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ENFAIT
ENABLING FUTURE ARRAYS IN TIDAL

AIM: Final Report

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1 Introduction

1.1 Preface

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.

1.2 Background

The EnFAIT project was carried out to allow for the effects of differing array layouts to be measured, modelled and demonstrated. An increased understanding of the effects of array layouts on performance and loading will help push tidal energy towards bankability and commercialisation.

The Nova Innovation EnFAIT tidal turbine array is located in Bluemull Sound. Bluemull Sound is between the islands of Yell and Unst in Shetland, Scotland. The tidal array is located just off the Cullivoe headland, Figure 1.

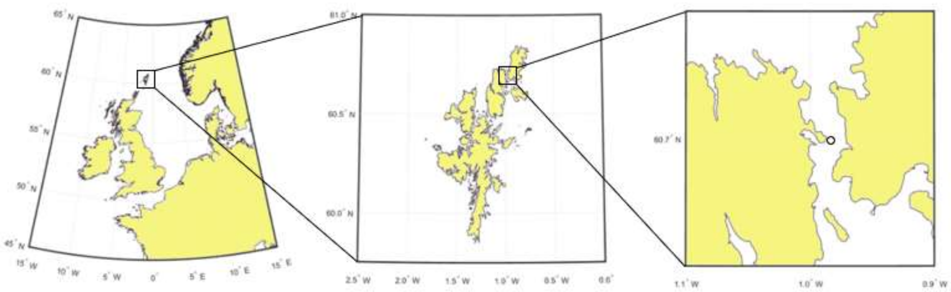

Figure 1 - Tidal array location - Bluemull Sound

To investigate tidal array effects, three additional turbines were installed in Bluemull Sound, Shetland to expand the existing array of three turbines. Tidal flow monitoring devices were installed alongside the turbines at various locations across the site. In addition, load and power performance measuring equipment was installed onto the turbines. The combination of the data streams from installed sensors, alongside modelling work, has provided powerful insights into array effects. These insights have influenced the placement of the second set of three turbines in the array and will further inform the layout of future tidal arrays.

The original three turbines in place on the site at the outset of the EnFAIT project were the Nova Innovation M100 turbines, with the additional three installed being a newer model; the M100-D. Both turbine models are rated at 100kW with a 9m and 8.5m rotor diameter respectively. Turbine 4 was installed in 2020, with turbines 5 and 6 being added to the array early in 2023.

Figure 2 - Nova M100-D Tidal Turbine (Nova Innovation, 2023)

1.3 Purpose

This document presents the synthesis and analysis of data and findings from the Array Interaction Model (AIM) and makes recommendations for further work. The AIM was specifically built to inform and optimise tidal array layout.

2 Array Interaction Model

2.1 Overview

The array modelling technique presented is based around 3 modelling methods: a site resource model; a wake model built using Computational Fluid Dynamics (CFD); and a Blade Element Momentum (BEM) model. The results from these three models are brought together in MATLAB to produce a tool to inform array design.

The modelling approach has been selected to offer a balance between complexity and computational efficiency. The AIM tool aims to be physically accurate, and useful for modelling array loading and power effects, whilst remaining practical to execute. The approach is semi empirical and is built upon high fidelity site and turbine data, and numerical simulations.

2.1.1 Model build

The array interaction model is built around the 3 detailed numerical models, site flow data and turbine data. A flow diagram illustrating the modelling approach is shown in Figure 3.

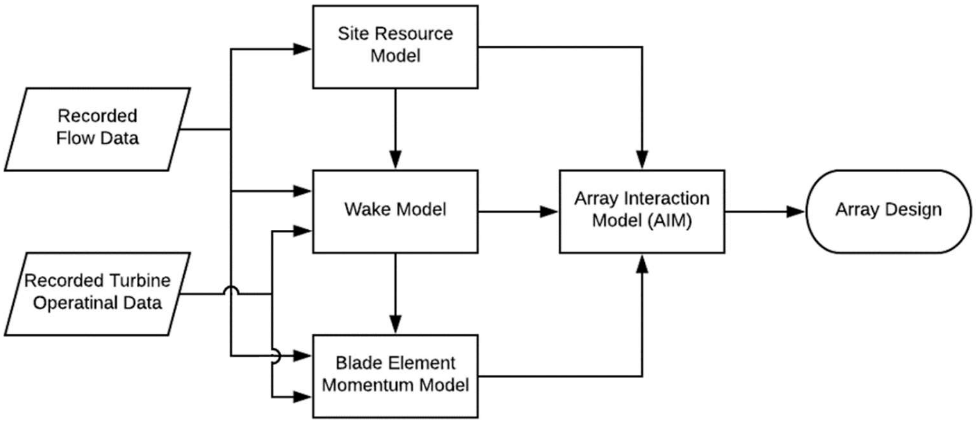

Figure 3 - Array model flow diagram

2.2 Site Resource

The site resource model includes modelling of both hydrodynamics and waves. Due to the complexity in accurately representing wave and current interactions, the hydrodynamic and wave components of the resource model are uncoupled. Both these aspects of the resource model have been validated using site installed ADCPs. The hydrodynamics show very good correlation with recorded data, the wave model less so. This is due to the effect the strong tidal current is having on the waves - were the model tends to under or over predict waves depending on direction.

For the hydrodynamic model, current and water level parameters were produced using a European, basin-scale flexible mesh hydrodynamic model, Figure 4. The underlying model has been developed using the MIKE21 2D modelling package, a comprehensive modelling system for two-dimensional water modelling developed at the Danish Hydraulic Institute (DHI).

For this project, additional resolution was incorporated into the model around the project area. In total, the model consisted of 223,215 triangular tessellations, the majority of which were in the Shetland area, with maximum horizontal resolutions of between 15-20m achieved in Bluemull Sound.

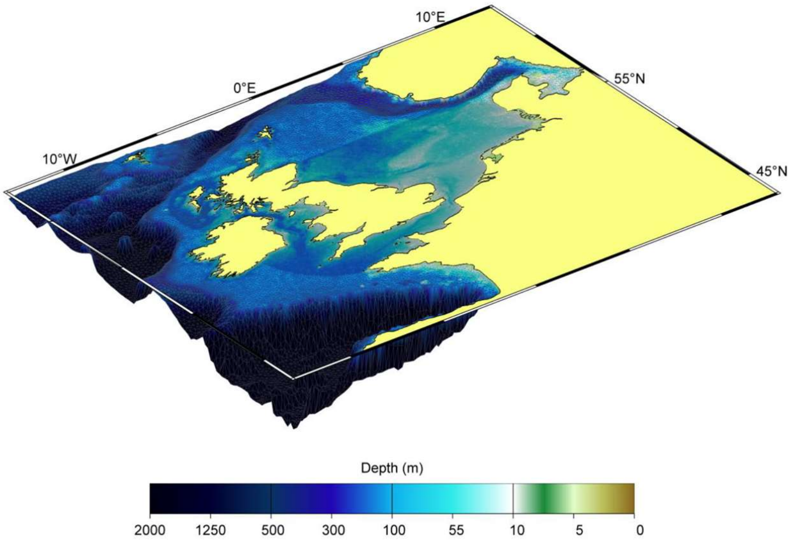

Figure 4 - Regional European MIKE21 flexible model mesh.

Tidal boundary conditions originated from the TPXO 7.2 Atlantic Ocean model. Maintained by the Oregon State University, TPXO7.2 is the latest version of a global model of ocean tides, which best-fits, in a least-squares sense, the Laplace Tidal Equations along with track-averaged data from the TOPEX/Poseidon and Jason satellites. The hydrodynamic model mesh can be seen, Figure 5.

