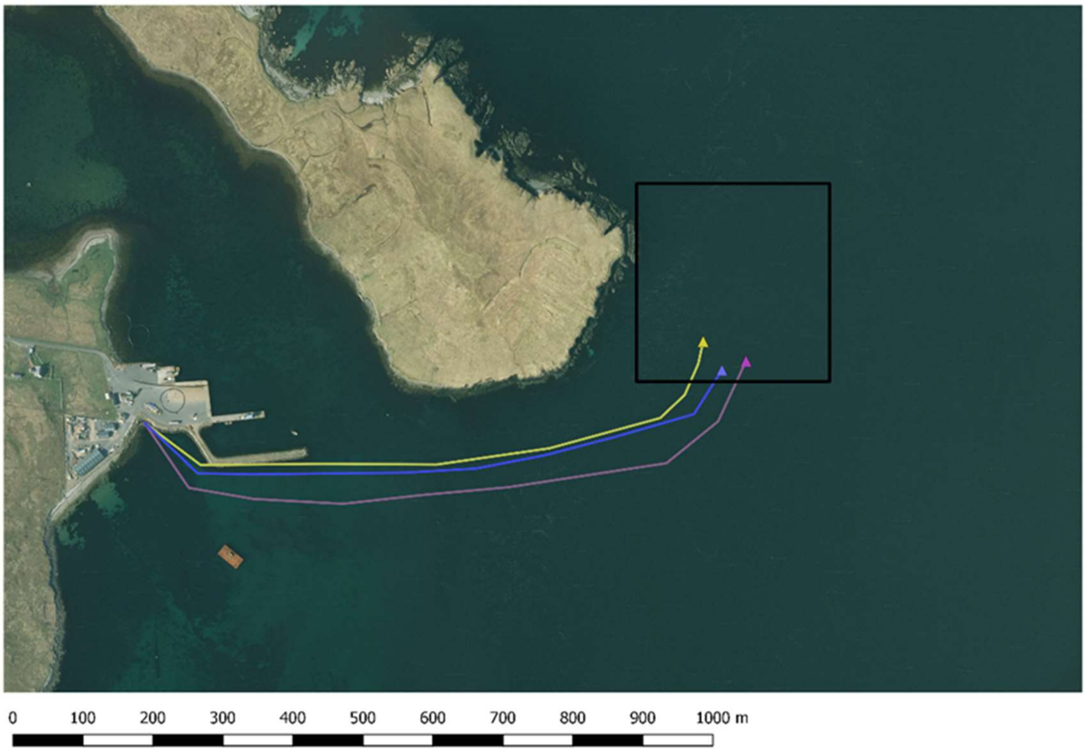


Figure 2-1: Layout of the Shetland Tidal Array as of August 2017 (T1-3)

2.6 Phase 6: Resource measurement and site surveys

A campaign of detailed resource measurement and site surveys was undertaken to gather quality data informing performance assessments, array optimisation and environmental impact assessment.

The aspects of measurement that were to be undertaken included:

- High Resolution Bathymetry: to ensure that device performance attributes can be compared to the seabed bathymetry;
- Seabed video of the new cable routes and of the locations for turbines;
- Tide: velocity, direction, turbulence at relevant points throughout the site;
- Measurement of velocity through the water column (magnitude and direction) and turbulence intensity;
- Background and turbine acoustic noise studies;
- Wave: historic data time-series and monitoring to use in modelling with Hs, Hmax, direction;
- Wind: historic data time-series to use in modelling;
- Wave-tide interaction: ADCP deployments for high resolution wave and tide data, at multiple locations to validate and inform modelling.

The main goal of this phase was to collect key data about the characteristics of the deployment site, turbines and array in order to provide the relevant input parameters to the DTOcean and Array Interaction Model (AIM) tools to be used in the modelling work package. This required a combination of numerical modelling, instrumentation design, procurement and deployment offshore, which was to be co-ordinated with the turbine operations work package. Data was also sourced from the historical Nova M100 turbine operations undertaken prior to the EnFAIT project.

3 Operation of the original M100 turbines

Operational data from the original M100 (T1-3) turbines was used to report KPIs and provide a baseline for comparing performance and improvements delivered during the project. In addition, a turbine nacelle was retrieved from the array to enable the drivetrain components to undergo forensic analysis as part of WP9.

3.1 Key Performance Indicators (KPIs)

This section outlines the EnFAIT approach to reporting KPIs from the Shetland Tidal Array. Through work with OREC's data team, the WP6 KPIs were defined and systems were created to automatically generate the KPIs from operational data, adapting principles from a wind industry standard (IEC TS 61400-26-1:2011) for use on tidal arrays.

3.2 Data sources

KPIs for the turbines on the Shetland Tidal Array utilise a range of different data sources, as shown below.

	Production	**Reliability**	**Logistics**	**Overheads**
	- Power generated - Operating hours - Capacity factor - Availability	- Number of failures - Type of failures - Downtime - Restricted generation - Cost to repair - Resolved remotely / required offshore intervention	- Marine ops mobilisations per year - Marine ops days per year - Cost per mobilisation - Vessel day rates	- General ops spend - Insurance costs
SCADA system	✓	✓		
Quality observations log	✓	✓		
Health and Safety observations log	✓	✓		
Procurement system / ERP		✓	✓	✓
Marine operations log		✓	✓	
Control centre log	✓	✓		

Nova optimised three new cloud-based logging systems to digitise information from the following areas:

- **Quality observations** – e.g. component failures
- **Control centre operations** – e.g. operator interventions for fault-finding, software updates, etc.

- **Marine operations** – an overview of offshore maintenance interventions

Combining information from these three data sources and the Shetland Tidal Array SCADA allowed Turbine KPIs to be analysed and reported. This included metrics such as generating hours, capacity factor, number of failures requiring marine operations to resolve, etc.

3.3 Operative states

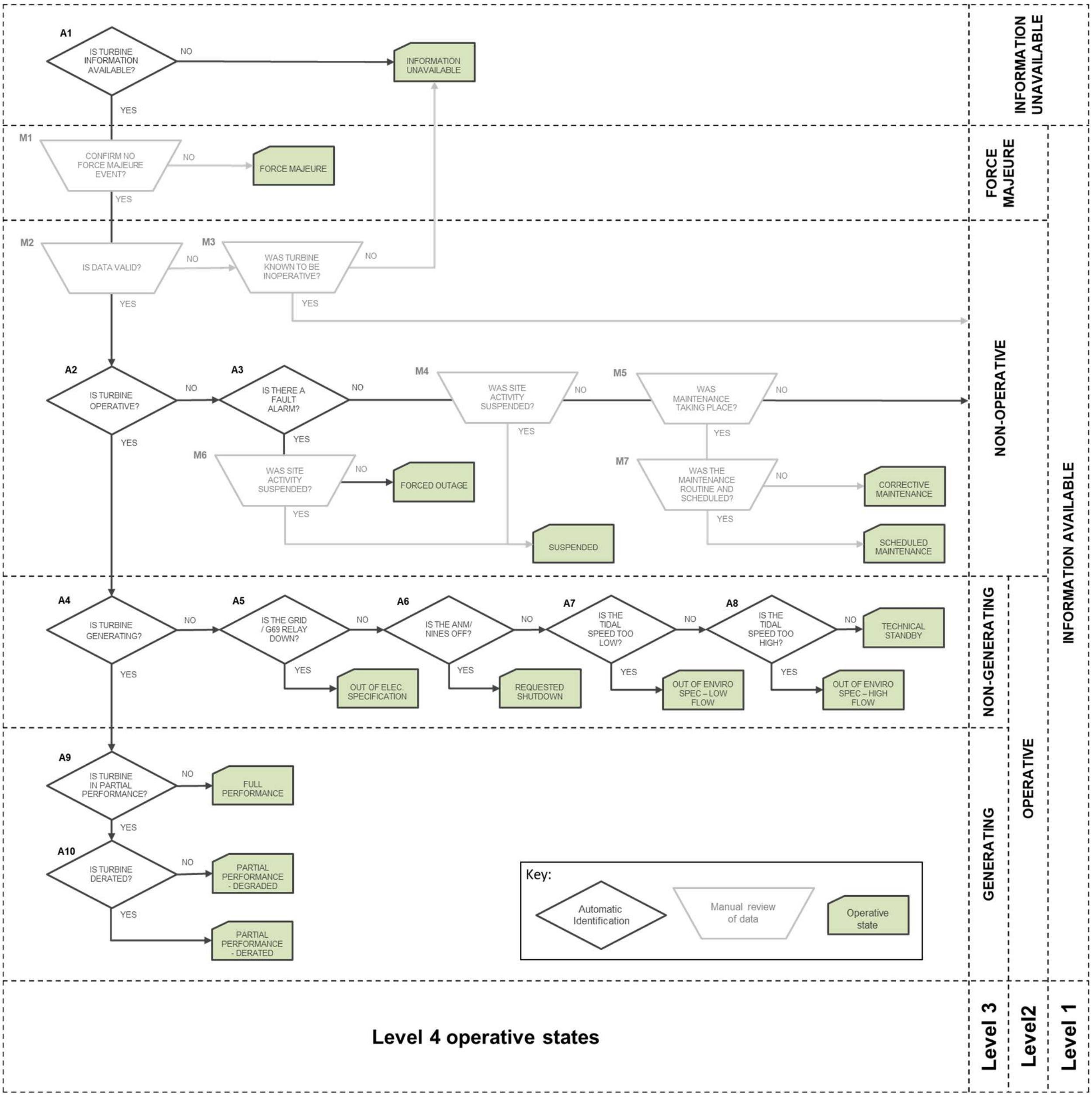
Operating states were defined by adapting guidance from IEC TS 61400-26-1:2011 (Time-based availability for wind turbine generating systems) for tidal energy. See definitions below.

Level 1	Level 2	Level 3	Level 4	Example
INFO AVAILABLE **(IA)**	OPERATIVE **(IAO)**	GENERATING **(IAOG)**	FULL PERFORMANCE **(IAOGFP)**	
			PARTIAL PERFOMANCE – DERATED **(IAOGPPDR)**	Commissioning / throttling due to grid curtailment
			PARTIAL PERFORMANCE – DEGRADED **(IAOGPPDG)**	Throttling to reduce loads
		NON-GENERATING **(IAONG)**	TECHNICAL STANDBY **(IAONGTS)**	
			OUT OF ENVIRONMENTAL SPEC - LOW FLOW **(IAONGENLF)**	Tidal flow insufficient for turbine cut-in
			OUT OF ENVIRONMENTAL SPEC - HIGH FLOW **(IAONGENHF)**	Tidal flow beyond turbine cut-out
			REQUESTED SHUTDOWN **(IAONGRS)**	Marine ops Software reboot Onshore site visit
			OUT OF ELECTRICAL SPECIFICATION **(IAONGEL)**	NINES / grid loss
	NON-OPERATIVE **(IANO)**	SCHEDULED MAINTENANCE **(IANOSM)**		
		PLANNED CORRECTIVE MAINTENANCE **(IANOPCA)**		Retrofit / upgrade / other
		FORCED OUTAGE **(IANOFO)**		Response / diagnostic
		SUSPENDED **(IANOS)**		
	FORCE MAJEURE **(IAFM)**			
INFORMATION UNAVAILABLE **(IU)**				

Both types of production-based availability were estimated in accordance with IEC TS 61400-26-2:2014 (BSI, 2017).

These operative states have been used to calculate KPIs such as downtime, generation hours and production-based availability. As can be seen from the flow chart below, some of the operative states require the data to be reviewed manually. While this is likely to remain the case for the T1-3 turbines, the operating software for turbines T4 onwards has been designed so that the need for the data to be reviewed manually is reduced and, where possible, eliminated.

Operative states were identified using the following logic developed by Nova, which contains a mix of automatic and manually generated inputs.



The detailed set of turbine and array-level KPIs are listed in the

Appendix 1: Key Performance Indicators (KPIs). These metrics go beyond what is required for evaluating the strategic KPIs. Thanks to this, he work undertaken helped to identify additional performance and operational improvements.

3.4 Example results

The full set of KPIs are confidential and commercially sensitive. However, Figure 3-1 shows an example operative state analysis for an individual turbine.

