Date of issue: June 2023

Deliverable ID: D6.7

ENFAIT
ENABLING FUTURE ARRAYS IN TIDAL

T1-6 Interim 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 period of interim T1-6 operations in April 2023, focussing on turbines T5 and T6 and the subsea cable hub.

Key achievements include:

Consistently higher power production and availability	Turbines T5 and T6 continue to deliver best in class performance, showing significantly higher output than the first three M100 turbines with a gearbox (T1, T2, T3) and moderately higher output than the first M100-D direct drive (T4) in the STA. The results show that the M100-D 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. During the reporting period, T5 and T6 achieved 98% availability, the highest since their deployment in January 2023.
Proven Subsea Cable Hub Reliability	Nova's subsea cable hub continues to successfully export power from turbines T5 and T6 along a single export cable. As the first subsea hub in the tidal energy industry to have multiple operational turbines, this is an industry leading technology demonstration. This innovation delivers significant savings on subsea cables, further reducing the cost of tidal power, essential as the industry scales-up. It reinforces Nova's position as an industry leader with the ability to deliver multi-turbine tidal arrays.
Record period of operation without maintenance	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.

The installation of the fifth and sixth turbine within the EnFAIT project made the Shetland Tidal Array the site with the largest number of operational turbines in the world. The EnFAIT project is delivering industry-leading results and 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.

The reliable operation of the subsea cable hub, developed as part of this project, is an industry-enabling result, demonstrating a low-cost route to multi-turbine tidal arrays. The continued best in class performance from the M100-D turbines is demonstrating that this ground-breaking project is delivering impacts and results which are accelerating the European tidal energy sector towards commercialisation.

EnFAIT

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 6.7
Document title	T1-6 Interim Operations Report
Document reference	EnFAIT-EU-0061
Description	Report on operation of turbines T1-6
WP number	WP 6
Related task	T6.8
Lead Beneficiary	Nova Innovation
Author(s)	Tom Wills
Contributor(s)	Seumas MacKenzie
Reviewer(s)	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	June 2023	Version for issue	Tom Wills, Seumas MacKenzie	John Meagher

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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.

This document reports on interim 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 became the array with the largest number of turbines anywhere in the world.

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

The turbines in the STA have been powering local homes and businesses in Shetland for more than seven 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 T6.8:

- **T6.8 Operate Full Array:** after commissioning 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 interim period of T1-6 operations during April 2023.

