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ENFAIT
ENABLING FUTURE ARRAYS IN TIDAL

D10.8 – Array Interaction Model (AIM) T1-4 Operational Report

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1 Overview

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 is produced to summarise the results and emerging findings to date in developing the EnFAIT Array Interaction Model (AIM) for assessing the effects of turbine array layout on the EnFAIT tidal site and is also to be submitted to satisfy deliverable D10.8 of the EnFAIT project. The deployment of sensor systems, designed in T10.7, which have allowed the gathering of data to feed the ongoing development of the AIM tool is discussed, as well as a preliminary PPA (Power Performance Assessment) carried out on the T4 turbine, which will support and feed into the AIM.

2 Array Interaction Model Progress

The array interaction model uses both site recorded and modelled data to predict the behaviour of the EnFAIT array. The multi model approach used is designed to model tidal turbine array interactions in a computationally practical yet physically accurate manner.

2.1 Site 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 concurrently across the turbine site to ensure good spatial resolution. The ADCPs were installed for a period of three months and recorded current data in 0.5m bins from 1.5m above the seabed to the water surface.

Shown, in Figure 1, are the recorded site flow velocity shear profiles. For comparison, a power law profile has been included.

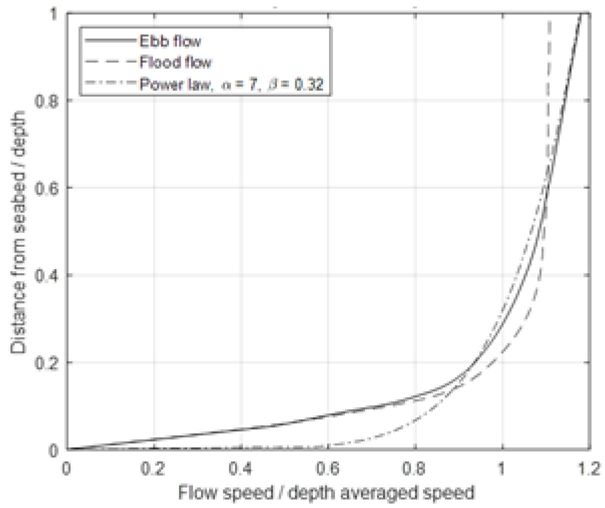

Figure 1: Site flow velocity shear profiles for ebb, flood and 7th power law

The ebb profile shows continued flow speed increase towards the surface in line with a typical power law governed profile. The flood profile, however, approaches peak flow speed around the middle of the water column and only marginally increases further towards the surface. This asymmetry in current speed profile is due to the difference in route to site the flow takes in ebb and flood.
During the north-going ebb tide, the flow is coming out of shallow water to the south and has longer to flow in a shallower channel. This means bottom friction is acting on the flow for longer, developing the shear profile further. During the south-going flood tide, the flow is coming out of deep water to the north, as a result, the shear profile does not develop to the same extent.
Wave conditions were also measured, on site, throughout the 3 seabed ADCP deployment campaigns to date. From the measured data a range of wave conditions have been observed. Figure 2 shows the wave climate occurrence during the second set of seabed ADCP deployments.

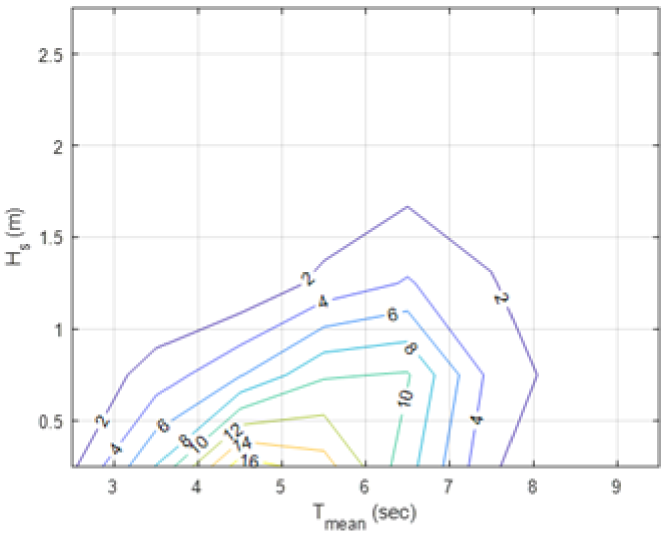

Figure 2: Site recorded wave climate occurrence map

Wave direction is predominantly from the North with a little resource from the south. The site is very sheltered from waves in all other directions. The island of Linga to the south of the site helps to reduce the wave resource coming from the south. The site is only exposed to open waters to the north, through the mouth of Bluemull Sound.

Looking at the occurrence map, Figure 2, it can be seen that, for the duration of the ADCP deployment, the majority of the wave resource is below 1 metre significant wave height. The recorded wave resource mean period also tends to be short.

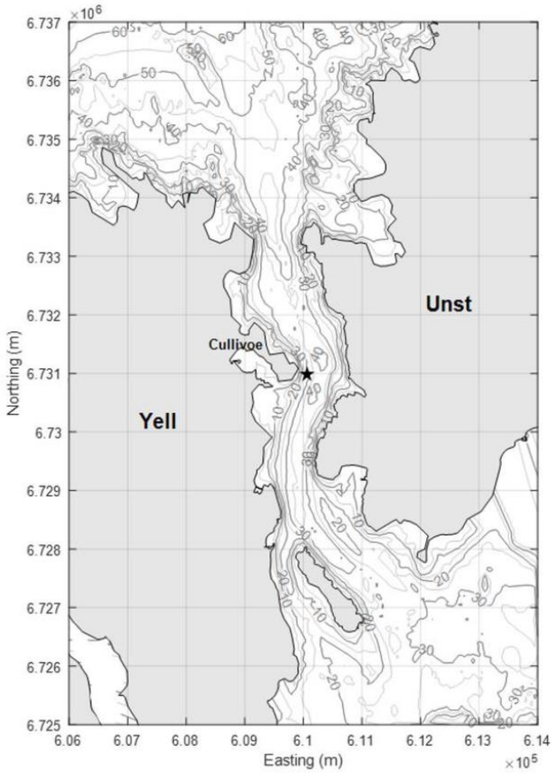

Figure 3: Site geography causing wave directionality

Turbulence has been characterised by turbulence intensity. For a measured point in the velocity field, turbulence intensity, Iu, is defined as the root mean square of the time series velocity fluctuations, u', divided by the mean velocity flow, ū.

