Date of issue: March 2023

Deliverable ID: D6.6

ENFAIT
ENABLING FUTURE ARRAYS IN TIDAL

T1-6 Initial 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. The reporting period covers the three months of initial T1-6 operations, from when turbines T5 and T6 were installed in January 2023, through March 2023.

Key achievements include:

Largest number of turbines in an array	In a world-first, Nova is now operating an array of six tidal turbines: the largest number of free-standing tidal stream turbines ever deployed in one location.
Consistently higher power production and availability	Recently installed turbines T5 and T6 are delivering best in class performance, matching reliability and output of the first M100-D turbine deployed at the STA (T4), confirming that this turbine model achieves around 30% capacity factor on this moderately energetic ("Tier 2") site – and should achieve capacity factors of 50% or greater on more energetic ("Tier 1") sites. Turbines T5 and T6 are matching turbine T4 availability figures of over 95%.
Proven low-cost subsea cable hub	Nova has deployed the company's first operational multi-turbine 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 (becomes challenging to have individual cables to shore from each turbine on multi-MW projects) and Nova develops larger sites with more turbines. This is an industry leading technology demonstration, as the first subsea hub to have multiple turbines connected exporting to the grid.
Reduced installation costs	For the first time, Nova installed two entire turbine systems (substructures, ballast, cables and nacelles) concurrently – thereby demonstrating a significant reduction in OPEX costs relating to turbine installation.
Excellent Health, Safety and Environment	Hazard observations and best practice suggestions have been (and continue to be) recorded on Nova's Safety Management System. Performance in this area continues to be excellent: there have been zero lost time or RIDDOR-reportable safety incidents associated with EnFAIT and the STA.

With the largest number of operational turbines anywhere, the EnFAIT project is delivering 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 turbines T5 and T6, this ground-breaking project continues to accelerate the European tidal energy sector towards commercialisation.

Document History

DOCUMENTATION SHEET	
Project Acronym	EnFAIT
Project Title	Enabling Future Arrays in Tidal
Grant Agreement number	745862
Call identifier	H2020-LCE-2016-2017
Topic identifier	LCE-15-2016
Funding Scheme	Research and Innovation Programme
Project duration	72 months (July 2017 – June 2023)
Project Officer	Francesca Harris (INEA)
Coordinator	Nova Innovation Ltd
Consortium partners	Nova Innovation, IDETA, SKF, University of Edinburgh, Wood, RSK Environnement, ORE Catapult
Website	www.enfait.eu
Deliverable ID	D 6.6
Document title	T1-6 Initial Operations Report
Document reference	EnFAIT-EU-0059
Description	Report on operation of turbines following T4 deployment
WP number	WP 6
Related task	T6.8
Lead Beneficiary	Nova Innovation
Author(s)	Tom Wills
Contributor(s)	
Reviewer(s)	Seumas MacKenzie, Gary Connor, John Meagher
Dissemination level	PUBLIC - This document in whole, or in part, may be used in general and public dissemination.
Document status	Issued
Document version	1.0

REVISION HISTORY					
Version	**Status**	**Date of issue**	**Comment**	**Author(s)**	**Reviewer**
1.0	Issued	March 2023	First Issue	Tom Wills	Seumas MacKenzie, Gary Connor, John Meagher

Contents

Table of Figures

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.

This document reports on initial operation of the Shetland Tidal Array turbines following deployment of turbines T5 and T6, based on analysis of data collected in T6.8 (Operate Full 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 M100-D 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) 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 the nacelle sits approximately 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. With the addition of turbines T5 and T6, the STA becomes the array with the largest number of turbines anywhere in the world.

