

ELEMENT: DI0.2 IN-SEA ESTUARY TESTING REPORT

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1. INTRODUCTION

A Funding Grant was awarded from the European Union's Horizon 2020 research and innovation programme to develop and validate an innovative tidal turbine control system, using the tidal turbine itself as a sensor, to deliver a step change improvement in the performance. This project will demonstrate Effective Lifetime Extension in the Marine Environment for Tidal Energy (ELEMENT), driving the EU tidal energy sector to commercial reality. This grant was awarded under the call LC-SC3-RES-11-2018: Developing solutions to reduce the cost and increase performance of renewable technologies.

This document reports on work undertaken as part of work package 10 (WP10) and is submitted to satisfy deliverable D10.2 of the ELEMENT project.

WP10 focused on the testing of Nova Innovation's RE50 turbine in the Étrel estuary (Ria d'Étel) in Brittany, France. This followed the previous onshore test phase where the RE50 turbine was tested at ORE Catapult (OREC) onshore test facility in Blyth, UK. The testing site for WP10 is adjacent to the premises of project partner Chantier Bretagne Sud (CBS). CBS manufactured the substructure for the turbine before the turbine was connected to the substructure on the slipway at the CBS site. The full assembly was then deployed to the test location using a marine vessel, and a subsea cable connected to the turbine was laid on the riverbed back to shore and connected to the onshore station. The onshore station housed the necessary power and control equipment for the turbine and also allowed live data streaming of all operating data throughout the test period.

The test phase allowed the turbine control system developed in the ELEMENT project to be deployed in the RE50 turbine and assessment of its performance in real world conditions. This has assisted in further development of the control system within the project and has generated vital data which will be fed into the final project testing phase, where the control system will be deployed in an existing Nova M100-D turbine installed in the Shetland Tidal Array (STA). A cabled acoustic doppler current profile (ADCP) sensor was deployed on the substructure to allow real time flow measurement in parallel to the turbine data measurement to aid performance assessment.

The test phase provided an opportunity to test a tidal turbine of this scale in a tidal estuary environment. The flow conditions and speed profile in estuarine sites is different from tidal sites located in marine headlands or channels, where the tidal stream flows between large seas or oceans surrounding the site. This report will quantify some of these differences and provide important lessons for future development of tidal estuary projects.



2. TEST SYSTEM OVERVIEW

An innovative turbine control system has been developed by ELEMENT project partners as described in Deliverable D6.1, Behavioural Model Specification. The control system was initially tested onshore using the Nova RE50 turbine at the ORE Catapult Blyth test facility, as described in Deliverable D8.1, Onshore System Test Report. This report describes the offshore testing of the control system using the RE50 turbine in the Étel estuary in France.

The pre-existing RE50 turbine was upgraded to suit the needs of the onshore and estuary test phases of the project. This included the addition of various sensors to monitor the turbine environment and the health of all onboard control and power systems. The turbine rotor was also modified to suit the flow conditions of the Étel estuary.



Figure 1: Nova RE50 Turbine and Substructure Assembly General Arrangement

Two cameras were mounted on either side of the turbine nacelle with a third camera mounted on the substructure front leg, each pointing towards the turbine rotor. These were intended to allow the turbine to be viewed during operation and to provide visual data of any interactions with the turbine with marine fauna in the estuary. In addition to the cameras, the substructure front leg also housed an ADCP to record real-time flow data throughout the test period. This data was used to analyse the turbine control system performance during testing.

The substructure was designed specifically for the RE50 turbine and the expected loads it would experience while operating in the Étel test site. The substructure was designed by French project partner Innosea and then manufactured by CBS on their site, using steel sourced from their French supply chain. The substructure was custom designed to accommodate ballast blocks to provide stability. The ballast was hired locally, which avoided the need to manufacture new ballast specifically for the testing, and thus minimised the cost and environmental footprint of the test programme.

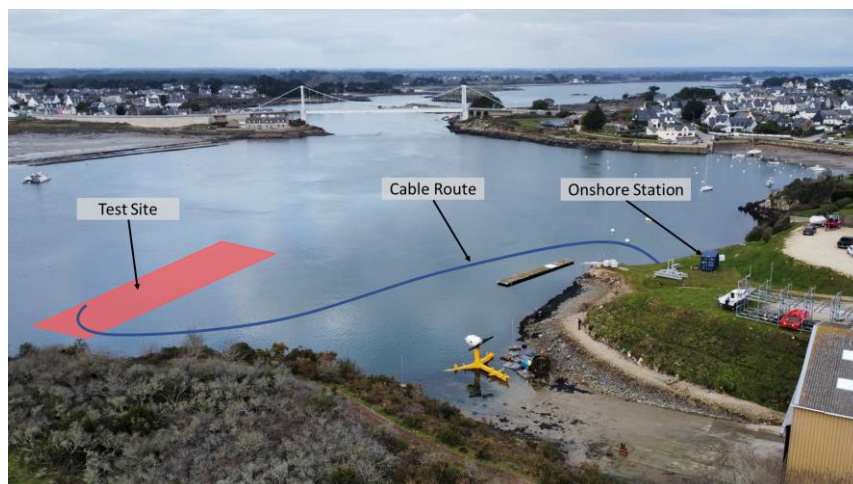


Figure 2: Test Site Layout at Ria d'Étel





Figure 3: Turbine Position in Ria d'Étel

The turbine was connected to the onshore station via an armoured subsea cable. The cable connection to the turbine used Nova Innovation's in-house underwater connector technology (NOVACan) that has been proven in multiple deployed turbines within the Shetland Tidal Array. The onshore station provided control power and communication to the turbine as well as the main export power connection from the turbine generator.