$$I_u = \sqrt{\frac{\langle u'^2 \rangle - noise}{\bar{u}}}$$

Equation 1

Mean velocity flow has been taken over 10-minute intervals. Velocity fluctuations have also been taken over 10-minute intervals, mean velocity fluctuations squared is defined by ⟨u'2⟩. Signal noise is removed to improve the estimate of turbulence intensity. For simplicity noise has been defined as the square of velocity fluctuations at slack tide.

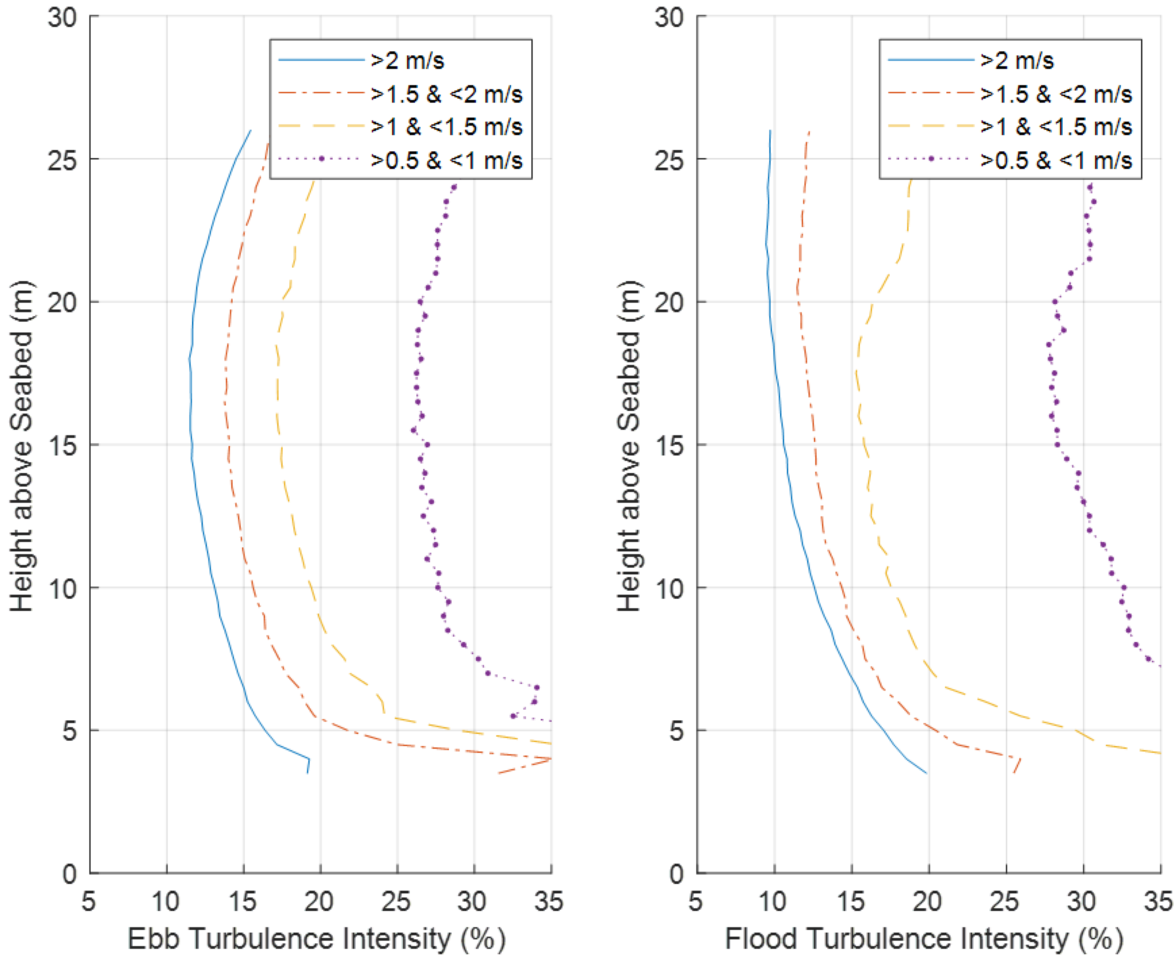

Figure 4: Site turbulence intensity

Turbulence intensity has been quantified through the water column, for ebb and flood flow, at a range of hub height flow speeds. There is an increase in turbulence intensity with decreasing flow speed. As turbulence intensity is calculated with velocity as the denominator, a similar level of velocity fluctuation will have a larger turbulence intensity at a lower flow speed.

From the analysis performed, it can be seen that in operational flow speeds (generally considered to be >1m/s) turbulence intensity varies from around 12 to 20%. Measured turbulence intensity values will be used to build and calibrate wake numerical models.

2.2 Array Model

The array modelling technique 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 is semi-empirical and is built upon high fidelity site and turbine data and numerical simulations.