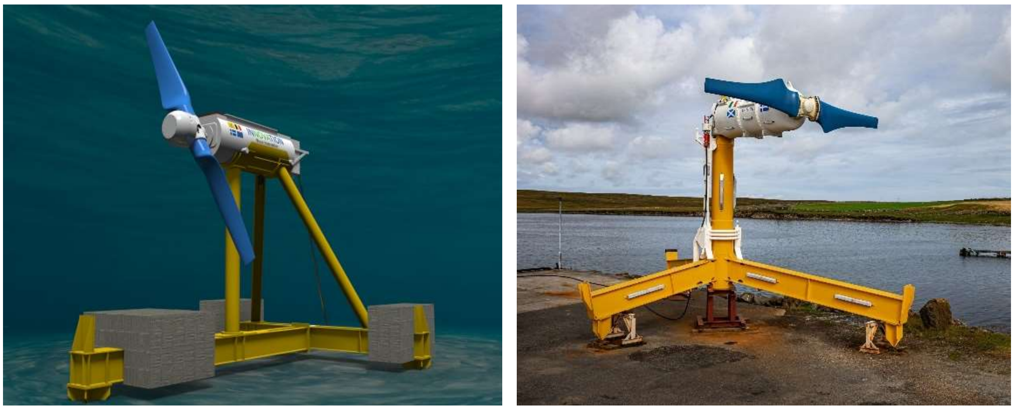


Figure 2: Nova M100 (left) and M100-D (right) Basic Architecture

The six Nova M100 turbines operating at the STA are powering local homes and businesses in Shetland. 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 T6.8:

- **T6.8 Operate Full Array:** after commissioning of T5 and T6 in WP5 operate the full 6-turbine array in unison. Continue to record and report key performance indicators for the turbines and the array. Co-ordinate with WP10 to demonstrate the effect of operating upstream turbines on the loads and performance of those downstream.

As mentioned above, this covers the initial period of T1-6 operations from January 2023 (T5 and T6 deployment) to March 2023.

2 T1-6 Operations Overview

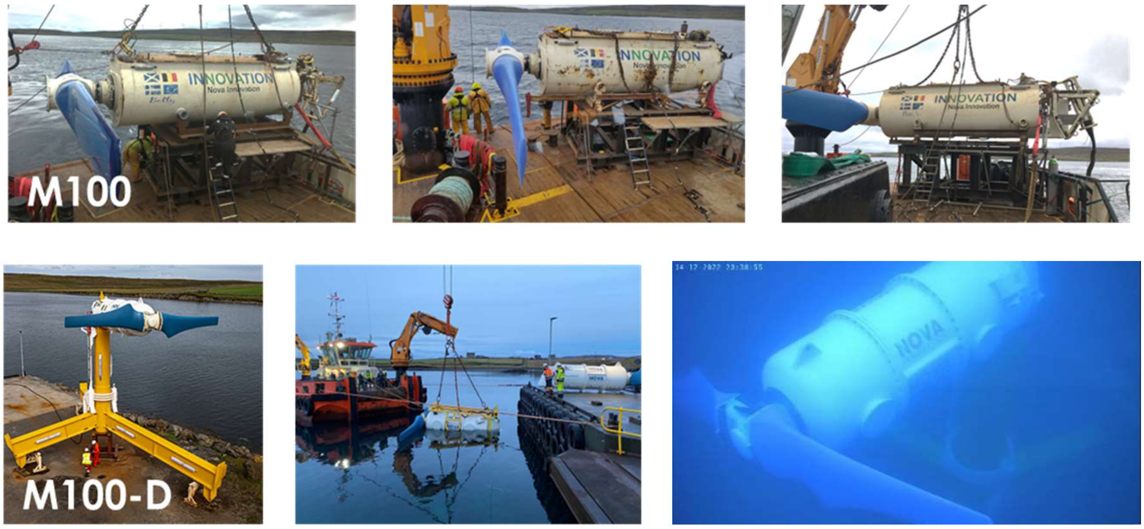


Figure 4: M100 (T1-3) and M100-D (T4-6) turbine models

Over the reporting period of full array operation (T1-6), the key achievements have been:

1. **Largest number of turbines in an array:** in a world-first, Nova is now operating 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 M100-D turbine deployed at the STA (T4), confirming that the M100-D model achieves around 30% capacity factor 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. Turbine T3 has at the time of writing now been operating continuously with no maintenance for 29 months: a new record.
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 (where single cables to shore from each turbine are no longer a viable solution) and Nova develops larger sites with more turbines. 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 entire new turbine systems (substructures, ballast, cables and nacelles) concurrently – thereby demonstrating a significant reduction in OPEX costs relating to turbine installation.
5. **Health, Safety and Environment:** hazard observations and best practice suggestions have been (and continue to be) recorded on Nova's Safety Management System. Offshore operations have now been safely undertaken during all seasons in both neap and spring tides. HSE performance continues to be excellent: there have been zero lost time or RIDDOR-reportable safety incidents associated with EnFAIT and the STA.

