Date of issue: June 2018

Deliverable ID: D 10.7

ENFAIT
ENABLING FUTURE ARRAYS IN TIDAL

AIM: Design report

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

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	60 months (July 2017 – June 2022)
Project Officer	Dana Dutianu (INEA)
Coordinator	Nova Innovation Ltd
Consortium partners	Nova Innovation, ELSA, SKF, University of Edinburgh, Mojo Maritime, Wood, HMK, RSK Environnement, ORE Catapult
Website	www.enfait.eu
Deliverable ID	D 10.7
Document title	AIM: Design report
Document reference	EnFAIT-EU-0030
Description	Report summarising instrumentation array design and results from initial array measurements and modelling.
WP number	WP 10
Related task	T 10.7 & T10.8
Lead Beneficiary	ORE Catapult
Author(s)	Sam Porteous (ORE Catapult)
Contributor(s)	Alasdair MacLeod
Reviewer(s)	Vicky Coy (ORE Catapult), Nova Innovation, Peter MacDonald (ORE Catapult), University of Edinburgh, Wood
Dissemination level	PUBLIC - This document in whole, or in part, may be used in general and public dissemination.
Document status	Final
Document version	1.0

REVISION HISTORY					
Version	**Status**	**Date of issue**	**Comment**	**Author(s)**	**Reviewer**
0.1	Draft	22/5/2018	Initial Draft for review	S Porteous	V Coy, A Macleod
0.2	Draft	23/5/2018	Draft for Nova Innovation review	S Porteous	Nova Innovation, Peter MacDonald
0.3	Draft	4/6/2018	Draft for consortium review	S Porteous	Nova Innovation, Wood, UOE
0.4	Draft	8/6/2018	Draft with implemented changes	S Porteous	P. MacDonald
0.5	Draft	11/6/2018	Final Draft with implemented changes	S Porteous	Nova Innovation, Wood, UOE
1.0	Final	21/6/2018	Version for issue	S Porteous	P. MacDonald, V. Coy, Nova Innovation

Contents

1 Introduction

1.1 Purpose

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

This document presents the approach taken in the design of the instrumentation used to characterise the tidal flow around the turbines on the site at Bluemull Sound, Shetland, as well as the complementary sensor array to measure turbine loading data. It is to be submitted to satisfy deliverable D10.7 of the EnFAIT project and to be also made available for public dissemination.

Different sensor deployments are discussed as well as ongoing and future instrumentation deployments. Measuring tidal flow characteristics in tandem with turbine loading enables the observation of array layout effects on turbine loading. Furthermore, the data gathered from this measurement campaign will provide the essential inputs and insight required to predict the effects of different array layouts on the extreme and fatigue loads experienced by the turbines. This will allow the development of a far deeper understanding of array effects.

1.2 Background

The EnFAIT project will allow for the effects of differing array layouts to be measured, modelled and demonstrated. An improved understanding of the effects of array layouts on performance and loading, will help take tidal energy towards commercialisation.

To enable an understanding of array effects, three additional turbines will be installed in Bluemull Sound, Shetland with the three turbines of the existing Shetland Tidal Array. Flow monitoring devices will be installed alongside the turbines. On board the turbines, load and power performance measuring equipment will be installed. The combination of the data streams from installed sensors, alongside modelling work, will provide deep insights into array effects.

The Nova Innovation tidal turbine technology is the core of the EnFAIT project. The M100 turbine is shown in Figure 1.1. The turbine is rated to 100kW and has a 9m diameter, two- bladed rotor. The turbine is attached to a gravity base foundation structure.

The turbine can be removed from the foundation and brought to the surface for inspection and maintenance.

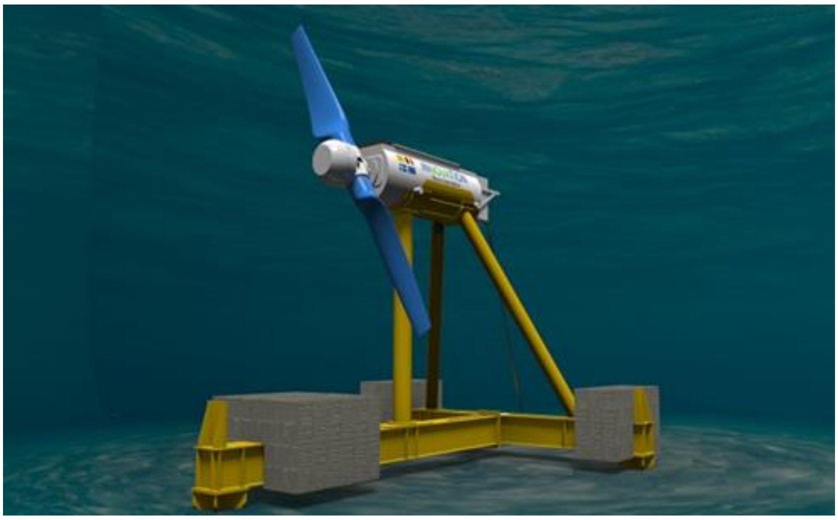

Figure 1.1: The Nova Innovation M100 tidal turbine

Key to the success of the EnFAIT project is the foundation type. The gravity base allows for the seabed position of the foundation to be altered.

To better understand tidal arrays, it is planned to configure the Bluemull Sound array in two rows of three turbines, Figure 1.2. This will enable the observation and investigation of array effects. Figure 1.2 shows the 6 turbines (T1 to T6) that will make up the EnFAIT array.

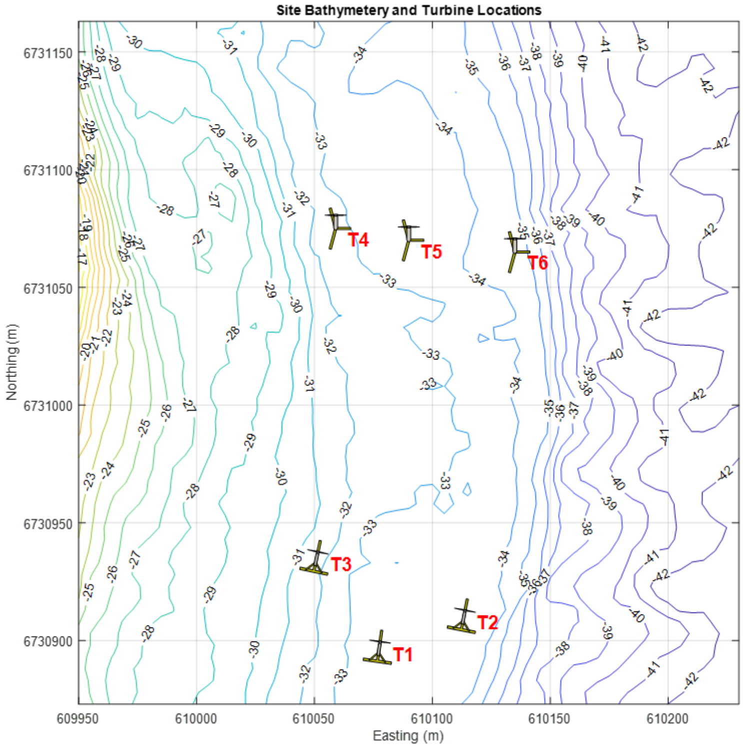

Figure 1.2: Array configuration 1

In the first array layout scenario, the rows of turbines will be separated to minimise wake effects. The array will be operated in this layout to establish how the turbines perform and the effect they have on the surrounding tidal stream.

