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ENFAIT
ENABLING FUTURE ARRAYS IN TIDAL

T1-4 Operations 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.

Executive Summary

This report summarises the activities and results from Shetland Tidal Array (STA) operations under the Enabling Future Arrays in Tidal (EnFAIT) project since turbine T4 was installed in August 2020, up to end December 2022 (prior to T5 and T6 installation in January 2023). Key achievements include:

Record-breaking performance	The Shetland Tidal Array has had its best performing year to date, setting new records for availability, generating hours and output. The new turbine T4 has achieved a capacity factor of around 30% on this moderately energetic ("Tier 2") site, proving that the M100-D turbine could achieve capacity factors of 50% or greater on more energetic ("Tier 1") locations.
Reduced operation & maintenance costs	For the first time, Nova undertook scheduled turbine maintenance locally in Shetland: the T4 nacelle was recovered in February 2022, 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 adding to the significant OPEX savings already demonstrated as part of the project.
Extended Service Intervals	Turbine T3 exceeded the previous STA record of a 12-month service interval by operating for 26 months with no maintenance over this reporting period (Aug 2020 to Dec 2022). At the time of writing, T3 has now clocked up 29 months of continuous operation. Turbine T4 also operated for 18 months from first deployment to first maintenance interval, which took place at the same time as other STA maintenance was scheduled. With this strong performance, Nova has further extended the intervals between scheduled maintenance interventions on this, the world's first tidal array. The longer turbines can operate without the need for servicing, the lower the cost of tidal energy.
Ability to deploy and retrieve in a wide range of conditions	Nova has again demonstrated recovery and redeployment of turbines in spring tides (the strongest part of the tidal cycle) and winter months, reducing turbine downtime and increasing yield. One nacelle deployment operation was successfully completed in a sea state of approximately 0.75m significant wave height (~1.5m max).
Anti-fouling coatings	New anti-fouling blade coatings have continued to improve the performance of the rotor. Further research is being undertaken to apply coatings to other areas.

These achievements demonstrate the significant impact the EnFAIT project is having on improving turbine performance by demonstrating best in class reliability and delivering cost reductions. This industry leading project is clearly powering the European tidal energy sector towards commercialisation.

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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 arrays.

Figure 1: STA Operations

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

This document reports on operation of the T1-4 Shetland Tidal Array turbines following T4 deployment and prior to T5 and T6 deployment, based on analysis of data collected in T6.7 (Operate expanded array).

1.2 The Shetland Tidal Array (STA)

The three Nova M100 tidal turbines (T1-3) each have a horizontal axis two-bladed rotor with a gearbox and medium voltage induction generator (Figure 2). The fourth turbine (T4) is a Nova M100-D turbine which also has a horizontal axis two-bladed rotor, 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) and each turbine is connected to a shoreside transformer by a subsea electrical cable. To give an idea of scale, the rotor diameter from tip to tip is 9m, the length of the nacelle is approximately 7m and it sits around 9m above the seabed. Nova Innovation began operating this, the world's first fully operational and grid connected 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.