3 Largest Number of Turbines 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, taking the total number of installed turbines to 6, making the STA the array with the largest number of turbines anywhere in the world, ever. Figure 5 below shows the indicative layout of the Shetland Tidal Array as now operating, with the M100 (T1-3) turbines to the south of the site and M100-D (T4-6) turbines to the north. Areas of high ambient tidal resource are shown in yellow/orange, with the areas of reduced resource downstream of each turbine shown in blue (the ebb tide is north-going and the flood tide is south-going). See drone photography of flood and ebb tides in section 7.3.

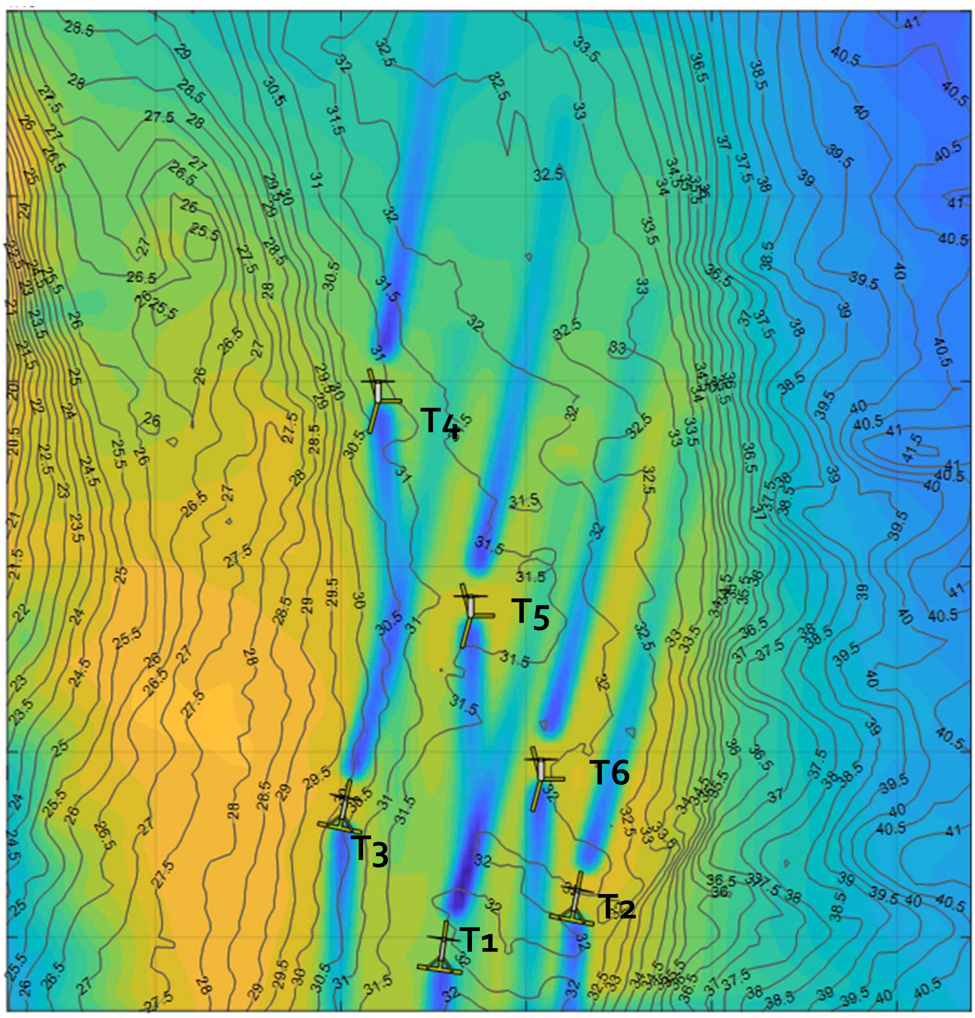


Figure 5: M100 (T1-3) and M100-D (T4-6) turbine model – indicative locations only

Turbine T4 currently has two live readouts of tide speed via seabed mounted ADCPs (Acoustic Doppler Current Profilers) deployed to the north and south of the turbine foundation 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 machine.