Once this learning has been exploited from the initial array layout, the layout will be reconfigured, as shown by the arrows in Figure 1.3.

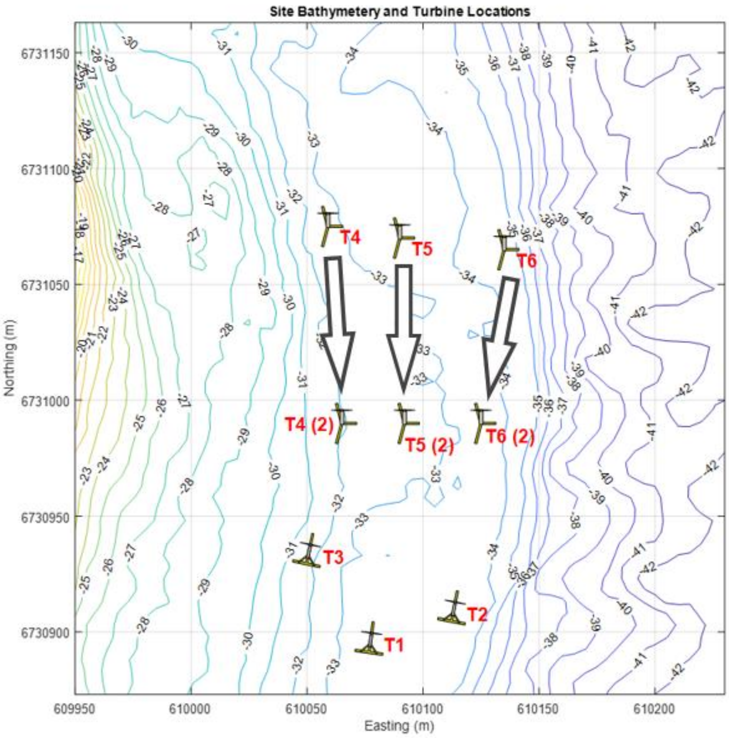

Figure 1.3: Array configuration 2

The new configuration will have a much closer spacing between turbine rows. This will encourage an increased amount of wake interaction. The effects of this interaction will be measured using the instrumentation described in this report. Modelling will be carried out to predict effects in detail. For the first time, a comparison between the operation of the turbine when exposed to wake effects and the operation in undisturbed tidal flow conditions will be undertaken. This will be able to provide key learning for all future array designs.

2 Tidal Flow Characterisation

2.1 Overview

An essential first step to modelling array interactions is understanding the real-life flow conditions in Bluemull Sound. A measurement campaign has been carried out to characterise the flow conditions in the channel and to gather operational data which will be used to input into and validate further computational array modelling. The selection and placement of flow measurement devices was informed in part by outcomes and methodologies from previous tidal energy projects, such as the TiME project, as well as standards and guides, such as the EMEC Assessment of Tidal Energy Resource guide.

2.2 First ADCP Seabed Deployment

2.2.1 Purpose

An initial deployment of ADCPs (Acoustic Doppler Current Profilers) was carried out to gather tidal flow readings at different locations within the channel.

2.2.2 Approach

Three Nortek Signature 500 ADCPs were deployed, each gathering three months of flow and tidal level data at a sampling frequency of 1Hz. The ADCPs were deployed in three locations north of the turbines, shown as ADCPs 1, 2 & 3 in Figure 2.1: ADCP deployment locations.

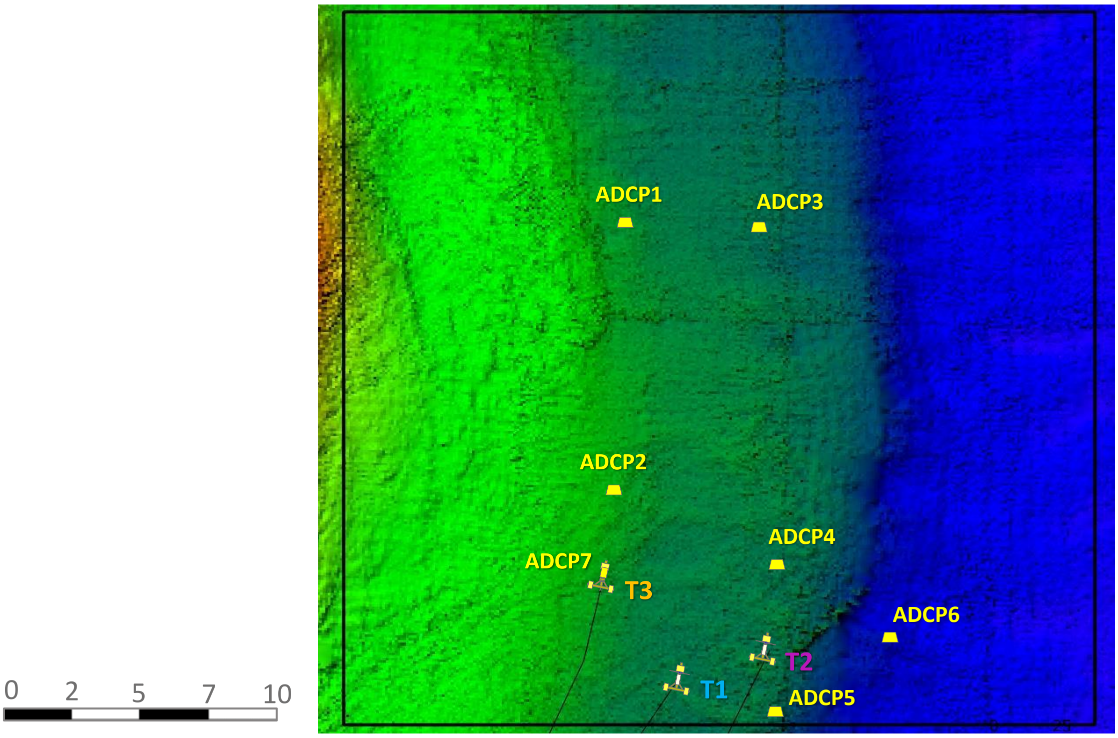

Figure 2.1: ADCP deployment locations

The ADCPs were deployed onto the seabed in stainless steel frames designed to hold them flat, orientated to face upward through the water column. The acoustic beams emitted from the top surface of the ADCPs and doppler shift observed when the beams return after being reflected off particles in the water, are used to gather flow readings. Figure 2.2 shows an illustration of the seabed mounted ADCP orientation in the water column.