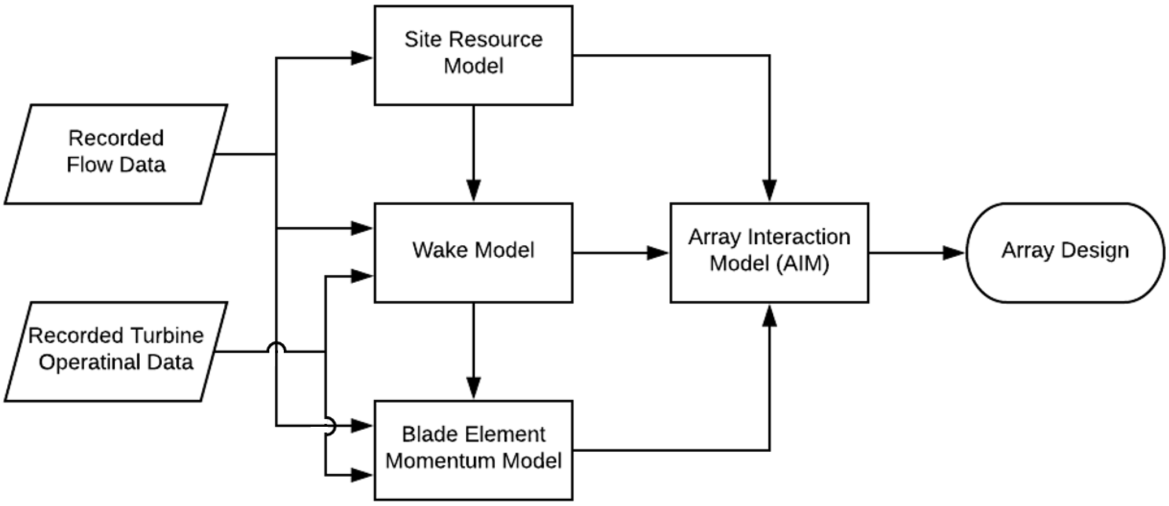

Figure 5: Modelling approach flow diagram

The array interaction model is built around 3 detailed numerical models, site flow data and turbine data. A flow diagram illustrating the modelling approach is shown in Figure 5.

All three of the models have been built. To date only the site resource model has been fully validated. The most recent ADCP data recorded will be used to validate both the wake and blade element momentum models.

Figure 6 shows a snapshot of a Large Eddy Simulation CFD analysis carried out as part of the wake model.

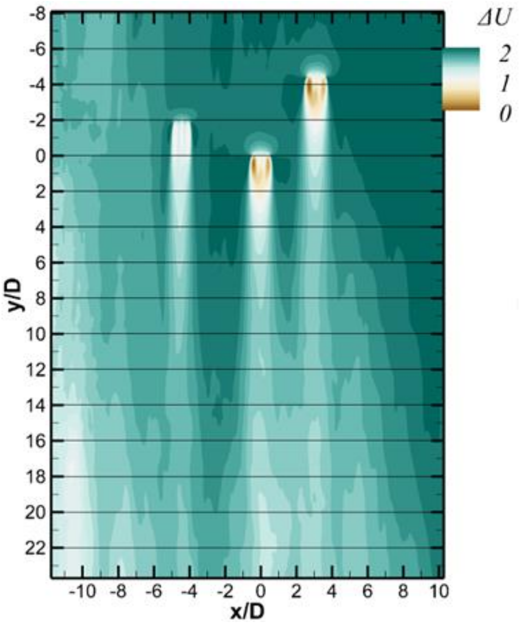

Figure 6: Wake model CFD analysis using Large Eddy Simulation

The inflow conditions that are then fed into the BEM model are made up of 4 components: shear profile, tower shadow, wave action and turbulence. These 4 flow components combine to produce a representative flow regime for the site that is fed into the BEM model.

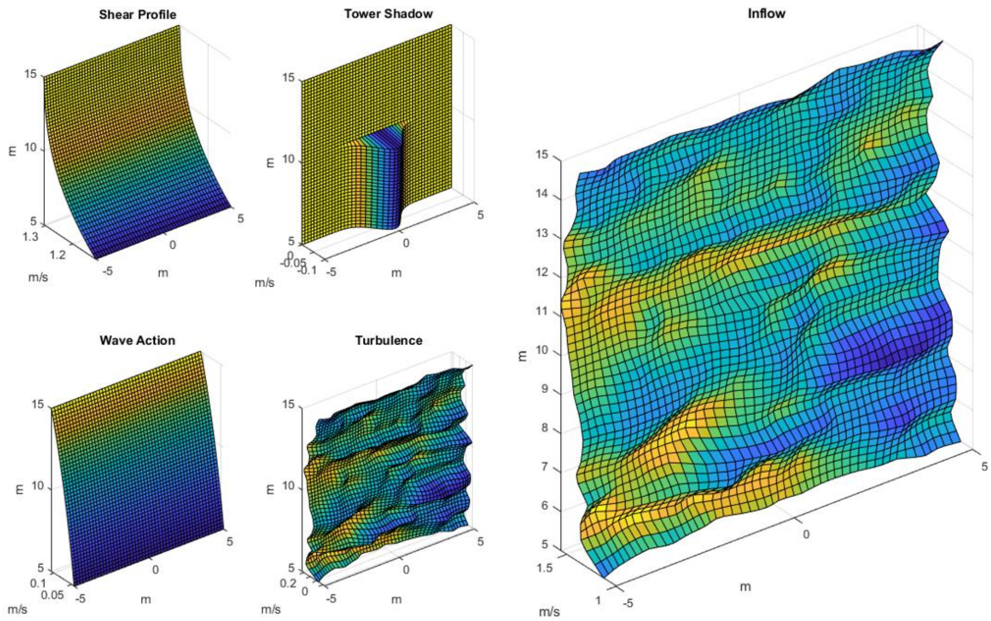

Figure 7: BEM model flow components combine to produce flow regime representative of site

Figure 8 shows an example of the results that are then produced by the AIM through combining all of the outputs from the other modelling steps. The model informed the position of turbine T4 and will inform the positions of the next turbines in the array.