Array interaction data is being collated and will continue to be gathered in the final months of the project. The results of this will feed into WP10 activity to validate OREC's Array Interaction Model.

4 Consistently Improved Performance and Availability

With turbines T5 and T6 joining turbine T4, which was deployed at the STA in 2020, Nova is now gathering operational data from three of the latest M100-D 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 around 30% capacity factor 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.

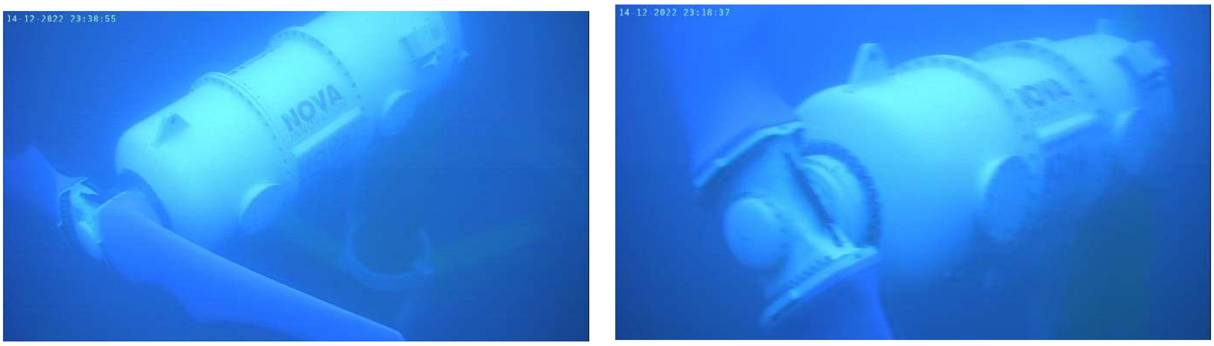


Figure 6: Subsea images of M100-D turbines T5 and T6

All three M100-D machines are producing around 50% more power than the older M100 turbines. The figure below shows a typical period of output from the M100-D 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 or other issues are shown in pink. Lost production due to partial performance is shown in green, which is primarily related to commissioning activities.

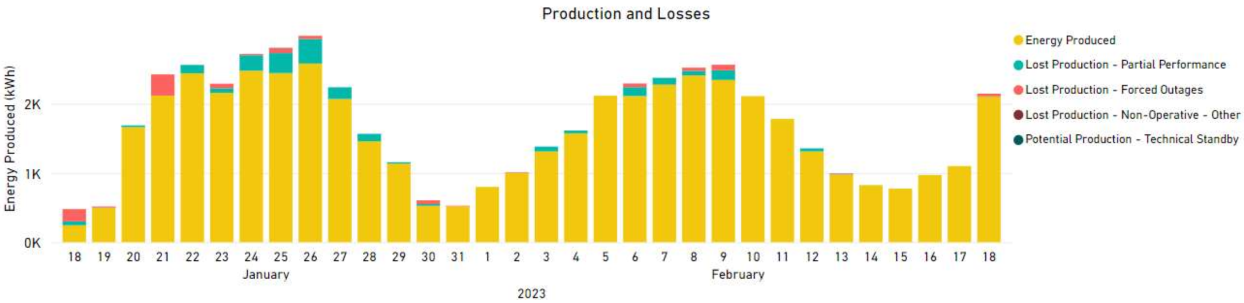


Figure 7: M100-D generation example

Turbines T5 and T6 are also matching turbine T4's availability figures of over 95%, while turbine T3 has at the time of writing now been operating continuously for 29 months: a new STA record for uninterrupted power generation.

5 Proven Low-Cost Subsea Cable Hub

Nova recently deployed and is now operating the company's first 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 8: T5/T6 subsea cable hub 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. By joining multiple turbines at one subsea hub and/or "daisy chaining" (linking in series) sets of turbines together, cable CAPEX and installation costs are reduced, and onshore cable landing is simplified by having fewer cables running to shore.