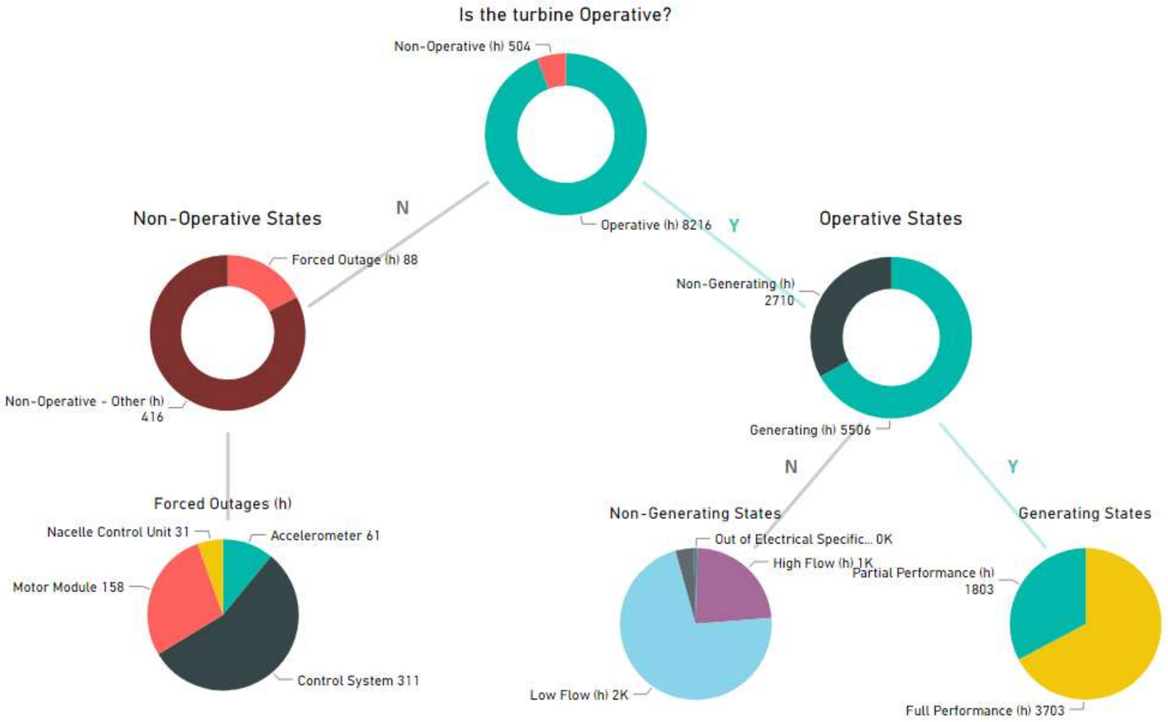


Figure 3-1: Operative states analysis for an STA turbine over a representative operational period

In this early EnFAIT example period, the turbine spent 6,009 hours in an operative state (where it was able to generate) and 572 hours in a non-operative state, which is to say that turbine availability was 91.3%. Of the generation time, most hours are spent in full performance mode, with the turbine operating to its design power curve. The hours relating to partial performance are due to the turbine being throttled due to grid constraints. Non-operative time relates to grid loss events (forced outages) and any control or component faults.

The identification of operative states in this way has helped Nova to better understand performance and identify priority areas for improvement. All commercial arrays, require this sort of easily interpretable information to enable optimum commercial operation.

4 T1-3 M100 turbine upgrade requirements

Based on transferable learnings from the wind industry, Nova was keen to develop and use general conditioning monitoring to optimise the performance and reliability of the turbines. For this task, Nova was particularly interested in:

- Enhancement of condition monitoring for LCOE reduction purposes;
- Power performance characterisation of M100 and M100D turbines;
- Gaining a better understanding of overall system efficiency.

The following sections discuss the instrumentation upgrades delivered.

4.1 Environmental data

4.1.1 Turbine mounted environmental instruments

Figure 4-1: Nova M100 turbine showing position of flow sensor (red circle)

The Nova M100 turbines originally featured one tidal flow sensor. On the T1-T3 turbines they are mounted on the rear of the nacelle as shown in Figure 4-1.

These electromagnetic flow sensors operated reliably, and their output data had been used successfully to determine when the local current speed is high enough for each turbine to begin generating. However, for wider research purposes, there were some limitations:

- They were installed within an area of flow disturbance created by the turbine structures which meant that they do not read free-stream tidal measurements.
- They were affected by marine growth which reduced their sensitivity, requiring periodic cleaning by divers and/or adjustments to the turbine control software to account for this.

- They could only supply data on the flow speed going past the sensor head. They could not provide information on the wider environment, water level, turbulence or waves.

The data from these electromagnetic flow sensors was therefore to be supplemented by deploying the following instruments:

- Acoustic Doppler Current Profilers (ADCPs) – these can provide information on tidal current, waves and turbulence intensity. These can be mounted horizontally to characterise the flow upstream or downstream from the turbine, or mounted on the seabed looking up, to characterise the flow profile through the water column. An appropriate industry grade ADCP capable of measuring the following parameters was used to measure:

    - Water velocity
    - Turbulence intensity
    - Wave height
    - Pressure
    - Temperature
    - Direction (Compass)
    - Sensor tilt

- Acoustic Doppler Velocimeters (ADVs) – these measure local current speeds and are the turbulence measurement tools of choice because they measure very small volumes and quantify very small turbulent structures.

4.1.2 Seabed mounted ADCPs

Seabed mounted ADCPs were deployed in several different configurations to gather information on the site-wide available resource, turbine performance, and wake effects from the operation of turbines T1, T2 and T3.

4.1.3 Substructure instrumentation skid

An instrumentation skid was developed which can be installed on any vacant substructure (e.g. when a turbine is removed for maintenance) to characterise the tidal environment at hub height (Figure 4-2). This included:

- Two horizontally orientated ADCPs, to measure the incident tidal current in both directions and to validate the measurements made by the seabed ADCPs and other devices;
- An electromagnetic flow meter (as used on the turbine nacelles), to see how this performs without the turbine in place and to sense check the results against the other devices;
- An Acoustic Doppler Velocimeter (ADV), to provide a secondary point measurement of tidal current at hub height and quantify turbulence intensity at hub height.

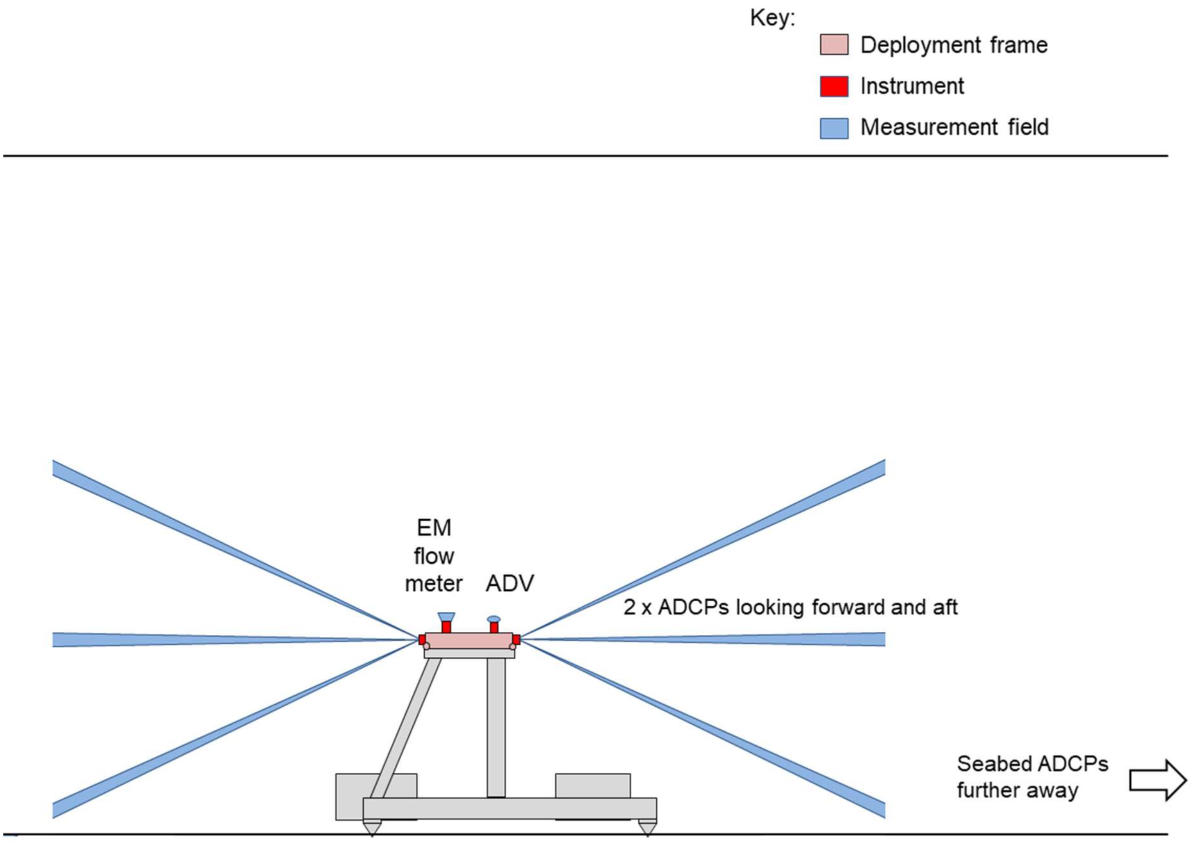


Figure 4-2: Side view of instrumentation skid to be deployed on vacant turbine substructure

4.2 Power performance characteristics

A power performance characteristic diagram detailing turbine power output as a function of tidal flow rate was needed as an input to the DTOcean model in work package 10. The industry standard for turbine power performance characterisation is IEC 62600:200. A new enhanced power metering solution was therefore needed to meet this standard.

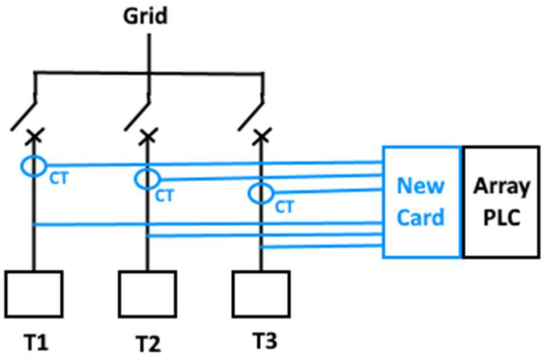


Figure 4-3: PLC based energy metering solution overview

It was decided to use an add-on ‘energy meter’ module for the existing turbine PLC. The additional hardware required includes current transformers and voltage tapping cables. Figure 4-3 above shows a high-level overview of the arrangement that provides high quality data at a relatively low cost.

4.3 Blade loads

Blade load measurement data was required for load modelling studies driven by OREC.

A proven solution was identified from the wind industry which involves embedding fibre optic strain measurement devices within the blade at points of interest and feeding data to acquisition hardware in the rotor hub. This Distributed Fibre Bragg Grating (FBG) was the preferred strain measurement technology. This principle involves periodically exposing fibre-optics to UV light and measuring change in UV reflection when strain is applied. A strain value is inferred by measuring the change in reflection. See Figure 4-4[1] below.

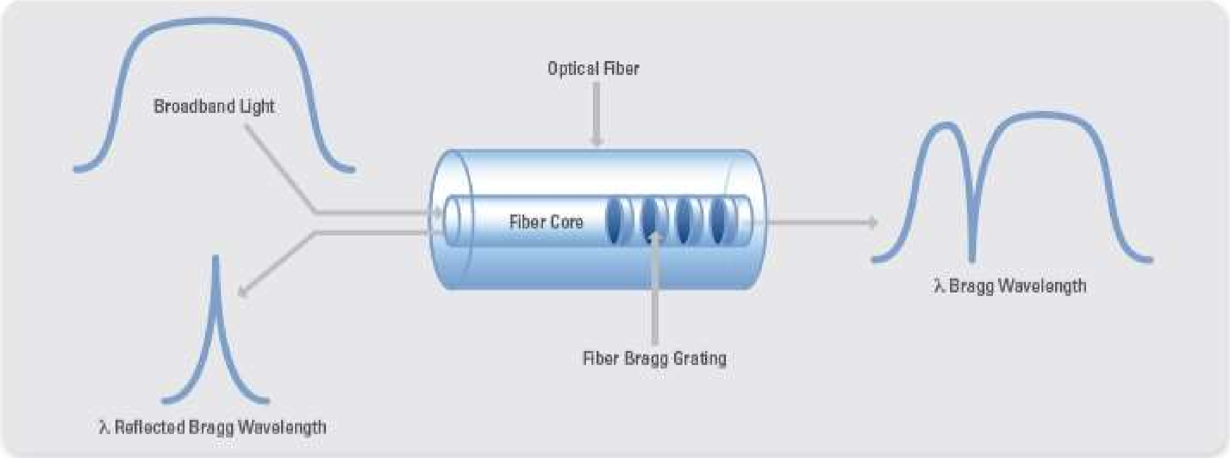


Figure 4-4: Fibre Bragg Grating technology

This philosophy can be applied to Nova tidal turbine blades with minor modifications. Figure 4-5[2] shows an example of Fibre Bragg Grating technology being applied to a wind blade for strain measurement. The principle is much the same when applied to a tidal blade. It was envisaged that fibre optic strings would be installed to existing Nova M100 blades, with associated data interrogating and logging to be housed in the rotor blade hub.