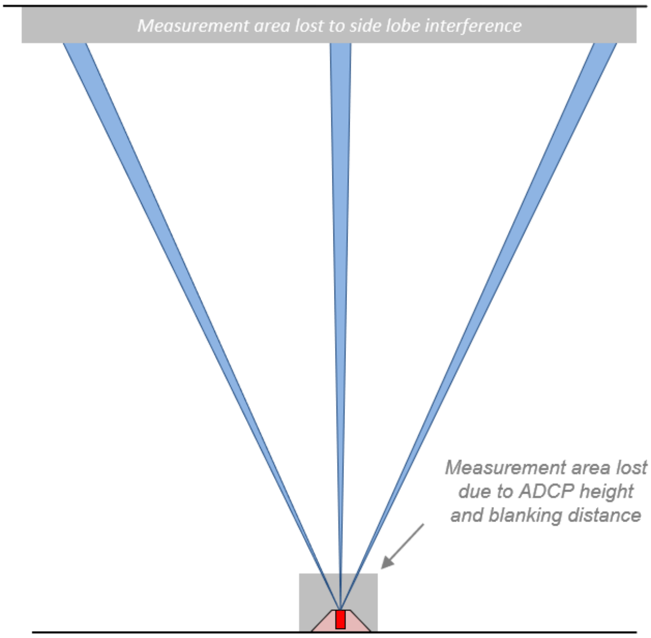

Figure 2.2: Seabed mounted ADCP orientation

2.2.3 Outcomes

These initial data recordings were analysed to provide further insight into the characteristics of the tidal flow in Bluemull Sound. The data recorded was also used to calibrate the tidal resource model which predicts flow conditions throughout the entire length of the channel.

2.3 Second ADCP Seabed Deployments

2.3.1 Purpose

A second deployment of three seabed ADCPs has been carried out to gather further tidal flow data. These deployments were particularly aimed at gathering flow information from the wake of one of the operational Nova Innovation turbines.

2.3.2 Approach

Three seabed mounted ADCPs were deployed in 2018 in the locations shown by the labels ADCP 4, 5 & 6 in Figure 2.1. At the time of this report, these ADCPs are still to be recovered from site.

2.3.3 Outcomes

The measurements taken by these ADCPs will enable a greater understanding of the site flow characteristics, particularly in the wake of the turbine. Analysis of the results gathered in this second

ADCP deployment campaign will benefit from the data analysis techniques developed from the first set of ADCP readings.

2.3.4 Lessons Learned from Previous Deployment

The practical experience gained, and lessons learned from the first ADCP deployments were employed in the second ADCP deployment campaign. Some key lessons applied were as follows:

1. The primary recovery method was altered to reduce costs - in the first deployment campaign, the primary recovery method of using pop-up buoys was ineffective as the mechanism for releasing the buoys failed due to corrosion. This method also added additional cost to the equipment. This primary recovery method was changed to a grappling method, where the ground line was caught with a recovery hook and the ADCPs were reeled in using the vessel winch.

2. ADCP acoustic signal interference was considered in more depth - upon inspection of the data from the first ADCP deployment, there was concern that the acoustic signals overlapped, producing noise in the signal. Ultimately this proved not to be the case but the additional consideration initially given to the issue meant that the ADCP spacing in the second deployment was selected to ensure that there was no signal interference between ADCP beams.

3. An underwater camera was identified as a valuable piece of equipment - the first deployment involved the use of an underwater camera with a live feed to the vessel. This proved to be a valuable asset in confirming the successful deployment on an appropriate area of seabed. The value of using this equipment drove further use in the second deployment campaign.

4. A greater mass of anodes for corrosion protection was attached to the frames in the second deployment - the first deployment period lasted longer than initially planned due to a rescheduling of the recovery. The combination of this and the highly oxygenated water flowing through the channel led to the depletion of the anodes, leaving the frame unprotected. In the second deployment, this issue was anticipated and mitigated by attaching a larger mass of anodes, whilst altering the deployment design to reduce the risk of electrical connections between different metals on the frames being formed.

5. Data analysed after the first deployment was used to inform the second deployment – selection of the locations of the second deployment was advised in part by the results observed in the previous deployment, alongside observations from the tidal resource modelling which was carried out. Initial Computational Fluid Dynamics (CFD) models were also run using Ansys Fluent software to give an indication of wake recovery downstream of the turbines, helping to further guide placement of the second ADCP deployment.

2.4 ADCP Seabed Frames

2.4.1 Purpose

Additional seabed-mounted ADCP deployments will be carried out over the course of the EnFAIT project to collect tidal flow data to further investigate the effects of the turbine arrays on the flow in the channel. To reduce operational costs over the course of the project, and to increase ADCP deployment flexibility, new seabed mounting ADCP frames will be fabricated.

2.4.2 Approach

The frames will rest on the seabed under their own weight with a ground line connected to a clump weight, used for recovery.

The frames have been designed to tackle deployment issues which were encountered in previous deployments. For example, some movement of the frames from the original ADCP deployment was observed. To discourage this, pointed feet were added into this new frame design, which will provide a firmer interface with the seabed.