6 Reduced Installation and Maintenance Costs

At the start of this reporting period and for the first time, 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.

Figure 9: 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 10 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 M100-D, demonstrated recently during the install of T5 and T6 which was completed in winter weather conditions, including significant waves, and spring tides.

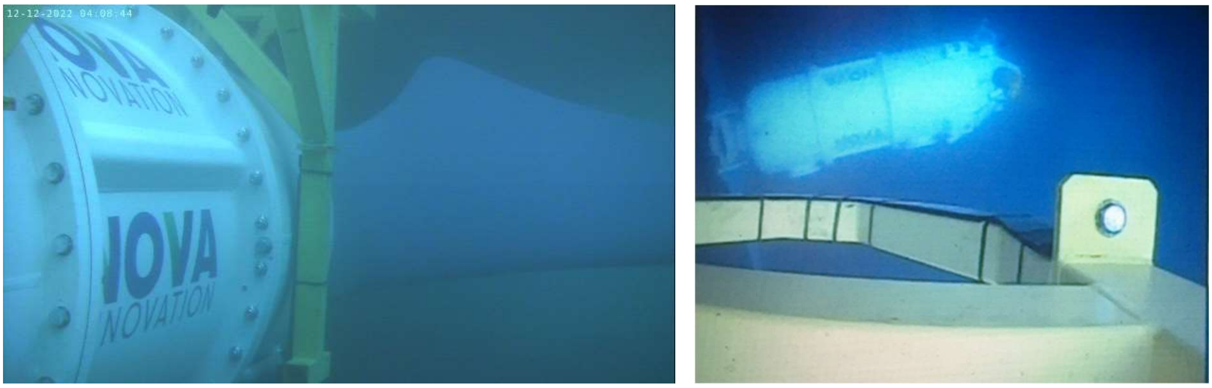


Figure 10: LARS camera views

Nova’s modular turbine design and the improvements in deployment and recovery methods developed and proven through the EnFAIT project are now consistently demonstrating that all major components of the turbine system (substructures, ballast, cable backpacks and nacelles) can be installed, maintained and decommissioned with tooling that is recoverable and reusable across the whole array without the need for divers. This is central to the cost reductions and safety improvements that have been proven through the EnFAIT project.

7 Other

7.1 HSE – No Lost Time Incidents

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. 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: this allows turbines to maintain their high overall production availability by the swift and safe O&M recovery or deployment at any time.

7.2 Community Engagement

As part of Nova's engagement with the local community under the EnFAIT project, children from the local school, Cullivoe Primary School, were invited to name one of the new turbines. They chose to call T6 "Hali Hope"; Hali, meaning 'of the sea, beautiful ocean' and, Hope, for the future of our planet. The children visited Belmont Pier (see Figure 11) just before the turbine was loaded into the water.

Figure 11: Cullivoe Primary School children with Turbine T6, which they named Hali Hope

7.3 Drone Photography of Flood and Ebb Tides

During this reporting period, Nova used a drone to capture images of the flood and ebb tides which are included here for interest. The images below are both taken looking north. The first image shows the ebb tide running north, with the eddy line trailing north-east off Cullivoe Ness then bending north – and with some wave against tide effects on the east side of the eddy line clearly visible. The image below shows the flood tide running south, with the eddy trailing south off Cullivoe Ness.