The onshore station housed the electrical distribution equipment and incoming power supply from the CBS electrical distribution system. It contained a variable frequency drive system that controlled the turbine generator, with additional cooling and control equipment. Data acquisition systems were also housed in the onshore station. An internet router transmitted all operating data to a cloud storage system that allowed the turbine data to be viewed remotely by Nova Innovation engineers based in Edinburgh, Scotland. The turbine could also be remotely controlled using this internet connection, and operating parameters could be loaded into the turbine control system, allowing operations to be scheduled in advance and run autonomously throughout the day without requiring constant supervision and monitoring. The various control system versions developed during the project could be selected from the user interface to allow the turbine to switch between control systems throughout the testing period.

2.1. Test System Preparation

The turbine, onshore station and cable system were prepared in advance at Nova Innovation's manufacturing facility in Edinburgh, Scotland. The turbine internal control, instrumentation and sensors were upgraded prior to the onshore testing. Additional equipment was added to facilitate the waterproof power and fibre optic connections to the subsea cable and also to the external cameras and ADCP.



Figure 4: Installing the Turbine Waterproof Connector System

The subsea cable was terminated to allow connection of fibre optic cores and single phase AC ancillary power to the turbine, and three phase power connection to the turbine generator. The onshore end of the cable was terminated with a weatherproof pluggable connector to allow ease of installation at site once the cable had been laid from the turbine to shore and to protect the termination from rainwater.



Figure 5: Cable Termination for Offshore (L) and Onshore (R) Connections

The onshore station equipment was installed inside a shipping container. This allowed the equipment to be fully installed, commissioned, and tested before being transported to the test site. The drive skid equipment used in the onshore testing phase was installed inside the container along with electrical distribution and protection equipment. Additional control and communications equipment were installed to allow both local and remote control of the turbine and to provide data logging from the external cameras and ADCP as well as all turbine operating data. Most of these systems are based on designs that have matured through Nova Innovation's other tidal sites and testing programmes, which reduced risk and allowed the works to be completed in the short

interval between onshore and estuary test phases. The turbine nacelle, turbine rotor, cable reel and onshore station were transported to CBS by road.



Figure 6: Substructure Lifted to CBS Slipway, Followed by Onshore Assembly of Turbine and Cable Prior to Offshore Deployment

The substructure was manufactured by CBS using design and manufacturing drawings created by Innosea. CBS welders and technicians manufactured the sections of the structure in their workshop and then assembled the final structure outside. On completion and after painting, the structure was lifted onto the slipway, ready for the turbine to be connected. Six 10 Tonne ballast blocks were hired from local suppliers and delivered to CBS for a trial fit on the substructure ahead of turbine deployment. The turbine was attached to the substructure and the cable connected to the turbine and secured to the substructure mast. Finally, the cameras and ADCP were installed onto the turbine nacelle and substructure. The turbine assembly, cable reel and ballast blocks were then lifted to the end of the slipway to await the installation vessel arrival on-site.

The ELEMENT project required permission from the local authorities to perform the RE50 estuary testing in the Ria d'Étel. The engagement with the relevant governing bodies was led by Guinard Energies Nouvelles (GEN), a third party partner of CBS, who have previous experience deploying a



tidal turbine at the site. Permissions were granted following a formal process, which authorised the consortium to deploy and operate in the designated concession area as proposed. Further engagement with the authorities was carried out by CBS to agree the detailed plans for deployment and recovery activities prior to the start of marine operations in the Ria d'Étel. All activities relating to the WP10 test phase were performed in accordance with the permissions granted by the governing authorities.

2.2. Test System Installation

A shallow draught multi-purpose vessel (or Multi Cat) was used for installation of the turbine assembly and cable laying. Four of the ballast blocks were added to the substructure at the end of the slipway, before the vessel crane was used to lift the assembly into the water. Transferring the assembly to the vessel main winch, the vessel then moved to the installation site and lowered the assembly to the riverbed, using moorings to stabilise the vessel position. Once the turbine assembly was landed, the cable was unreeled from the cable reel and laid on the riverbed back to shore.



Figure 7: Turbine Assembly, Cable Reel and Ballast on Slipway Before Installation

The cable end was pulled ashore and connected to the onshore station. The turbine was powered for the first time and control and communication checks were carried out to confirm there were no faults with the cable or connections. Finally, the vessel returned to the turbine assembly and installed the final two ballast blocks onto the substructure to provide full stability for all operating conditions of the turbine.