2 T1-6 Operations Overview

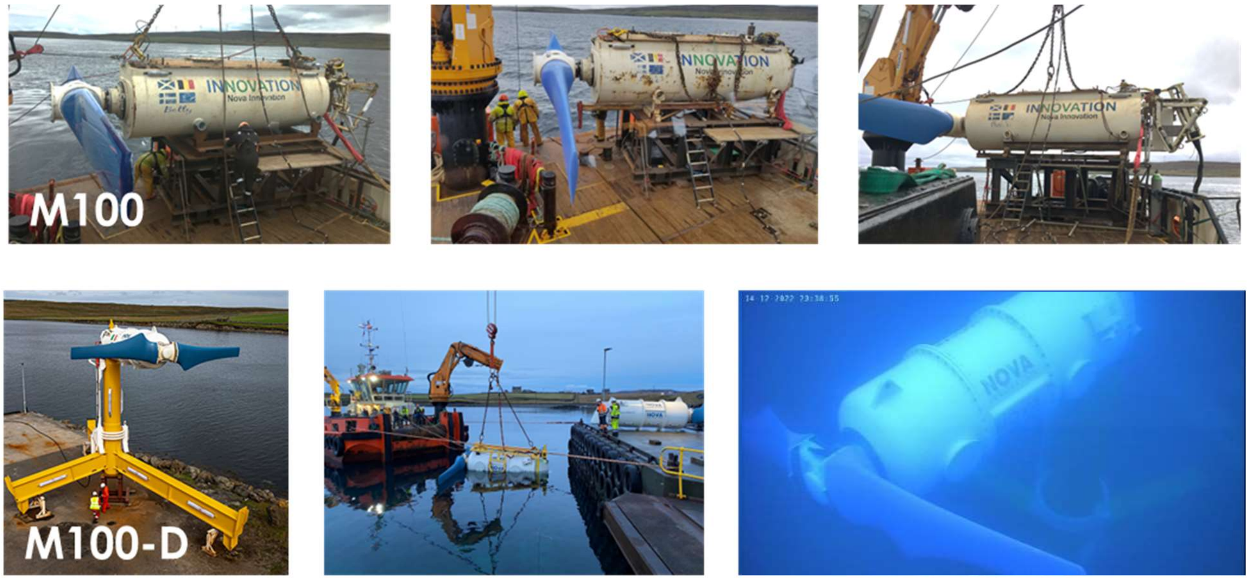


Figure 4: M100 (T1-3) and M100-D (T4-6) turbine models

Over the reporting period of interim T1-6 array operations, the key achievements have been:

1. **Increased power production and availability:** Turbines T5 and T6 continue to deliver best in class performance, showing significantly higher output than the first three M100 turbines with a gearbox (T1, T2, T3) and moderately higher output than the first M100-D direct drive (T4) in the STA. The results show that the M100-D model achieves a capacity factor of up to 29% for this moderately energetic ("Tier 2") site – and could therefore achieve 50% or greater on more energetic ("Tier 1") sites. During the reporting period, T5 and T6 achieved 98% availability, the highest since their deployment in January 2023.
2. **Proven subsea cable hub reliability:** Nova's subsea cable hub continues to successfully export power from turbines T5 and T6 along a single export cable to the grid. As the first subsea hub to have multiple operational turbines, this is an industry leading technology demonstration. This innovation delivers significant savings on subsea cables, further reducing the cost of tidal power, essential as the industry scales-up. It also reinforces Nova's position as an industry leader with the ability to deliver multi-turbine tidal arrays.
3. **Record period of operation without maintenance:** 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.

3 Increased Power Production and Availability

With turbines T5 and T6 having joined turbine T4 in January 2023, Nova is now gathering operational data from three of the latest M100-D turbines. This has enabled turbine performance data to be analysed and compared. The results show that the minor improvements made to T5 and T6 based on learnings from the project and operation of T4, have delivered notable improvements. The output from T5 and T6 was 3% higher than T4. With the M100D turbines achieving a capacity factor of up to 29% on this moderately energetic ("Tier 2") site, it shows great potential for the turbines to lower the cost of tidal energy further at more energetic ("Tier 1") locations. Sites such as the Bay of Fundy in Canada and the Pentland Firth or the Falls of Warness in Scotland could potentially achieve capacity factors of 50% or greater, further helping to make tidal energy more competitive and commercial.