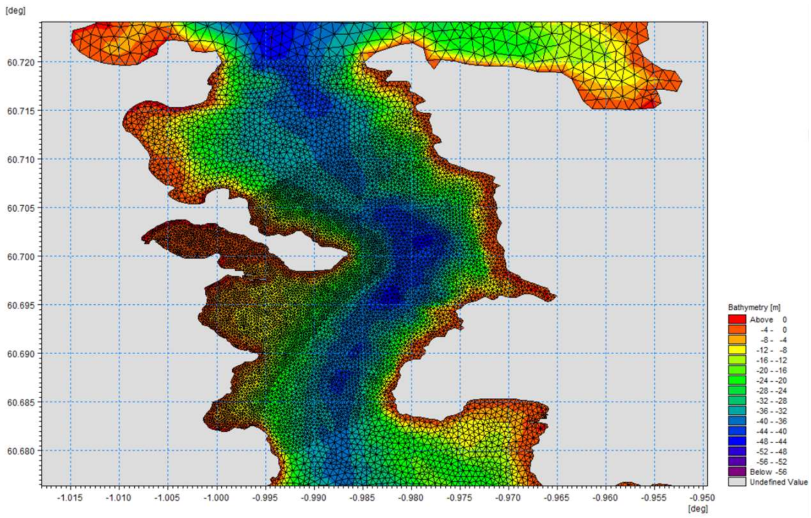

Figure 5 - Local MIKE21 flexible model mesh.

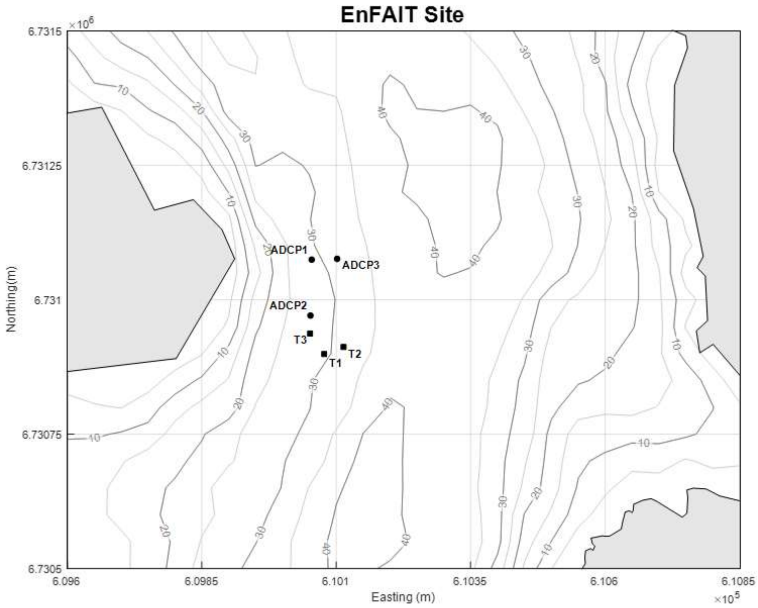

Figure 6 - ADCP measurement campaign 1 deployment locations relative to turbines T1, T2 and T3.

The hydrodynamic model was calibrated against water levels and velocities measured from ADCP measurements. Modelled water levels from the hydrodynamic model are compared with measurements at three ADCP locations across the site, Figure 6. A good correlation can be seen across all three deployed ADCPs, Figure 7.

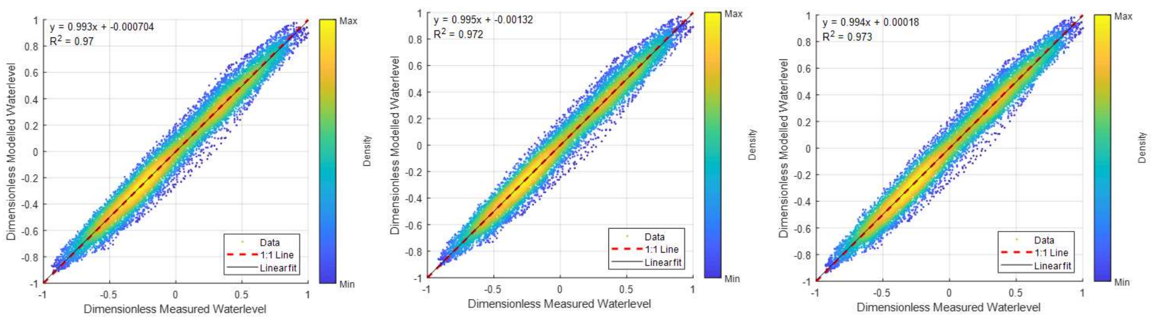

Figure 7 - Water Level comparisons at 3 ADCP Locations

A high resolution (9km) European Shelf wave model, which has been run to produce a 39-year European wave hindcast, provided boundary conditions to a high-resolution nested wave model local to the Shetland Islands and Bluemull Sound for the 20-year period from 1998 to 2017. The deployment of a high-resolution nested wave model that properly accounts for shallow water processes is necessary to account for the complex regional bathymetry and coastline which affects the evolution of the local wave climate. The Shetland area model had a regularly spaced grid with a horizontal resolution of 1km whilst the final nest of Bluemull Sound was unstructured and had a maximum horizontal resolution of 60m in the vicinity of the study area.

The underlying wave models have been developed using SWAN (Simulating WAves Nearshore), a third-generation wave model, developed at Delft University of Technology (TU Delft), which computes random, short-crested wind-generated waves in coastal regions and inland waters. SWAN accounts for the following physics:

- Wave propagation in time and space, shoaling, refraction due to current and depth, frequency shifting due to currents and non-stationary depth.
- Wave generation by wind.
- Three- and four-wave interactions.
- Whitecapping, bottom friction and depth-induced breaking.
- Wave-induced set-up.
- Transmission through and reflection (specular and diffuse) against obstacles.
- Diffraction.

Significant efforts were made to include hydrodynamics in the unstructured nested wave model of Bluemull Sound. However, the study area is so complex in terms of wave/current interactions that it ultimately proved too expensive both in terms of time and computational effort to achieve good calibration. As a result, the final wave model did not include hydrodynamics.

Comparisons of measured and modelled waves (without currents) are given in Figure 8. These plots demonstrate that the wave model without currents sufficiently describes the mean wave behaviour.

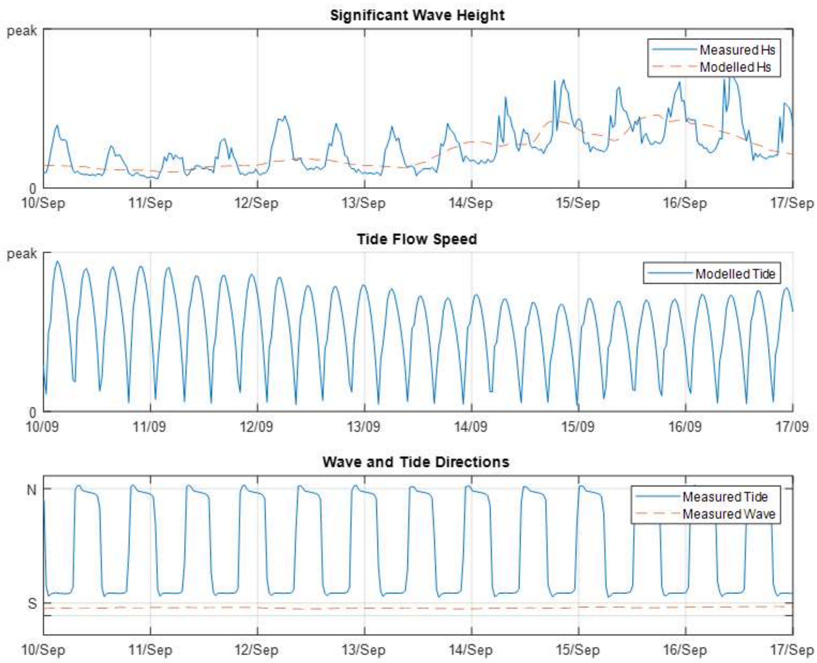

Figure 8 - Time series of measured and modelled waves.

It can also be seen, from these plots, that there is a significant relationship between tide speed, tide direction wave direction and whether Hs is under or over predicted, Figure 9.