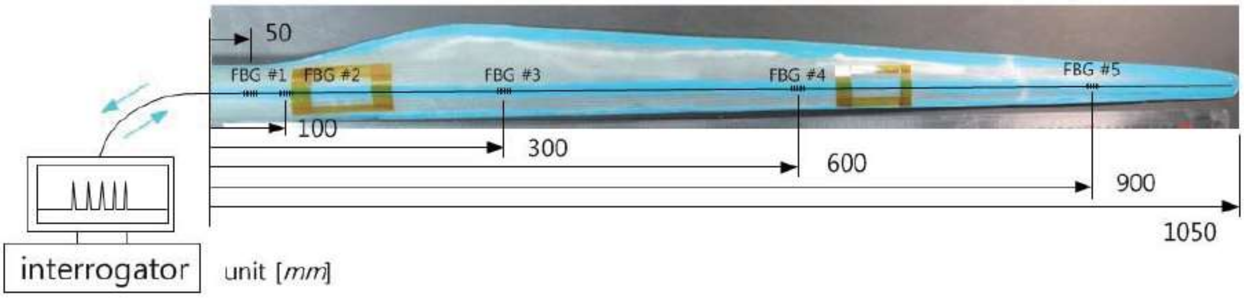


Figure 4-5: Wind Blade Example of using Fibre Bragg Grating technology

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[1] National Instruments , "Fundamentals of Fiber Bragg Grating (FBG) Optical Sensing," Jan 2016. [Online]. Available: http://www.ni.com/white-paper/11821/en/

[2] K. E.-H. R. M.-S. S. P. L. I. K. I.-B. Kim Sang-Woo, "Structural Performance Tests of Down Scaled Composite Wind Turbine Blade using Embedded Fiber Bragg Grating Sensors Kim Sang-Woo, Kim Eun-Ho, Rim Mi-Sun, Shrestha Pratik, Lee In, Kwon Il-Bum," Oak Central, 30 Dec 2011.

4.4 Shaft torque

Shaft torque measurement data was required for OREC modelling studies in work package 10.

The options for retrofitting torque measurement on Nova M100 turbines were limited due to tight space constraints. An inductive power and data transmission style torque transducer was chosen. This has a collar ‘rotor’ attached to the rotating shaft. A standard strain gauge is mounted and wired to the ‘rotor’. The ‘stator’ aligned with the rotor is mounted to a fixed static bracket. High resolution torque measurement data is transmitted by induction to the stator’s integrated receiver. The advantages of this type of system are the ease of installation, excellent data quality, inductive powering and slim profile. Figure 4-6 below[3] shows an example system similar to that to be installed on Nova M100 turbines.

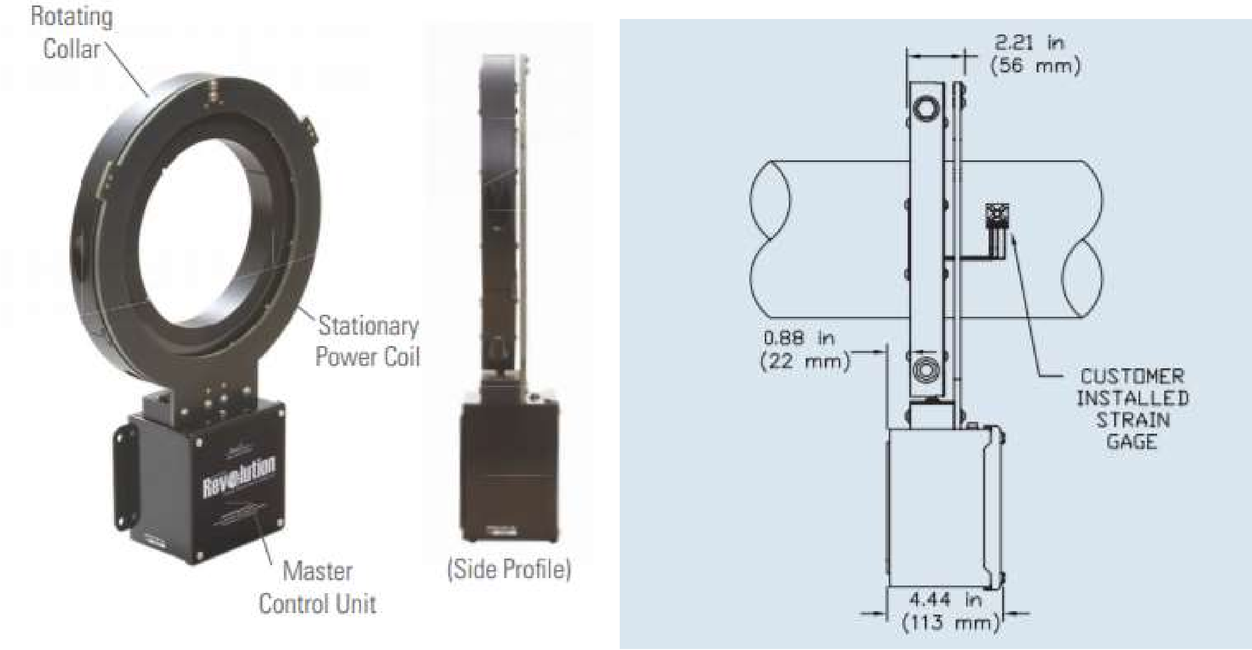

Figure 4-6: Induction torque transducer

4.5 Vibration monitoring

Two ways in which the EnFAIT project has helped to drive down the cost of tidal energy is by understanding and improving the reliability of equipment within an array, and by optimising the maintenance strategy for equipment deployed within a tidal array. Appropriate condition monitoring can contribute to both objectives. Remote monitoring of machines is conducted by measuring specific variables. The most important measured variables are those that best describe the state of the machine. Mechanical vibration is of special significance in this regard.

There are a great variety of vibration types, measured variables and characteristics when describing mechanical vibration. Various symptoms on running machines allow inferences to be made about the machine condition, such as an impending damage to the machine. Fault symptoms indicating a condition include:

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[3] Binsfeld, “TorqueTrak Revolution,” [Online]. Available: http://www.binsfeld.com/torquetrak/torquetrak-revolution/

- Changes in air-borne noise
- Displacement of machine components
- Rising bearing temperatures
- Changed mechanical vibration characteristics

Mechanical vibration is vibration that can be sensed and measured on the surface of objects. When dealing with machine monitoring, this especially includes the surfaces of machines, components and foundations. Vibration largely originates from the centrifugal forces on rotating machine parts. This may be caused by:

- Unbalance
- Misalignment of machine drive trains
- Bearing damage
- Gear defect
- Magnetic, hydraulic and / or other functional alternating forces

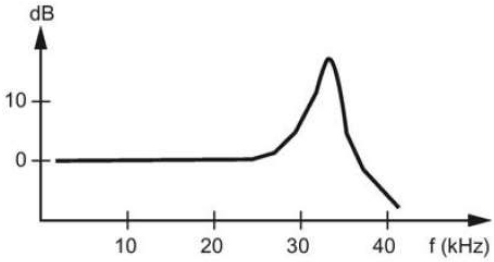
Acceleration sensor	Typical frequency response (resonance at 34 to 36 kHz)
	

Figure 4-7: Piezoelectric sensor example

Piezoelectric sensors are used for the frequencies and frequency bands to be covered for vibration monitoring. These sensors generate an analogue voltage signal that can be further processed in response to dynamic compressive and tensile forces. Static acceleration forces, such as acceleration due to gravity, are not picked up by these sensors. An industrial standard for piezoelectric sensors is IEPE (Integrated Electronics Piezo-Electric). Figure 4-7 above shows a typical vibration sensor to be installed on the turbines.

4.6 Turbine ambient temperature

Measurement of the temperature profile across the nacelle enables a greater understanding of the M100 generator air cooling system, which makes use of fans to circulate air throughout the turbine to draw heat from the generator towards the nacelle walls. Eight PT-100 air temperature probes were selected to be installed evenly across the nacelle to provide a comprehensive temperature profile.

4.7 Summary

Within the EnFAIT project, a consortium of European partners developed a range of tidal energy modelling design tools, enabling future arrays to be more cost effective. Nova has already successfully deployed and operated an array of tidal turbines, which feature state of the art instrumentation systems. However, as part of the EnFAIT project, these turbines were further upgraded to produce high-quality, research-grade data to maximise the learning extracted from this unique resource.

To gather the required research data, the following turbine upgrades were identified:

- Improvements to tidal resource data gathering capability;
- Modifications to the existing array power metering scheme;
- Installation of blade load measurement instrumentation;
- Installation of turbine torque measurement equipment;
- Modification of turbine vibration monitoring system;
- Expansion of existing turbine temperature monitoring system.

5 Implementation of T1-3 M100 turbine upgrades

This task included the purchase of the specified instrumentation and control equipment defined in T6.3, and the recovery of the existing turbines to refit them with the new instrumentation packages. Additionally, new stand-alone instrument support structures were built, assembled, tested and commissioned. Finally, new more reliable and cost-effective subsea electrical connectors were designed and implemented.

5.1 T1 turbine rotor strain gauging

Nova and OREC fitted strain gauges to the T1 turbine rotor (see Figure 5-1 below) and gathered data over this operational period. The results were fed into OREC's work to characterise the cyclic loadings that Nova's turbines experience as they operate through ambient turbulence and wave action as reported in WP10. Better data on these cyclic loadings informs both an understanding of the array environment (WP10) and the design of future turbine components and operating strategies (WP9 Optimise array reliability, maintainability & availability).

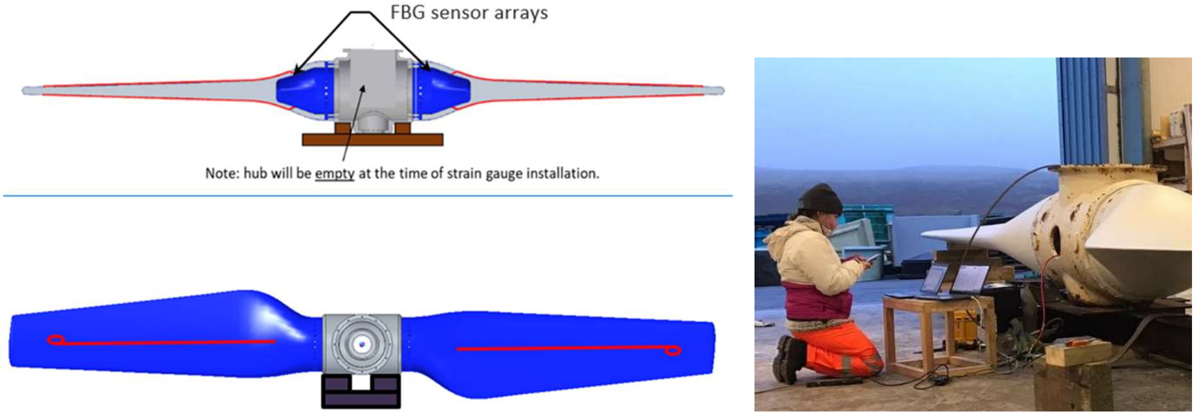


Figure 5-1: T1 rotor strain gauging

5.2 Maintenance and additional upgrades

Each of the upgrades outlined in '

Implementation of T1-3 M100 turbine upgrades' were implemented and tested on the three original STA turbines: T1-3.

One of the major upgrades trialled on the T3 machine involved replacing a failure-prone third-party dry-mate subsea cable connector with a new dry-mate connector designed by Nova, the "Nova-Can". The period of array operations over the winter of 2018/2019 confirmed that the new connector was robust in operation and a great success. Nova took advantage of a scheduled maintenance window in May 2019 to significantly upgrade the electrical connections on the two other turbines in a recovery and redeployment "pit stop" for all three turbines.

