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ReDAPT MC7.3 Public Domain Report: Final

DOCUMENT CONTROL

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-	27/07/2015	ALL	ALL	First Issue – For ETI review
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TABLE OF CONTENTS

1 ACRONYMS

ADCP	Acoustic Doppler Current Profiler
CAPEX	Capital Expenditure
CB	Circuit Breaker
CDM	Construction, Design and Maintenance
CFD	Computational Fluid Dynamics
DART	Drifting Acoustic Recorder and Tracker
DEEP-Gen III	Deep water Efficient Electrical Power Generator III
DEEP-Gen IV	Deep water Efficient Electrical Power Generator IV
DG4.1	DEEP-Gen 4.1 (Oceade™)
EHM	Equipment Health Monitoring
EHS	Environment, Health and Safety
EMEC	European Marine Energy Centre
ER	Engineering Recommendation
ETI	Energy Technology Institute
HPU	Hydraulic Power Unit
HSS	High Speed Shaft
I/O	Inputs and Outputs
IEC	International Electrotechnical Commission
LCOE	Levelised Cost Of Electricity
LSS	Low Speed Shaft
MMO	Marine Mammal Observer
MP	Maintenance Period
NTP	Network Time Protocol
O&M	Operations and Maintenance
OEM	Original Equipment Manufacturer
OPEX	Operating Expenditure
PML	Plymouth Marine Labs
PWRA	Power Weighted Rotor Averaged
ReDAPT	Reliable Data Acquisition Platform for Tidal
ROC	Rate of Change
ROV	Remotely Operated Vehicle
SBD	Single Beam Device

SCADA	Supervisory Control And Data Acquisition
SIMOPS	Simultaneous Operations
THD	Total Harmonic Distortion
TRN	Test Request Note
TSR	Tip Speed Ratio
UTM (co-ordinates)	Universal Transverse Mercator

2 INTRODUCTION

One of the key developments of the marine energy industry in the UK is the demonstration of near commercial scale devices in real sea conditions and the collection of performance and environmental data to inform permitting and licensing processes. The Energy Technology Institute's (ETI) ReDAPT (Reliable Data Acquisition Platform for Tidal) project has seen an innovative 1MW buoyant tidal generator (Alstom's DEEP-Gen IV turbine) installed at the European Marine Energy Centre (EMEC) in Orkney in January 2013.

With an ETI investment of £12.6m, the project involves Alstom, E.ON, EDF, DNV GL, Plymouth Marine Laboratory (PML), EMEC and the University of Edinburgh.

The project has demonstrated the performance of the tidal generator in different operational conditions. The project's aim was to increase public and industry confidence in tidal turbine technologies by providing a wide range of environmental impact and performance information, as well as demonstrating a new, reliable turbine design. [http://www.eti.co.uk/project/redapt/]. The first year of operation was reported in MC7.2 (1).

This document provides an overview of the second year of operation and the post-test inspection of the DEEP-Gen IV tidal turbine. The DEEP-Gen IV turbine has completed two years of operation over seven deployments at Berth 2 at the EMEC. Having generated & exported over 1.2GWh to the Scottish grid the turbine was retrieved and underwent a series of inspections to maximise the learning after an extended period of operation.

3 SUMMARY

In the second year of the DEEP-Gen IV 1MW turbine operation the deployments were of longer periods than in the first year and this allowed not only the collection of detailed turbine performance data but also the collection of a large amount of data on the environment and the interaction of the turbine with the environment.

Several power curves were created for the turbine following the new IEC 62600-200 standard methodology (2). This measured power curve correlated well with the predictions derived using the DNV GL tool Tidal Bladed. The real life turbine performance and load measurements were used to validate the DNVGL Tidal Bladed (3): this validation now means that the industry has a tool with which to assess and predict the loads and performance of turbines deployed in a given set of site conditions.

The second year of operation presented additional opportunities to learn lessons about the design, maintenance and operation of a commercial scale tidal turbine. A detailed turbine inspection activity was carried out at the end of the ReDAPT programme of testing to maximise the return on experience and key lessons are presented.