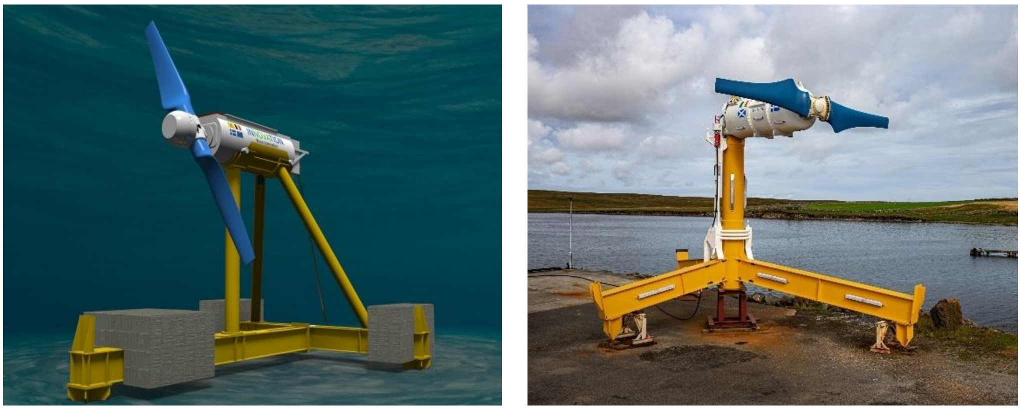


Figure 2: Nova M100 (left) and M100-D (right) Basic Architecture

Three Nova M100 turbines have been installed and operated in the Shetland Tidal Array (STA), powering local homes and businesses in Shetland for more than six years. The fourth turbine (T4), the Nova M100-D, has been operational for over two years. The array is in Bluemull Sound, which lies between the islands of Yell and Unst in Shetland (Figure 3). Bluemull Sound is an excellent location for a tidal energy project, 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.

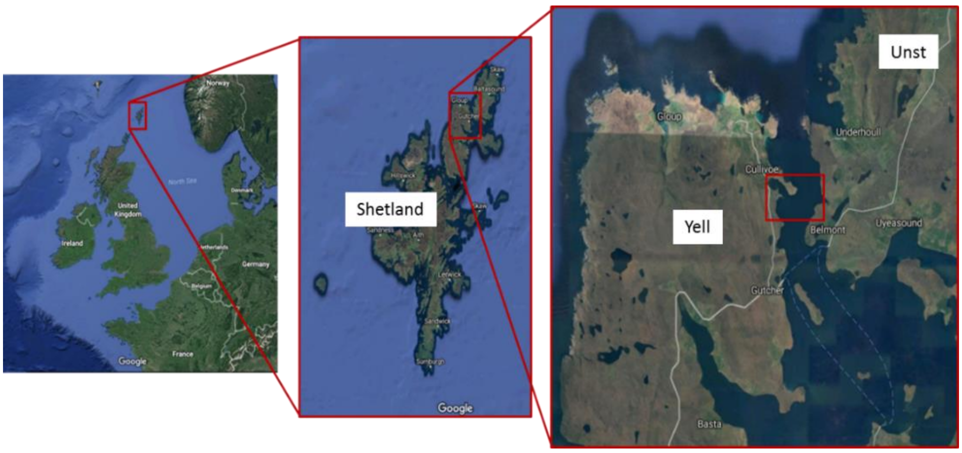


Figure 3: Bluemull Sound Location

1.3 Scope of This Report

The purpose of this document is to report on the operation of the expanded array, based on analysis of data collected in T6.7:

- **T6.7 Operate expanded array**
  Once the first new turbine (T4) has been commissioned in WP5, continue to operate as described in T6.4 but now including the additional turbine. Capture learning from the new machine and feed this back to allow any further improvements to be implemented. Co-ordinate with WP10 to ensure quality data are provided for load and performance assessment purposes.

As mentioned above, this covers the period from August 2020 (T4 deployment) to end December 2022 (just before T5 and T6 deployments).

2 T1-4 Operations Overview

Over the reporting period of expanded (T1-4) operations the key achievements have been:

- Record performance since T4 deployment:
    - Nova's new M100-D turbine is consistently producing around 50% more power than the previous M100 models, through improved performance and reliability.
    - The M100-D 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 M100-D nacelle after 18 months' operation.
    - At the time of writing the T3 machine has now been operating continuously with no maintenance for 29 months (26 months over this reporting period)
    - Nacelle recovery and deployment operations have been undertaken without divers in under three hours between quayside and offshore site, during a single slack tide and also during spring tides, expanding the window of opportunity for these operations.