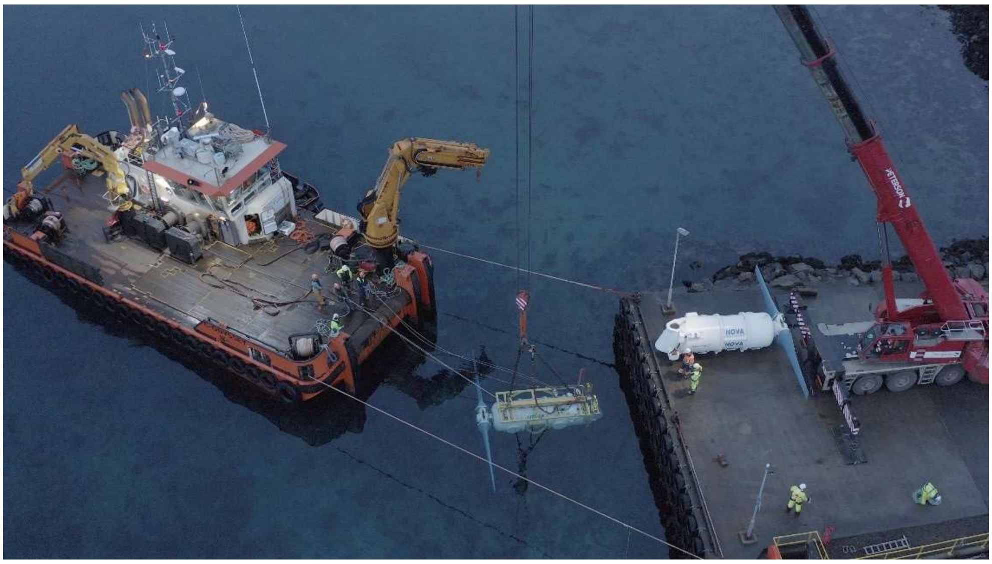


Figure 5: Image of M100-D turbines T5 and T6 during deployment activities

The new M100-D machines are producing more than 50% power than the older M100 turbines. The figure below shows the output from T5 and T6 during the 4-week period prior to planned marine operations commencing at the end of April. It shows the higher periods of generation associated with stronger spring tides and the lower periods of power generation associated with weaker neap tides. Forced outages due largely to grid curtailment or other issues are shown in pink. When there is grid curtailment, Nova's battery energy storage system is utilised and the electricity stored is released back to the grid once the curtailment is lifted. Lost production due to partial performance is shown in green and is primarily related to research and development activities.

Figure 6: T5 and T6 generation example

4 Proven Subsea Cable Hub Reliability

Nova's subsea cable hub continues to operate reliably since its deployment in January 2023. This Nova-designed piece of equipment incorporates three of Nova's dry-mate NovaCan connectors (which have cumulatively delivered many connector-years of fault-free operation on T1-3, including multiple maintenance cycles) and connects turbines T5 and T6 to their export cable. Since their deployment, turbines T5 and T6 have been exporting power to shore along the subsea hub's single export cable, proving this low-cost hub design which is scalable to larger arrays.

Figure 7: T5/T6 subsea cable hub on deck prior to installation

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.

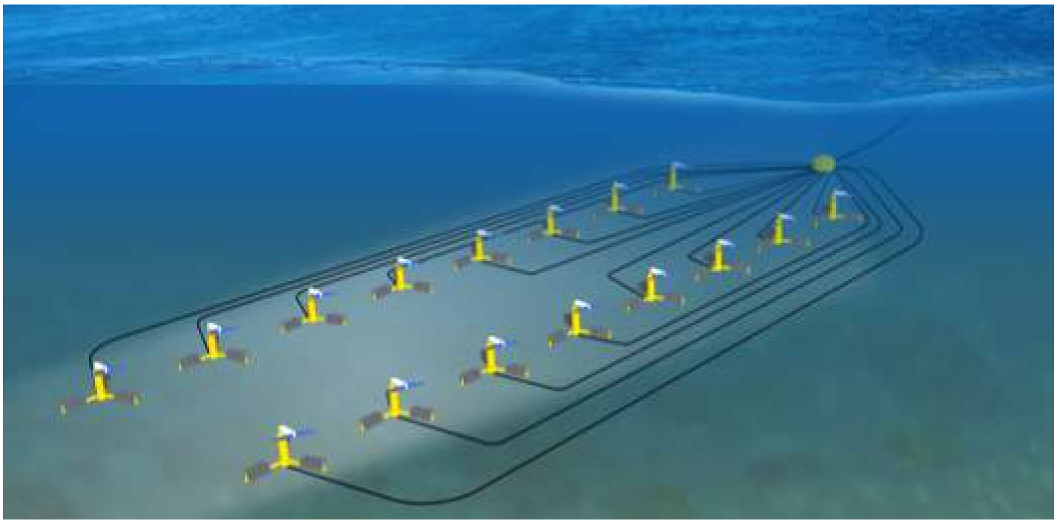


Figure 8: Illustrative offshore electrical architecture concept for multi-turbine arrays

By connecting multiple turbines to a subsea hub as shown in Figure 8 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.

5 Conclusion

This report has outlined the results from interim T1-6 array operations at the STA, focussing on turbines T5 and T6 and the subsea cable hub, part of 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:

- **Increased power production and availability from turbines T5 and T6, confirming best in class M100-D performance.**
- **Proven subsea cable hub reliability, with the Nova-designed low-cost subsea cable hub successfully exporting power from turbines T5 and T6 along a single cable to shore.**
- **Record period of operation without maintenance: Turbine T3 completed 883 days (29 months) of continuous operation with no maintenance at the time of writing: a new record.**

The installation of the fifth and sixth turbine within the EnFAIT project made the Shetland Tidal Array the site with the largest number of operational turbines in the world. The EnFAIT project is delivering industry-leading results and 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.