The conceptual design of the frames can be seen below in Figure 2.3:

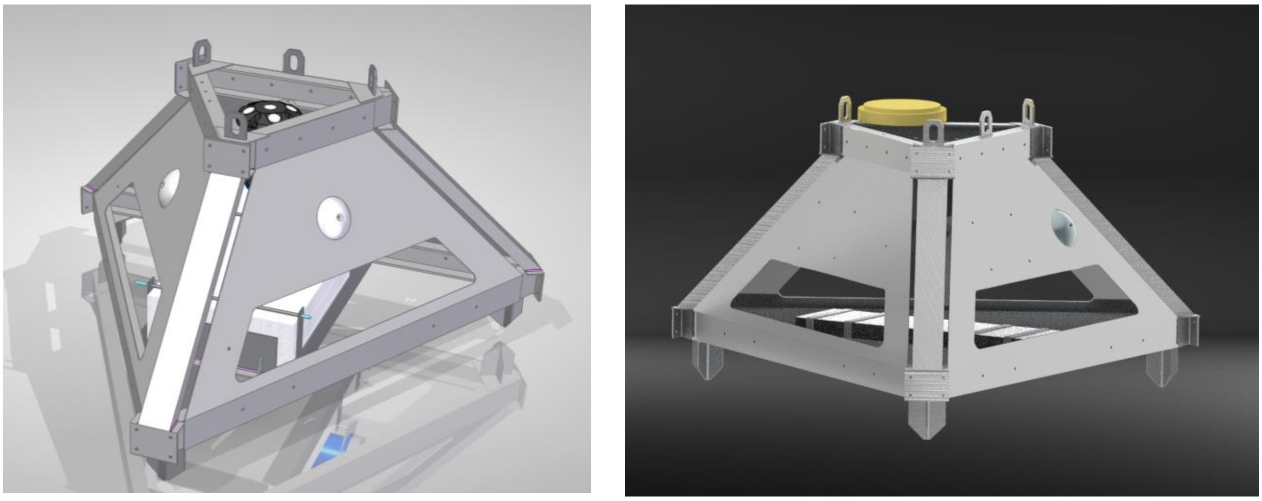

Figure 2.3: ADCP Seabed Frame Model

2.4.3 Outcomes

The three frames fabricated will allow three sea-bed mounted ADCPs to be operated in tandem with two other ADCPs on the instrumentation skid. Hire costs will be minimised over the course of the project and flexibility in deployment will be increased.

2.5 Instrumentation Skid

2.5.1 Purpose

The tidal flow through Bluemull Sound is disrupted in part by the presence of the turbines in the flow. To characterise the flow in the turbine locations, when no turbines are present, a method was established to measure the undisturbed flow at turbine hub height. An instrumentation skid was designed and deployed to gather hub height flow readings. These hub height readings will lead to a greater understanding of the characteristics of the oncoming flow that drives the turbines.

2.5.2 Approach

A frame was designed which is lowered through the water column onto any available, temporarily vacant turbine substructure, Figure 2.4. The frame then remains in place on the substructure under its own weight and gathers flow data. The frame has mounts for horizontally mounted upstream and downstream facing ADCPs, allowing flow measurements to be taken upstream and downstream in both flood and ebb tides. Various mounting locations were also included in the design to enable the simple attachment of other sensors and instruments in the future.

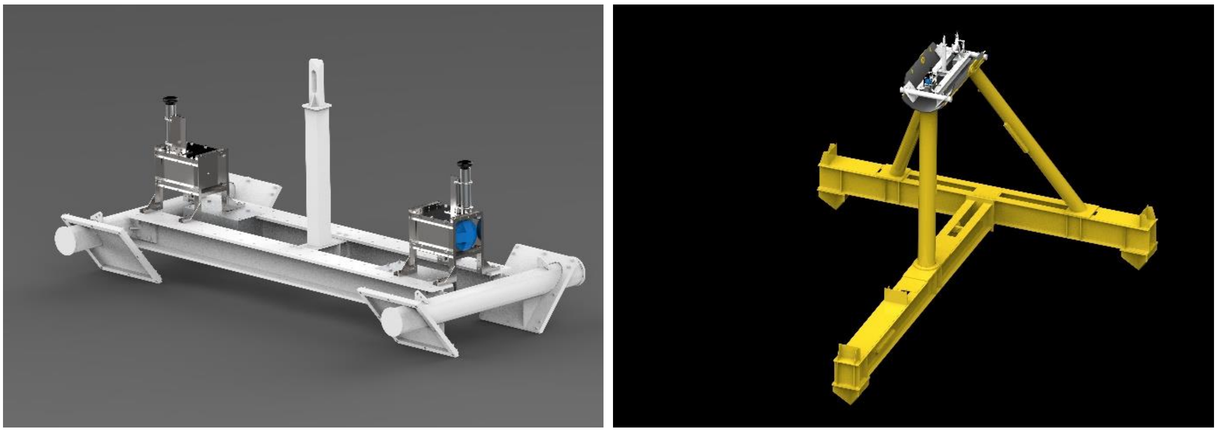

Figure 2.4: Instrumentation Skid Concept and Placement

The instrumentation skid was designed, fabricated, instrumented and successfully placed on one of the turbine substructures in 2018, Figure 2.5. An ADCP faces north up the channel and has been gathering flow readings of both the flood and ebb tidal flows in Bluemull Sound at turbine hub height.

2.5.3 Outcomes

Following the recovery of the skid and the mounted ADCP, the data which is stored locally in memory cards within the ADCPs will be analysed allowing the observation of the characteristics of the turbine hub height flow. Analysis of the data will also shed light on data quality and improvements for future data recording campaigns. Experience gained from the first deployment and recovery will be applied to future deployments to further optimise the deployment and recovery processes of the skid.

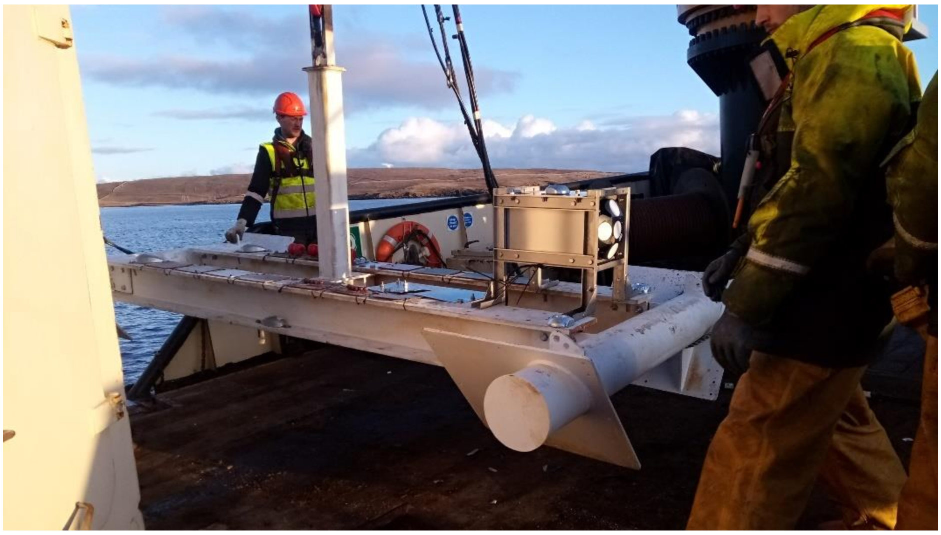

Figure 2.5: Instrumentation Skid Deployment

2.6 Future Deployments

2.6.1 Purpose

Different instruments will allow the gathering of other insightful data to aid in developing a deeper understanding of array interactions in Bluemull Sound.

