TIDAL STREAM INDUSTRY ENERGISER

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MeyGen array development / optimisation model updates resulting from recent field work and impacts on Raz Blanchard sites

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Disclaimer

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1 Introduction

The “MEY-21-2-REP-002-F-Meygen & Raz Blanchard Array Development And Model Optimisation_Rev2” report below summarises the MeyGen array development / optimisation model updates resulting from high-fidelity flow data field work and data analysis undertaken at the MeyGen site in 2022-2023 (as reported in T1.6.6 - “MEY-21-2-REP-001-F-MeyGen- 2022 Field Work Analysis Report”), and also the related learning and impacts (if any) on Raz Blanchard site development.

This work was undertaken in the TIGER project in order to integrate the field measurements taken at MeyGen with the MeyGen tidal stream array development / optimisation model and then apply the learning to the ongoing Raz Blanchard site development (itself supported under TIGER).

As array development / optimisation models for tidal stream are relatively scarce, this work was of significant interest to Normandie Hydroliennes for the development of its tidal stream project at Raz Blanchard, France, as well as the wider tidal stream sector.

Normandie Hydroliennes hopes, and anticipates, that this publication will assist the whole tidal stream industry as it develops larger-scale arrays.

Report on MeyGen array development / optimisation model updates resulting from recent field work and impacts on Raz Blanchard sites

This technical report summarises the MeyGen array development / optimisation model updates resulting from high-fidelity flow data field work and data analysis undertaken at the MeyGen site in 2022-2023, and also the related learning and impacts (if any) on Raz Blanchard site development.

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Abbreviations

ADCP	Acoustic Doppler Current Profiler
SMADCP	Seabed-mounted ADCP
TMADCP	Turbine-mounted ADCP
VMADCP	Vessel-mounted ADCP
IEC	International Electrotechnical Commission
LAT	Lowest Astronomical Tide
mab	Metres above (sea)bed

1 INTRODUCTION

This technical report summarises the MeyGen array development / optimisation model updates resulting from high-fidelity flow data field work and data analysis undertaken at the MeyGen site in 2022-2023 (as reported in “MEY-21-2-REP-001-F-MeyGen- 2022 Field Work Analysis Report”, and also the related learning and impacts (if any) on Raz Blanchard site development.

This work included:

- Field measurements integration with the array development / optimisation model for the MeyGen site.
- Applying the learning to a global Raz Blanchard model to provide a ‘sense check’ for the installed capacity and GWh figures which underpin the Normandie Hydroliennes development business case.

Section 2 outlines the integration of the field measurements, as described in “MEY-21-2-REP-001-F-MeyGen- 2022 Field Work Analysis Report”, with the array development / optimisation model for the MeyGen site.

Section 3 outlines the application of the learning from Section 2 to the Raz Blanchard site development, as perceived by Normandie Hydroliennes.

2 INTEGRATION OF FIELD MEASUREMENTS WITH ARRAY DEVELOPMENT / OPTIMISATION MODEL FOR MEYGEN

"MEY-21-2-REP-001-F-MeyGen- 2022 Field Work Analysis Report" describes the field work and data analysis undertaken at the MeyGen site in 2022-2023, and that detail is not repeated herein.

However, Section 2.1 outlines the main conclusions of the field work which are taken forward to allow integration of the field measurements with the array development / optimisation model for MeyGen.

2.1 Summary conclusions of the field work

The main conclusions of the 2022-2023 field work described in "MEY-21-2-REP-001-F-MeyGen- 2022 Field Work Analysis Report" were:

2.1.1 Turbulence

- Detailed analysis of the turbulence at the SMADCP location was undertaken, including the removal of data when wave $Hm_0 > 0.5$m to allow the differences in turbulence parameters to be clarified and to demonstrate the importance of assessing turbulence in calm conditions.

- Turbulence intensity (TI) was also calculated using the 4-beam method, to demonstrate the differences which might be expected between application of a 4-beam ADCP when compared to a 5-beam ADCP. The 4-beam method leads to an overestimation of TI in the horizontal directions, with various offsets that vary with distance above the seabed, with TI typically being assessed as c. 20-25% higher when using the 4-beam approach.