Figure 8: Multi Cat Vessel Preparing to Lift the Turbine Assembly from Slipway

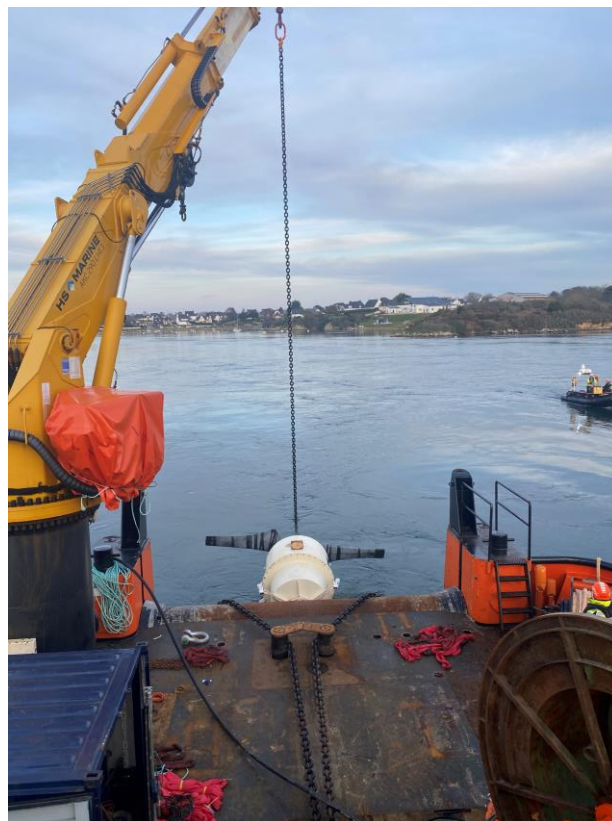


Figure 9: Turbine Assembly Suspended Over Installation Site



Figure 10: Vessel Landing Turbine on Riverbed

The main challenge addressed during these activities was that the water visibility was extremely poor (discussed further in Section 3.1). This affected the deployment of ballast blocks and also the turbine assembly. Despite this and other challenges associated with performing novel marine operations at a new site, and the first estuarine deployment of a Nova Innovation turbine, the deployment was safely and successfully completed in line with the operation procedures and plan set out by Nova Innovation engineers. An in-depth review process on the operation was held subsequently, to ensure lessons are learnt and captured in future operations.

3. TESTING OVERVIEW

The ELEMENT project has developed an improved control system for a fixed pitch, stall regulated tidal stream turbine. The turbine control system has many components, but the main component that has been developed during the project is the turbine controller – the component of the control system that manages the turbine speed and power operation. The ELEMENT project uses a **baseline** controller from Nova’s M100 turbine, referred to hereafter as basic speed controller. Two novel controllers were developed within the project – the **advanced speed** controller and **advanced torque** controller.

The two speed controllers regulate the turbine power by optimising the rotation **speed** during operation and the advanced torque controller regulates the turbine power by calculating and controlling the optimal **torque** during operation. All three controllers (the baseline and the two advanced controllers) were utilised in the RE50 control system as part of offshore testing, to compare their performance and demonstrate that they could provide reliable and stable operation in real world conditions.

3.1. Resource Characteristics of the Ria d’Étel

The test phase provided the opportunity to test a fully functional, grid-connected turbine in an estuary tidal stream. Most commercial tidal stream turbines are deployed further offshore in marine tidal streams, or in tidal barriers, and so the data gathered from this test period will help to inform the commercial viability of tidal estuaries for future tidal stream energy projects. The flow resource was measured using a Nortek Signature 1000 ADCP mounted on the substructure. This provided important data for assessing the performance of the turbine controller as well as providing more general data on the site flow conditions.

Figure 11 shows the tidal flow averaged speed occurrence at the test site as measured by the ADCP during the test period covering multiple spring tide cycles. It demonstrates that the flow speeds in the ebb direction (negative values in Figure 11) are faster than the flood direction, which is expected in a tidal estuary where the river flow opposes the flood tide and assists the ebb tide. As this effect was known in advance, the turbine was deployed with the fixed turbine orientation of the rotor facing into the ebb tide, to ensure the turbine and structure would not shadow the rotor blade on the stronger ebb tide. Aligning the “tower shadow” in the flood direction maximised output and minimised the impact on the test results as the turbine did not often generate in the flood tide due to the lower potential power in the flow.

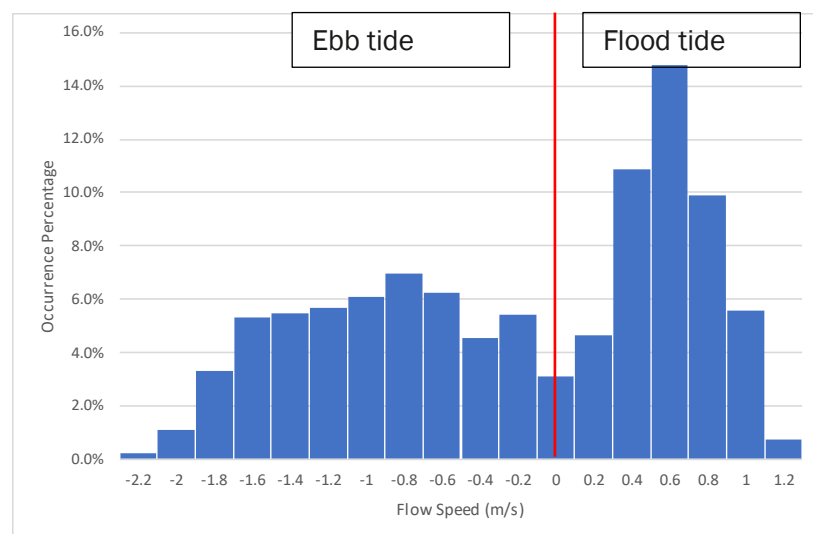


Figure 11: Five Minute Average Flow Speeds at Turbine Rotor Height in Test Site. (Positive Values are Flood Tide)

Asymmetric flow is one of the main potential drawbacks of operating a tidal stream turbine in a tidal estuary, with the ebb tide having faster flow speeds than the flood tide. Because the maximum potential power generated by a turbine is proportional to the cube of the flow speed, higher flow speeds typically provide the majority of the output and revenue for a turbine and so are a significant contributor to the commercial viability of a project.