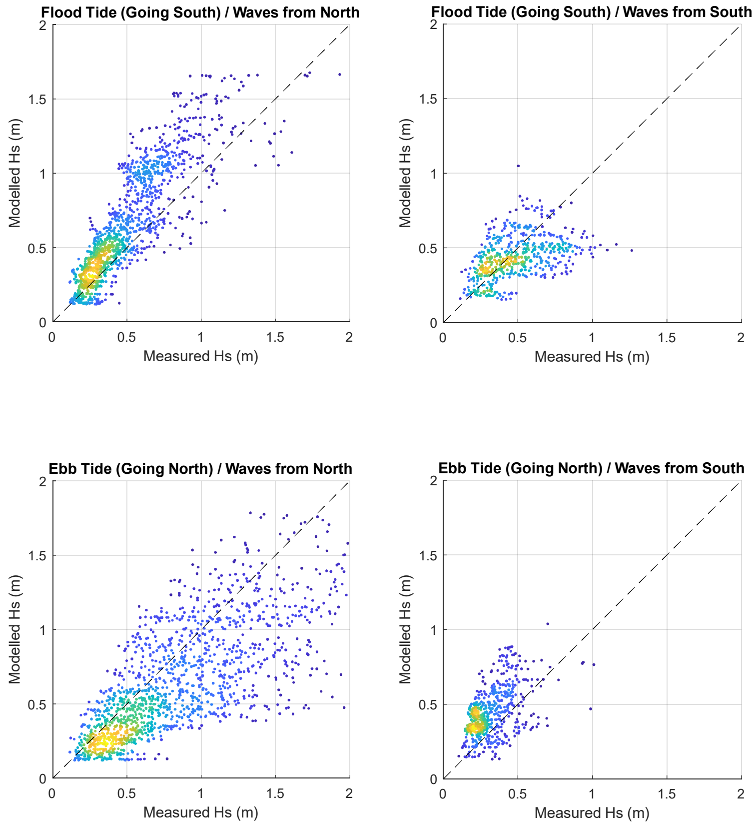

Figure 9 - Comparison of measured and modelled Hs on an Ebb tide with waves from the north, Plot coloured by tide flow speed

Looking in more detail at the comparison of predicted Hs to measured, it can be seen that the tide alters the wave climate. For the case of the tide running in flood (from north to south) and waves coming from the north it can be seen that Hs tends to be over predicted. When the tide and the waves are running in the same direction Hs is reduced from predicted.

The opposite can be seen with the tide flowing in ebb (from South to North) and the waves coming from the south, Figure 9. The model tends to under predict wave height. When the tide and the waves are running in opposite directions Hs is increased from predicted. There is less data available when waves arrive at site from the south. This is due to the site geography. The relationships established are less obvious but still apparent.

Looking in more detail at Ebb tides with opposing waves from the north, Figure 10, it can be seen that there is a relationship between tide speed and the prediction of Hs. The model under predicts Hs to a greater extent with greater flow speed. It can also be seen that at the lowest flow speeds the model over estimates Hs. When the tide is flowing against the waves it has the effect of increasing the wave height. This happens as the tide reduces the wave speed but not the energy contained within the wave. When wave and tide are flowing in the same direction the tide increases the wave speed, reducing the average wave height.

The complex relationship between flow speed, flow direction, wave direction and wave height make prediction of wave induced flow velocity fluctuations at the turbine difficult. Further research needs to be performed to properly inform future array load modelling. The impact this has on the AIM is to make predictions of wave induced loading less accurate. However, over time, the average wave climate is well represented. This can be accounted for in the AIM.

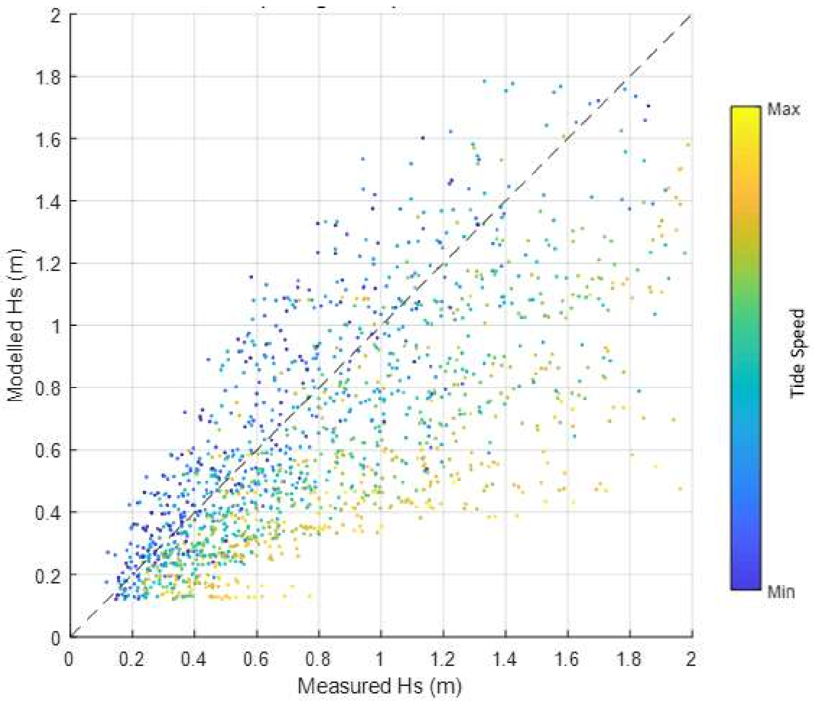

Figure 10 - Comparison of measured and modelled Hs on an Ebb tide with waves from the north, plot coloured by tide flow speed.

2.3 Bathymetry

Site bathymetry data has been used from several sources. Data has been taken from EMODnet, the UKHO INSPIRE portal, Oceanwise raster charts and a site bathymetric survey carried out on behalf of Nova Innovation. The regional coastline was discretised using the Global Self-consistent, Hierarchical, High-resolution Geography (GSHHG) Database.

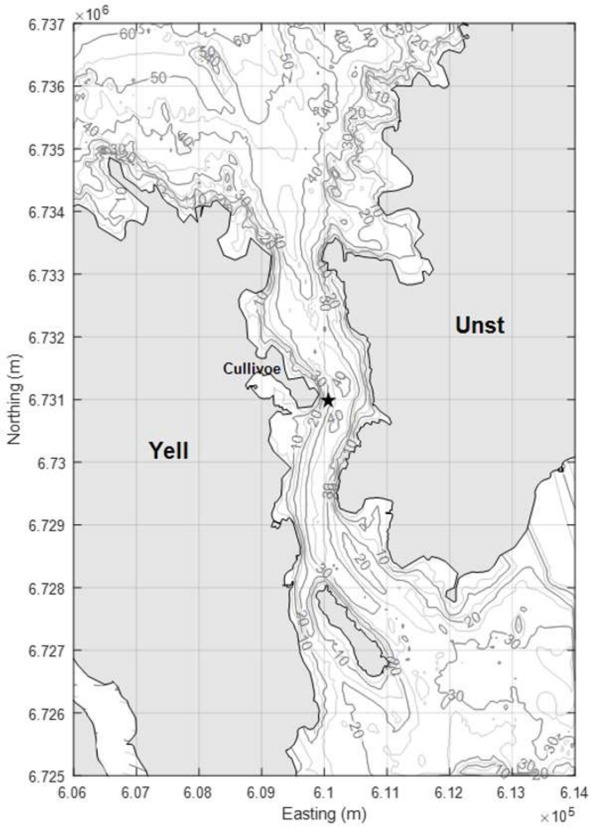

Figure 11 - Bluemull Sound tidal site shown with bathymetric depth contours.
The star indicates the tidal turbine site location.

2.4 Flow data

Site recorded data has been used to seed and validate the models built as part of the EnFAIT project. Acoustic Doppler Current Profilers (ADCPs) were installed across the turbine site to ensure good spatial resolution, Figure 6.

2.5 Array interaction Model (AIM) Analysis steps

The array model runs following the steps outlined here.