  This performance demonstrates that tidal energy is an emerging investable asset class.
- 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 Catapult's Array Interaction Model (AIM), which characterises turbine wakes and their impact on downstream devices in order to optimise tidal array design.
- The impact of biofouling on turbine performance continues to be studied and coatings selected through EnFAIT research are improving performance compared to previous approaches.
- Many positive and negative hazard observations and best practice suggestions have been (and continue to be) recorded on Nova's Safety Management System. There have been zero lost time or RIDDOR-reportable safety incidents associated with EnFAIT and the STA.

3 Array Performance

The following sections outline array performance information captured over this operational period. Appendix 1 provides details of KPI definitions and reporting methodology.

3.1 Increased Power

As forecast in D6.4 (T1-3 Operations Report), the new M100-D (T4) machine is delivering around 50% more power than the M100 (T1-3) models, primarily through increased performance and higher availability / better reliability.

Figure 4 below shows T4 power production over a representative 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.

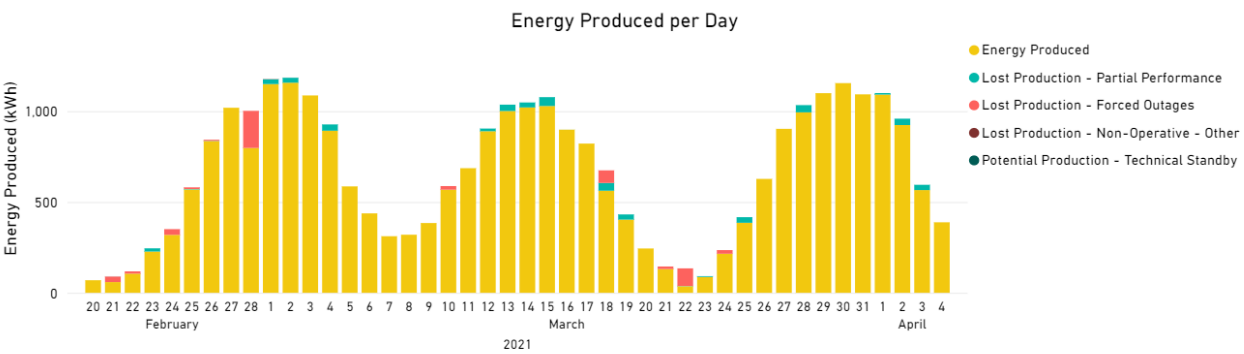


Figure 4: T4 turbine performance over a representative operational period (March/April 2021)

Nova aims to further improve T4 performance through research and development into improved control techniques, harnessing crossover learning from the EU funded ELEMENT project (Project Number – 815180) which is also now generating learnings from the operation of the Shetland Tidal Array turbines. The level of performance that has been achieved on this moderately energetic ("Tier 2") site of around 30% corroborates the predictions made in D6.4, that Nova's M100-D turbine will be capable of achieving capacity factors of over 50% in more energetic commercial ("Tier 1") locations.

Put another way, the M100-D 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 power communities across the world.

3.2 Higher Availability

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 (and grid reliability is a major component of the limited time where turbines are unavailable). 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.