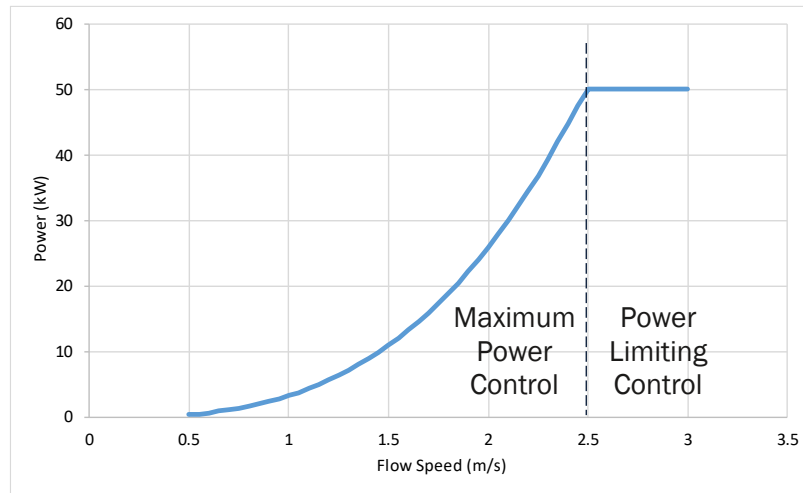


Figure 12: RE50 Maximum Potential Rotor Power for Flow Speeds

Figure 12 shows the power that the RE50 rotor can produce across flow speeds that could occur at the test site. Combining this with Figure 11 shows that 91% of the test site's electricity yield is from the ebb tide. This would significantly lower the capacity factor for the turbine compared to a site with symmetric flows where flood tide matches the ebb tide speed. All else being equal, a lower capacity factor results in a higher levelised cost of energy (LCOE) and so reduces the commercial viability for that tidal project. However this might be offset by the site-dependent commercial advantages in operating in an estuary, including proximity to shore, grid, maintenance facilities and sources of local electricity demand.

The Étél site was selected to provide a “sandbox” for proving the new turbine controllers offshore. The site is quicker, easier, and cheaper to access than an offshore tidal site, and the less energetic flow limits the load on the turbine blades and provides longer windows for offshore operations. It therefore provides an important stepping-stone between onshore testing and full offshore tidal testing, to be conducted in the ELEMENT project in the Shetland Tidal Array.

The relatively low flow speeds even in the ebb tide mean that the ELEMENT controllers operate somewhat differently than they would in a more energetic site. The ELEMENT controllers all use stall regulated power control since there is no pitch control on the rotor blades. Under stall control, the turbine speed must be reduced to limit output power beyond a certain flow and rated power. The RE50 turbine is rated for 50kW and the blades were designed to match the profile and scaled performance of Nova Innovation's larger, stall regulated turbine blades installed on the three M100-D turbines deployed in Shetland. The shallow waters of the test site and the need to allow sufficient draught above the turbine meant the RE50 turbine blade diameter had to be limited below the optimum diameter for the turbine. The turbine generates 50kW at rated flow speeds of 2.5m/s (see Figure 11), however the flow regime at the test site means that the device was unlikely to generate 50kW for a sustained period. The RE50 power limit was therefore capped at 25kW (half rated power) to demonstrate controller performance under stall control. This meant the device was operating comfortably within its design limits, and generated test outputs that can be directly transferred to commercial turbines such as those operating in the STA. The turbine occasionally went into stall control during periods of turbulent higher flows or during peak spring tides, but most of the turbine operation occurred during maximum power tracking or in the fixed speed region that occurs in advance of the power limiting region. More discussion is provided on the turbine operation related to the site flow conditions in the subsequent section.

Nova Innovation generated a tidal flow prediction model for the testing period using ADCP measurement data generated earlier in the ELEMENT project by project partner France Energies Marine (FEM), in combination with published tidal coefficient data and tide times for the Étrel area. The model was a relatively simple correlation model using measured flow speeds and tidal coefficients as well as measured times of peak and zero flow correlated to published tide times. The model was helpful when planning deployment operations to predict what the tide speeds would be and what time the slacks occurred between tides. It was also used to create the test plan by estimating how the peak tide speeds varied throughout the testing period.

The model was relatively accurate at predicting the time of slack tide and the time of peak flow but there was some variation between the predicted and actual peak flow speeds. As the data was monitored over time, it was observed that recent rainfall affected variation in peak flow speeds. This association was expected, since the flow speeds on the ebb tide increase as recent rainfall adds to the river freshwater supply from upstream. In turn, the flood tide speeds are reduced as the same effect opposes the flood tidal flow. The flow data used in the model was measured in the autumn and likely during higher rainfall average than during the test period as it generally over-predicted ebb and under-predicted flood speeds. Figure 13 below shows an example of this where the variation between predicted and actual flow speeds changes over a 14 day period as rainfall varies.

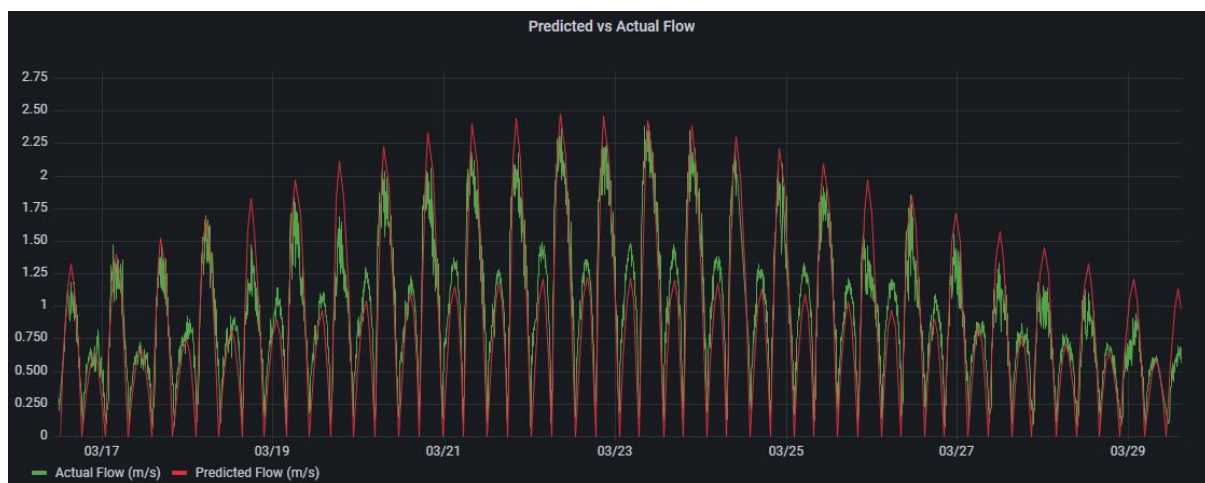


Figure 13: A 14 Day Sample During Testing Showing Actual and Predicted Flow Speed in m/s.