2.5.1 Step 1 – Establish undisturbed flow

Data taken from the pre-run numerical flow models is loaded into the model. This data includes:

- Position
- Depth
- Depth averaged flow speed
- Depth averaged direction

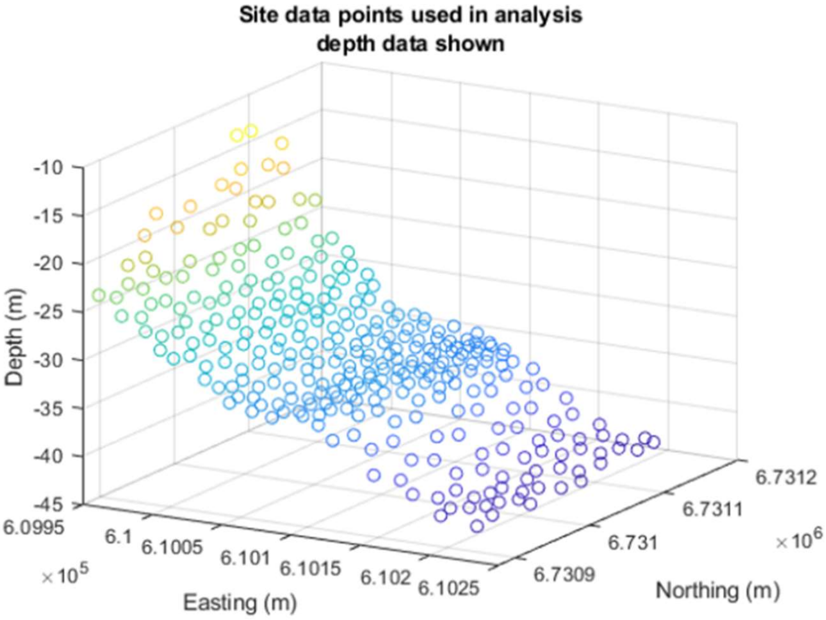

Figure 12 – data points loaded for area of study

2.5.2 Step 2 – Define turbine performance curves

The second step is to define the base performance of the turbine. This includes using the power curves developed from the EnFAIT turbine benchmarking exercise undertaken, an example of a typical power curve is shown in Figure 13.

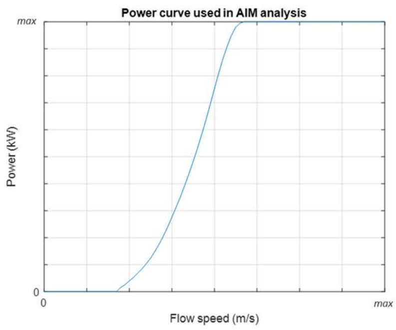

Figure 13 - Typical power curved used in tidal performance modelling.

2.5.3 Step 3 - Find hub height flow speed across site

For the range of depths and flow speeds possible, in the data set, the average hub height flow speed is calculated, and stored within the model, based on:

- the flow direction (Ebb/Flood)
- the depth
- the depth averaged flow speed
- the shear profile

2.5.4 Step 4 – Define turbine locations

For the installation scenario to be considered the turbine locations are defined. In optimisation runs this step can be skipped.

2.5.5 Step 5 – Define solve grid

The model solution time is affected by the number of grid points that are solved. By allowing for grid definition in the model, areas of greatest interest can be allocated the most solve locations. This keeps fidelity in the areas of interest while maintaining an acceptable solve time.

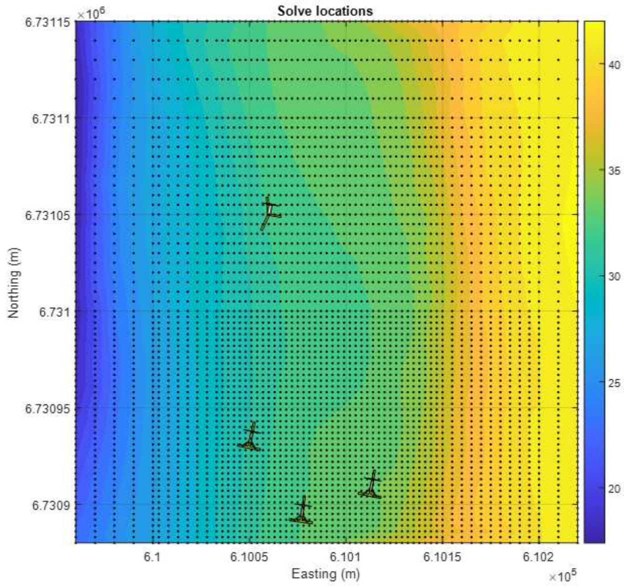

Figure 14 - Example of a solve grid in a 4-turbine scenario.

2.5.6 Step 6 – Loop through timesteps

With the model data loaded, the turbine locations defined and the solve locations identified the next step is to solve the flow field for each time step, Figure 15. This process is done following these points:

- Generate velocity and direction interpolants for the site for the current time step
    - An interpolant function is created for the gridded solve points from the pre-modelled flow data
- At each turbine location generate a wake based on flow speed and direction
    - A wake model is overlaid on the pre-solved flow field to produce waked flow areas at each time step
- Sum wake velocity deficit with site velocity
- Calculate and store site available power
    - Calculated using the defined turbine power curves and the calculated flow speed
- Exit loop

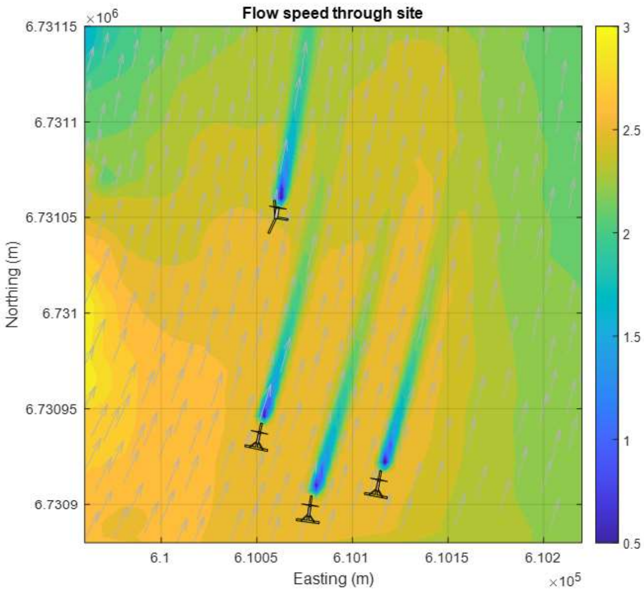

Figure 15 - AIM time step snapshot showing calculated site flow speed.

2.5.7 Step 7 - Sum available site power from all saved loop executions

At each time step turbine power was recorded. Once the analysis loop is finished the power values can be summed together for overall energy yield performance analysis.

2.5.8 Step 8 – Apply inflow angle modifier

At each turbine location analysed for power, the power is calculated at a range of predefined inflow angles. Summation of power results at these angles allows for a plot of installed angle performance to be produced. The peak of this plot dictates the most powerful angle for turbine installation at a calculated turbine position.

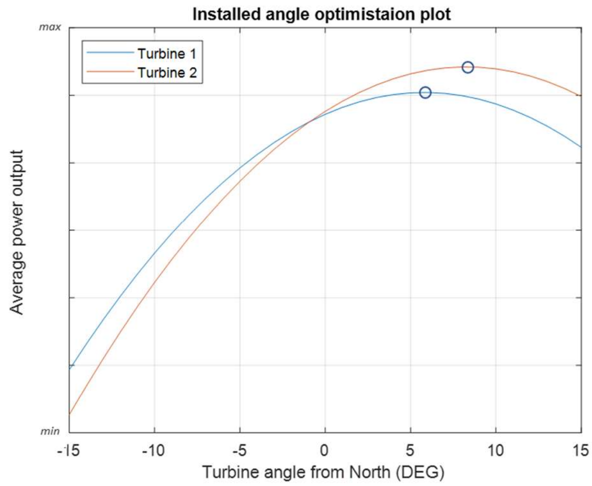

Figure 16 - Turbine performance variation with installed angle.
Note peaks at 6 and 8 degrees for scenarios considered.

2.6 Wake model

The wake model uses 2 different gaussian decays for two directions. One set of decay variables define the wake dissipation down-stream of the turbine, the other across the stream. The wake model has been validated using site data and CFD of the site and turbines. It is scaled based on flow speed and tracks the flow direction.

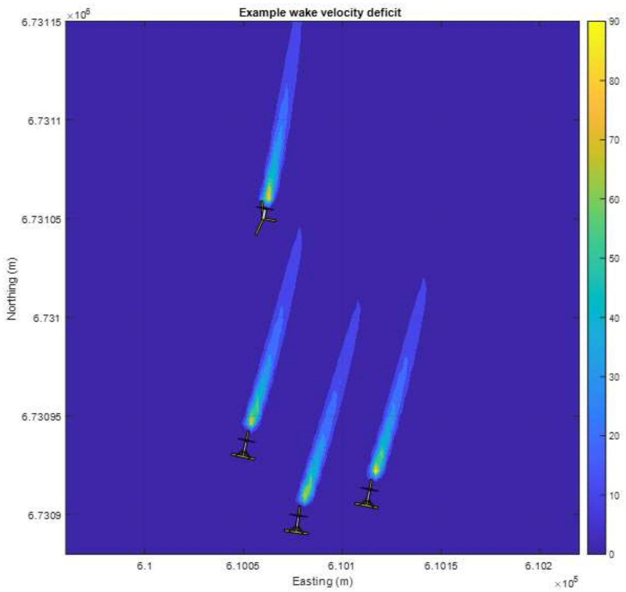

Figure 17 - Example of wake deficient model.