Figure 5-2: STA turbine recoveries and redeployments, May 2019

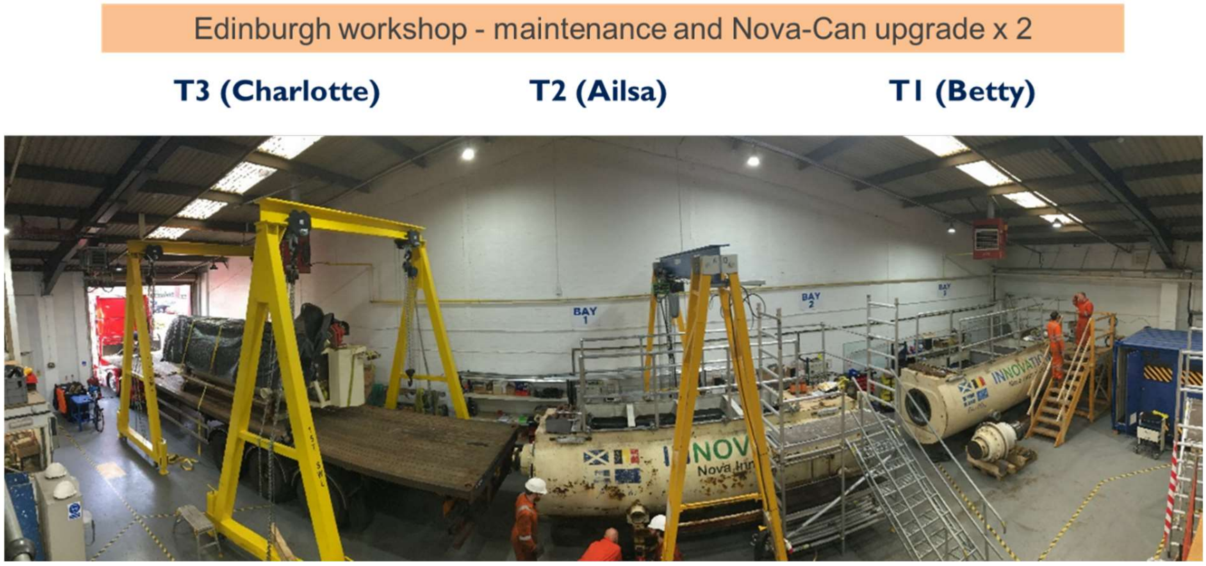


Figure 5-3: Three-turbine 'pit stop' in Nova workshop, Edinburgh, May 2019

5.3 Temperature measurement for cooling verification

Nova also employed an Engineering Doctorate student to develop condition monitoring algorithms and system improvements, in partnership with SKF and the WP6 activities. This was based on a methodology that balances risk and cost reduction in condition monitoring system design and considered:

- Improved gearbox heat rejection prediction with measured efficiency.
- Development of algorithms, using data from upgraded EnFAIT instrumentation, to model quasi-static heat transfer using an empirical model of heat exchangers and a derived heat transfer coefficient as a condition indicator.
- Relationships between temperature and pressure data observed over time, with data divided into three sets corresponding to control system activity, resulting in an indicator of degradation based on the Root Mean Square Error of Cumulative Density Function of Kernel Density distributions.

As a result of this work, one of the EnFAIT turbines was fitted with a package of additional sensors to better understand the performance of the turbine cooling system and increase turbine reliability.

5.4 Spares / consumed components

In order to implement the EnFAIT array spares strategy (as well as to streamline the manufacturing process ready for production quantities), Nova Innovation moved from an R&D procurement system to a Production System. The work carried out in WP9 to understand spares-holdings and the need for planned-maintenance, has informed this transformation at every stage. The SKF planned-maintenance team were consulted and informed about the progress within Nova of the ERP system. This supports the WP6 requirement to supply information to WP9 (Optimise array reliability, maintainability & availability) to inform the array spares strategy based on operational learning.

The information arising from EnFAIT forensic inspections and ongoing scheduled maintenance activity have also been combined with the data gathered via Nova’s quality system, to inform the ongoing development of the array spares strategy.

6 Operation of the Upgraded T1-3 Turbines

In this task we reinstalled and operated turbines T1-3 at Bluemull Sound and continued to collect data from the new instrumentation to report KPIs for the turbines and the array. There was also close co-ordination with WP10 to ensure quality data was provided for wake modelling and performance assessment purposes.

6.1 T1-3 operations overview

Turbines T1, T2 and T3 (Ailsa, Betty and Charlotte) were deployed in the Shetland Tidal Array in 2016 and 2017. The EnFAIT project began in July 2017 and as described above, T6.3 and T6.4 specified and procured a range of upgrades, which were implemented in 2018. Following completion, the three upgraded Nova M100 turbines (T1–T3) were again redeployed and installed on the seabed. The turbines were subsequently retrieved for their annual scheduled maintenance intervention in May 2019 and then redeployed. See Figure 6-1.

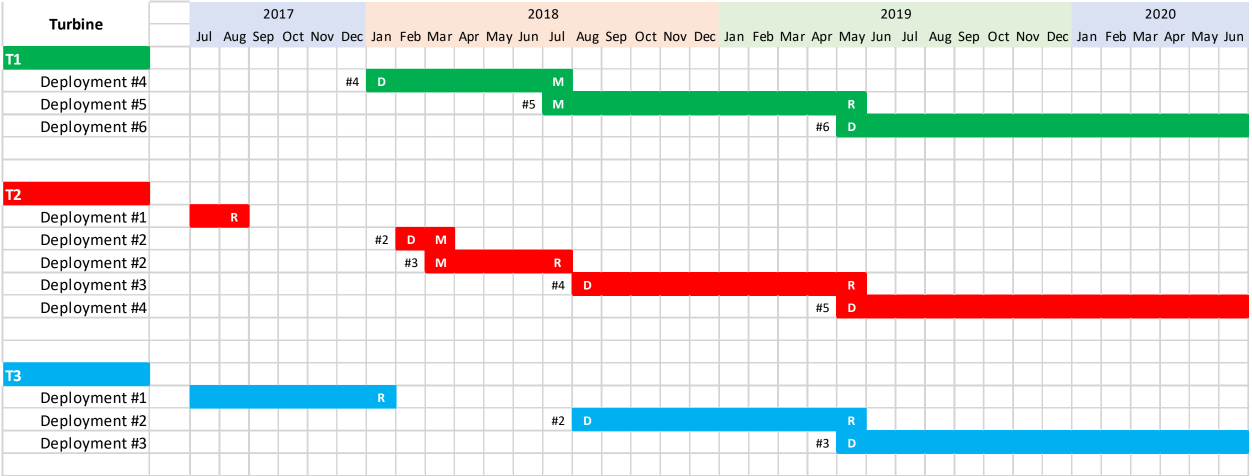


Figure 6-1: T1-3 turbine deployments during the EnFAIT project, prior to T4 installation

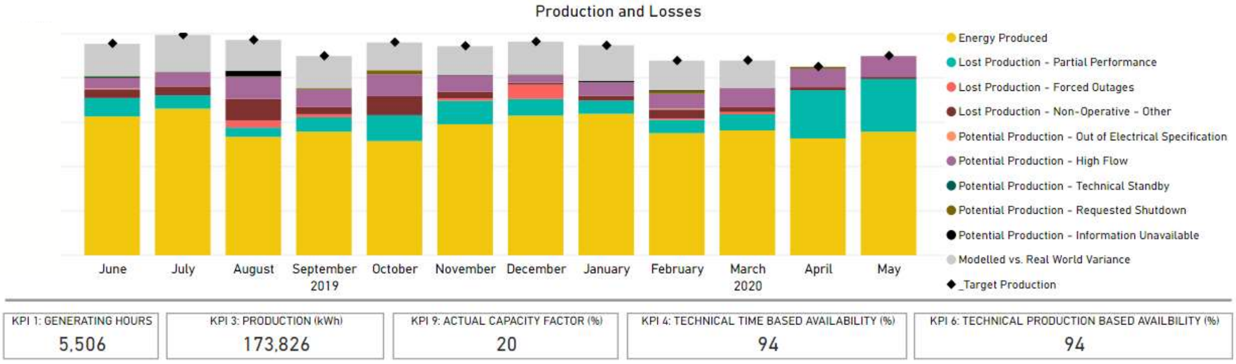
The key achievements over the period were:

- Record performance post the EnFAIT upgrades demonstrating that tidal energy had moved beyond the prototype stage towards becoming an investable asset class:
    - Total annual power production from the Shetland Tidal Array more than doubled compared to performance before the EnFAIT upgrades.
    - All turbine availabilities are now consistently over 85%
    - The time between offshore maintenance intervals has increased by 50% compared to the first EnFAIT deployments
- The comprehensive programme of data gathering and modelling by EnFAIT partners means that the STA is likely now the world’s best characterised tidal array.
- In May 2019, Nova carried out a three-turbine “pit stop” in record time (three weeks), reducing operational costs by 50% by completing workshop maintenance and significant planned EnFAIT upgrades on all three turbines simultaneously, then redeploying. Longer periods of operation between service intervals as reliability increases is a key factor in helping to drive down the cost of energy.

- Offshore operations to recover and redeploy the turbines were carried out in spring tides for the first time, expanding the window of workable conditions and therefore reducing downtime: turbine recovery during spring tides is believed to be a first for the tidal sector and is an important component of reducing the cost of energy.
- Load and performance data were continuously recorded and informed improvements to the Nova turbines and array architecture, as well as to the development of design tools such as ORE's Array Interaction Model (AIM) being developed in WP10, which characterises turbine wakes and their impact on downstream devices in order to optimise tidal array design.
- Physical modelling and data driven analyses were used to evaluate the effectiveness of Condition Monitoring System (CMS) upgrades and to develop new variables to use as CMS performance indicators, enabling early identification and prevention of fault modes that reduce production. These are reported in the WP9 deliverables.

6.2 Turbine production and KPI reporting

Figure 6-2 shows the production over a 12-month period from an original M100 turbine at Bluemull Sound which is a moderately energetic 'Tier 2" site. Monthly totals for energy produced are shown in yellow, with lost production arising from partial performance shown in turquoise (note on the Shetland tidal array this is largely due to local grid constraints), potential production from higher flow speeds shown in purple and forced outages and fault modes shown in light and dark red respectively. The grey band (Modelled vs. Real World Variance) arises from a) deviations between the modelled tidal data and the actual tidal conditions and b) averaging errors in the classification of operative states - primarily due to the fact that 5-minute averaged data is used in the analysis.



KPI 1: GENERATING HOURS	KPI 3: PRODUCTION (kWh)	KPI 9: ACTUAL CAPACITY FACTOR (%)	KPI 4: TECHNICAL TIME BASED AVAILABILITY (%)	KPI 6: TECHNICAL PRODUCTION BASED AVAILBILITY (%)
5,506	173,826	20	94	94

Figure 6-2: Example turbine production and KPI reporting

6.3 Deployment of standalone subsea instruments

During this period further instruments were deployed to continue to build the site velocity and turbulence dataset in order to validate the AIM being developed in WP10.

Figure 6-3: Seabed mounted ADCP instrumentation deployment

Project partners OREC made multiple visits to Shetland to coordinate the deployments of seabed ADCPs (see Figure 6-3) and substructure-mounted instrumentation skid deployments (Figure 6-4).

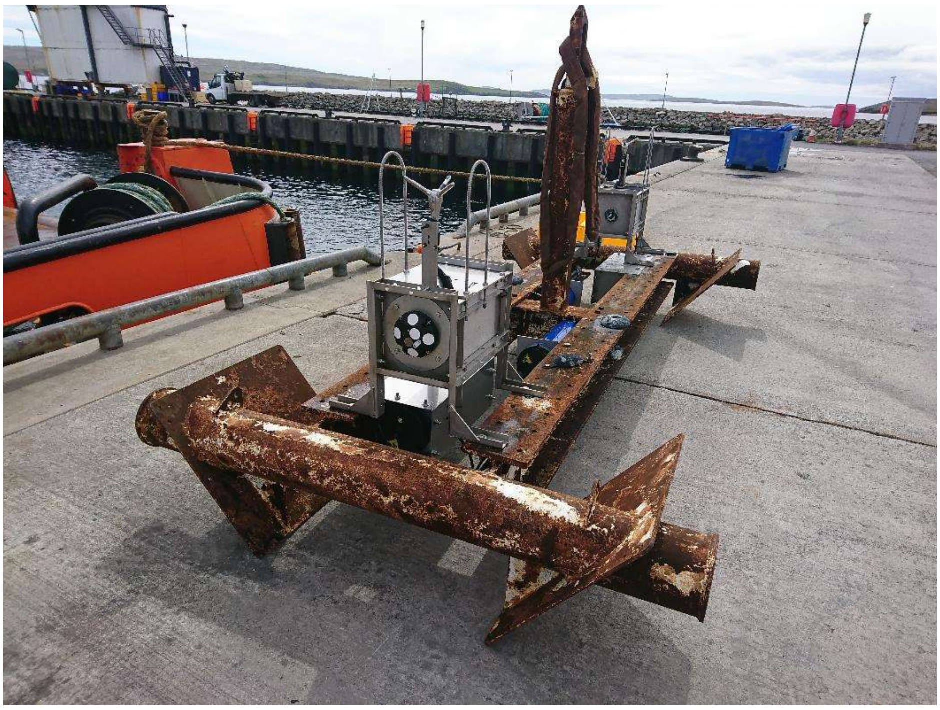


Figure 6-4: Instrumentation skid recovered

7 Use of Turbine and Array Data

In this task, turbine operational data relating to performance and loads was analysed. Investigation was undertaken into methods of optimising operational methods to increase energy output and/or reduce fatigue loading to extend turbine service intervals. Coordination with WP9 enabled development of condition monitoring algorithms which allowed turbine health to be understood and maintenance to be planned.