Significant weather events can have a transient effect on local tide heights through storm surges, and thus impact on flow speeds, in all tidal sites, and this has been observed by Nova Innovation at the STA. The effect of significant rainfall is likely to increase the asymmetry of estuarine tidal sites with faster ebb tide speeds and slower flood tide speeds, as observed in this project. This has the potential to increase turbine yield compared to a period of less rainfall, though it adds to the complexity of estimating project yield at the planning stage. Any sampled flow speed measurement data would need to also measure rainfall amounts during the sample period and account for seasonal, and longer term, rainfall variation when predicting the flow occurrence over a project lifetime. This adds complexity and uncertainty in predicting turbine yield, which is a critical factor in assessing the LCOE of a potential tidal project. It also has an impact on the predictability of project output, which is an important advantage and differentiating factor of tidal energy compared to other renewable sources.

An additional observation about operating in the Étrel estuary was that water visibility was poor throughout most of the testing period. Tidal sites across the world vary in water visibility, with sediment washed into the water by rainfall and disturbed from the seabed during high flow speeds. Some sites, including Nova Innovation's Shetland Tidal Array, have a rocky seabed and so water visibility is very clear, but the Ria d'Étrel site has much poorer visibility. With an abundance of sediment being present in riverbeds, poor visibility is probably a feature of most river estuaries.

The visibility does not affect turbine performance, but it does make marine operations for deployment and recovery more challenging, increasing the complexity and time required for subsea operations and increasing the risk of delay and cost overruns. Subsea cameras used to monitor the turbine and substructure therefore also had limited visibility during testing, which limited the ability to observe the near-field environment around the turbine. This particularly affected the ebb tide following periods of rainfall, when the river was heavy with sediment and the visibility was further reduced.



Figure 14: Substructure Front Camera Visibility Examples of Best (L) and Worse (R) Conditions During Daylight



Figure 15: Turbine Left Camera Visibility Examples of Best (L) and Worse (R) Conditions During Daylight

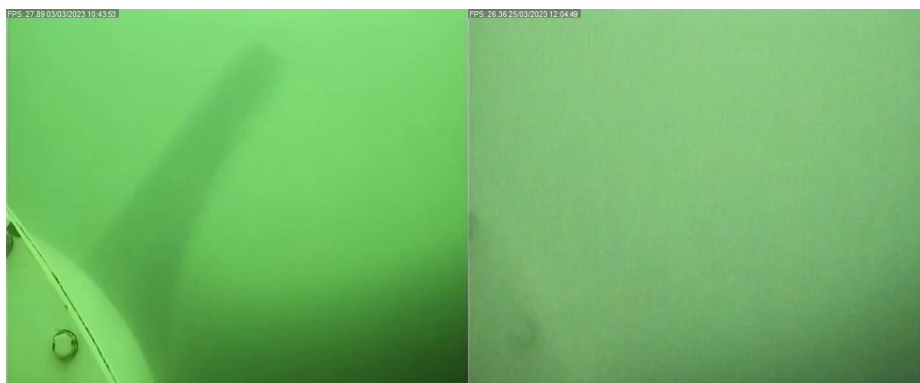


Figure 16: Turbine Right Camera Visibility Examples of Best (L) and Worse (R) Conditions During Daylight

The camera footage from testing was recorded on a motion detection trigger and the footage analysed. No collisions with wildlife were observed during the test phase, which is consistent of the findings of other tidal stream projects, including the STA¹.

¹ For example, see environmental monitoring reports from the H2020 EnFAIT project located here: www.enfait.eu/publications/

3.2. Test Setup and Commissioning

Once the turbine was deployed and the cable connected to the onshore station, communication was established with the turbine on-board instrumentation and control equipment. The turbine was powered and motored to rotate the shaft during slack tide to confirm turbine stability and speed control. Turbine operation was then ramped up over a number of tides to allow the turbine to maximum planned generation capacity, and teething issues with the onshore electrical system addressed before embarking on the test plan. The turbine was demonstrated to be physically stable on the riverbed throughout the full tidal cycle, including ebb and flood direction. The stability of the control system was also demonstrated, including both basic and advanced controllers. ADCP data was processed to provide the turbine control system with a measure of real-time flow conditions. This feature is not a requirement of the commercial ELEMENT control system, since the objective is to demonstrate a “sensorless” control system that minimises the need for external sensors in order to minimise cost and maintenance requirements. However, this set-up a key part of the test programme, since it accelerated the commissioning of a new turbine in a new site, as well as enabling an analysis of control system performance as the tide speed varied. Nova Innovation engineers initially operated the turbine in manual mode, supervising it throughout operation for the first few tide cycles, until stability had been proven and the system moved to fully automatic operation.

3.3. Controller Testing

Following this initial period of observation, the turbine was switched into auto mode. ADCP flow data was used to trigger the turbine to start as the flow speed increased after slack tide. A scheduler was deployed to determine which control system settings were to be applied for each tide. This allowed the turbine to run continually throughout the day, overnight and through the weekend without supervision, though engineers were on-hand to observe operation, and a system of automatic alerts would inform engineers of any faults arising. Data was reviewed daily to check how the turbine was performing and regular analysis conducted to assess the behaviour of the control system.