The reliable operation of the subsea cable hub, developed as part of this project, is an industry-enabling result, demonstrating a low-cost route to multi-turbine tidal arrays. The continued best in class performance from the M100-D turbines is demonstrating that this ground-breaking project is delivering impacts and results which are accelerating 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

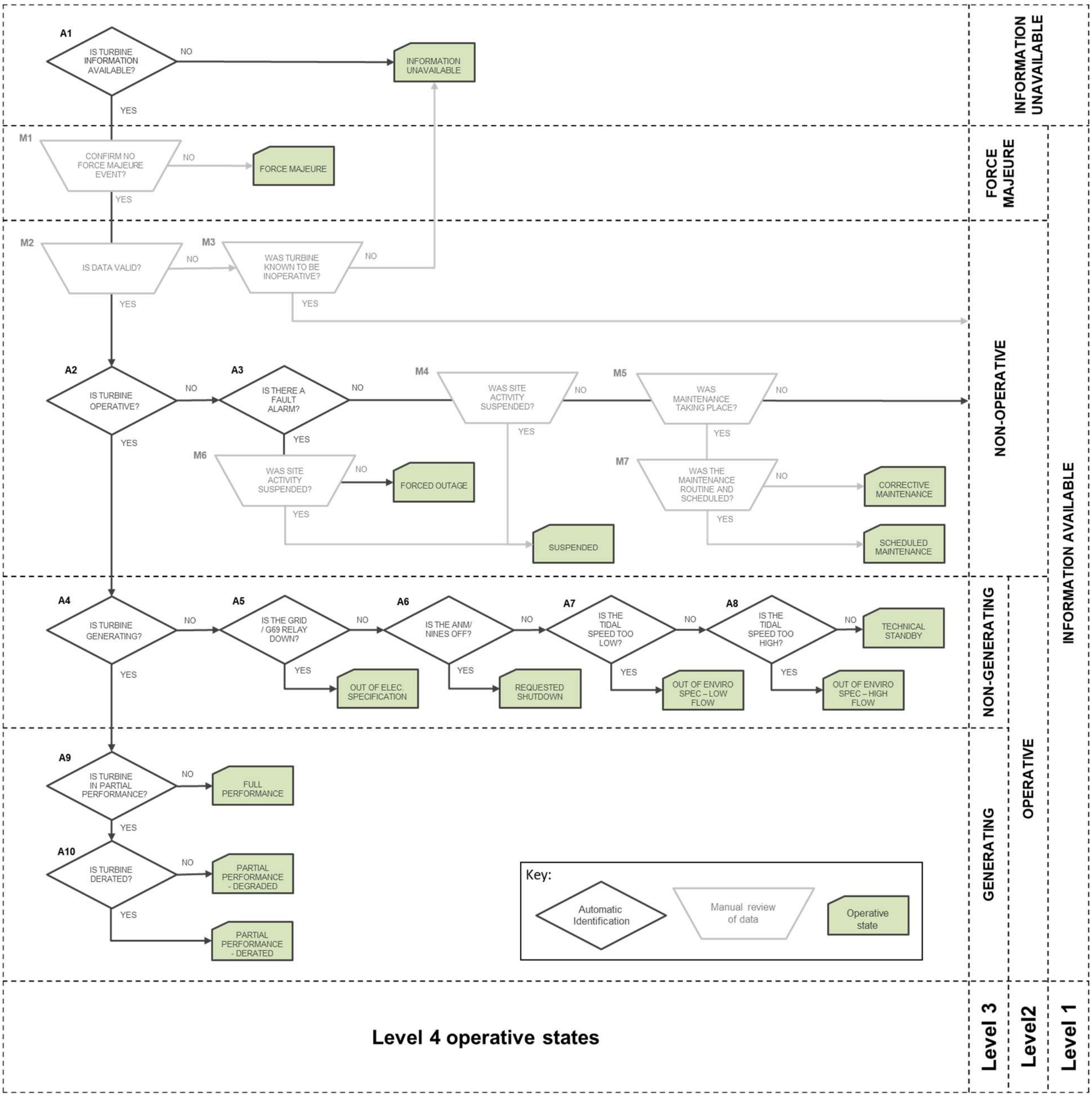
Operating states were defined by adapting guidance from IEC TS 61400-26-1:2011 (Time-based availability for wind turbine generating systems) for tidal energy. See definitions below.

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, some of the operative states for the T1-3 turbines required considerable manual input. However, 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.

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