The modelling and flow measurement work on the Shetland Tidal Array have enabled Nova to validate the turbine power curve and to develop a fully validated site resource model, with good alignment between modelled and measured current speeds.

7.1 Performance validation and Array Interaction Modelling

This resource modelling work has confirmed Bluemull Sound as a “Tier 2” site with moderate resource: an ideal location for proving technology on the world’s first tidal array. However, it should be noted that there are a large number of more energetic “Tier 1” sites across the globe. For example, Nova’s site in Petit Passage in Canada is one such Tier 1 site and learnings from EnFAIT operations have already been transferred to the development of that site.

The in-depth site resource and turbine measurements continue to support WP4 design work, WP9 reliability analysis and WP10 modelling work as shown in the diagram below.

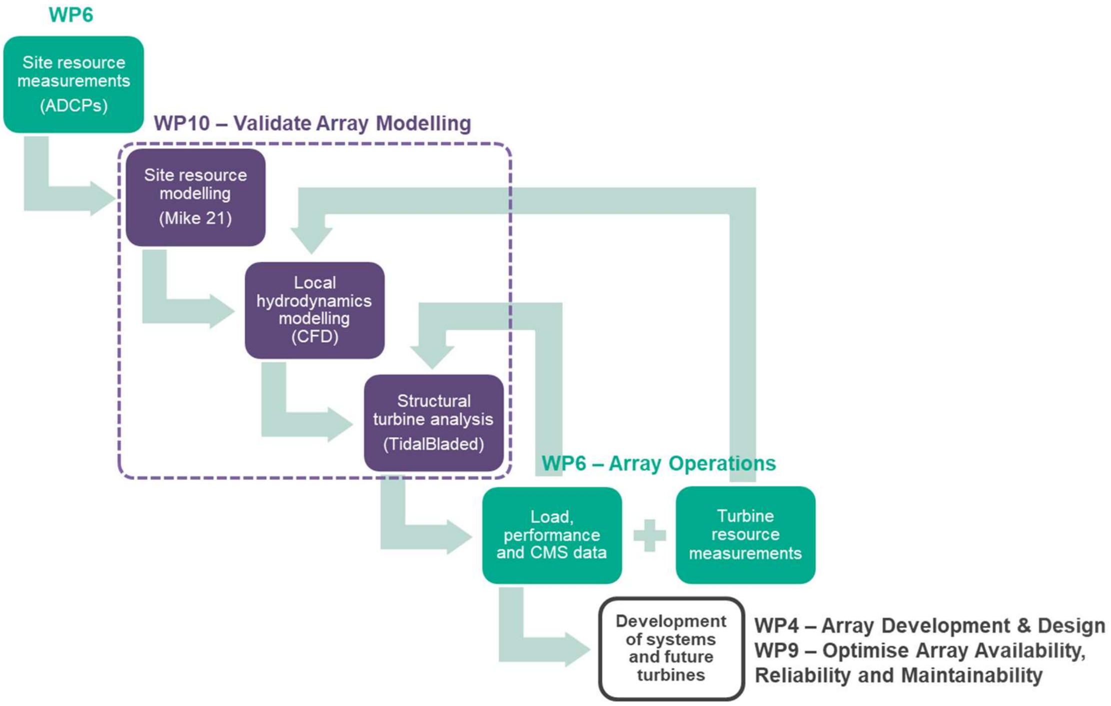


Figure 7-1: Information flows from turbine operations to other EnFAIT work packages

Turbine and resource data continue to feed into OREC Catapult’s CFD model of the flow incident on the turbine (see figure below). In turn, the turbine torque and strain gauge load measurements were used to validate the expected loads generated by this CFD model and the turbine loading analysis generated by Tidal Bladed.

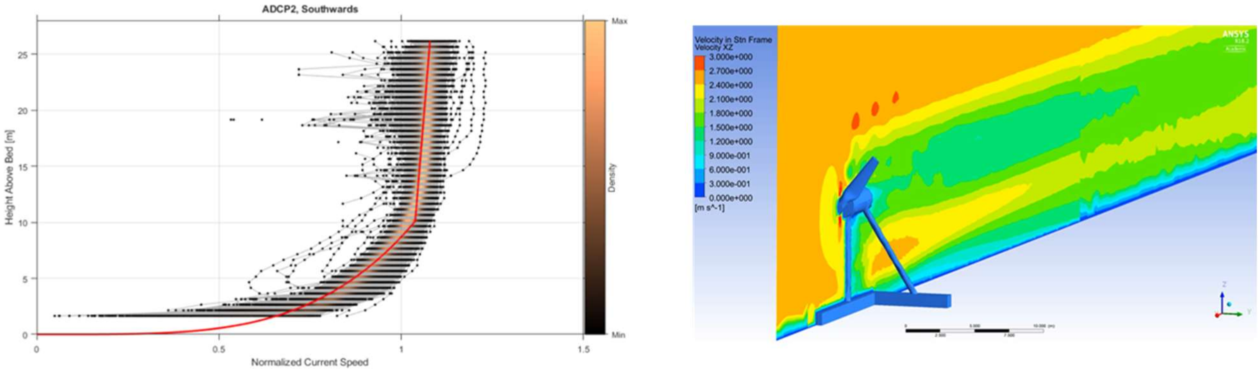


Figure 7-2: ADCP measurement results and screenshot from CFD modelling of turbine wakes

8 Operation of Expanded Array: T1-3 & M100D T4

Once the first new M100D turbine (T4) had been commissioned in WP5, operation continued as described in T6.4 but with the additional turbine. Learnings from the new machine were captured and fed back to allow any further improvements for future turbines T5 and T6 to be implemented.

8.1 M100D - T4 deployment

The first M100D Eunice was deployed at the Shetland Tidal Array in Q3 2020. The M100D is Nova's 3rd generation state-of-the-art direct drive tidal turbine and is shown in Figure 8-1.

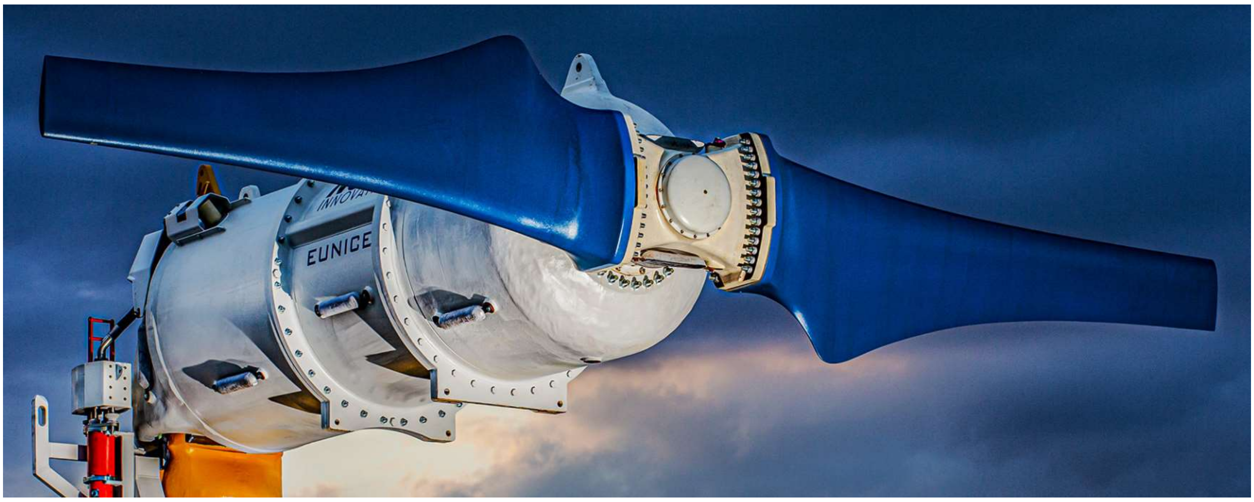


Figure 8-1: Eunice (T4) – the first 3rd generation M100D tidal turbine

8.2 M100D power curve validation

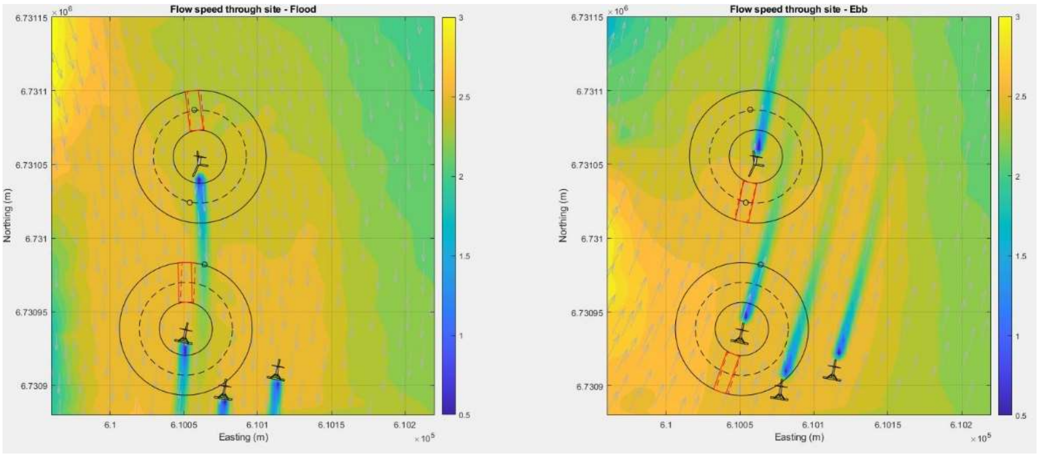


Figure 8-2: T4 seabed ADCP deployments

The flow measurement work on the Shetland Tidal Array has enabled Nova to validate the M100D turbine power curve in line with IEC requirements – Figure 8-2 shows the ADCP positions deployed to validate this.

8.3 T1-4 operations overview

The initially expanded array (T1-4) operational key achievements have been:

- Record performance since T4 deployment:
    - Nova’s new M100D turbine is consistently producing around 50% more power than the previous M100 models, through improved performance and reliability.
    - The M100D machine has consistently achieved availability over 95% and as high as 99% in multiple different months.
    - Proven the efficient recovery and redeployment of the new M100D nacelle after 18 months’ operation.
    - Nacelle recovery and deployment operations have been undertaken without divers in under three hours: from quayside to offshore site and return to quayside.

8.4 Array performance

The following sections outline array performance information captured over this operational period. 0provides details of KPI definitions and reporting methodology.

8.4.1 Increased power

Figure 8-3 shows T4 power production over a lunar cycle in March/April 2021. The peaks of generation during stronger spring tides can be clearly seen, along with the periods of lower generation during weaker neap tides. The difference in power production between spring and neap tides is more pronounced here than at other times of the year when the weekly peak/trough cycle is reduced.

Power production from the T4 machine is shown in yellow and peaks at well over 1,000kWh in spring tides. Lost production due to partial performance (shown in green) denotes periods of time where the turbine was operating at below its optimal output, for example due to torque limiting as turbulent tidal gusts were passing through. The periods of forced outages shown are largely related to Shetland’s active network management system grid constraints, where the Shetland Tidal Array may be requested to limit its production by the grid operator.

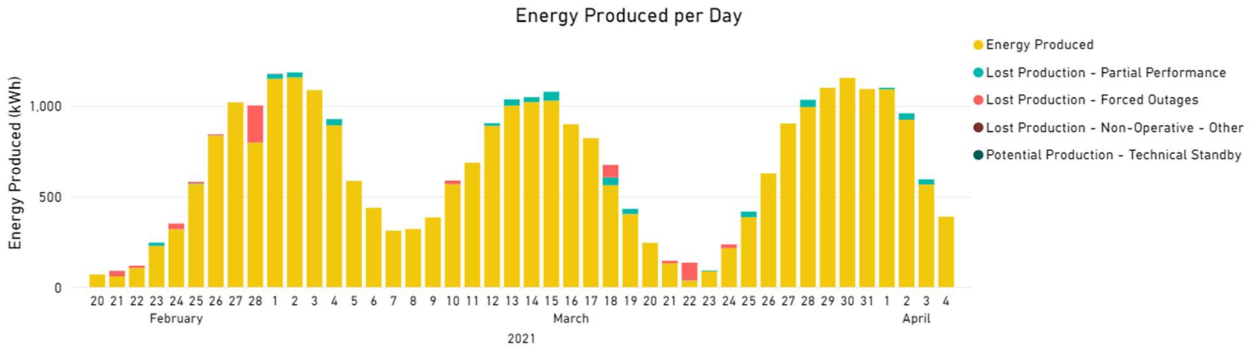


Figure 8-3: T4 turbine performance over a representative operational period

The level of performance that has been achieved on this moderately energetic (“Tier 2”) site of up to 29% corroborates the predictions made in D6.4, that Nova’s M100D turbine will be capable of achieving capacity factors of over 50% in more energetic commercial (“Tier 1”) locations.