- Turbulent kinetic energy (TKE) was also assessed similarly, and this showed that the 4-beam method overestimates the TKE by c. 25-50% depending on the height above seabed.

- Where data is only available using 4-beam ADCPs, this suggests that resulting TI and TKE data is likely to be c. 25% too high (with consequent implications for design conservatism).

2.1.2 Wake development and dissipation

- Various measurements of the wakes of MeyGen's operational 18m 1.5MW rated turbines were undertaken, including drifts, drive-ups, repeat transects at distances from -4D to +14D (D being turbine diameter and positive being downstream of the turbine) and stopovers[1], to better understand wake development and dissipation. Some of these measurements were undertaken with the turbines switched between operational and non-operational states.

- Drift and drive-up measurements were not always conclusive, but appear to show that some significant wake impacts continue to around 10D.

- Repeat transects (each transect was repeated 5 times to obtain satisfactory results), especially with the turbines switched between operational and non-operational states to enhance the differences, showed velocity reductions in the wake until c. 9D in flood tide and until c.11D in ebb tides. It is expected that the differences relate to the differing levels of underlying turbulence (with turbulence greater in flood tides).

- Stopover measurements showed that the power-weighted depth-averaged velocity magnitude over the expected rotor disk area was potentially reduced by c. 10% at +10D and by c. 5% at +14D, although it was noted that these low values are close to the uncertainties in the method.

2.1.3 Correlation of stopover VMADCP data with SMADCP data

- A novel approach of using VMADCP data collected from stopovers (of c. 5-7 minutes) every hour for a c. 12 hour tidal cycle at a proposed future turbine location and correlating the

[1] Almost-stationary data collection for short periods (typically c. 5-7 minutes).

resultant stopover data to the concurrently-collected data from the nearby SMADCP which was deployed for > 35 days was hypothesised to attempt to overcome practical issues in applying industry-standard approaches within IEC TS 62600-201[2].

- The approach was initially developed based on an analysis of existing measurements and hydrodynamic modelling of the MeyGen site.

- The method was initially tested for the ability of a relatively standard (non-moored, non-dynamically positioning) vessel to remain almost-stationary in the highly turbulent and fast currents at the MeyGen site, and whether suitably robust VMADCP data could be collected.

- After the success of these practical trials, the main survey work used c. 5-7 minute stopovers at potential future turbine locations (and over the SMADCP) every hour in spring tides. This stopover data was correlated to the concurrent SMADCP data via linear regressions analysis, and that correlation then used to predict the flow occurrence at each potential turbine location.

- The results showed an excellent correlation between velocity magnitudes from VMADCP data at the SMADCP location and the actual SMADCP data. For the power-weighted depth-averaged velocity magnitude over the expected rotor disk area (the key metric of interest), the VMADCP measurements of velocity magnitude at the SMADCP match the SMADCP data to within < 1% (whether measurements were taken continuously or by the c. 5-7 minute stopover approach), with R values of > 0.99.

- For potential turbine locations less than 200m away from the SMADCP, R values were on average > 0.97, and above 0.95 for potential turbine locations up to c. 500m away from the SMADCP. Lower R values (for potential turbine locations beyond 500m from the SMADCP) may be related more to shear lines in the flow rather than solely distance.

- In summary, the results generally show a very strong correlation between velocity magnitudes from the VMADCP data at the potential turbine locations and the SMADCP data, providing high confidence in the technique's applicability.

2.2 MeyGen's array development / optimisation model

Full details of MeyGen's array development / optimisation model need to remain confidential, due to their inherently confidential nature and also due to competition issues related to the UK's Contract for Difference scheme. However, this section sets out in broad terms (to the extent possible) how the field measurements have been integrated with the array development / optimisation model for MeyGen. MeyGen's array development / optimisation model is a combination of hydrodynamic models; GIS models, layers and related visualisation software; and MATLAB and Excel models.