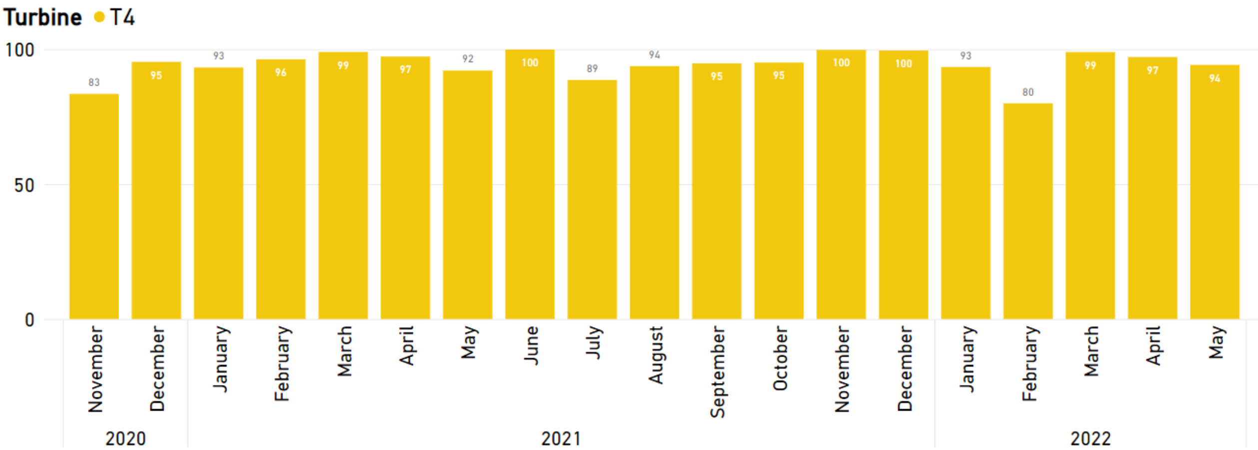


Figure 5: Turbine T4 availability over a representative operational period

3.3 Improved STA Reliability

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, the T3 machine had operated for 26 months with no maintenance.

4 T4 Maintenance

After 18 months of operation, T4 was recovered for a scheduled maintenance intervention. This was completed without divers and for the first time, the onshore inspection and maintenance work was carried out at a local facility in Lerwick, Shetland.

4.1 Rapid Recovery and Redeployment

Nova's new Launch and Recovery System (LARS) allows M100-D turbine nacelles to be deployed and recovered without the need for divers and within one tidal slack, including during stronger spring tides. Nacelle recovery after 18+ months operation, overcoming the challenges associated with biofouling, has now been proven.

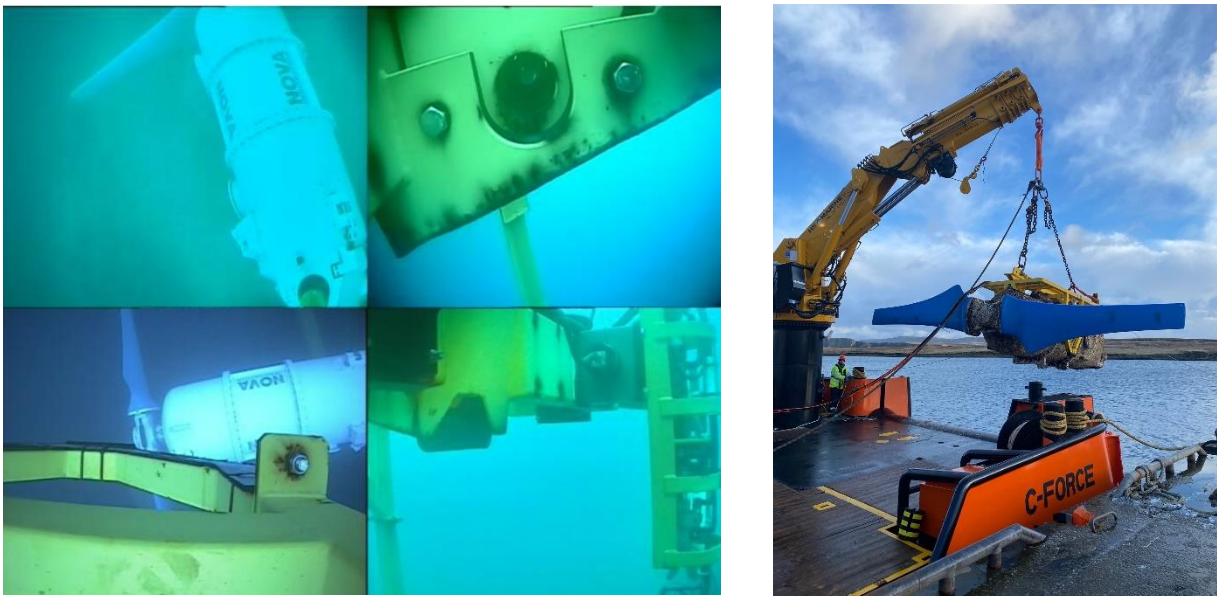


Figure 6: LARS camera views; T4 recovery using vessel crane

4.2 Local Scheduled Maintenance

For the first time, Nova completed a full turbine service at a remote 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 7: T4 local maintenance; M100 nacelle and T4 ready for redeployment