Put another way, the M100D model is supplying >60 homes in Shetland and could therefore supply >100 in more energetic locations currently being developed worldwide. This demonstrates the potential for Nova's modular and scalable technology to reliably supply power to coastal communities across the world.

8.4.2 Higher availability and reliability

The T4 machine achieved an average availability of 94% over this reporting period, with availability figures outside of maintenance periods (Nov 2020 and Feb 2022) consistently over 95% and as high as 99% or 100% in multiple different months (grid reliability is a major component of the time where turbines are unavailable). Please see Figure 8-4. This record-breaking performance demonstrates the impressive reliability of Nova's latest direct drive turbine and paves the way for making tidal energy an investable asset class.

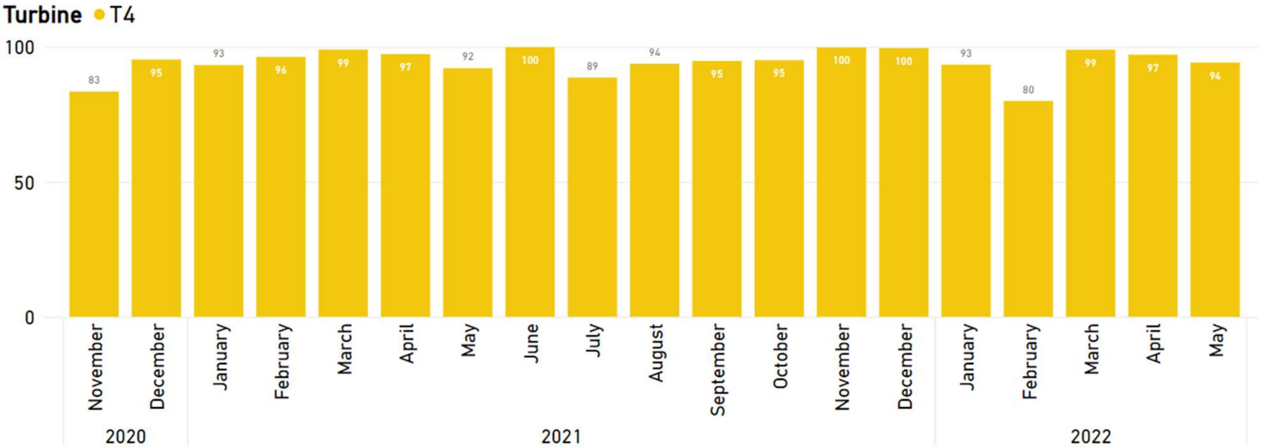


Figure 8-4: Turbine T4 availability example

In addition to the reliability improvements of the new T4 machine, the reliability of Nova's earlier turbine models continues to improve. By the end of this reporting period, an M100 machine had operated for 29 months with no maintenance.

8.5 T4 Turbine – fast turn-around local maintenance

After 18 months of operation, T4 was recovered for a scheduled maintenance intervention.

8.5.1 Rapid recovery and redeployment

Nova's new Launch and Recovery System (LARS) allows M100D turbine nacelles to be deployed and recovered without the need for divers and within one tidal slack in all tidal states. Nacelle recovery after 18+ months operation, overcoming the challenges associated with biofouling, has now been proven.

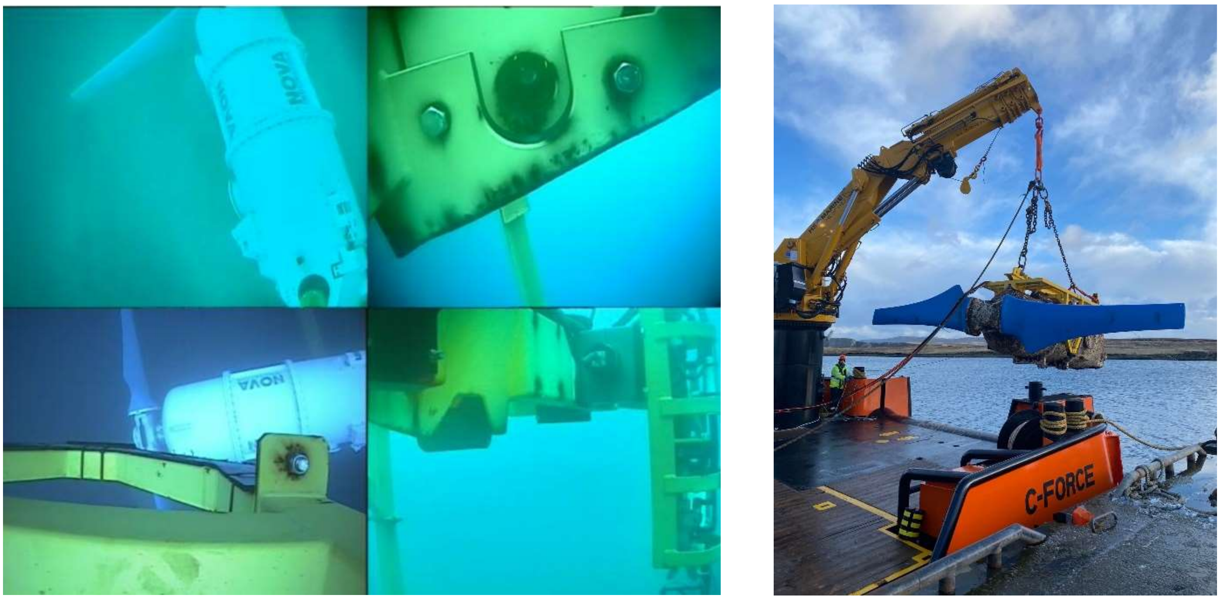


Figure 8-5: LARS camera views; T4 recovery using vessel crane

8.5.2 Local scheduled maintenance

For the first time, Nova completed a full turbine service at a remote local facility in Lerwick, Shetland, rather than at the company's Manufacturing Facility in Leith, Edinburgh. This avoided the transport and logistics costs associated with a return road/ferry journey, and the quick local maintenance turnaround meant that Nova was able to redeploy the turbine in the same neap tidal window – further reducing OPEX costs.

Figure 8-6: T4 local maintenance; M100 nacelle and T4 ready for redeployment

8.5.3 Nacelle-mounted ADCP deployment

Nova and OREC also worked together to deploy a nacelle-mounted ADCP on the T4 machine during the local maintenance period previously mentioned. This supplied information on the north-going (ebb) resource and south-going (flood) wake behaviour, supporting OREC's WP10 work to validate array modelling.

Figure 8-7: Nacelle-mounted ADCP installed on turbine T4

8.6 Biofouling

Following work completed by an Engineering Doctorate student (see Figure 8-8), an environmentally friendly coating was selected for the turbine rotor to reduce biofouling. The selected coating is providing excellent performance on rotors – see Figure 8-9 below of negligible growth on T4 blades after 24 months, thereby avoiding the reductions in performance associated with marine life increased surface roughness and to ensure maximum energy yield.

Figure 8-8: M100 turbine blades after >1 year of operations; biofouling test pieces

Figure 8-9: Negligible marine growth on T4 rotor after 24 months of operation

9 Operation of Full 6 Turbine Array

After the commissioning of T5 and T6 in WP5, the full 6-turbine array was operated in unison. Nova continued to record and report KPIs for the turbines and the array, while co-ordinating with WP10 to demonstrate the effect of operating upstream turbines on the loads and performance of those downstream.

9.1 Reduced installation and maintenance costs

Nova completed the installation of two entire turbine systems (substructure, ballast, cables and nacelles) concurrently, with T5 and T6 installations being completed within a day of each other in January 2023.

Previously, Nova mobilised a vessel and site crew to Shetland for each whole-system turbine installation:

- T1 – October 2015
- T2 – August 2016
- T3 – January 2017
- T4 – August 2020

Sharing vessel, crane and site crew mobilisation costs across multiple machines reduces the CAPEX per turbine significantly and provides an evidence base for future cost reductions as turbines are installed in larger numbers and the tidal energy industry moves towards mass manufacturing and deployment.

Figure 9-1: T5 and T6 turbine load-out (LARS frame in yellow)

Nova’s bespoke turbine Launch and Recovery System (LARS) shown above has also now been used successfully across three turbines, demonstrating further cost reductions through keeping deployment tooling on recoverable, reusable equipment. Figure 9-2 below shows the camera views from the LARS display prior to turbine release (left-hand image) and as the LARS is recovered to surface (right-hand image). The LARS enables extremely efficient and safe deployment of the M100D, demonstrated recently during the install of T5 and T6 which was completed in stormy winter weather conditions, including significant waves, and spring tides.

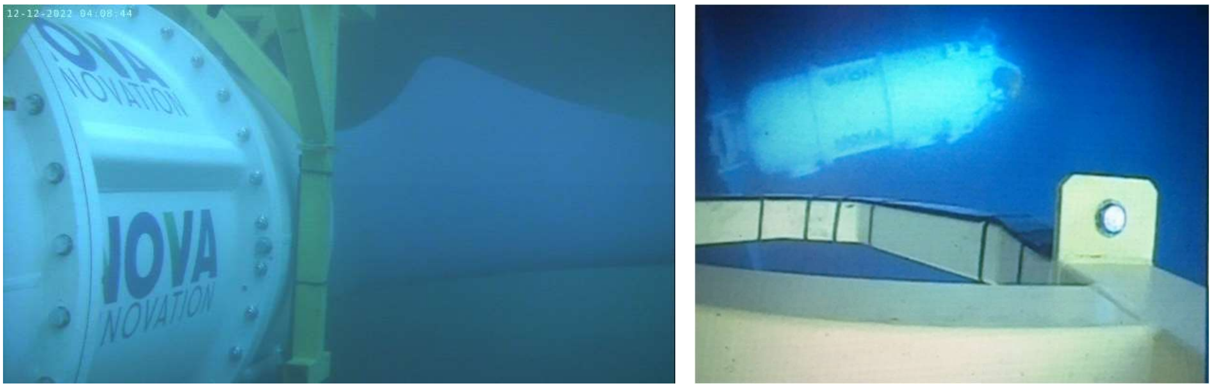


Figure 9-2: LARS camera views

9.2 Largest number of turbines operating in an array

Turbines T5 and T6, named Grace and Hali Hope, were installed at the STA in January 2023. They join turbines T1-4 (Ailsa, Betty, Charlotte, Eunice), taking the total number of installed turbines to 6, thus making the STA the array with the largest number of turbines anywhere in the world. Figure 9-3 below shows the layout of the Shetland Tidal Array in Q1 2023, with the M100 (T1-3) turbines to the south of the site and M100D (T4-6) turbines to the north. Areas of high ambient tidal resource are shown in yellow/orange, with the areas of reduced resource downstream (wake) of each turbine shown in blue.

Figure 9-4 shows a typical screenshot from the fully automated STA control centre, summarising the operation of the array and each turbine.