2.2.1 Overview of MeyGen array development / optimisation model

MeyGen's array development / optimisation model includes the following aspects:

- Consents (e.g., consented offshore, nearshore and onshore areas and related constraints/opportunities);

- Grid connection options (e.g., capacity availability, timing and cost);

- Tidal resource (the subject of the survey work outlined in Section 2.1 and discussed below);

- Bathymetry (water depth, turbine rotor clearances, and various foundation options including micro-siting constraints and installed cost);

[2] Marine energy – Wave, tidal and other water current converters – Part 201: Tidal energy resource assessment and characterization. Edition 1.0. 2015-04. https://webstore.iec.ch/preview/info_iec62600-201%7Bed1.0%7Den.pdf

- Turbine options (e.g., number, diameter, turbine rotor clearances, rated power, power curve, foundation options, array electrical architecture options, array losses to grid, installed cost, operational cost, availability, timing, other constraints).

Whilst all of these are important to project success, and some are an absolute requirement to being able to develop further tidal capacity at MeyGen or elsewhere (e.g., consents, grid), the key array development and optimisation parameters include the tidal resource intensity and many of the turbine parameters. The turbine parameters are not discussed within this report, due to confidentiality and as they are generally not directly relevant to the approach used to integrate the field measurements.

2.2.2 Tidal resource and integration of field measurements

The expected energy production from a particular array is determined by:

- Undisturbed (baseline) tidal resource;
- Disturbances to the baseline tidal resource from other turbines and ancillary equipment such as foundations (e.g., through turbine wakes, and local blockage and global blockage effects);
- Turbine parameters (e.g., number, power curve(s), array losses to grid, availability etc.).

As discussed above, the turbine parameters are not discussed within this report. The integration of the field measurements with the array development / optimisation model is otherwise fully discussed below.

2.2.2.1 Disturbances to the baseline tidal resource

The key parameter of interest to MeyGen in the short-term (in terms of disturbances to the baseline tidal resource) is the potential impact of existing and future turbine wakes on future turbines, as MeyGen doesn't (i) intend to utilise any potential benefits from local blockage in the near-term (due to other constraints on very close turbine spacing), and (ii) expect any significant global blockage effects in the short-term development of the site (as the extracted energy will remain a small portion of the total energy flowing through the Inner Sound/MeyGen site).

Therefore, the findings in Section 2.1.2 are of significant interest to the overall array development / optimisation model. The model was developed based on the following approach:

- Based on previous industry and academic literature, previous model iterations have tended to focus on wakes dissipating over a length of c. 10D (D is turbine diameter), with the wake direction based on hydrodynamic model data.
- Newly defined turbine wakes (as a result of this work) are based on the flow directions determined from the 2022-2023 survey work, as measured by the stopovers at each potential future turbine location, partially adjusted for a flow curvature across the site (as the flow direction varies across the site).
- Where possible, future turbine locations are determined based on fully avoiding the expected wakes from any current and future turbines, where the wake dissipation length was defined as c. 12-15D based on the results outlined in Section 2.1.2.
- Where this is deemed to result in an overly conservative turbine array layout, a further assessment is made as to whether an exception to the approach is warranted in particular instances, through weighing up the potential benefits of a tighter turbine array layout (e.g., to a 10D separation, due to access to better baseline tidal resource, reduced cost of cabling etc.) against the potential disadvantages of locating a future turbine in the wake of another turbine.

2.2.2.2 Undisturbed (baseline) tidal resource

The key parameter of interest to MeyGen (in terms of the baseline tidal resource) is the tidal resource at potential future turbine locations. Therefore, the findings in Sections 2.1.1 and 2.1.3 are of significant interest to the overall array development / optimisation model. The model was developed based on the following approach:

- Previous array development / optimisation model iterations have used two hydrodynamic models to define potential future turbine locations, as in-situ SMADCP data collection on site has previously been limited to only a few locations. These hydrodynamic models had been previously calibrated and validated to earlier SMADCP data.

- These hydrodynamic models have previously provided output flow data which can then be manipulated to provide power-weighted, rotor-averaged flow speeds for a typical year. This output data was recently corrected by a further calibration factor to match the outputs from the four turbines already installed at MeyGen. This calibration factor varied between the four turbines, and despite the uncertainty in how this factor varies across the wider site (away from these four turbines) an average factor could then be applied across the entire site.