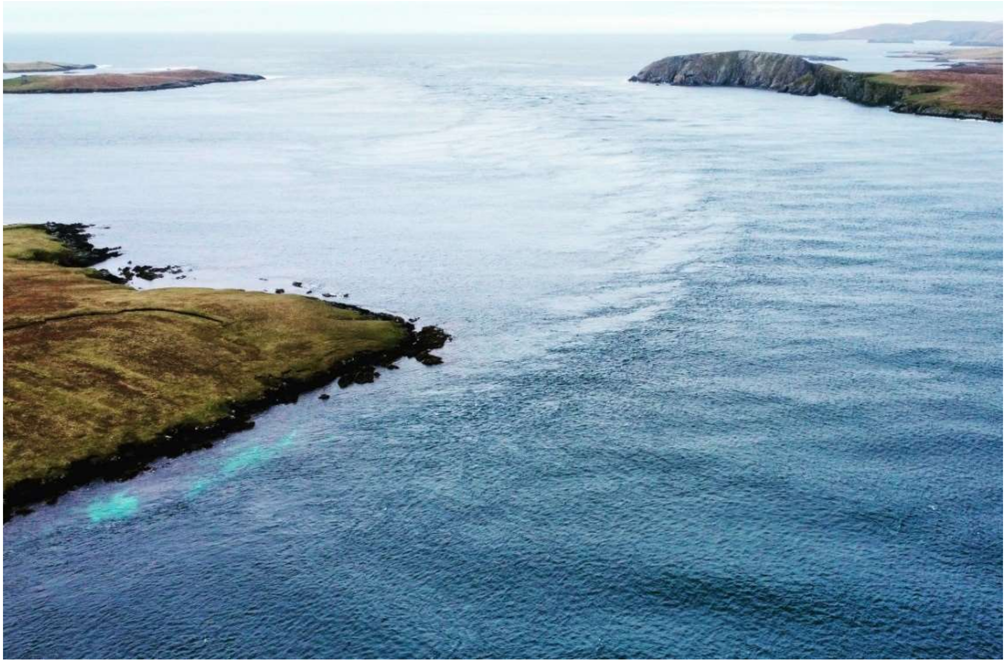


Figure 12: Ebb tide running north

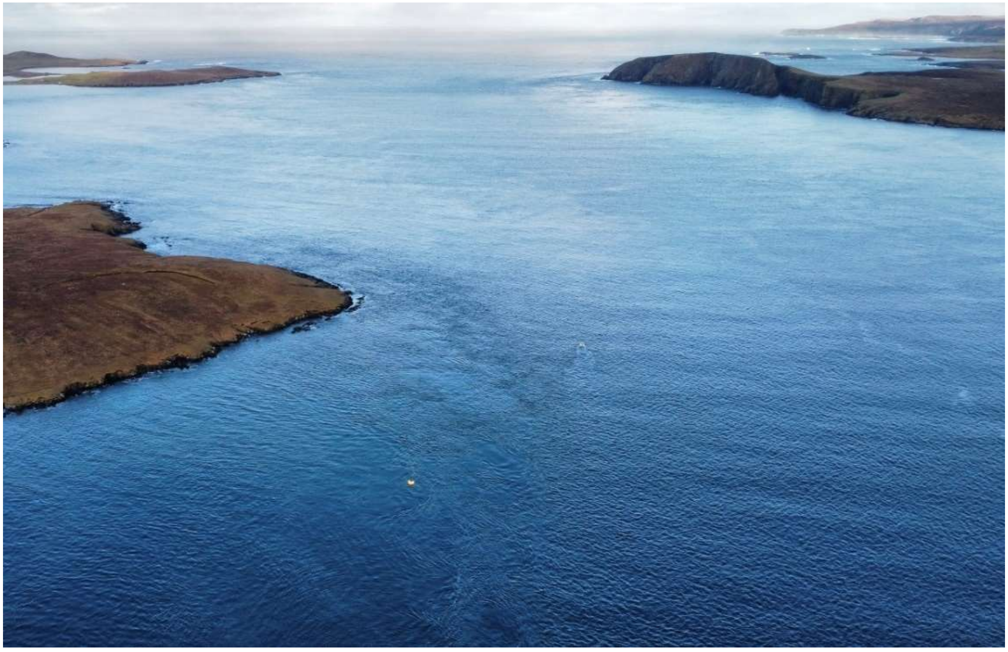


Figure 13: Flood tide running south

8 Conclusion

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

Key achievements over this period include:

- **Largest number of tidal turbines in an array to date globally**
- **Consistently improved higher power production and availability – with T5 and T6 machines confirming best in class M100-D performance improvements achieved by T4 in the last reporting period**
- **Proven a low-cost subsea cable hub with multiple turbines T5/T6 exporting power along a single cable to shore**
- **Further reduced installation costs through concurrent whole turbine system deployments**

With the largest number of operational turbines anywhere, the EnFAIT project is delivering 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 turbines T5 and T6, this ground-breaking project continues to accelerate the European tidal energy sector towards commercialisation.