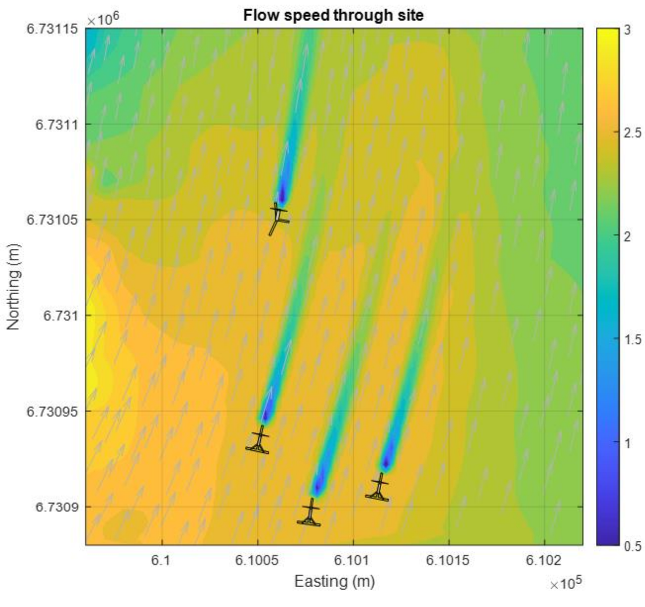

Figure 8: Example AIM results

3 Instrument Deployments

A range of sensor systems have been deployed on the tidal turbines and at sea. These systems are described here.

3.1 ADCP Instrument Seabed Deployments

Seabed mounted ADCP instruments were deployed in November 2020 to gather flow measurements through the water column at locations near to turbine T4. The deployment locations in relation to the installed turbines can be seen in Figure 9. The instruments were recovered in March 2021 and the data gathered will be used to further augment the AIM (Array Interaction Model).

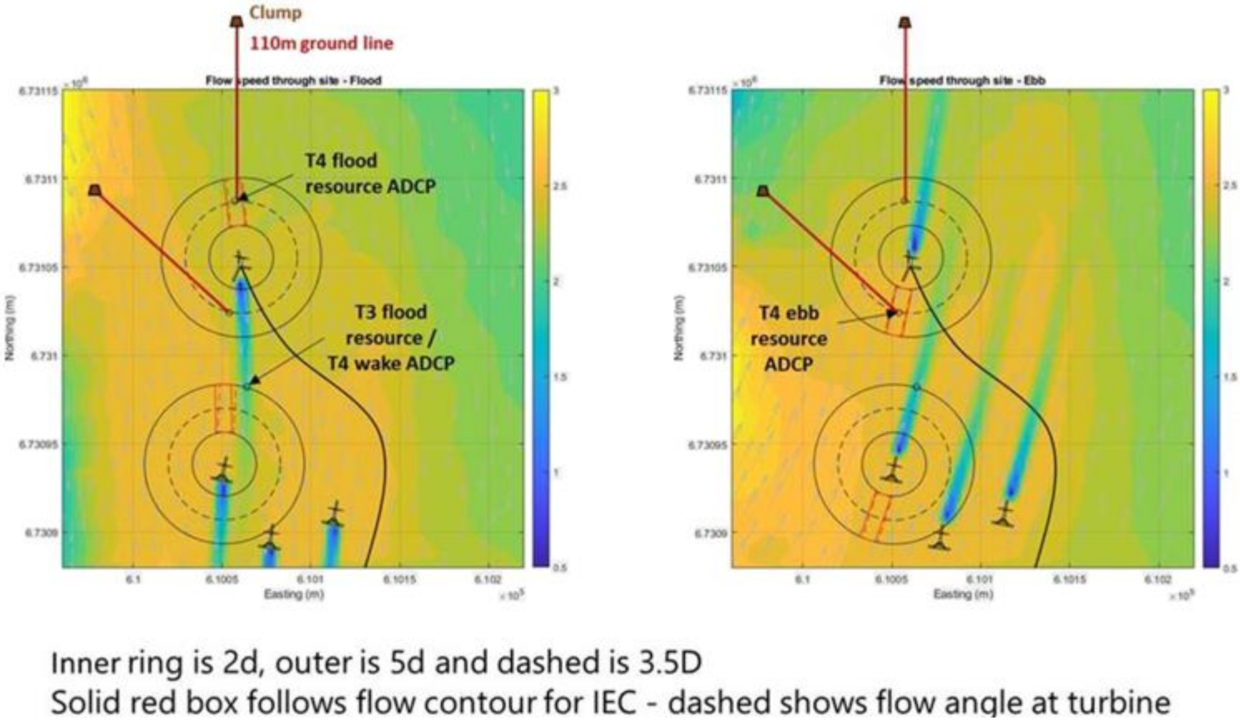

Figure 9: T1-4 turbine locations and ADCP seabed deployment locations

3.2 T3 Blade Strain Gauging

An optical fibre strain gauging system was installed in the turbine blades of T3. The system consists of optical fibre strings running up the front and back surfaces of both blades, meeting inside the turbine rotor hub. The data gathered by this system will allow the loading on the turbine blades to be better understood. This will further feed the AIM and provide insight into the effects of array configuration on turbine loading. The strain gauging system was installed and deployed in November 2020. The data gathered by the system is stored on a USB storage device mounted inside the rotor hub and will be recovered during the next available maintenance window.