- Based on the findings outlined in Section 2.1.3, output data from the 2022-2023 survey work, as well output data from the two hydrodynamic models, was combined with turbine power curves to derive three estimates of the expected annual energy production (AEP) at each of the potential future turbine locations.

- Comparison of the results, together with MeyGen's detailed knowledge of the specifics of the site (from having conducted many vessel operations across the site) and the potential future turbine locations, allowed MeyGen to draw conclusions on which of the three estimates (based on the survey data outputs and two hydrodynamic model outputs) was likely to be most accurate for each potential future turbine location. For example:

    - For potential future turbine locations close to existing turbines where the hydrodynamic model outputs have been further calibrated (as outlined above), the calibrated hydrodynamic model outputs may be most appropriate, especially if these locations are far away from the SMADCP acting as the reference to which to correlate VMADCP data.

    - For potential future turbine locations far from existing turbines, the survey data outputs may be most appropriate, especially if these locations are close to the SMADCP acting as the reference to which to correlate VMADCP data.

- Based on the three data sets and the approach above, a high-level assessment of expected uncertainty was undertaken, allowing for uncertainties inherent in ADCP measurements and for uncertainties in the correlation of the VMADCP at each potential future turbine location to the reference SMADCP data.

- Based on the above, the expected AEP (and any wake impacts) was integrated back into the array development / optimisation model and used to further define future developments, as outlined in Section 2.2.1.

3 APPLYING THE LEARNING TO RAZ BLANCHARD SITE DEVELOPMENT

3.1 NH1 project description

The NH1 pilot array being developed by Normandie Hydroliennes (NH) will be installed within a consented area of approximately 0.2km^2 (20 hectares), situated around 3km west of the coast of Cap de la Hague in Normandy, France. The size of the concession area allows the placement of the 4-turbine array in a number of different microsites. However, a detailed assessment of the site through refined bathymetry data from a geophysical survey highlighted locations that are unsuitable due to physical restrictions such as insufficient water depth and seabed flatness. As was the case during MeyGen's site development since its inception, this constrains the locations for the (24m diameter rotor) turbines that are proposed for the project.

This project will strike a balance between the amount of power generation from the extremely high energy site, lowering the cost of energy through innovation, and maintaining a high confidence through using reliable and tested aspects of the technology. This balance will be achieved whilst taking a conservative approach where possible, to learn lessons to reduce risks of future array development and aid progression of buildout of the tidal site.

3.1.1 Array location

The location of the array was proposed to be at the northern boundary of the concession area. This was mostly driven by the following:

1) There is sufficient depth, with the shallowest depth complying with a minimum distance above the rotor to LAT as granted in the consents;

2) The seabed is relatively flat and therefore reduces the complexity of installation of the foundations;

3) It is significantly far away from highly varying seabed levels identified to the south of the concession zone, and so less affected by the turbulence generated from this area during the flood tides;

4) It is at the furthest point from a neighbouring tidal site under development, which is around 1km to the southeast of the site, and therefore reduces the possibility of any minor interactions between the two projects;

5) It is situated closest to the port in Cherbourg which will be used to mobilise equipment, therefore less transiting cost when performing turbine installations and maintenance works.

The main downside to this location is that there is a slightly lower mean flow compared to other areas in the site, which impacts the potential energy for extraction and results in a lower available yield.

3.1.2 Array layout

The proposed turbine placements are in a staggered arrangement with three turbines in a row facing the ebb tide, with the fourth turbine further south. There were 4 main considerations for this:

1) To reduce the area of consented space taken up to minimise impact on potential locations for future build out;

2) To ensure the arrangement and tip to tip distances were consistent with those in the present consents;

3) To prevent positioning turbines directly in the wakes of one another;

4) To assess the effects of blockage from the front line of turbines in accelerating the flow and therefore increased potential energy yield.

In future consents for site build out, the required distances may be revised based on environmental monitoring and learning from the pilot array which may enable shallower areas and closer configurations to be considered. As this is a first in class pilot project, there is an extensive monitoring programme outlined to gain a better understanding of the environment and the interactions with the turbines that will be used to justify selections in future consent applications.