2.6.2 Approach

Instruments to be deployed in future include:

- Acoustic Doppler Velocimeters - ADVs will be mounted on the instrumentation skid at different locations to characterise rapid turbulence and velocity changes across a smaller measurement volume. They allow the characterisation of turbulence of a smaller length scale than is possible from the data from ADCPs. ADVs have three or more converging beams that are used to measure, with high sampling rates, the velocity and changes in the velocity at a small point, where the beams intersect, Figure 2.6.

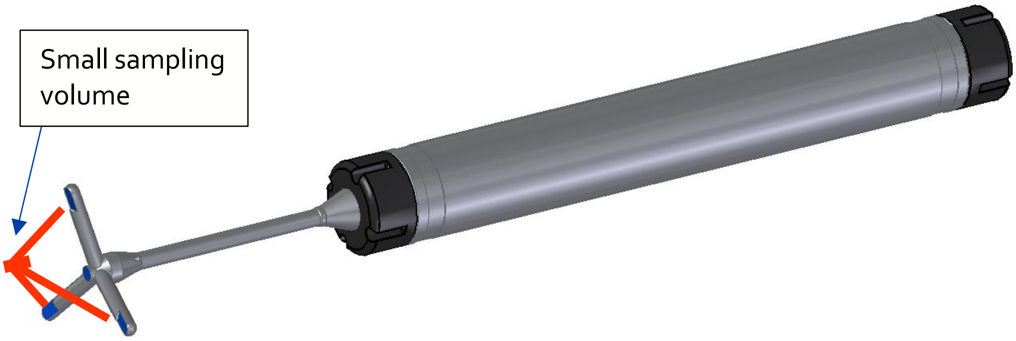

Figure 2.6: ADV showing beam intersection

- Electromagnetic flowmeters – these will be employed to measure the flow speed at different locations on the instrumentation skid. These instruments use a different method of measuring flow than the acoustic devices, employing electromagnetic fields rather than acoustic beams, and will provide local flow readings along the length of the instrumentation skid. The ability of these instruments to take accurate local flow readings whilst being relatively low in cost make them a valuable addition to the instrumentation array.

Figure 2.7: Electromagnetic flowmeter (image taken from www.valeport.co.uk)

Different mounts will be fabricated to allow attachment of these different instruments to the skid. Future deployments of the instrumentation skid will incorporate the use of multiple instruments simultaneously, each taking measurements in different flow fields. Figure 2.8 shows the layout of a fully instrumented skid on a turbine substructure.

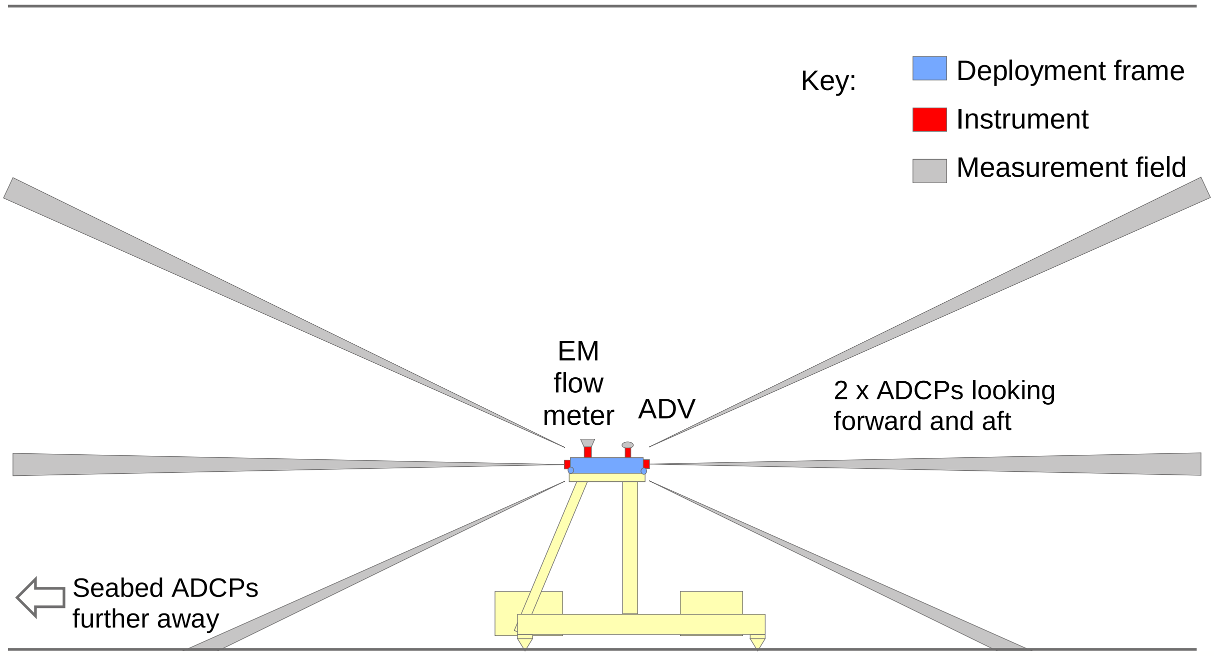

Figure 2.8: Instrumentation skid with array of flow instruments

2.6.3 Outcomes

Data gathered in future deployments will be used to further characterise the flow in the channel at different locations and to develop a better understanding of the flow behaviour.

2.7 Overall Outcomes of Tidal Flow Characterisation

Data recorded in this first phase of instrumentation usage will be used to both input into array modelling and inform future array spacing and placement.

3 Complementary Turbine Sensor System

3.1 Purpose

Pairing tidal flow measurements with related turbine measurements enables the investigation of the relationship between the tidal flow characteristics and the turbine loading and performance. The tidal flow measurement has already been discussed, and now the complementary turbine instrumentation system will be presented.

Instrumentation of the tidal turbine was implemented to investigate loading on different turbine components, whilst an onshore power performance monitoring device was installed to provide enhanced information on turbine output.

With the experience developed from this initial instrumentation process, further enhanced instrumentation of the other turbines will be undertaken.

3.2 Torque Measurement

3.2.1 Purpose

Directly measuring shaft loading is key to understanding the effect of the tidal flow and turbulence caused by array layouts on the loading of the turbine drivetrain.

3.2.2 Approach

A torque transducer is being fitted to one of the Nova Innovation M100 turbine shafts to assess torque present in the shaft. This instrument will also measure the shaft speed and derives the mechanical power being transmitted by the shaft. The transducer consists of three key components:

- Strain gauges - placed on the shaft to measure torsional strain in the shaft, and from this torsional strain the torque will be derived.
- Flexible rotor assembly – transmits the strain gauge readings to the stator (then into the data logger). The assembly also transmits shaft speed to stator.
- Stator – induces power in the rotor assembly, allowing operation of the rotor and strain gauges.