3.3 Shaft Torque Transducer

Torque transducers were installed on the turbine shafts of T3 and T4, enabling the monitoring of the drivetrain torque, speed and power for each turbine. The data gathered by the transducer on T4 was used for the power performance assessment outlined in Section 4.

3.4 Instrumentation Skid Deployment

A frame was fabricated which was designed to rest on a vacant substructure of T1-3 and gather inflow measurements. The frame was deployed onto the vacant T2 turbine substructure whilst the nacelle was removed for maintenance works. Two ADCP instruments, one facing upstream and one facing downstream, were mounted onto the frame along with two Acoustic Doppler Velocimeter (ADV) instruments to gather flow measurements immediately upstream and downstream of the turbine during flood and ebb. The flow data gathered from this deployment is to be used in further AIM work as the tool is developed.

Figure 10: Instrumentation skid with ADCP and ADV mounted

3.5 Vessel Mounted ADCP

A vessel mounted ADCP survey was undertaken in February 2021. The survey involved the use of a downwards facing ADCP which was mounted to the side of a vessel. As the vessel moved around the EnFAIT tidal site, the ADCP gathered flow measurements down through the water column. The primary purpose of this survey was to gather data showing the locations and characteristics of the wakes caused by the current turbine array layout. With the survey now complete, work will be carried out to analyse the data gathered. This analysis will feed into the AIM and will be of great benefit in validating the estimates previously made by the model on turbine wake locations and characteristics.

Figure 11 shows results from one of the survey runs performed using the vessel mounted ADCP setup. The flow speed can be seen to be reduced downstream of the turbine, showing a clear wake produced by the operating turbine.

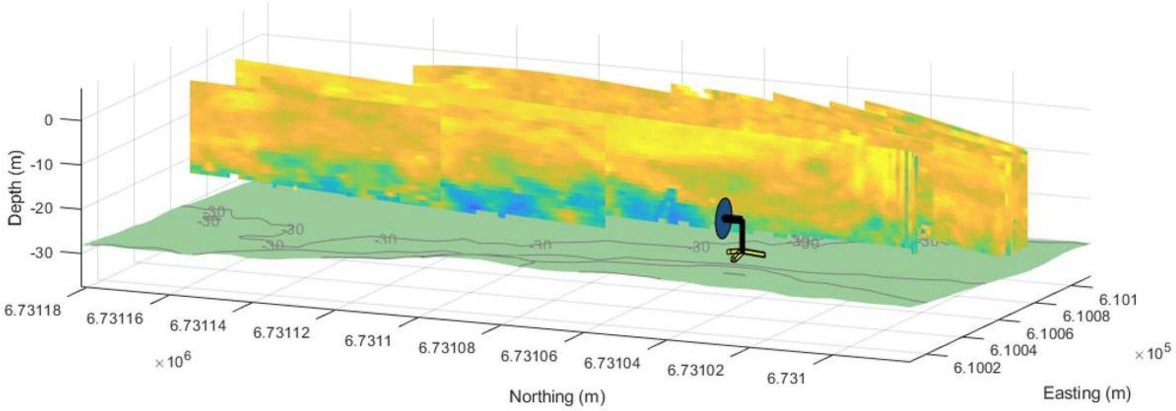

Figure 11: Vessel ADCP survey showing velocity deficit downstream of turbine

4 T4 Turbine Power Performance Assessment (PPA)

4.1 Background

A power performance assessment (PPA) was carried out to assess the performance of the T4 turbine on the EnFAIT site using the data collected from the torque transducer installed on the turbine as part of T10.9. The PPA forms a baseline to which further performance measurements can be assessed when the array layout is reconfigured in the later stages of the EnFAIT project.

Guidance was taken from the EMEC document 'Assessment of Performance of Tidal Energy Conversion Systems' (EMEC, 2009) to perform the performance assessment, with the process outlined in the document followed where possible.

The PPA carried out used the data gathered by a torque transducer fitted to the T4 turbine shaft in conjunction with the predicted flow speeds provided by the synthetic tide prediction. These flow predictions have been previously validated using measured data from ADCP instruments deployed on the site and are used to inform the operations of the turbines. The PPA used data over a 4-week period from 1st to 31st December 2020.

4.2 T4 Turbine Configuration

An overview of the T4 turbine technical specifications is shown in Table 1.

Table 1 T4 turbine technical information

Rated electrical power (kW)	100
Rated flow speed (m/s)	2
Flow speed range (m/s)	0.5 – 6
Rotor speed range (rpm)	10 to 27
Rotor diameter (m)	8.5

Hub height above seabed (m)	9.5
Fixed or variable pitch	Fixed
Number of blades	2

The location of the T4 turbine within the array during the timeframe of the analysis performed is shown in Figure 12 and Figure 13.