Appendix: 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

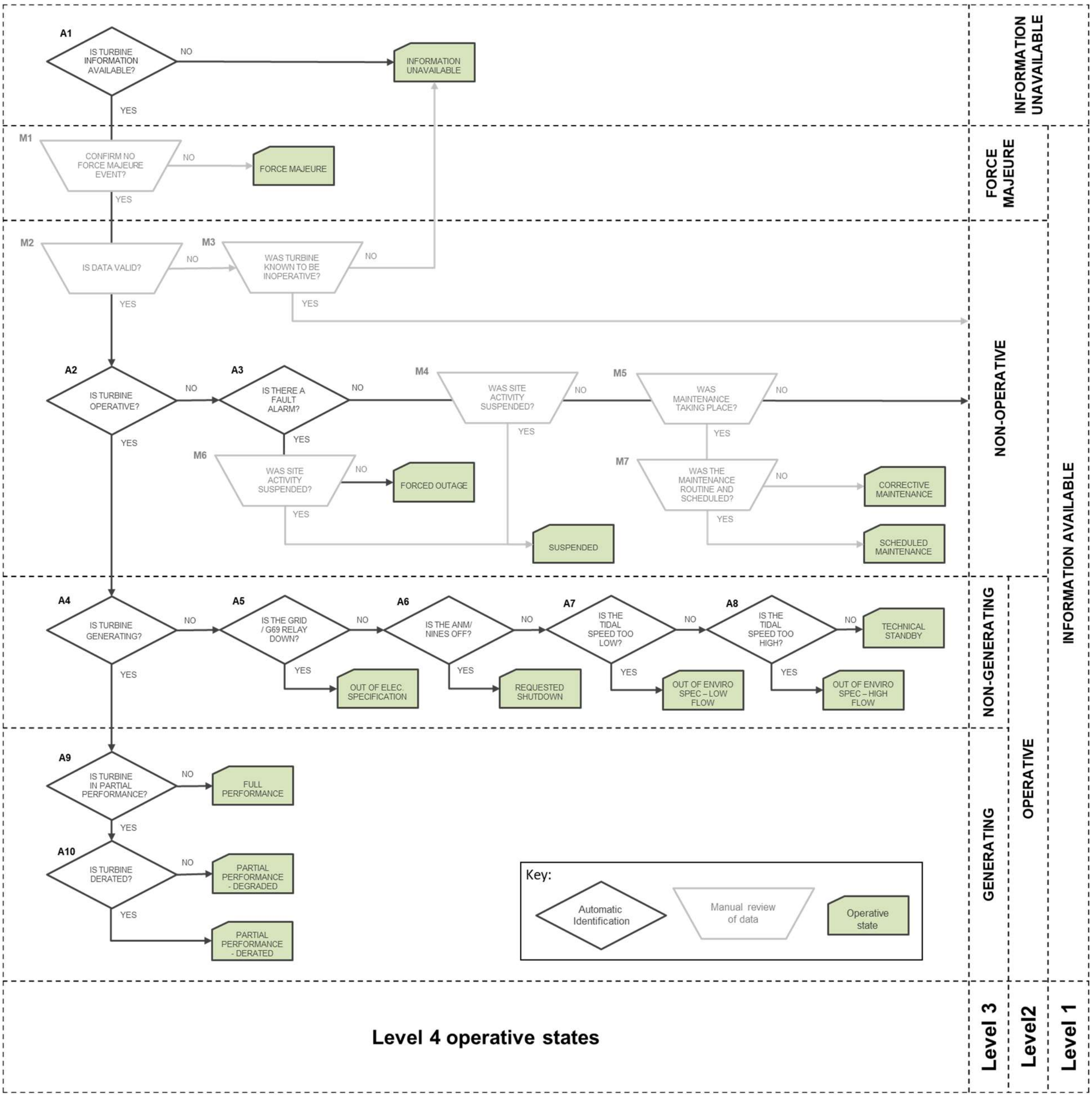
Operating states were defined by adapting guidance from IEC TS 61400-26-1:2011 (Time-based availability for wind turbine generating systems) for tidal energy. See definitions below.

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