The commercial ELEMENT control system uses sensors located within the turbine to activate the turbine start-up control mechanism by identifying when the flow is fast enough to generate power after slack tide. The optimal calibration of this start-up mechanism takes some time, so this feature will be demonstrated as part of long-term testing of the M100-D turbine in Shetland as part of work package 11 of the ELEMENT project, where data has been gathered over several months of operation. To make the most use of the time available, the Étel test programme focused on the performance of the control system during turbine operation.

Each of the basic speed, advanced speed and advanced torque controllers were tested during the test period. A plan was created to run these controllers consecutively throughout the test period. This allowed for data to be generated and analysed while the other controllers were running, with improvements identified and implemented before the next run of each controller. Figure 17 below shows a high-level schedule for controller testing. The basic speed controller was operated less as it requires no tuning: this is the baseline controller against which the other two controllers were compared. A separate test run was also used to explore blade performance under different flow conditions and turbine rotation speeds.



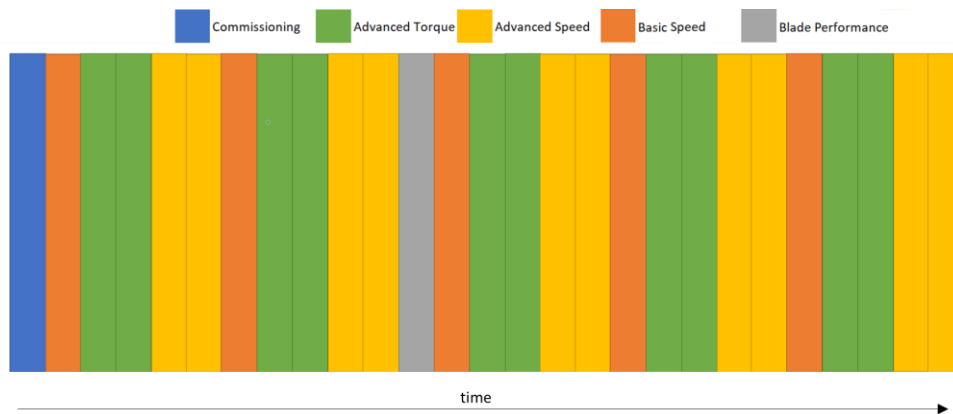


Figure 17: Test Plan Overview Timeline for Turbine Controllers

There are two aspects to **calibrating** the controllers when operating them for the first time in a new turbine and site combination. Subsequently there is a further phase of **optimisation** once the initial calibrations are completed.

The first calibration step (turbine calibration) adjusts the controller to match the specifics of the turbine. The ELEMENT control system is developed for a generic fixed pitch, stall-regulated turbine. The controller is pre-loaded with parameters that reflect the turbine design, such as the blade diameter and performance curve, turbine inertia and the generator geometry design. These parameters were loaded into the RE50 control system in advance of the onshore testing and remained unchanged for the offshore test phase. The first calibration consists of adjustments to the control system based on measured data from the turbine operating in a tidal stream. This data was gathered, and the required adjustments made, following initial operation of each controller at the test site.

The second calibration step (site calibration) consists of adjusting the control system to reflect the flow conditions experienced by the turbine at the site. For example, sites with high turbulence require different control parameters to sites with lower flow turbulence, and sites with higher average flow speeds require different parameters to sites with lower flow speeds. While no significant waves were observed during testing, the test site had a high turbulence factor with large variations in the flow. Most turbulence was observed at periods of 1 to 10 minutes, which is likely explained by the draining of various “storage pools” in the upstream river, where the broad, shallow edges of the river basin flood during the flood tide and then quickly drain out as the water height drops below a threshold. The flood tide was less turbulent but was of a lower velocity, so the turbine was not generating during most flood tides. In this deployment, the initial pre-set control parameters set were found to be suitable for all three controllers tested and no adjustments were required.



Figure 18: 30 Second Average Flow Speed and Turbine Output Power Time Series for a Typical Ebb and Flood Tide Cycle (Ebb Tide Shown with Negative Speed)

The final controller optimisation stage relates to stall control. In this deployment, due to low flow speeds, the controllers were largely operating in the fixed tip speed ratio (TSR) region, where rotor speed increases in proportion to the flow speed. This mode of operation is relatively stable, and the controller can react easily to maintain turbine stability in turbulent flow. During periods of high flow speeds the turbine enters stall control, where the rotation speed is reduced to limit power output and loads. A common characteristic of stall control is that the controller is less accurate at maximising power output under turbulent flow. This is a typical trade off, where the controller can be tuned to change the turbine speed more aggressively to stay on the maximum power operating curve, but at the cost of more aggressive variations in torque and thrust which contribute to fatigue over time. This trade-off is balanced to give a good level of power tracking yet allow some deviation from optimum power to reduce peak torque loads and fatigue loads. During this test phase, while limited operating time was spent in the stall region of control, some filter adjustments were made to the advanced torque controllers to prevent speed oscillations under stall control, as the turbine reacts to changes in flow speed. Further testing will be conducted on the M100-D turbine in the STA under WP11 to fully optimise the controller in the stall control region.

All three controllers – basic speed, advanced speed, and advanced torque – demonstrated stability and the ability to control the turbine at all speed and power ranges. The controllers’ real-world behaviour was similar to that modelled at the controller design stage and observed during onshore testing. Given the relatively short period of estuary testing and the high “noise” level generated by flow turbulence, no statistically significant difference was observed in the performance of the different controllers in this test phase. However, successful completion of this step provides confidence to move to offshore testing under WP11. The comparative controller analysis undertaken for onshore testing (WP8) will be extended during offshore testing (WP11), in conditions of higher flow, lower turbulence, and where testing can be undertaken over a longer period of time. The controllers each showed they can react to flow turbulence and successfully track the flow speed without directly measuring it, through sampling of the turbine shaft speed and electrical output power.