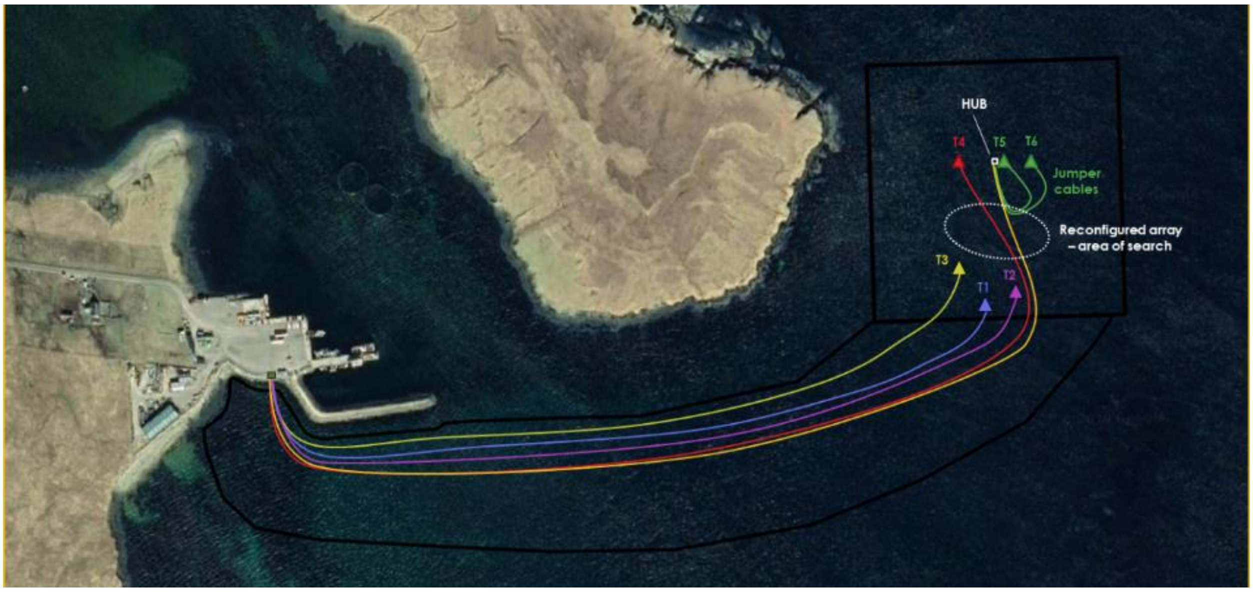

Figure 12: EnFAIT Site

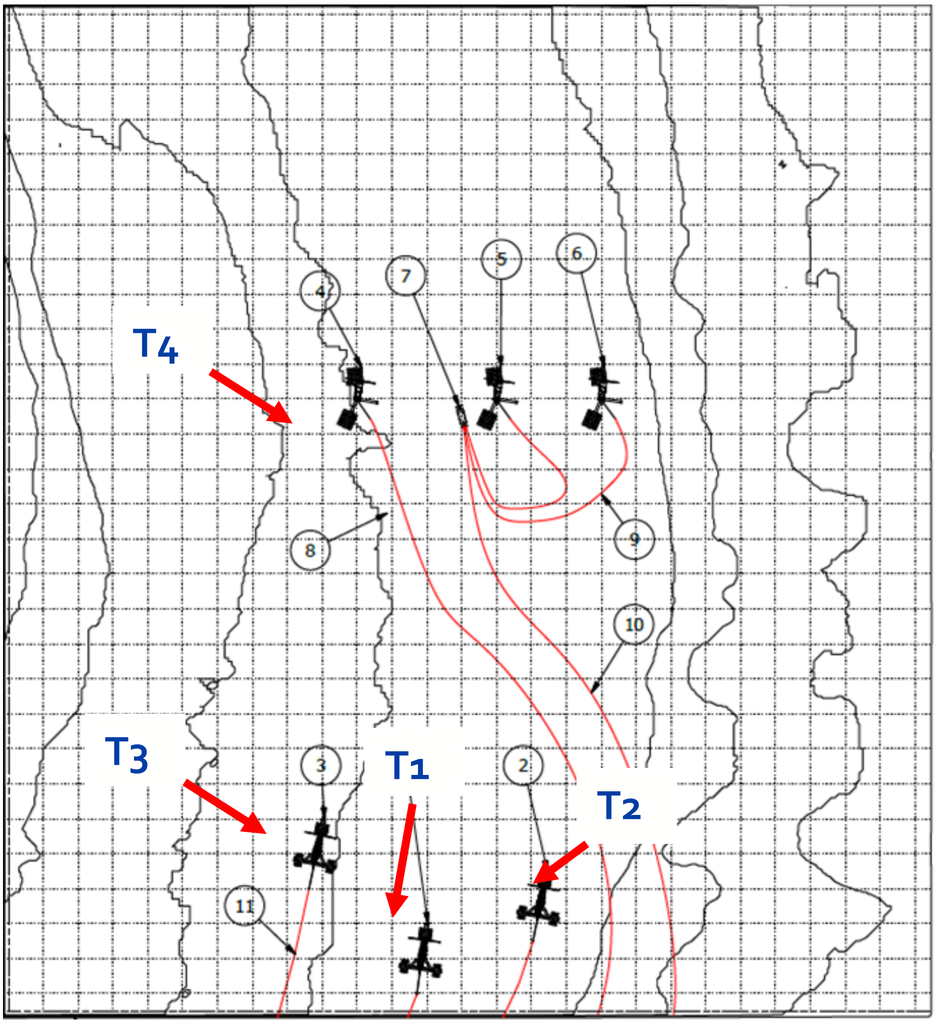

Figure 13: Tidal turbine locations on site - T1-4 installed to date.

4.3 Site Description

A detailed overview of the Bluemull Sound site with flow distributions throughout the tidal cycle can be found in the D10.2 report completed earlier in the EnFAIT project. A summary of the site bathymetry can be seen in Figure 14.