Power will be provided to the stator through the turbine data monitoring system, with the output signal being fed live to shore.

The equipment used can sample torque data at the rate of 10 samples per second. Should a higher sampling rate be desired in the future, the equipment can increase the sampling rate to a maximum of 2000 samples per second. This range of sampling rates will enable the observation of different loading effects on the shaft. Data logging with the high sampling rate capability alongside the high accuracy of this instrumentation will enable detailed investigation of shaft loading due to array turbulence effects.

3.2.3 Outcomes

The measurements taken with the torque transducer will allow the investigation of the effects of array layouts and turbine wakes on the loads experienced by the turbine shafts.

In addition, measuring shaft speed and power will be of great value in monitoring turbine operation and performance, and for the first time will provide access to real time shaft power measurements. Furthermore, monitoring shaft power in different flow conditions can help to shed light on the loading on other turbine components, for example the drivetrain or blades. Using known loading could enable the creation of appropriate hydro-elastic models of key components, which in turn could allow for the determination of consumed fatigue life within the rotor, drivetrain, and structural components without continuous visual inspection.

3.3 Blade Strain Gauging

3.3.1 Purpose

Another component of the turbines which will be affected by array interaction is the turbine blades. Measuring blade loading will enable the investigation of array effects on the loads experienced by the turbine blades.

3.3.2 Approach

Strain sensors are being placed in a set of turbine blades to gather loading data. Fibre Bragg Grating (FBG) optical strain sensors have been selected to record blade strain. The FBG sensors are placed within the core of a standard optical fibre, which is fed along the length of the blade. This method allows for the output signals to be interrogated simultaneously by a single instrument, meaning that strain can be monitored across several different locations in the blades at a low cost and system complexity. Strain gauges will be placed in four strings, each with six strain sensors at different locations along the length of the blades. The locations have been selected as areas of interest where strain readings should accurately represent strain in the blades. The cables are connected in parallel by an optical fibre which is fed to the interrogator and data logger in the turbine hub.

The selected optical strain instrumentation measures a strain range of ±9.000 µstrain with a strain resolution of 0.4 µstrain. Measurements are fed into the compact interrogator, which scans outputs at a scan rate of 2.5kHz+ and allows outputs to be logged at a very high resolution on a USB device.

3.3.3 Outcomes

The comparison of the loading data gathered in undisturbed flow, with loading data gathered from a turbulent array orientation, will help in understanding the driving effect of array layout on the loading effects on the turbine blades.

3.4 Further Instrumentation

Similar instrumentation will be applied to future tidal turbines to assess loading effects at different locations within the array. In addition to this, further opportunities will be available to install instrumentation to gather more valuable loading data.

4 Array Interaction Modelling

4.1 Purpose and Approach

The data gathered and observations made from operation of the tidal array will be input into, and be informed by, array modelling work. To date, a large amount of work has been carried out in gathering site measurements which will allow for the development and validation of further detailed modelling work. The modelling work to date is laid out in this section, with plans for further modelling also being discussed.

The modelling approach is illustrated in Figure 4.1. To better understand proposed array layouts, it uses three main models:

1. site flow conditions,
2. wake effects and
3. turbine performance and loading.

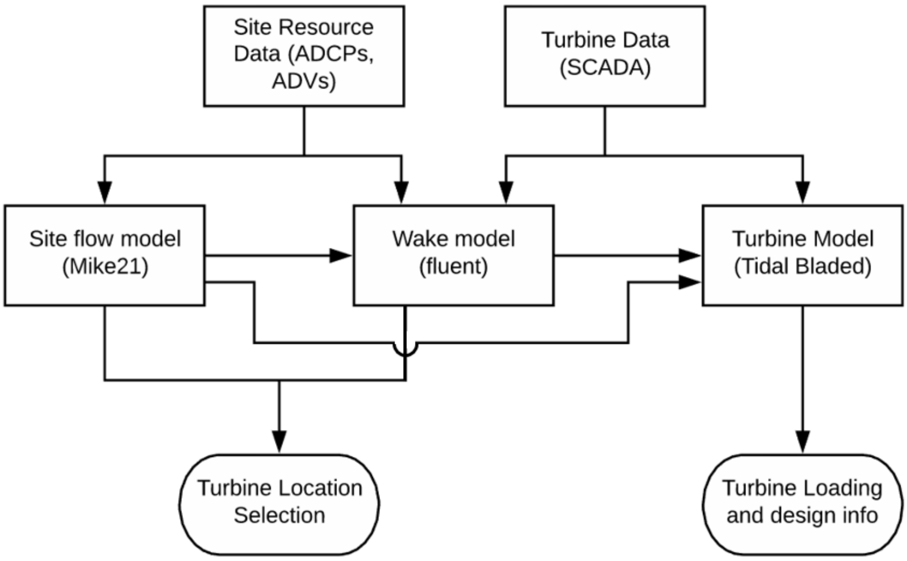

Figure 4.1: Modelling approach

These three models will be combined with site measured data to develop a deep understanding of array interactions.

4.2 Site resource

A site flow model has been built, Figure 4.2. It provides detailed information on the tidal resource across Bluemull Sound. Current and water level parameters were modelled using a European, basin-scale flexible mesh hydrodynamic model developed by MetOceanWorks with sub-kilometre resolution in the coastal zone. The model was established using the MIKE21 2D FM modelling package, a comprehensive modelling system for two-dimensional water modelling developed at the Danish Hydraulic Institute

(DHI). For more detailed information on the site flow model developed, see the deliverable report D10.2: Bluemull Sound Site Resource Map.