Shown, Figure 17, is an example of the velocity deficit (as a percentage) for one example timestep of the AIM.

3 Results

3.1 Site selection

The AIM was used to determine the optimum turbine installation positions for turbines 4 to 6 (T4, T5 and T6) of the 6 turbines installed in the Shetland Tidal Array. Turbines 1 to 3 (T1, T2 and T3) were previously installed based on optimum resource availability, from early site resource models, and site seabed conditions, Figure 18.

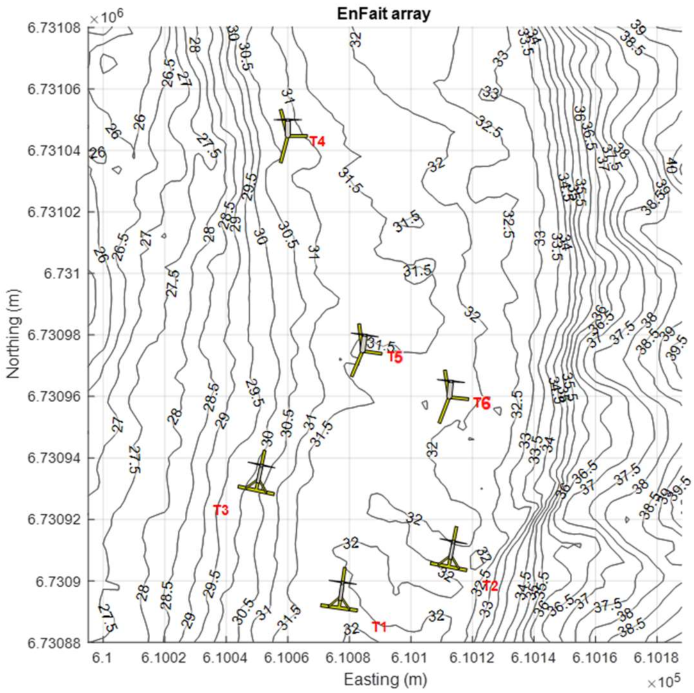

Figure 18 - As installed EnFAIT tidal array.

Turbine number 4 (T4) was installed to the north of the site, around 115m north of turbine 3 (T3). This site was selected to prove T4 wake dissipation over this distance. This was proven as T3 performance remained unaffected by the installation of T4.

Through AIM iterations, sites for T5 and T6 were selected.

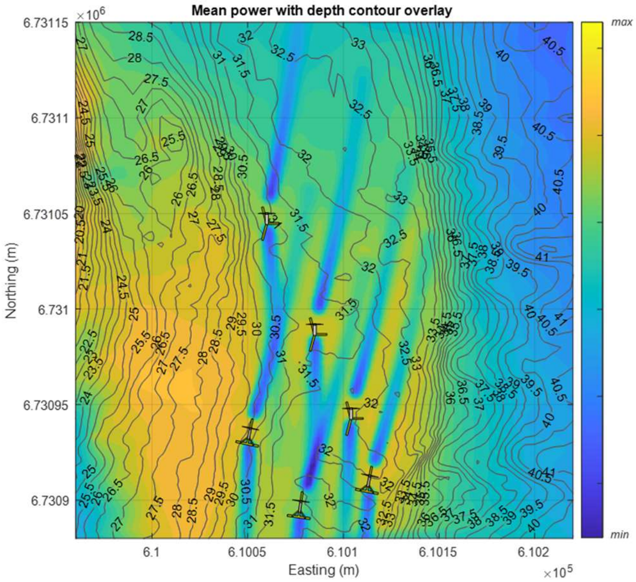

Figure 19 - AIM average power result plot.

The particular turbine sites were selected based on optimising power across the array while maintaining locations that were most practical for installation.

4 Validation

4.1 Dashboarding

In order to visualise the performance of the turbines on a consistent basis, ORE Catapult developed a dashboard for analysing the availability and reliability of the turbines for any given time period. Over the course of the project, this dashboard and its methodology was developed for ease of use, efficiency and to ensure high quality of outputs.

4.1.1 Development

Engineers from Nova and ORE Catapult collaborated to develop a methodology for studying the performance and reliability of the array using a number of key performance indicators (KPIs). The dashboard was used to access KPIs and also allow benchmarking of the array.

The data was stored in a SQL server and processed using a number of SQL based scripts to update the tables with new data and define the operative state of the turbine at each timestamp. The data was then aggregated, metrics were calculated and graphs created. The dashboard was updated frequently and used primarily for updating stakeholders and AIM validation.

4.1.2 Operative states and KPIs

Data was supplied in the form of 5-min aggregated SCADA, power curves and flow data (modelled from ADCP measurements). From this, the turbines could be defined as being in one of a number of operative states, defined below, that were adapted from the IEC TS 61400-26-1:2011 (IEC, 2011).

The operative states, defined every 5 minutes, and the accompanying potential power from flow data allowed the calculation of a number of highly useful KPIs:

- Operating Hours
- Production (MWh)
- Downtime (hours)
- Lost Production (MWh)
- Time-based availability (%) (technical and operational)
- Production-based Availability (%) (technical and operational)
- Capacity factor (%) (actual and potential)
- Number of forced outages (split by general component type)

4.1.3 Outputs

The key outputs from the dashboarding, in relation to the AIM, were the installed turbine performance figures.

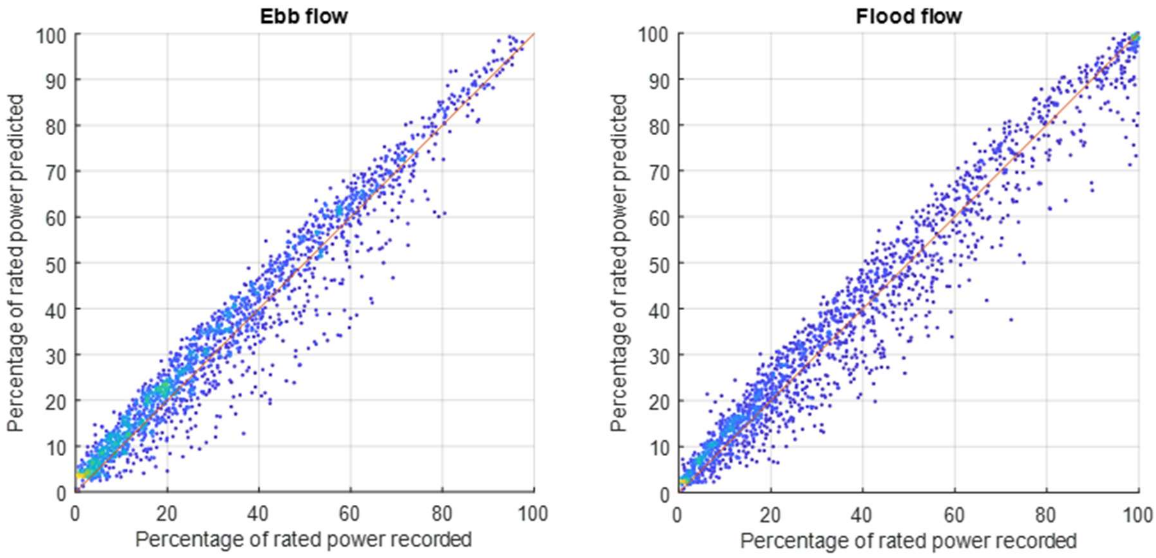

Figure 20 - Recorded turbine performance figures against AIM performance figure predictions for turbine T4.

Figure 20 shows recorded turbine power figures (as a percentage of rated power) plotted against the power figures predicted by the AIM. The fit of the data is achieved by tuning the power curve in the AIM. Very good power correlation can be seen in the AIM if real world data is available, for fine tuning, for a modelled turbine. The key to accurate AIM performance is good site and turbine data.

4.2 Wakes

Turbine wake measurements have been recorded using fixed and vessel mounted (VM) ADCPs.