During onshore testing, a turbine model was developed that used electrical output power and speed measurement to predict the rotor torque loads without direct measurement. This model was run in the turbine throughout the estuary test phase and proved very effective at allowing more accurate control of the turbine rotor torque and speed than using power alone. This approach relies on an accurate loss model of the turbine drivetrain components across various speed and power operating points, which enables accurate prediction of the rotor torque. This allows the controller to more accurately control the rotor at its optimum speed/torque operating point, and so maximise output power through improved stall control. Estuary testing provided a valuable validation of this approach to rotor control and demonstrates the value of thoroughly characterising the turbine drivetrain onshore before being deployed offshore.

Stall controlled turbines typically generate most of their yield in the stall control region. This region is also a significant contributor to the damage caused through fatigue by shaft torque and thrust variations. Improved stall control can therefore have a significant impact on Levelised Cost of Energy (LCOE) through increased turbine yield and lifetime. Each controller successfully demonstrated the ability to provide stable output power during operating periods in the stall region. This is an important stage in de-risking operation of the advanced controllers in a more energetic site, as an unstable controller in this region could cause the turbine to experience loads outside its design capability. This test phase allowed for validation of the onshore test phase findings in real-world flow conditions at a relatively sheltered site and allows the controllers to be fully demonstrated and further developed during the offshore test phase in WP11.

3.4. Rotor Performance Testing

The test phase presented an opportunity to measure the rotor performance during operation in real-world flow conditions. The measured ADCP data allowed a comparison to be made between the predicted design performance of the rotor and actual performance. This knowledge allows turbine designers to validate or correct the predicted performance at design and simulation stage, and improves the accuracy of yield predictions for a turbine at a given site with a specific flow velocity profile, thus improving the accuracy of yield and LCOE forecasts for a tidal energy project.

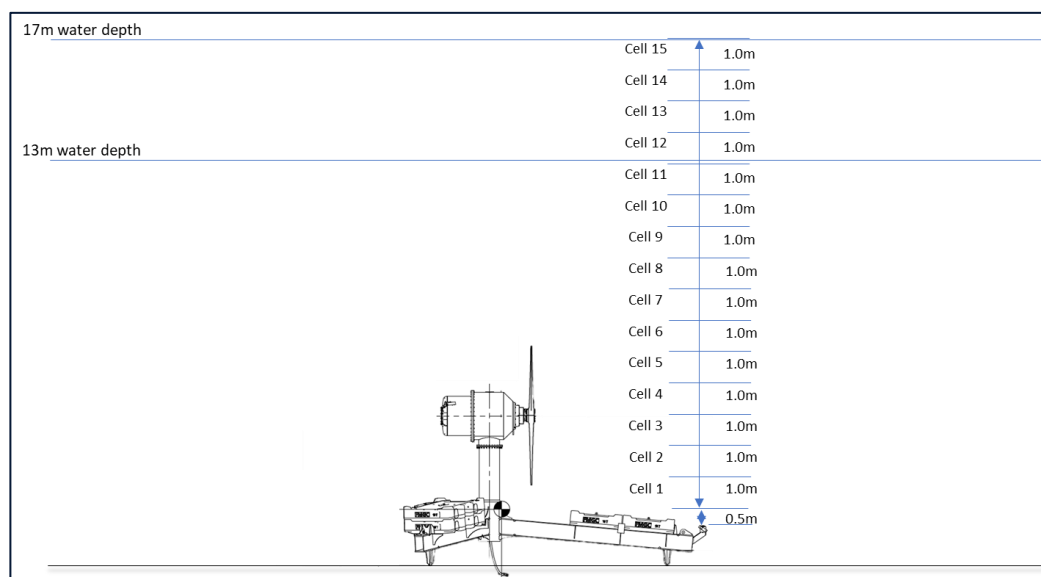


Figure 19: ADCP Cell Positions and RE50 Turbine Assembly

The ADCP measured the flow speed in the water column at a sampling rate of 4Hz. The water column was split into 15 cells of 1m depth as shown in Figure 19, and the ADCP reported the flow in each cell. The data was processed by the instrument to produce 1 second average flow speed and direction for each cell. This 1Hz data was then transmitted back to an onshore computer over ethernet, where the data was encoded and uploaded to cloud storage using scripts developed by Nova Innovation. The flow in the cells that cover the rotor swept area was then processed to create an equivalent flow speed for the rotor plane. Shear profile in the water column (the change in flow speed as a function of depth) was also calculated, allowing for an improved understanding of the flow dynamics within the river channel where the turbine was installed.

To measure the rotor performance, a test was conducted with the turbine rotor operating at fixed rotational speeds. The shaft speed was held stable over a period of 30 seconds for a range of speed points across the operating speed range. The flow was measured as above and post-processing calculated an average rotational speed, flow speed and turbine power to calculate the

rotor performance coefficient (C_p) and tip speed ratio (TSR). Sampling across a range of rotational speed points and averaging the flow speeds, allows approximate C_p and TSR values to be calculated and plotted on a graph. Figure 20 below shows the data using a 3 second averaging filter on the measured turbine and ADCP data, with outliers removed, up to peak operating TSR.