4.3 HSE Performance

There have been zero RIDDOR-reportable or lost time incidents during EnFAIT operations to date. Hazard observations (which can be positive or negative) and near misses are continually logged on the Nova Safety Management System and reported monthly.

5 Array Interaction Modelling

Project partners OREC have continued with further deployments of seabed and vessel-mounted ADCPs (Acoustic Doppler Current Profiler) at the Shetland Tidal Array to inform the Array Interaction Modelling work being completed as part of the project.

5.1 M100-D Power Curve Validation

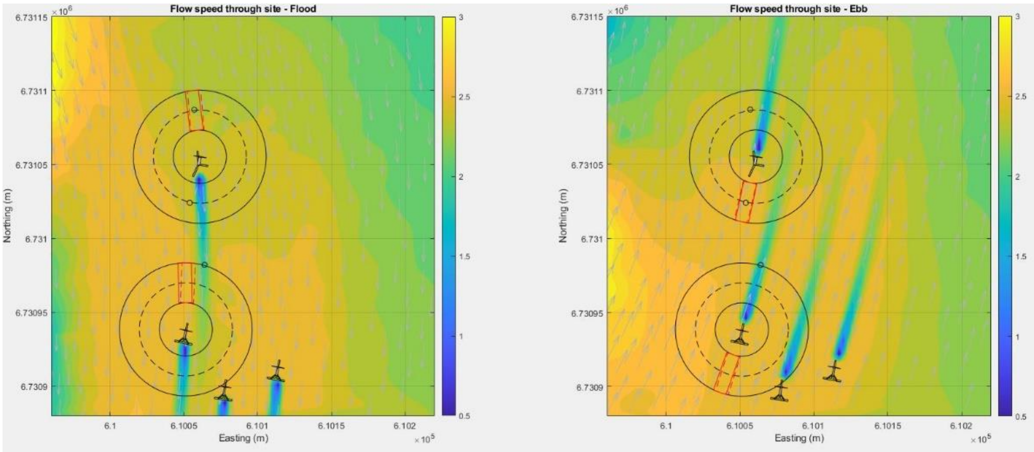


Figure 8: T4 seabed ADCP deployments

The modelling and flow measurement work on the Shetland Tidal Array have enabled Nova to validate the M100-D turbine power curve in line with IEC requirements and to develop a fully validated site resource model, with good alignment between modelled and measured current speeds being observed. Further ADCP deployments were carried out around the recently deployed T4 machine as part of the ELEMENT project, with data currently being captured and analysed. Site resource and turbine measurements continue to support, WP9 reliability analysis and WP10 modelling work.

5.2 Vessel-mounted ADCP Deployments

OREC were also on site during the reporting period to coordinate vessel-mounted ADCP deployments to characterise the wakes produced by the STA turbines, as shown in the image below.

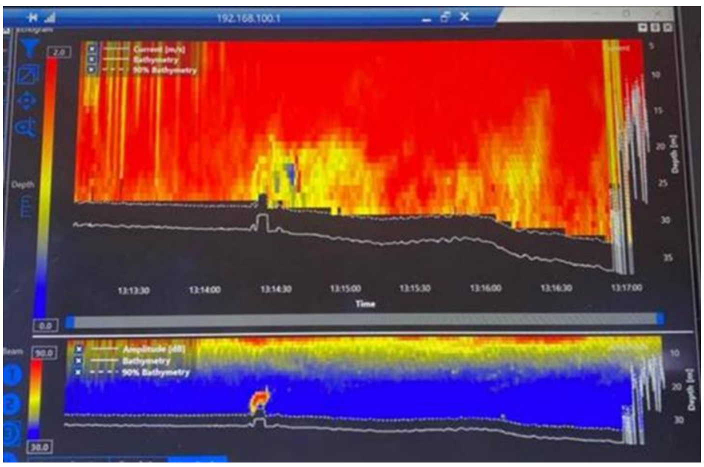


Figure 9: VMADCP survey showing T4 wake (upper image) and T4 substructure (lower image)