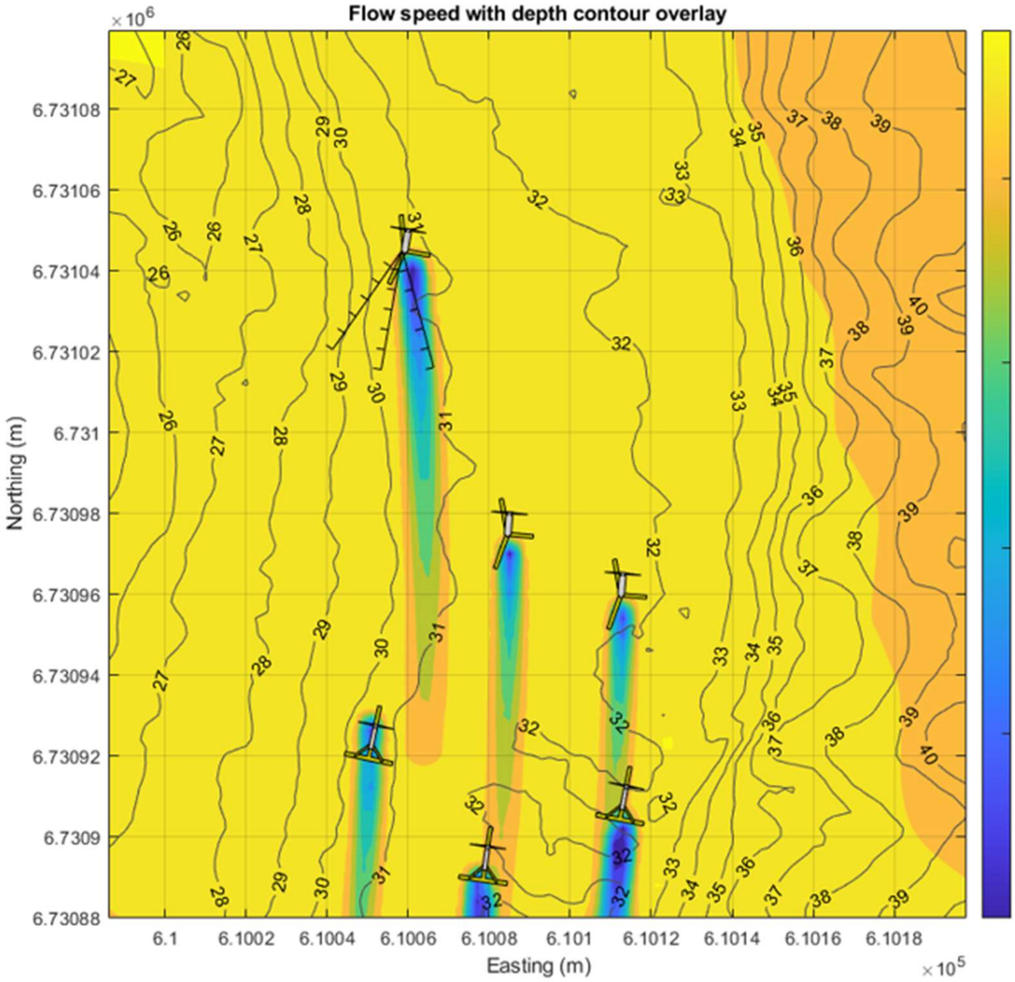

Figure 21 - AIM solve time step with ADCP beams indicated at turbine T4.

A rear facing, horizontally mounted ADCP was installed on turbine T4, Figure 21. This turbine mounted ADCP recorded flow directly through the wake.

Flow speed recorded on the ADCP beams were converted to stream wise velocities. Wake flow speed data was then binned based on nearby freestream flow speed and averaged to give wake flow speed measurements for various inflow speeds, Figure 22.

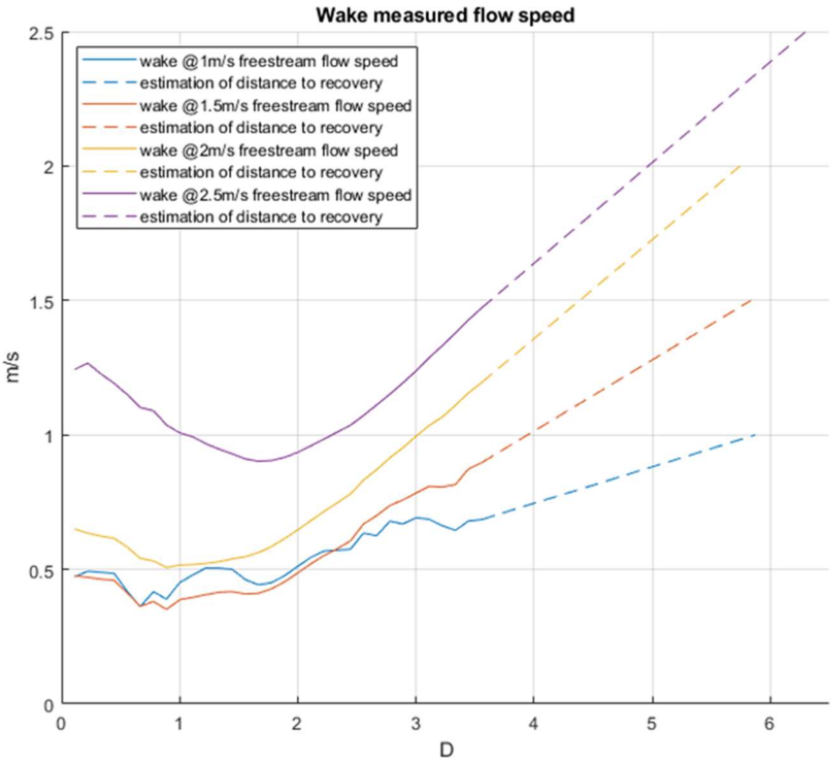

Figure 22 - Recorded wake flow speeds at various freestream flow speeds.
Wake recovery prediction beyond turbine ADCP range shown by dashed lines.

Shown, in Figure 22, are recorded wake velocities, at numbers of turbine Diameters (D), down-stream of the turbine. Due to the limited range on the ADCP, the distance of full recovery to the freestream velocity has been estimated and plotted as a dashed line. Estimation was done by projecting a straight line back from the best fit of the last 1.5D of data points.

This method of wake estimation shows that the wakes modelled in the AIM are conservative; the wakes in the AIM take more distance downstream to fully recover than those recorded in reality. The wakes in the AIM were left conservative to ensure any errors in measurements or wake analysis do not result in real-world sub-optimal energy yields from turbine placement.

4.2.1 Wake Vessel Mounted (VM) survey

VM ADCP survey runs were carried out across the EnFAIT site to gather downstream wake measurements in various locations. The equipment was mounted onboard a multicat vessel and survey sweeps were recorded by moving the vessel upstream of the turbines, idling the engine and allowing the vessel to drift over the site as the ADCP recorded flow measurements down through the water column.

VMADCP survey work carried out previously on the project was used to inform placement of turbines 4,5 and 6. A further VMADCP survey campaign was carried out across three days after the installation of turbines 4, 5 and 6 to gather validation datasets for the AIM wake predictions.

Shown, in Figure 23, is a survey run that took place during a flood tide. The wake of T5 is clearly shown, beginning at the far left of the cross-sectional slice, indicated by the slowed blue flow, and carrying on downstream towards T1. Comparing this observation with the AIM wake path prediction, a good consensus is seen.