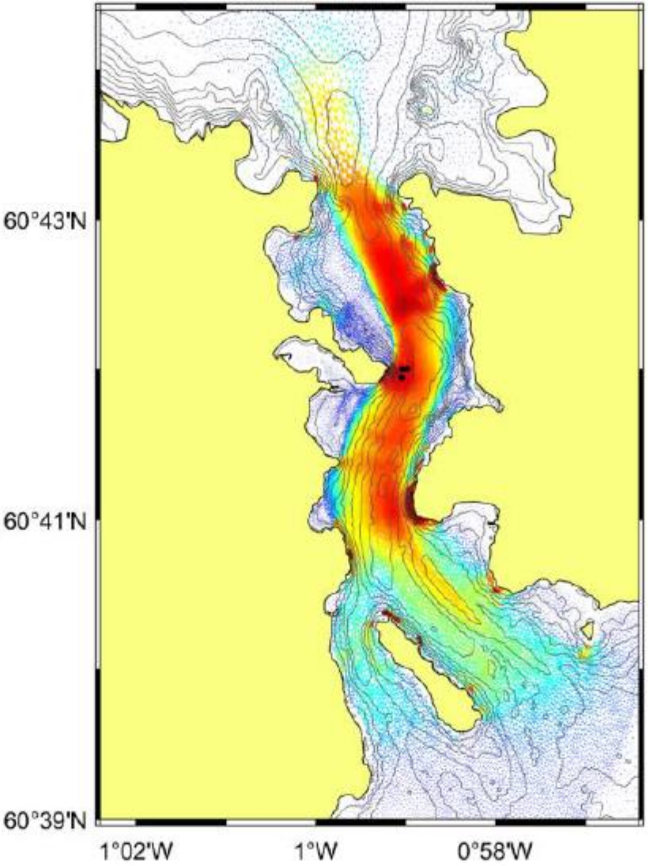

Figure 4.2: Bluemull Sound site resource (flow speed from spring tide Nov 2017)

The model was calibrated using site recorded flow data. Flow data was recorded, at three locations, using ADCPs as previously discussed. The ADCP locations were selected to best measure the resource around the existing turbines, Figure 4.3.

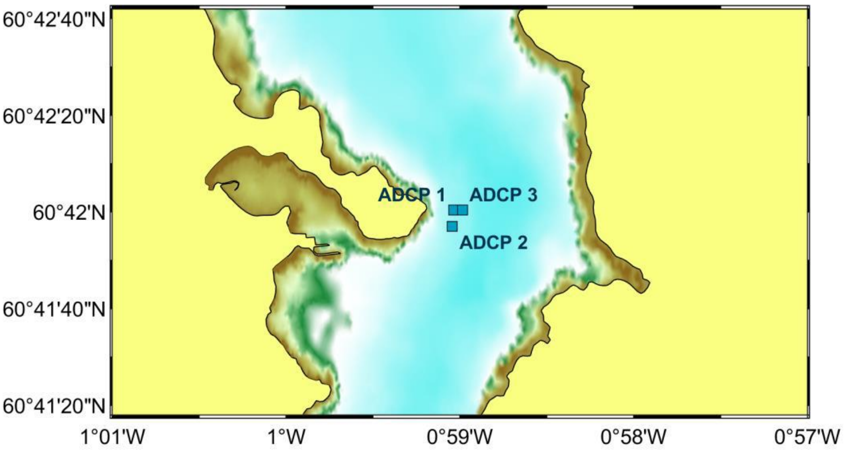

Figure 4.3: ADCP locations

Harmonic Analyses of the data from each ADCP, alongside corresponding analysis for the closest UK National Tide Gauge from Lerwick, were carried out on the water depth signals. The outputs from these analyses were used to drive the site flow model.

A comparison of the water level results from the numerical model to those recorded at one of the ADCPs shows good correlation, Figure 4.4. This correlation gives confidence in the modelled results.

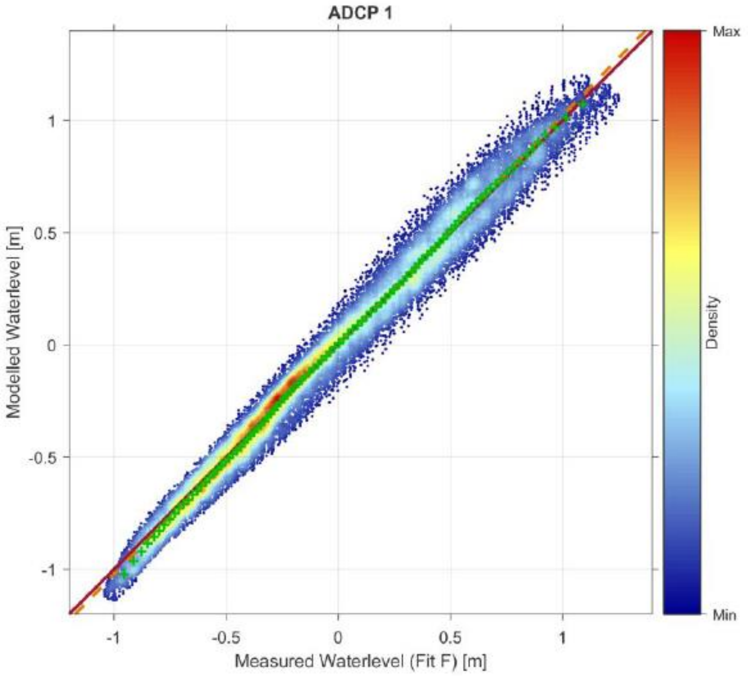

Figure 4.4: Measured vs modelled water level results

4.3 Wake model

4.3.1 Initial Modelling

There is good understanding of the undisturbed site flow from the measured site data and the site numerical resource model. This understanding is being used to inform detailed local wake models for the turbines, Figure 4.5.

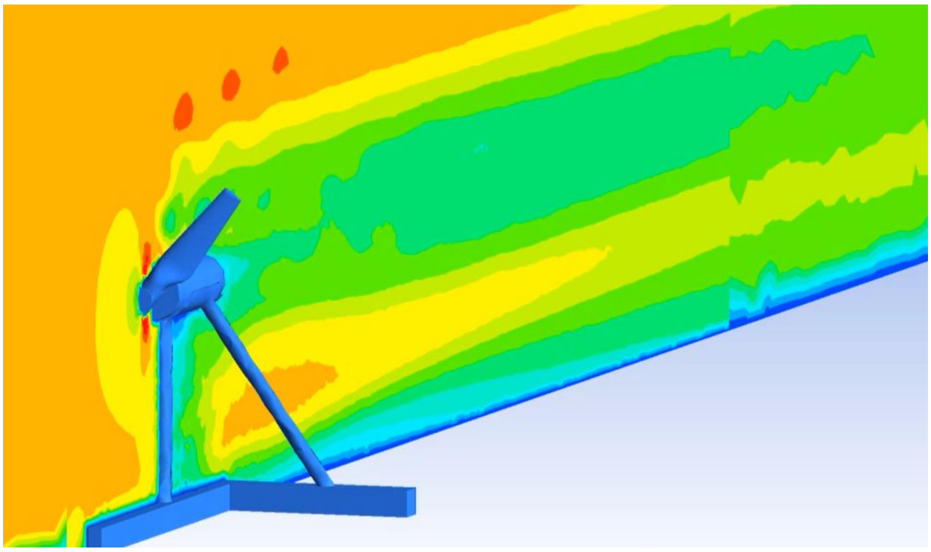

Figure 4.5: Turbine wake model

A Reynolds-averaged Navier Stokes (RANS) model has been built and is being tuned using the collected site data. The outputs from the initial model have aided in developing a greater understanding of wake recovery downstream of the turbines. These observations are being combined with the recorded site flow data to build array interaction understanding. The wake model has been built using a full turbine representation. The turbine blades are modelled using a rotational mesh. This method is believed to provide a good wake representation. The shear profile and turbulence observed from the collected ADCP data will be used as inputs in further modelling.