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 and yellow in the image above, with wake recovery observed: the wake mixing with the ambient flow as distance from the turbine increases.

5.3 Nacelle-mounted ADCP deployment

Nova and OREC also worked together to deploy a nacelle-mounted ADCP on the T4 machine in the same local maintenance period mentioned in 4.2. 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 10: Nacelle-mounted ADCP on turbine T4

5.4 T1 Turbine Rotor Strain Gauging

Nova and OREC fitted strain gauges to the T1 turbine rotor (see Figure 11 below) and gathered data over this operational period. The results are now feeding into ORE Catapult's work to characterise the cyclic loadings that Nova's turbines experience as they operate through ambient turbulence and wave action. 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).

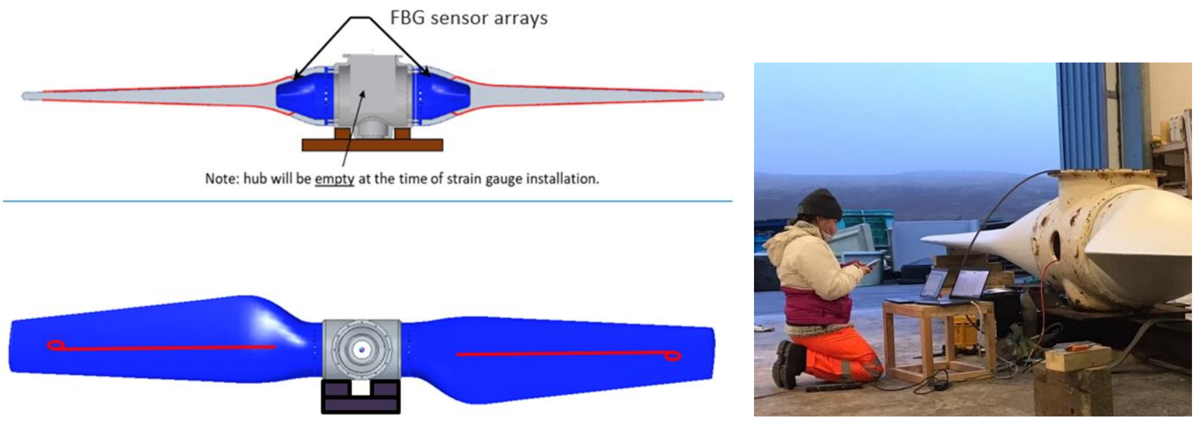


Figure 11: T1 rotor strain gauging

5.5 Comparison of Site Flow Data

In addition to the STA survey work, the EnFAIT project is also benefiting from other ADCP deployments carried out at the Morlais Marine Energy Demonstration Zone in Wales (Figure 12) and in Yell Sound, Shetland (Figure 13). These datasets will enable comparisons to be made of how shear profiles and turbulence vary at different locations, and therefore how applicable EnFAIT learnings are to other tidal sites.