3.1.3 SMADCP Campaign

A 2-month data collection campaign between March and April 2022 was carried out using three 5-beam SMADCPs located around the proposed array location to the North of the concession area. All 3 ADCP datasets have been processed to characterise the mean flow, shear profiles and turbulence at the microsite. The data has been extrapolated using a harmonic analysis method for the duration of the project life which has been used to calculate the expected yield and input into a project financial model.

3.2 Applications of the lessons learned from MeyGen

There is very high commonality between the NH and the MeyGen projects, as well as between the Raz Blanchard and Pentland Firth tidal sites generally. This enables the lessons learned from the fieldwork presented in Section 2 to be directly usable by NH in the development of its own array development and optimisation assessments.

3.2.1 Baseline resource assessment

As with MeyGen, a key parameter of interest to NH (in terms of the baseline tidal resource) is the tidal resource at the proposed locations. As previously discussed, the location and layout for the NH1 pilot has been selected based on the physical constraints of the bathymetry of the concession area, as well as compliance to certain requirements that were predefined within the original consents. Data gathered from the SMADCPs in 2022 has been used in the characterisation of the tidal resource across the relatively small area of the proposed pilot.

The findings in Sections 2.1.1 and 2.1.3 are of significant interest for the future buildout of tidal arrays in the Raz Blanchard site, as:

- The novel stopover approach of using VMADCPs as a highly cost-effective method of mapping the resource around the site would very likely be used to calculate the expected annual energy production (AEP) at each of the potential future turbine locations. This is extremely valuable information that would support decision making on key aspects of future arrays such as the turbine configuration, consenting considerations, and financial planning. Adopting this method would potentially overcome practical issues in applying industry-standard approaches.

- Section 2.1.3 discusses the strength of correlation as a function of distance from the SMADCP and the VMADCP, which would be considered when assessing appropriate locations for the placement of a reference ADCP during such a campaign. The limitations of the method at greater distances are noted.

- VMADCPs have been shown to be effectively correlated against TMADCPs. The pilot turbines are planned to be fitted with flow measuring equipment that could be used as the reference flow measurements during a data collection campaign for potential locations in the concession area.

- The results from the turbulence assessment presented in Section 2.1.1 are very compelling, and relevant to the NH site assessments of turbulence. This is hugely important for parameterising the environment as it will influence loading assessments that affect the entire system design. This study clearly identifies a significant difference between the 4 and 5 beam results. NH intend to use these findings in decision making for ADCP configurations for future campaigns, as well as to ensure that the different methods of data processing are considered.

3.2.2 Disturbance to baseline tidal resource

As with MeyGen, a key parameter for NH in the short term is to consider the effects of the wakes from the turbines on the global flow dynamics around the Raz Blanchard site. The results outlined in Section 2.1.2 are of significant interest to the NH array developments for the following aspects:

- For the pilot, these will be the first turbines installed into the area and have sufficient space to avoid any downstream wake interactions. However, the lesson learned from MeyGen is to consider as early as possible how the presence of wakes of the pilot will affect the options for possible locations of future turbines in larger buildouts.
- Where possible, future turbine locations will be determined based on fully avoiding the expected wakes from pilot and future turbines, where the wake dissipation length was defined as c. 12-15D. In addition, the measurements from the transects gives indications on wake expansion that can also be used in array layout optimisation.
- There are two concession areas that are presently being developed within the Raz Blanchard, where the proposed array locations are approximately 1km apart. Considering a worst case of 15D would mean that the wake would dissipate 360m away from the NH1 pilot. This gives confidence in there being more than sufficient distance downstream for the wake to dissipate, limiting the risk of influence on the neighbouring site for this deployment.
- A new set of wake studies will be very likely carried out to assess the differences of the higher power, larger rotor turbines on wake dynamics, using the lessons learned around the wake measurement and characterisation methods presented by MeyGen.
- Initial studies on the transects of the wake will be used to further investigate any potential local blockage and bypass effects. The lateral separation distance of the turbines in the pilot has been consented at 1.8D tip to tip. The power increase of any potential flow acceleration of the flow between the two rotors will be directly measured from a turbine to be installed downstream of this spacing. The combined information within the datasets from NH and MeyGen will progress the understanding of local blockage and bypass effects within real site conditions to potentially increase the power extraction potential of the site.

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