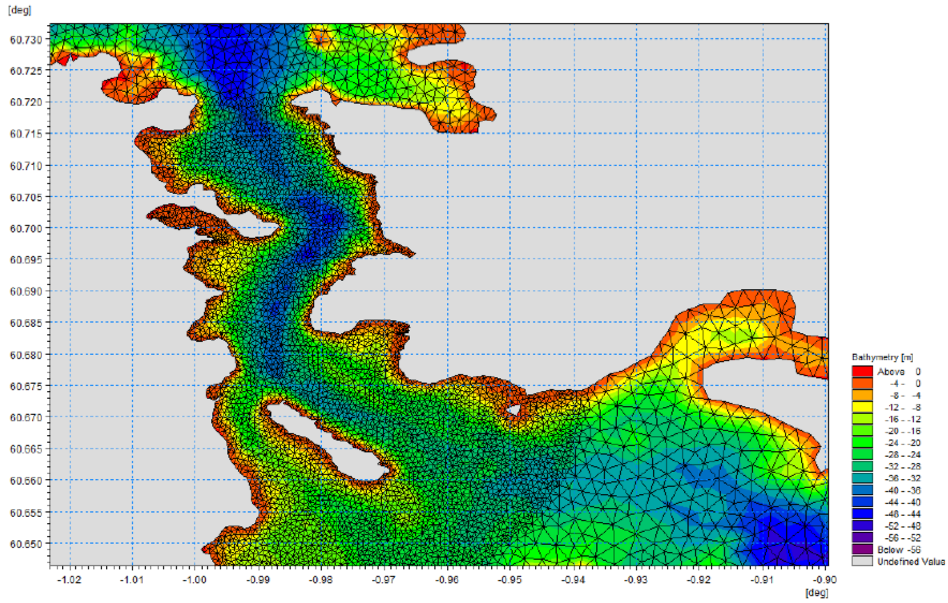

Figure 14: Site bathymetry

The tidal resource predictions for the year 2020 were fed into the PPA over the 4-week power measurement period. Flow speed and direction were normalised to the T4 turbine heading to assess the available power. Graphics of flow speed distribution across the site in Flood and Ebb tidal cycles, from the numerical model, during a typical spring tide period are shown in Figure 15 .

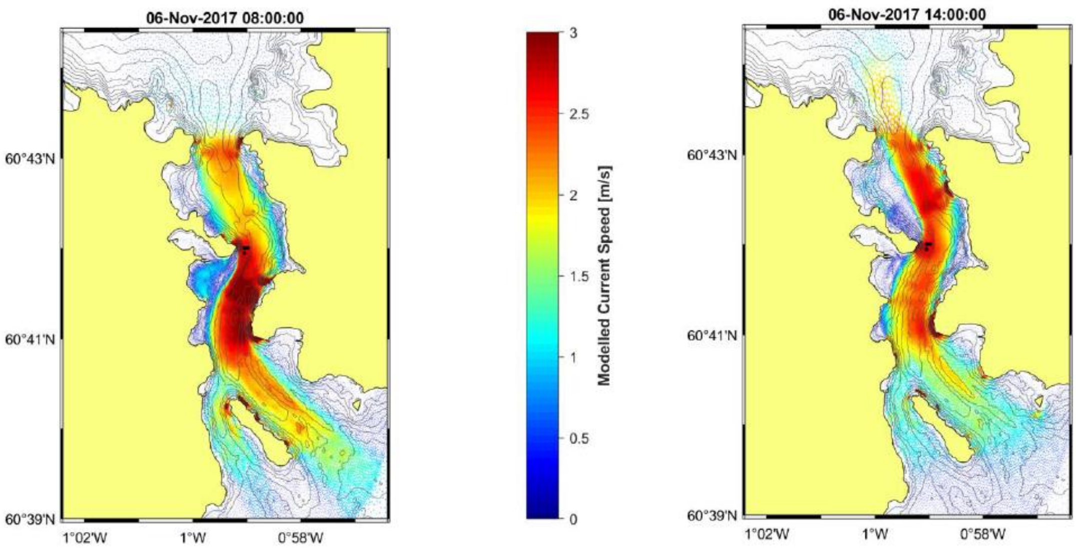

Figure 15: Flow speed distribution across site in flood and ebb

4.4 Test Equipment

A Datum Electronics Commercial Shaft Power and Torsion Meter was fitted to the T4 turbine shaft. The meter was set to record shaft torque, power and speed continuously at a sampling rate of 2Hz. The equipment can transmit average power readings at up to 5Hz, however, due to communication limitations, in the turbine data acquisition system, the sampling rate was limited to 2Hz. A measurement period of 4 weeks was used for the PPA which captured two full spring to neap tidal cycles, allowing the analysis to well represent the turbine power performance through the tidal cycle. The shaft power and torsion meter is shown in Figure 16.

Figure 16: Datum Electronics Commercial Shaft Power and Torsion Meter

Flow speed predictions from the synthetic tide data used to predict tidal flow speeds in 5-minute intervals across the site throughout the year 2020 were used to represent the flow conditions throughout the 4-week measurement period. This predicted flow data has proven to be accurate by validation with past ADCP deployments (MetOceanWorks, 2018).

4.5 Analysis Procedure

The procedure employed to perform the PPA was derived from the EMEC Marine Renewable Energy Guide document Assessment of Performance of Tidal Energy Conversion Systems (EMEC, 2009), as well as the IEC standard IEC TS 62600-200:2013 (IEC, 2013).

Firstly, the power available from the flow normal to the turbine rotor in ebb and flood was calculated from the tidal flow velocity predictions using Equation 2:

$$P_{KE} = \frac{1}{2}\rho A U_{perf}^{3}$$

Equation 2

The average velocity across the cross-sectional area of the rotor was then calculated. The flow shear profile through the water column had to be considered as the flow prediction model generates depth averaged velocity, however, in reality the velocity varies vertically across the rotor due to the flow shear profile. The average performance velocity calculation is shown in Equation 3.

$$U_{perf} = \left[\frac{1}{A}\sum_{k=S}^{k=1} U_k^3 * b_k * z_k\right]^{1/3}$$

Equation 3

Area of capture surface, A is given by:

$$A = \sum_{k=S}^{k=1} b_k * z_k$$

Equation 4

Where,

B_k = width of horizontal slice k through power capture surface

S = number of horizontal slices of the power capture area, normal to the direction of tidal current flow