Figure 12: Nova and OREC team members on site in Wales

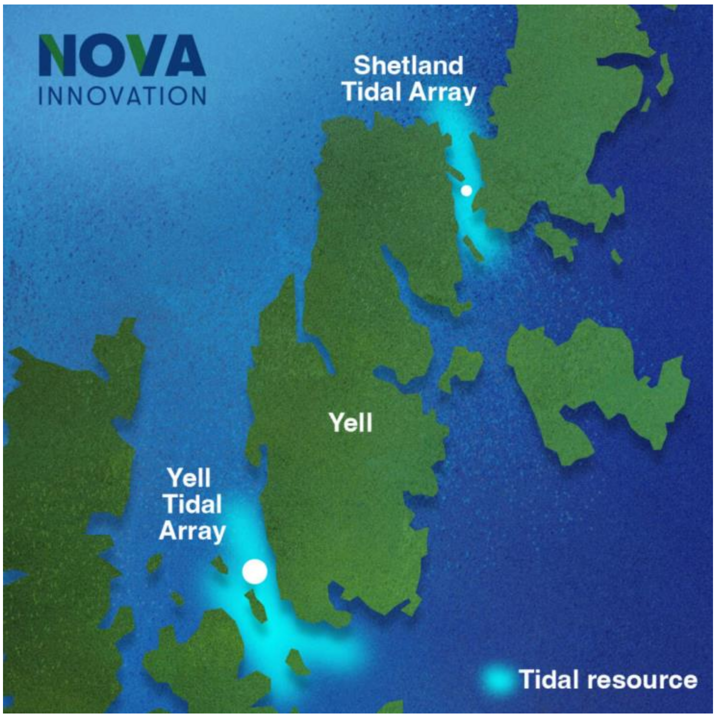


Figure 13: Approximate location of Yell Sound ADCP deployment relative to the STA

6 Biofouling

Nova continues to monitor the extent and type of biofouling on the deployed turbines to inform maintenance intervals and coating performance. Following work completed by an Engineering Doctorate student, an environmentally friendly coating was selected for the turbine rotor to reduce biofouling. The selected coating is providing excellent performance on T4 rotor – see Figure 14 below of negligible growth on T4 blades after 18 months, thereby avoiding the reductions in performance associated with marine life increased surface roughness and thereby ensuring maximum energy yield from Nova's turbines.

Figure 14: Negligible marine growth on T4 rotor after 18 months of operations

7 Conclusion

This report has outlined the activities and results from expanded (T1-4) operations on the Shetland Tidal Array (STA), under the Enabling Future Arrays in Tidal (EnFAIT) project. As the world's first grid-connected tidal array, the STA provides a unique opportunity to gather learnings which can accelerate the commercialisation of tidal energy.

Key achievements over this period include:

- **Record-breaking performance from Nova's new M100-D turbine model**
- **Reduced operation & maintenance costs, through rapid local maintenance**
- **Extended service intervals through further improved reliability**
- **Proven deployment and recovery in a wide range of challenging site conditions**

These achievements demonstrate the significant impact the EnFAIT project is having on improving turbine performance by demonstrating best in class reliability and delivering cost reductions. This industry leading project is measurably helping power the European tidal energy sector towards commercialisation.

Appendix I Key Performance Indicators (KPIs)

This appendix outlines the EnFAIT approach to reporting KPIs from the Shetland Tidal Array.

Through work with ORE Catapult's data team, the WP6 KPIs have been defined and systems created to report KPIs automatically from operations data, adapting principles from a wind industry standard (IEC TS 61400-26-1:2011) for use on tidal arrays.

Data sources

KPIs for the operation of the EnFAIT 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 allows Turbine KPIs to be analysed and reported: this includes all aforementioned metrics such as generating hours, capacity factor, number of failures requiring marine operations to resolve, etc.