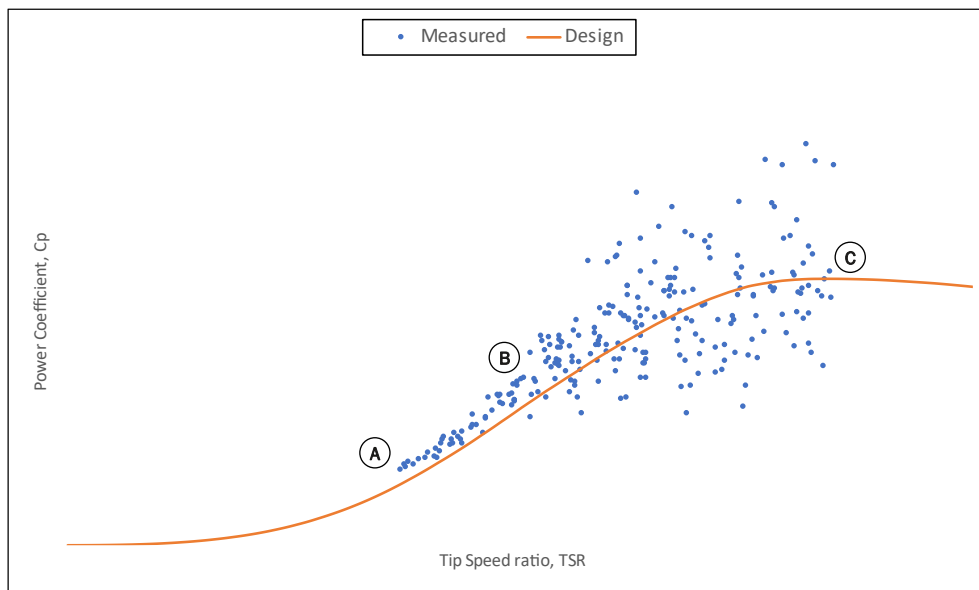


Figure 20: Graph Showing Measured Rotor TSR and C_p Relationship and Rotor Design Relationship

The graph shows low variance in the measured C_p for TSR values up to the point “B”. Beyond this, the scatter in the graph increases, giving less confidence in the actual measured C_p /TSR relationship. Between points “B” and “C”, the average C_p is slightly lower than the design data, but for TSR values below “B”, the C_p is higher than the design data. This is consistent with other research conducted by Nova Innovation in the past and suggests that the industry-standard blade simulation software underestimates the performance of the rotor blade at low TSR levels. This is important, since low TSR operation is characteristic of stall control, which accounts for much of the turbine yield. The implications of this, and the optimal control of the turbine under stall control, will be explored further in this project during offshore testing in WP11.

Overall, the rotor performance is similar to that predicted from design simulations. Variance in the data at high TSR levels illustrates the difficulty in gathering data on rotor performance in low flow, high turbulence conditions with low turbine power output. Being able to operate the turbine at higher powers for higher TSR values (as will be done in WP11) should increase the accuracy of the torque measurement and generate better steady state data, as will operation at a less turbulent site.

3.5. DC Braking Control

During onshore testing, it was demonstrated that the drive system could bring the turbine to a controlled stop in the event of a grid loss or load rejection event. Typically a fixed pitch turbine drivetrain would rely on a fully rated mechanical brake system to stop the shaft from accelerating into an overspeed scenario in such events. The RE50 turbine was equipped with an integrated electrical braking system, connected to a resistive load. This provided a means of safely and seamlessly exporting power from the turbine generator in a load rejection event, allowing the controlled deceleration of the turbine to a standstill. This function was successfully demonstrated during both during onshore testing and under real-world operating conditions during estuary testing. This demonstrates that the turbine can be fully controlled in this type of event. By reducing peak torque loads, this electrical braking system can potentially replace or work in combination

with a mechanical brake system, reducing turbine capital costs by limiting required mechanical braking power.

3.6. Turbine Recovery

Once testing was completed, the cable, ballast and turbine assembly were all recovered from the water using a multi cat vessel in a reversal of the deployment process. The turbine and substructure assembly were returned to the slipway and inspection revealed no significant damage to the turbine.



Figure 21: Vessel Preparing to Recover the RE50 Turbine in Ria d'Étel.

The turbine internal instrumentation confirmed there was no water ingress into the turbine throughout the test period, and there were no faults with the turbine or subsea cable throughout the test period. The ADCP and external underwater cameras operated continually throughout the testing, with the cameras showing minor biofouling on the lens window but no more than expected for this site. All equipment was successfully recovered from the test site within a 48 hour window, with no observed negative impact on the riverbed and immediate environment as a result of the testing.

4. OFFSHORE TESTING – CONCLUSIONS

The RE50 turbine was successfully deployed, tested, and recovered from the Ria d'Étel for the estuary test phase of the project. The turbine was demonstrated to successfully export power through generation from the combination of riverine and tidal stream currents at the site. The expected asymmetry of flow speeds between the flood and ebb tide was observed, with the ebb tide accounting for nearly all the power generated during testing. Rainfall was observed to have an impact on the flow speeds and visibility in the water. Turbulence in the flow meant that the turbine output power varied significantly during testing.

Three different controllers were tested on the turbine: basic speed, advanced speed, and advanced torque controllers. All three demonstrated stable control of the turbine speed and output power throughout testing, maintaining the turbine within its operating limits. This testing phase has demonstrated that there can be confidence in the reliability and stability of both of the novel, advanced controllers, de-risking the next test phase, which involves demonstrating the controllers on the larger M100-D turbine in Nova Innovation's grid-connected tidal site in Shetland.

During the testing there were no negative impacts observed on the river wildlife or other users of the waterway. Boats were able to pass over the turbine during operation, and deployment and recovery marine operations were conducted over a short period of time with minimal restrictions in place for other users. These factors provide further demonstration that gravity based tidal stream turbines can be safely and quickly deployed and recovered without negative impacts on the human or natural environment, including in close proximity to coastal communities.

Overall, the test phase has demonstrated that the ELEMENT control system can successfully control a tidal turbine in autonomous operation and export power to shore. This provides further validation of the two advanced controllers that have been designed and developed in the project and successfully demonstrated in onshore testing. Results from simulated control in the laboratory settings provided by onshore testing, have now also been demonstrated in the real-world operating environment. Following successful completion of this estuary test, the ELEMENT project team can proceed with confidence to offshore testing of the control system at Nova Innovation's in the Shetland Tidal Array.



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