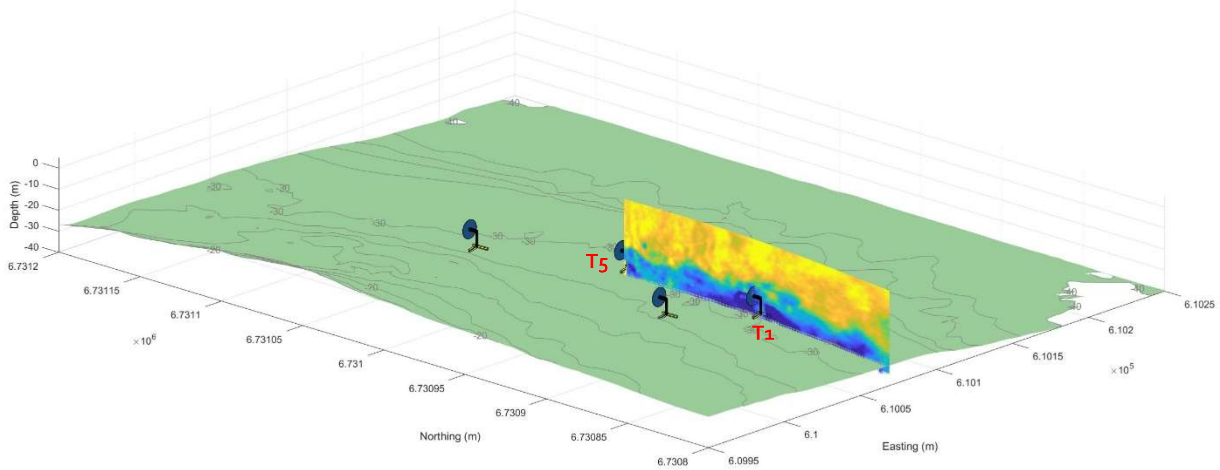

Figure 23 - Flood survey run over T5 & T1 showing wake paths

For the survey run shown, in Figure 23, the hub height velocity downstream of turbines 5 and 1 were plotted to analyse wake recovery, Figure 24Figure 25. With a free stream flow speed of around 2.5 m/s, the wakes can be seen to recover across a distance closely comparable with the wake predictions from Figure 22. The similarity in wake recovery behaviours across the 6 rotor diameter distance downstream of the turbines recorded using the nacelle ADCP and the VMADCP survey data is closely comparable with wake recovery predictions made using the AIM.

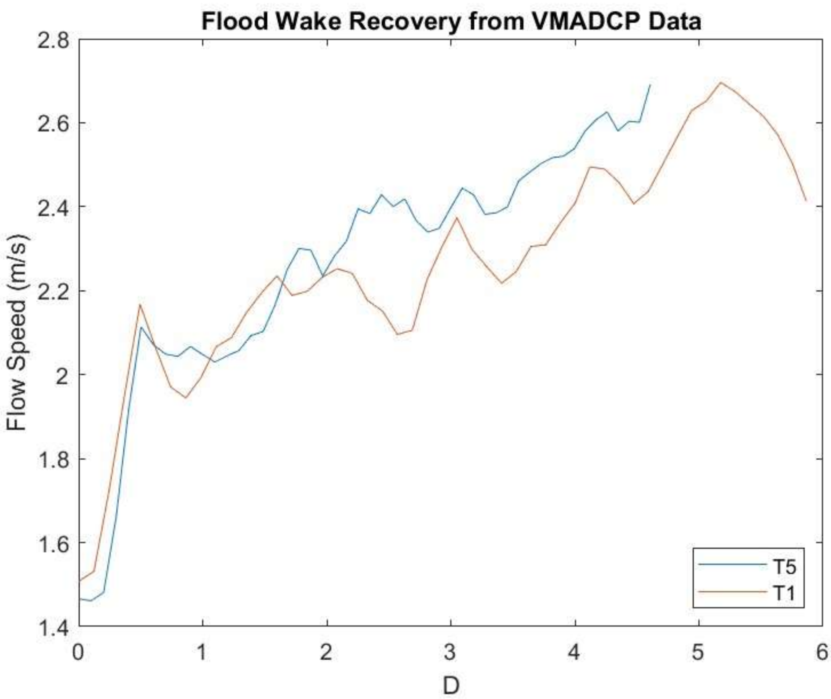

Figure 24 - Wake recovery downstream of turbines, D is turbine diameters

Cross sectional VMADCP survey runs across the site were also carried out, such as that gathering the measured flow field shown in Figure 25. The wakes of various turbines can be seen downstream of them, giving an indication of the initial paths of the wakes immediately downstream from the turbines.

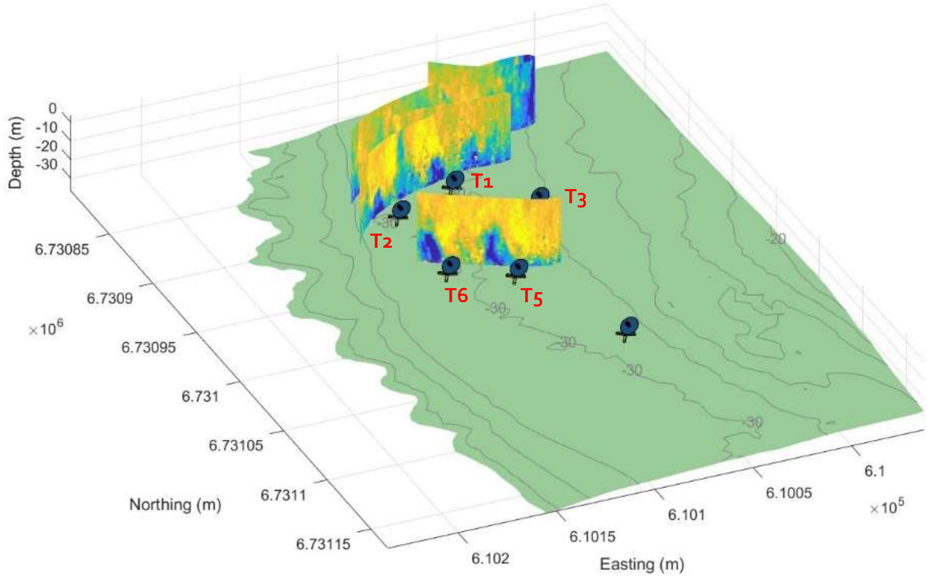

Figure 25 - Cross sectional survey runs showing various wake locations

A survey run during an ebb tide is shown in Figure 26, with the path of the run passing directly over turbines T1 and T6. The wake recording behind turbine T1 shows an obvious initial slowing before abruptly speeding up further downstream before the survey run reached T6. This is due to the survey vessel drifting eastward from the T1 wake and picking up the free stream flow incident with the T6 inlet. Again, this indicates that the T1 wake path passes north and through the gap between T5 and T6, as predicted in the AIM.

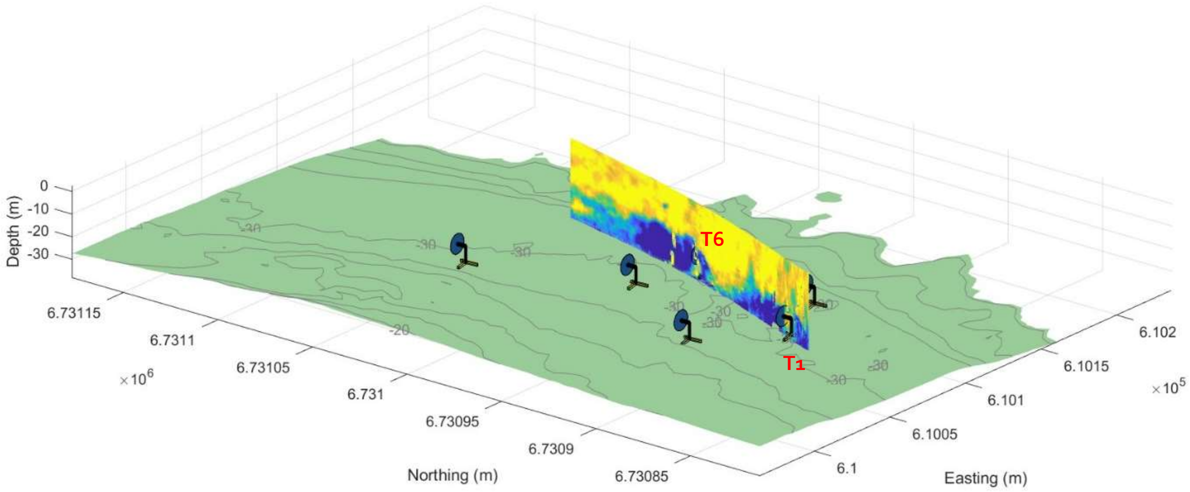

Figure 26 Ebb survey run directly over T1 and T6 showing wake paths

Both the vessel mounted and turbine mounted ADCP data show wake recovery. The VM data suggest around 6 diameters, at higher flow speeds (2.5m/s), for wake recovery. While the Nacelle mounted ADCP data suggested around 7.5D. There are various possible reasons for the differences observed, e.g. if the VM run did not fully track the middle of the wake it could have exited the wake early, or it could also be suggested that the wake recovers more quickly at higher flow speeds; more research is required to confirm this.