Operative states

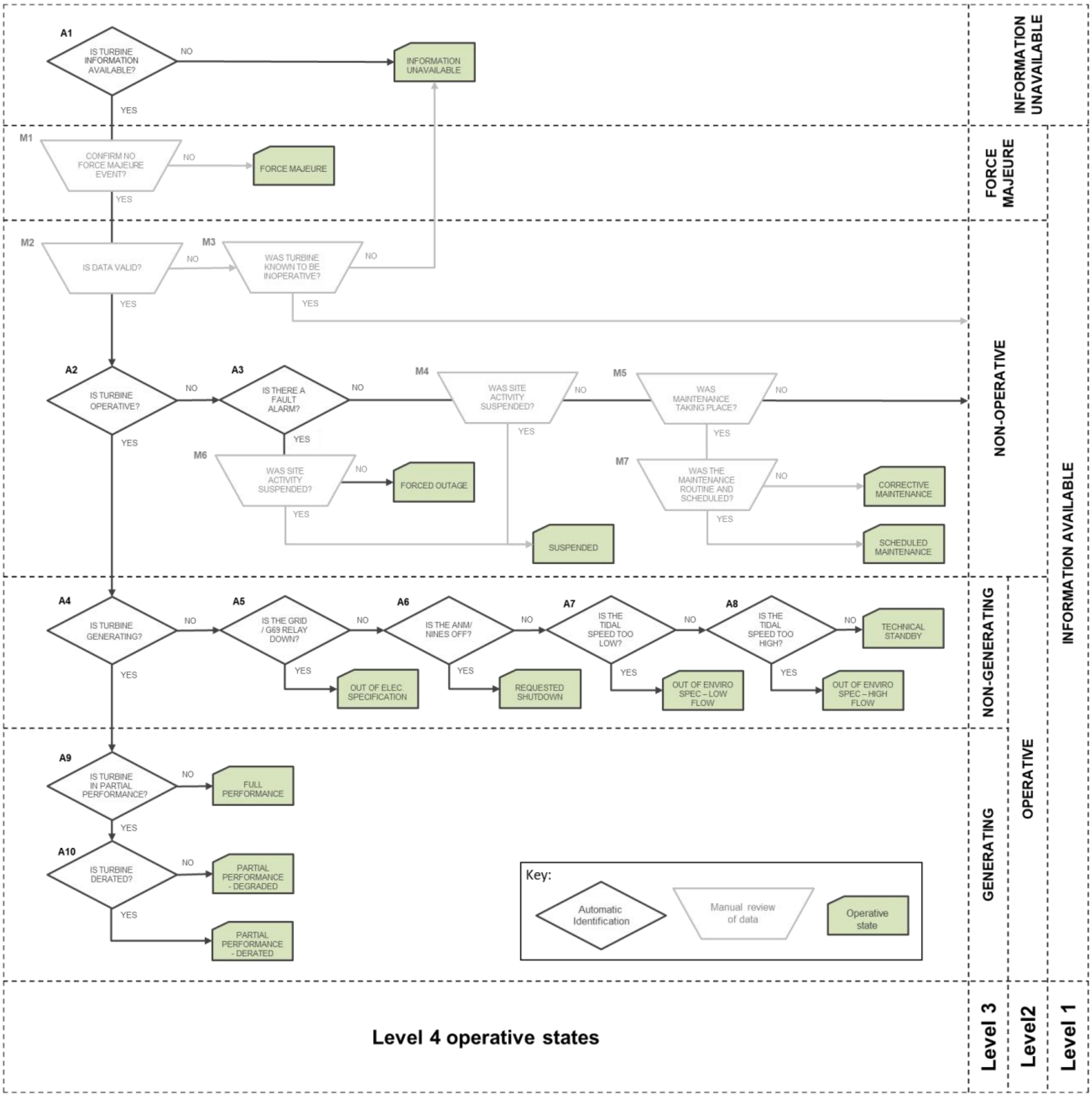
Operating states were defined by adapting guidance from IEC TS 61400-26-1:2011 (Time-based availability for wind turbine generating systems) for tidal energy. See definitions below.

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 can then be used to calculate KPIs such as downtime, generation hours and production-based availability. As can be seen from the flow chart above, there are some operative states that require manual review of data to identify. 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 data to be reviewed manually can be 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 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.

Contact

HEAD OFFICE

Nova Innovation
45 Timber Bush
Edinburgh
EH6 6QH

Tel: +44 (0)131 241 2000
Email: info@enfait.eu

www.enfait.eu