K = subscript number of the horizontal slice centred around speed U_k

U_k = speed of flow of the tidal current normal to the power capture surface and flowing through the k^{th} horizontal slice of the power capture surface

Z_k = height of slice k taken horizontally through the power capture surface

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 recorder power values for each bin were calculated using Equation 5 and Equation 6.

$$U_{perf(i)} = \frac{1}{N_i}\sum_{j=1}^{N_i} U_{perf(i,j)}$$

Equation 5

$$P_i = \frac{1}{N_i}\sum_{j=1}^{N(i)} P_{(i,j)}$$

Equation 6

The resulting average normalised flow speed and corresponding average power in ebb and flood are summarised in Figure 17. The power coefficient was calculated using Equation 7. The power coefficient value for each flow speed bin was recorded.

$$C_p = P/[\frac{\rho A U_{perf}^3}{2}]$$

Equation 7

Where,

A = power capture area of the device

P = recorded power output (kW)

U_{perf} = average performance velocity of the tidal current

4.6 Results

The Ebb and Flood power curves are plotted together in Figure 17**Error! Reference source not found.**. The performance of the turbine can be seen to be closely comparable in ebb and flood, with the turbine generating a higher level of power output in flood at the highest production flow speeds. This difference in performance is likely due to the tower shadow present during ebb flow, which is not present during flood.

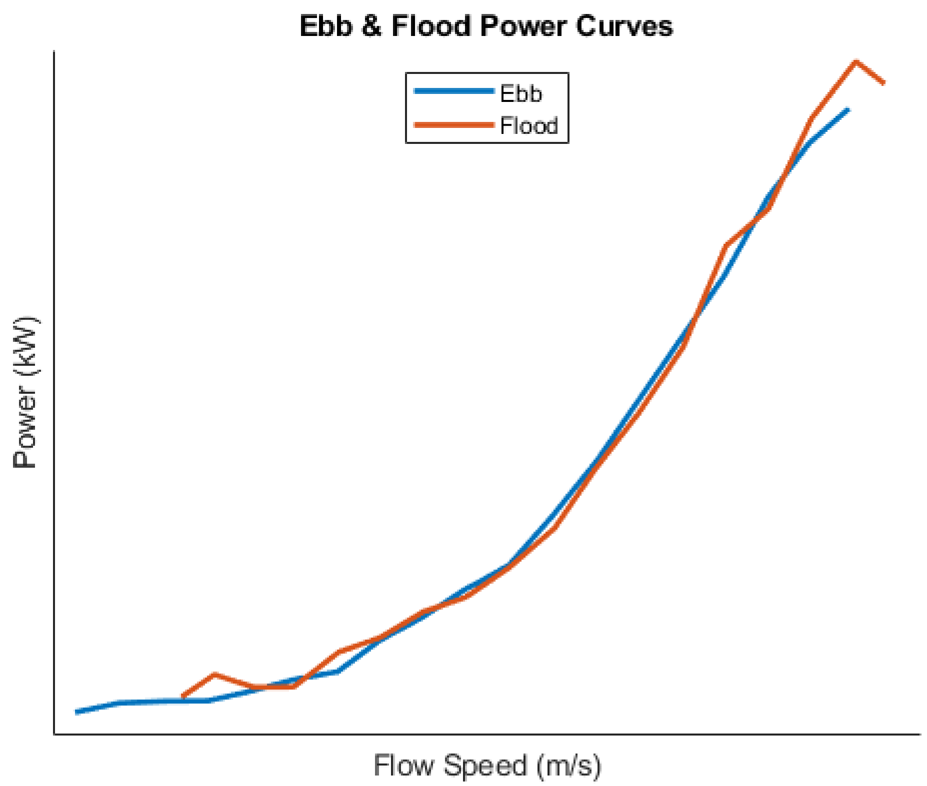

Figure 17: Combined Ebb and Flood power curves

4.7 Further PPA Work

The analysis performed used modelled flow predictions as inputs for the velocity. Some inaccuracy is associated with using this method as the point at which the predictions were made was around 200 metres away from the T4 location. Further PPA work will be carried out to gain more accurate result using flow data from an ADCP deployed near to the T4 turbine. This ADCP deployment has already taken place, as described previously, and analysis of the data is ongoing as discussed below.

5 Further Work

The results of the PPA outlined above, along with the data gathered from the various instrumentation deployment campaigns described will be used to further tune and validate the existing AIM.
The full analysis of the data gathered in the various instrumentation deployments is ongoing.
The data gathered from the recent vessel mounted ADCP work will be of particular use in validating the position and direction of the wakes on site caused by the current turbine array layout, helping to develop the understanding of the array interactions currently taking place.

A high-level overview of next steps in tuning and validating the AIM are as follows:

- Analyse data gathered by the torque transducer on the T4 shaft with concurrent seabed ADCP data from the recent ADCP deployments to better understand the effects of wakes on turbine loading. The focus here will be on turbine drivetrain loading, rather than power production.
- Process vessel mounted ADCP survey data and use to tune and validate wake paths and interactions in the AIM.
- Collect T3 blade strain gauging data when available and perform analysis of data concurrent with seabed ADCP deployment to look at turbine blade loading during operation and investigate the effects of wake interactions on blade loading.
- Analyse flow data from recent seabed ADCP deployments to validate site flow assumptions and observe wake characteristics over the course of a neap to spring tidal cycle.

With the AIM further refined and validated from the analysis of the data gathered so far, a plan will be developed for re-arranging the array layout on the site based on the predictions made in the AIM. This will allow for further investigation of array effects on flow conditions, turbine loading and power production, allowing a greater understanding of array layout optimisation to be gained.

6 References

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