4.3 Power Performance Analysis (PPA)

Power performance analysis (PPA) was performed on the turbines within the EnFAIT array, Figure 19. The key to assessing the success of the AIM was a PPA on turbine T2 as the turbine most likely to be affected by an upstream wake, Figure 21.

The IEC Standard for the power performance assessment of electricity producing tidal energy converters was used as guidance to perform the PPA (IEC, 2013).

The PPA carried out used turbine electrical power output data recorded in conjunction with flow data from the ADCP validated numerical model. The PPA was carried out following these steps:

- Firstly, the power available from the flow normal to the turbine rotor in ebb and flood was calculated from the tidal flow velocity predictions.
- The average velocity across the cross-sectional area of the rotor was then calculated. The flow shear profile through the water column being considered as recorded through the ADCP depth bin measurements.
- The average performance velocities and corresponding recorded power values were then placed in flow speed bins in 0.1 m/s intervals from 0 m/s to 3 m/s and the average performance velocities and recorded power values for each bin were calculated.
- The recorded power values were multiplied by the efficiency factor of 0.99, provided by Nova Innovation, to account for losses in the line transformer prior to the binning operation.
- Flow speed bins corresponding to an estimated hub height of 8.5m above the seabed were used for the performance velocity calculation. The bins selected provided average flow speed and direction over a vertical range of 1m from 8m – 9m above the seabed.
- Finally, the Annual Energy Production (AEP) was calculated.

A PPA on turbine T2 shows a clear performance drop after turbines T5 and T6 were installed on the site. Turbine T6 is around 70m to the North of turbine T2, this is ~7.8 turbine diameters. Analysis shows that T2 performance dropped by ~25% (on flood tide direction only) due to the impact of waked flow, Figure 27.

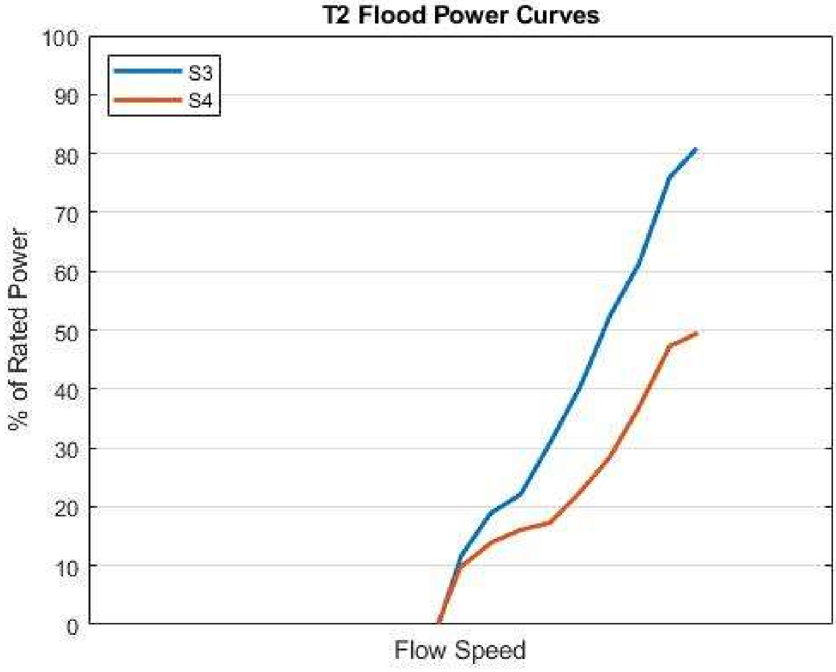

Figure 27 - Flood power curve comparison for T2 pre (S3) and post (S4) installation of T5&6 showing decrease in power production

Comparing the performance of T3 in flood before and after T5&6 were installed (Figure 28) little or no performance change was observed. This behaviour indicates that it is in fact the waked flow on T2 from T6 that causes the drop in performance of T2.

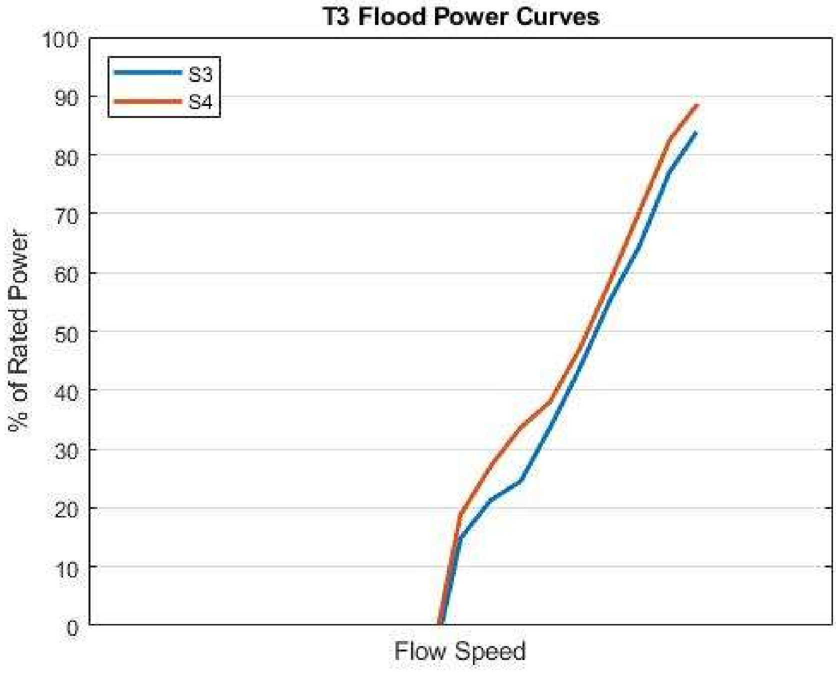

Figure 28 - Flood power curve comparison for T3 pre (S3) and post (S4) installation of T5&6, showing little or no change in performance

To further prove that the performance drop seen in T2 during flood is caused by waked flow, the performance in Ebb was plotted in Figure 29 before and after the installation of T5&6. As expected, the ebb performance remains unchanged with the installation of T5&6 as they are placed downstream from T2 during ebb flow.

Figure 29 - Ebb power curve comparison for T2 pre and post T5&6 installation showing no change in performance

The AIM model predicted closer to a 15% performance drop. As has been shown in Figure 22, the wake model used in the current AIM is not fully representative of what has been recorded on site, and this will have impacted power results on the turbines installed near wakes of others. There are also differences in the flow data predicted at the turbines and that present in real life (any on-turbine flow monitoring is effected by the blades and thus less reliable) so power estimates are calculated on modelled flow data. This makes power estimates less accurate, this factor also impacting AIM accuracy.

While there is inaccuracy present in the AIM, the work done shows it can successfully predict near optimal tidal array layout with modest computational overhead combined with engineering input.

4.4 Summary

The AIM can produce accurate estimates of optimal array layout. The modelling and site recorded data, at the EnFAIT site in Bluemull Sound, show excellent correlation and an optimally designed array.

The AIM does not perfectly predict yield where turbines are within the wakes of others. It predicts yield well for turbines which are not in the main wake of others, however, predicts less well those turbines which are in the wakes of others. This is not a failure of the model as wakes are challenging to predict and an optimal array layout will not include heavily waked turbines.

The AIM is good at predicting yield for turbines in un-waked flow. The AIM can produce array layouts which are optimal for power. Combining this with solve speed and engineering decision making, the tool can rapidly help designers produce optimal array designs.

The AIM tool demonstrates the importance of wake location and optimal array layout. Site data suggests that turbine wakes will have dissipated around 7 to 8 diameters back from the turbines. With array sites all being individual, change in flow speed from ebb to flood and change in direction from ebb to flood being two of the major considerations for array layout, it is not as simple as stating arrays should have a 7 to 8 diameter spacing. The AIM shows that tighter spacing can be achieved if the flow regime, including wakes (avoidance), is considered as a whole.

5 Further Work

Future work identified for further AIM improvement post EnFAIT could include:

- Developing a fuller understanding of VM survey results and incorporating these findings into improved wake modelling.
- Combine VM ADCP understanding with high resolution fluid flow simulation of wakes to produce very accurate wake models.
- Apply AIM to another site to produce array layouts and compare to other tools for validation.
- Work to improve power performance estimates by improving wake models and inferred flow speed estimates.

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