Turbine location planning is being undertaken by combining the resource and wake model outputs. Figure 4.6, indicates an output from this work. Future ADCP deployments will target the turbine wakes to give detailed wake flow data. This data will be used to improve the turbine wake models.

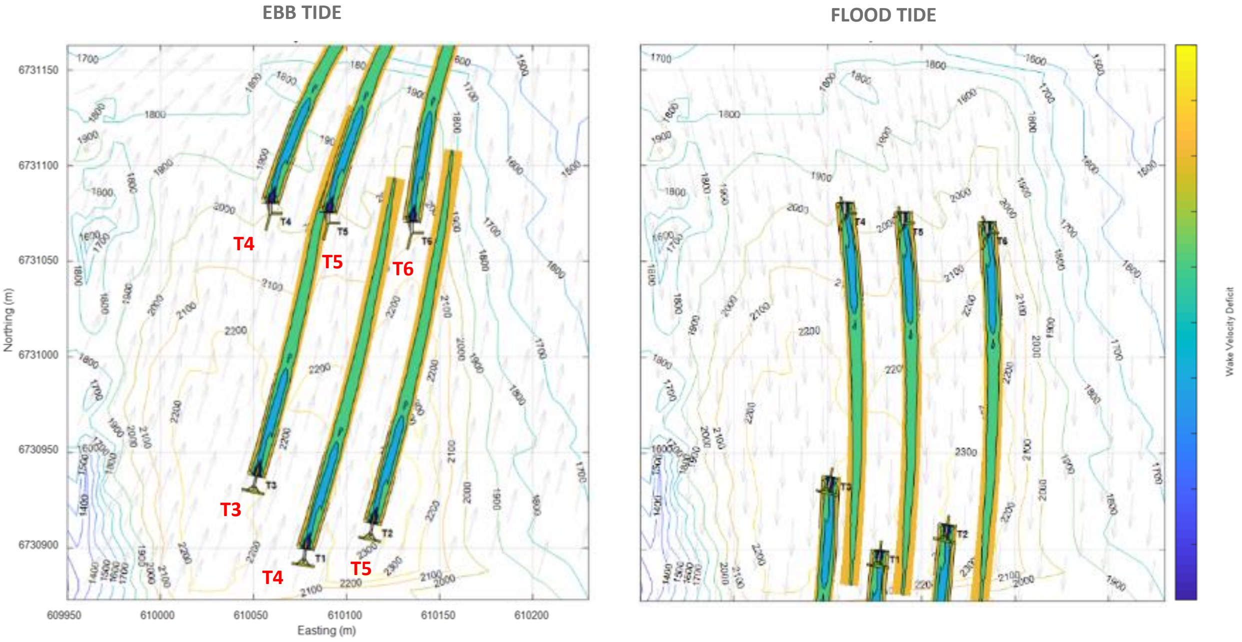

Figure 4.6: Array interaction

4.3.2 Future Wake Modelling Work

Initial modelling work has been carried out to gain an understanding of the wake behaviour of the turbines. Further CFD work will be now be performed to tune and develop the existing models, enabling a deeper investigation into the characteristics of the turbine wakes in the array to take place. In the development of these models, learnings from previous projects, including the ReDAPT and PerAWaT projects, will be consulted. Building upon previously carried out projects in tidal turbine wake modelling will be key in understanding and modelling more accurately the wake interactions in the EnFAIT tidal array.

4.4 Turbine performance and load

Turbine load and performance models can be run using a detailed understanding of the resource and wakes. These models are under development and will be run in a Blade Element Momentum (BEM) code using DNV Tidal Bladed software.

A CFD model has been created to generate blade lift and drag polars for the turbine which will be used in the BEM model. The turbine blade geometry model was cut into sections at 0.5m intervals along its length. CFD models were run with each blade section rotating 360 degrees through the flow. An incoming tidal flow speed was used to simulate an operational condition, with the relative velocity increasing proportionally for the stations along the blade, to simulate the rotation of the hub in the flow. The blade performance outputs generated from this simulation will serve as inputs to the BEM modelling.

5 Summary

EnFAIT calls for the prediction of the impacts of array layouts on turbine loading and is directly driven by the measurements taken in this work. The process of modelling the site characteristics is underway. A summary of the instrumentation and analysis work to date is as follows:

- Two ADCP seabed deployments were carried out to record and characterise site flow characteristics.
- An instrumentation skid was deployed to gather undisturbed turbine hub height flow readings
- A torque transducer will be fitted to the turbine shaft to investigate array turbulence effects on shaft loading.
- Strain gauges will be fitted to the turbine blades to assess loading induced by wake turbulence, as well as loading during normal operating conditions. The data gathered will inform hydro-elastic modelling to determine fatigue life.
- Tidal resource modelling was carried out which predicts flow characteristic throughout the length of Bluemull Sound.
- Initial wake modelling was carried out to inform further ADCP placement and array spacing
- Lift, drag and moment coefficients of the turbine blades have been generated at a set tidal flow speed for use as inputs in BEM modelling.

In summary, the additional data gathered from the instrumentation discussed in this report will provide further insight into flow characteristics and subsequent loading effects experienced by the turbines in the array. These real-world measurements will then be used to validate and drive computational models which will predict the effects of array layout on turbine loading. Understanding the real-world recordings and data will be key in driving the ongoing modelling to be carried out later in EnFAIT.

6 Conclusions

The instrumentation of the site itself, as well as the turbine, is enabling an increased understanding of the site and the effects that the tidal turbines have on the flow. Some key flow characteristics of the site have been observed, both in undisturbed areas and in turbine wake areas. Work is underway to investigate the loading effects experienced by the turbine shafts and blades, with plans for instrumentation placement on the turbines underway. Modelling has been carried out using the data recorded from the instrumentation to date, with some wake behaviour and other key flow characteristics being observed.

Current and future sensor placements will further increase understanding of the flow characteristics and corresponding loading effects on the turbines. This will allow for further array modelling to be performed which will be key in understanding the relationships between turbine array placements and the fatigue and extreme loads experienced by the tidal turbines.

Contact

HEAD OFFICE

Nova Innovation
45 Timber Bush
Edinburgh
EH6 6QH

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

www.enfait.eu

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