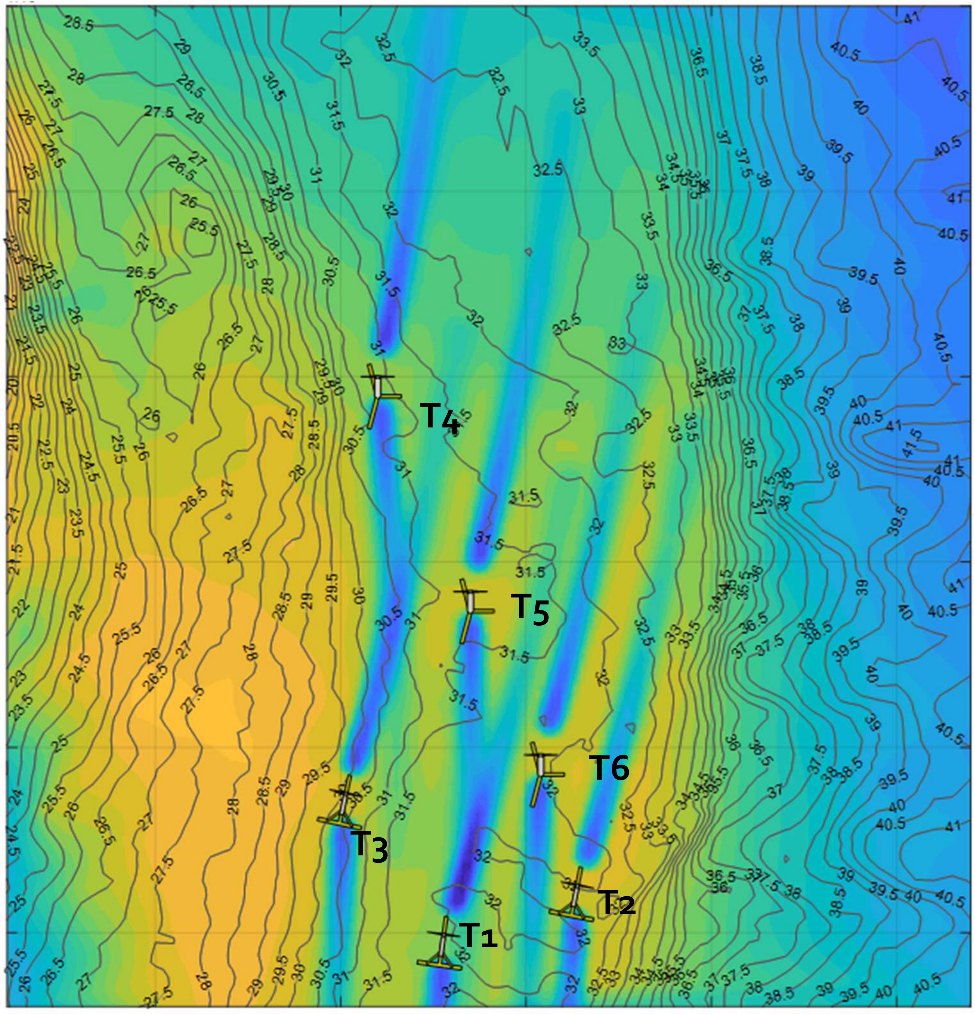


Figure 9-3: Layout of STA with M100 (T1-3) and M100D (T4-6) turbines

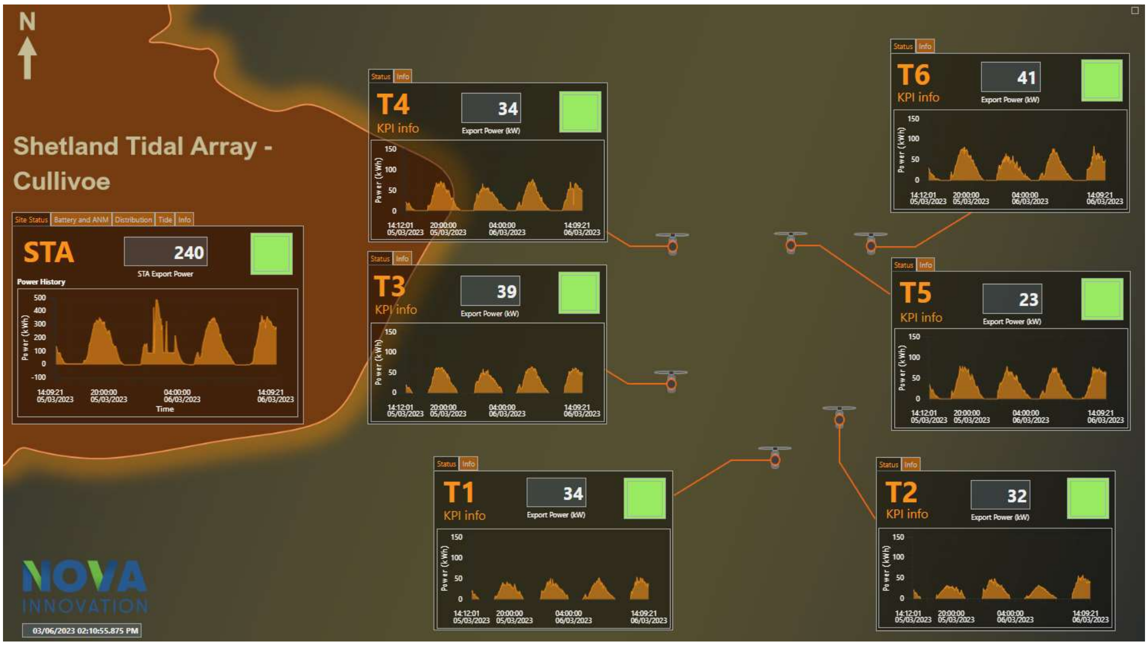


Figure 9-4: Example of STA control room performance summary

9.3 Proven low-cost subsea cable hub

Nova also deployed a subsea cable hub. This Nova-designed piece of equipment incorporates three dry-mate NovaCan connectors (proven previously on turbines T1-3) and connects turbines T5 and T6 to their export cable. The installation sequence was as follows:

- Subsea hub landed on seabed and main export cable laid to shore
- T5 cable backpack landed on T5 substructure and jumper cable laid to hub
- T6 cable backpack landed on T6 substructure and jumper cable laid to hub
- Hub and jumper cables recovered to deck; jumper cables connected to hub (see image below)

Figure 9-5: T5/T6 subsea cable hub on deck prior to installation

Turbines T5 and T6 are now exporting power to shore along the subsea hub's single export cable, proving this low-cost hub design which is scalable to larger arrays.

Particularly on sites which are far from a grid connection point, subsea hubs are essential to avoid the need for each individual turbine to have its own cable to shore. This subsea cable hub technology demonstrated as part of the project can also play a critical role for the scaling up of the industry and delivery of multi-turbine tidal arrays.

By connecting multiple turbines to a subsea hub as shown in Figure 9-6 and/or “daisy chaining” (linking in series), cable CAPEX and installation costs are reduced and onshore cable landing is simplified in terms of cost, consenting and engineering by having fewer cables running to shore.

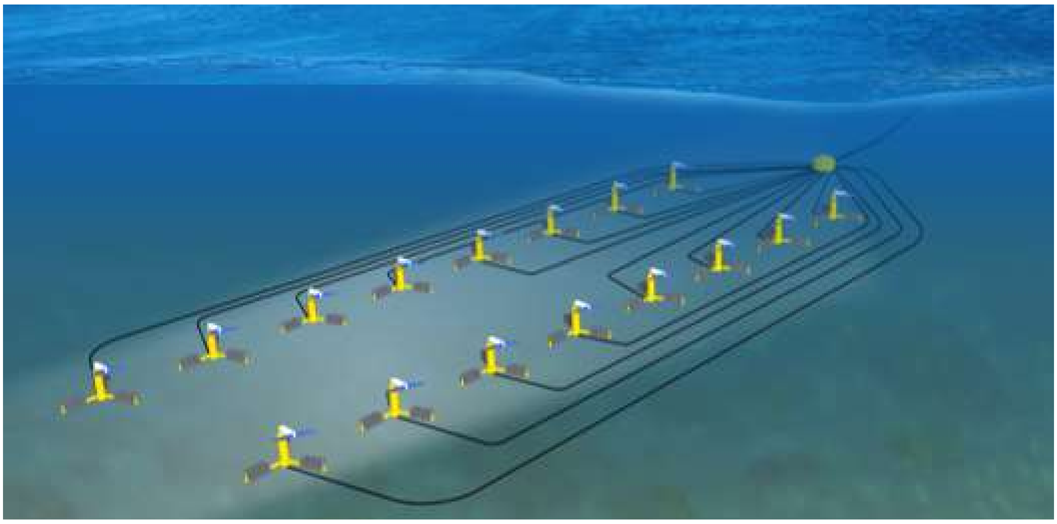


Figure 9-6: Illustrative offshore electrical architecture concept for multi-turbine arrays

10 Array Turbine Interactions and Performance

Although there is sufficient space in the seabed lease area to deploy all 6 of the STA turbines side-by-side in a single non-interfering row, the EnFAIT project provided the means to deploy turbines T4-6 at varying distances in front of the existing T1-3 turbines in an industry first. This allowed direct measurement data related to intra-array turbine performance, including load predictions and direct turbine wake effects to be provided to WP10 for comparison with KPI predictions.

10.1 Vessel-mounted ADCP surveys

A number of vessel-mounted ADCP (VMADCP) survey campaigns were completed to characterise the wakes produced by the STA turbines. An example is shown in the image below.

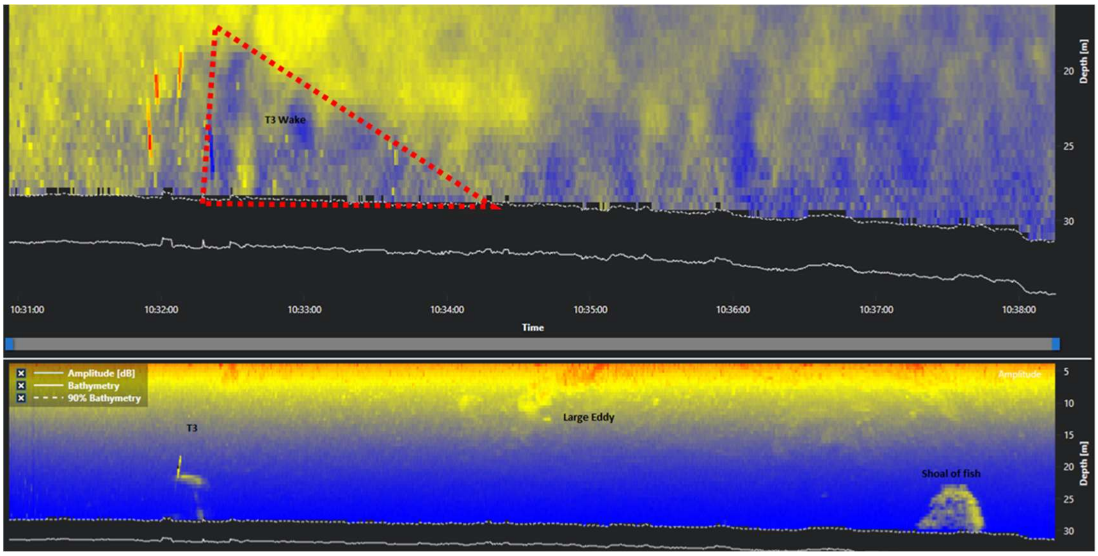


Figure 10-1: VMADCP survey showing T3 wake (upper image) and T3 substructure (lower image)

Through a combination of static (moored) measurements and vessel drifts through the operational site, turbine wakes were characterised, supporting array interaction modelling work in WP10 (Validate Array Modelling Tools). The lower flow speeds just downstream of the turbine can be clearly seen in blue in the image above, with wake recovery observed thereafter.

10.2 AIM validation data for intra-array turbine effects using VMADCPs

All 6 turbines in the Shetland Tidal Array were operated as normal over a number of tidal cycles while a Vessel Mounted ADCP (VMADCP) survey was carried out to determine water velocities across the site at different times – see Figure 10-2.

Additionally it was also possible to systematically turn turbines on and off during tidal cycles while ‘scanning’ the array wakes utilising the VMADCP to collect extensive data-sets allowing WP10 to match wake measured velocity deficits to simultaneous actual power outputs. These results are described in deliverable D10.10.

Figure 10-2: STA turbine positions and VMADCP survey ‘scans’ (blue dashed arrows)

10.3 AIM validation data for turbine wakes

In addition to the rich VMADCP data collected during array operation, Turbine T4 had two live readouts of tide speed via seabed mounted ADCPs deployed to the north and south of the turbine foundation (see Figure 10-3) which were installed as part of the European Commission H2020 funded ELEMENT project (Project no. 815180). This means that Nova can measure both the incident resource as well as characterising the impact on flow speeds and turbulence in the wake downstream of this M100D machine.

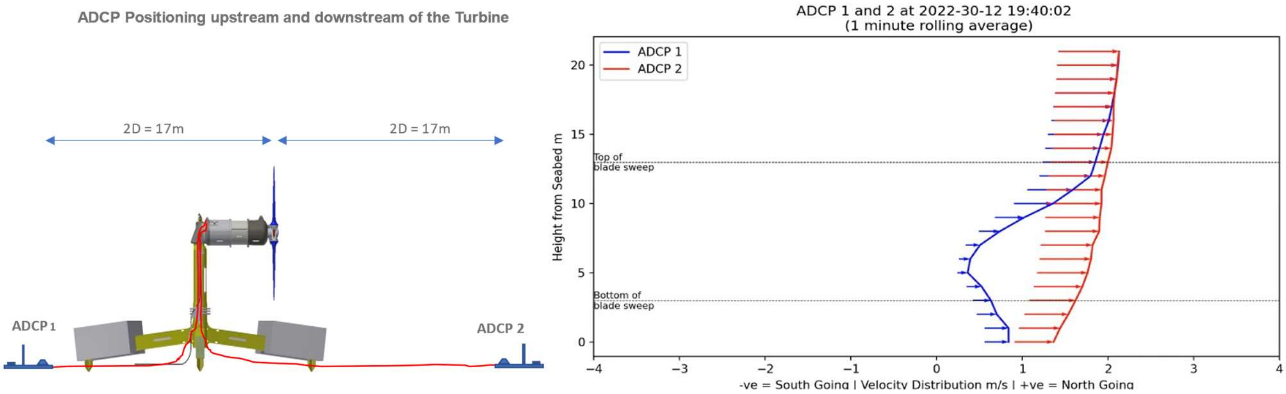


Figure 10-3: T4 typical velocity distribution during operation showing wake velocity deficit

10.4 Consistently improved performance and availability

With turbines T5 and T6 joining turbine T4 (deployed Q3 2020), Nova gathered much operational data from three of the latest M100D turbines. This has enabled the (T4) performance improvements outlined in D6.5 to be further validated by analysis of T5 and T6. The results confirm that all three machines are achieving a capacity factor of up to 29% on this moderately energetic (“Tier 2”) site – meaning they could achieve capacity factors of 50% or greater on more energetic (“Tier 1”) sites such as the Bay of Fundy in Canada, Pentland Firth or the Falls of Warness in Scotland.

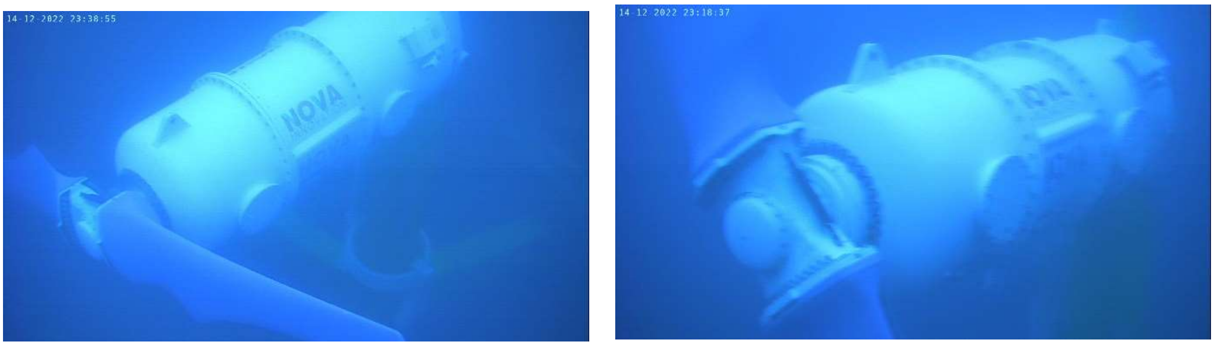


Figure 10-4: Subsea images of M100D turbines T5 and T6

All three M100D machines are also producing around 50% more power than the older M100 turbines. The figure below shows a typical period of output from the M100D machines, showing the higher periods of generation associated with stronger spring tides and the lower periods of power generation associated with weaker neap tides. The non-operative states at the start of the period (dark red) are associated with turbine commissioning in the days immediately following deployment. Forced outages due largely to grid curtailment are shown in pink. Lost production due to partial performance is shown in green, which was primarily related to early commissioning activities.

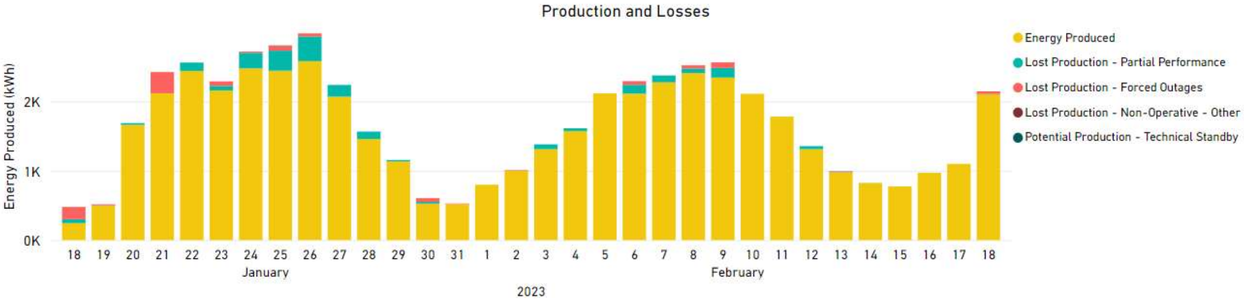


Figure 10-5: M100D generation example

Even in the early months, turbines T5 and T6 are matching turbine T4's high availability figures of over 95%

10.5 Consistently longer maintenance intervals

Although the EnFAIT project necessitated removal of turbines for various valuable R&D activities outside of normal operations, e.g. instrument upgrades, in-depth forensic component analysis after set periods, biofouling research, etc., the operating periods of turbines in the STA between interventions (both R&D and maintenance) significantly increased over the duration of the project. This is an excellent result and demonstrates the industry enabling impact of the EnFAIT project.

Turbine T3 completed 883 days (29 months) of continuous operation with no maintenance at the time of writing: a new record. This is a remarkable achievement, particularly as T3 is one of the original M100 turbines with a gearbox. This bodes well for T5 and T6 which are based on our new high reliability direct drive generator design, which does not have a gearbox and has fewer moving parts. The initial operation of T5 and T6, with their high availability figures, shows that they are well placed to exceed the record set by T3. Extending the length of time of operation between service intervals is something which has been excellently demonstrated through the EnFAIT project and is an important step for lowering costs of tidal stream energy.

11 Conclusion

This report has outlined the activities and results from array operations (T1-6) at the Shetland Tidal Array (STA), under the Enabling Future Arrays in Tidal (EnFAIT) project. As the world's first grid-connected offshore tidal array, the STA has provided a unique opportunity to gather sector leading learnings and accelerate the commercialisation of tidal energy.

Key operational achievements during EnFAIT include:

1. **Largest number of tidal turbines in an array:** in a world-first, Nova operated an array of six tidal turbines: the largest number of free-standing tidal stream turbines deployed in one location.
2. **Consistently higher power production and availability:** turbines T5 and T6 are delivering best in class performance, matching reliability and output of the first M100D turbine deployed at the STA (T4), confirming that the M100D model achieves a capacity factor of up to 29% on this moderately energetic ("Tier 2") site – and could therefore achieve 50% or greater on more energetic ("Tier 1") sites. T5 and T6 are also consistently matching turbine T4 availability of 95% or better.
3. **Proven low-cost subsea cable hub:** Nova deployed the company's first subsea cable hub, which is now exporting power from turbines T5 and T6 along a single export cable. This innovation delivers significant savings on subsea cables, further reducing the cost of tidal power, essential as the industry scales-up to larger sites with more turbines (where single cables to shore from each turbine are no longer a viable solution). This is an industry leading technology demonstration, as the first subsea hub to have multiple operational turbines connected and exporting to the grid.
4. **Reduced installation costs:** for the first time, Nova installed two complete new turbine systems (substructures, ballast, cables and nacelles) concurrently – thereby demonstrating a significant reduction in OPEX costs relating to turbine installation.
5. **Rich environmental and resource dataset:** a very large number of bird, mammal, fish, ADCP, VMADCP, ADV and other surveys have been undertaken to provide a superbly comprehensive dataset for Bluemull Sound and the STA. These have been used to meet Licensing requirements and provide data to other work packages, for example the key Array Interaction Modelling in WP10.
6. **Reduced turbine maintenance periods and costs:** a simultaneous rapid recovery, maintenance (in Edinburgh) and redeployment of all 3 M100's (T1-3) within a three-week period significantly reduced scheduled maintenance costs by 50%. Later in the project and for the first time, Nova undertook scheduled turbine maintenance locally in Shetland: the T4 nacelle was recovered, serviced in a local Lerwick facility and redeployed within the same neap tide window, eliminating Shetland-Edinburgh transport costs and the need for an additional vessel mobilisation, further significantly reducing maintenance costs.

7. **Significantly increased maintenance intervals:** turbine maintenance periods have increased across the project, the EnFAIT upgrades to the M100 turbines swiftly increasing this above the initial 12-month project target to multiple years. The current record-breaking period of operation for an old M100 turbine T3 is 883 days (>29 months) of continuous operation with no maintenance. The longer turbines can operate without the need for servicing, the lower the cost of tidal energy.

8. **Biofouling issues eliminated:** the EnFAIT project has allowed identification and implementation of biofouling solutions for all parts of a tidal turbine system. Notably the blades have remained biofouling free with an environmentally friendly coating system for periods greater than 3 years.

9. **Health and Safety:** there have been zero RIDDOR-reportable or lost time incidents during EnFAIT operations. Hazard observations (which can be positive or negative) and near misses have been continually logged on the Nova Safety Management System.

10. **Highly increased metocean operational windows:** offshore operations have now been safely undertaken during all seasons (including T5 and T6 deployment in extremely challenging winter storm conditions), in both neap and spring tides: previously operators only recovered or deployed turbines during the weaker neap tides effectively reducing deploy or recovery time to only 50% of any year. This allows turbines to maintain their high overall production availability by the swift and safe O&M recovery or deployment at any time.

With the largest number of operational turbines anywhere, the EnFAIT project has delivered industry-enabling results, demonstrating the scalability of tidal energy. The cost reductions and improvements in reliability and performance that the project has proven are demonstrating the bankability of this relatively untapped completely predictable renewable energy resource. Through the additional installation and excellent performance of the subsea hub and third generation M100D turbines, this ground-breaking project has helped to accelerate the European tidal energy sector towards commercialisation.

Appendix I: Key Performance Indicators (KPIs)

The following KPIs can be reported for individual turbines:

- Turbine KPI 1: Generating hours
- Turbine KPI 2: Downtime
- Turbine KPI 3: Production
- Turbine KPI 4: Technical time-based availability
- Turbine KPI 5: Operational Time-based Availability
- Turbine KPI 6: Technical Production-based Availability
- Turbine KPI 7: Operational Production-based Availability
- Turbine KPI 8: Actual capacity factor
- Turbine KPI 9: Potential capacity factor
- Turbine KPI 10: Number of failures (total operations impact)
- Turbine KPI 11: Number of failures (partial operations impact)
- Turbine KPI 12: Number of failures requiring marine operations to resolve
- Turbine KPI 13: Number of forced outages
- Turbine KPI 14: Lost Production due to Major System Repairs
- Turbine KPI 15: Lost Production due to Major System Repairs
- Turbine KPI 16: Grid curtailment operational hours

Turbine KPIs can then be aggregated to report the following array level KPIs:

- EnFAIT KPI 1: Aggregated turbine generating hours
- EnFAIT KPI 2: Average turbine generating hours
- EnFAIT KPI 3: Aggregated turbine downtime
- EnFAIT KPI 4: Average turbine downtime
- EnFAIT KPI 5: Grid loss hours
- EnFAIT KPI 6: Production
- EnFAIT KPI 7: Technical Time-based availability
- EnFAIT KPI 8: Operational Time-based availability
- EnFAIT KPI 9: Technical Production-based availability
- EnFAIT KPI 10: Operational Production-based availability
- EnFAIT KPI 11: Actual capacity factor
- EnFAIT KPI 12: Potential capacity factor
- EnFAIT KPI 13: Total number of failures (total operations impact)
- EnFAIT KPI 14: Total number of failures (partial operations impact)
- EnFAIT KPI 15: Average number of failures per turbine (total operations impact)
- EnFAIT KPI 16: Average number of failures per turbine (partial operations impact)
- EnFAIT KPI 17: Total number of forced outages
- EnFAIT KPI 18: Average number of forced outages per turbine
- EnFAIT KPI 19: Lost Production due to Major System Repairs
- EnFAIT KPI 20: Lost Production due to Major System Repairs
- EnFAIT KPI 21: Number of offshore interventions
- EnFAIT KPI 22: Number of onshore interventions
- EnFAIT KPI 23: Number of manual restarts
- EnFAIT KPI 24: Vessel contract days

- EnFAIT KPI 25: Vessel mobilisation/transit days
- EnFAIT KPI 26: Vessel working days
- EnFAIT KPI 27: Vessel weather standby days
- EnFAIT KPI 28: Vessel technical standby
- EnFAIT KPI 29: Number of tidal slacks used for marine operations
- EnFAIT KPI 30: Number of dive team hire days
- EnFAIT KPI 31: Number of dives completed
- EnFAIT KPI 32: Number of Non-access Days Due to Weather
- EnFAIT KPI 33: Mean Time to Successful Remote Restarts

This detailed set of turbine and array-level metrics goes beyond what is required for evaluating strategic KPIs but should help identify performance and operational improvements. The practicalities and value of reporting each KPI are being evaluated as the project progresses.

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