A discussion is presented of how the performance of the DEEP-Gen IV turbine accords with the current industry view of the Levelised Cost of Electricity (LCOE) (as represented in the ETI/UKERC roadmap) and then what key challenges in achieving the ETI targets going forward need to be addressed.

An assessment of the power quality performance (voltage flicker, power factor and harmonics) is presented along with a summary of supply interruptions at the Eday substation. This assessment confirms that the DEEP-Gen IV turbine complies with grid regulations and provides control of power factor.

Information has been gathered on the performance of materials and coatings in terms of biofouling and corrosion. The instrumentation fitted to the turbine allowed an assessment of marine life interaction through strain gauge monitoring; this concluded that there were no unwanted interactions and began to show how marine mammals generally avoided the device. Acoustic surveys were carried out to determine the noise footprint of the turbine and this data has been submitted to Marine Scotland for review.

Throughout the course of this project a significant number of lessons have been learned in a variety of areas associated with testing a tidal turbine at a remote site within a complex multi-partner R&D programme. Lessons are presented in the areas of programme management, marine operations, maintenance activities, testing activities, daily operations and the EHS management.

4 TURBINE OVERVIEW

The Alstom DEEP-Gen IV demonstration turbine is a three-bladed horizontal axis tidal stream turbine, with a rated power output of 1MWe. The turbine utilises a collective pitch system to regulate the power extracted from the flow.

To support the ReDAPT project the turbine was highly instrumented internally with sensors capable of measuring temperature, pressure, load, accelerations and many other parameters. Externally it also carried instruments for tests to be carried out by ReDAPT partners such as ADCPs, AWACs, single beam devices, acoustic monitors, cameras and paint panels.

Figure 1: DEEP-Gen IV tidal turbine; modelled on the tripod (left) and prior to the first deployment (right)

The Alstom tidal turbine design philosophy is to extract as much energy as possible from the available tidal flow. For this reason the design has the following key features:

- Pitching Blades –
    - Optimum hydrodynamic design of blade for optimum energy extraction
    - The maximum power can be controlled
    - The maximum thrust load is limited
    - Counter-act power and speed fluctuations caused by waves and turbulence
    - Safe shutdown under extreme conditions
- Yawing Nacelle – Sites often do not have the Ebb and Flood tides that are 180° apart, accurate yawing allows the turbine to face the oncoming flow to:
    - Maximise energy extraction from the flow
    - Minimise structure loads
    - Yawing also ensures that rotor is up-stream of turbine and foundation, this minimises inlet flow distortion and structural dynamic issues

- Frequency Conversion in the Nacelle
    - one power converter per turbine is required offshore as "group" control would increase structural loads on individual turbines
    - control over a long distance with single cables to a shore-based frequency converter is difficult and unproven
    - the buoyant nacelle is maintained at atmospheric pressure with controlled humidity and anti-condensation heaters to provide an appropriate and stable working environment for the electrical system. It also provides a ready solution to the O&M of the electrical system, avoiding the need for a subsea converter in a separate maintainable unit.

The Alstom tidal turbine design philosophy is based on the requirement to have a rapid and low cost installation and retrieval process. A cost-effective deployment and recovery mechanism is essential to both the short-term (to de-risk small-scale projects) and the long-term (to achieve sustainable tidal farm economics).

The opportunity to deploy or retrieve a turbine is currently available in the slack-water periods at the turn of the tide: these periods are often short and seldom have completely stationary flow conditions. Alstom's solution is to have a buoyant nacelle that is winched down onto the foundation; the winch (also buoyant) is detached once deployment is complete and recovered to the vessel for use on other turbines. The whole process is unique and patented Alstom IP. This solution has the following advantages:

- Low cost vessel –small work-class vessel with and ROV (Remote Operating Vehicle) is required to tow and install the turbine; these have a significantly lower day rate compared to heavy–lift station-keeping vessels.
- Rapid deployment and retrieval – slack water can range from 5 minutes (Spring Tides) to one hour (best Neap Tides). Alstom's processes have been successfully demonstrated at EMEC with deployments at the EMEC site in less than 30 minutes and retrieval in less than 10 minutes.
- No complex lifts or alignment operations – as the turbine is free-floating no lifting is required at sea and the turbine does not require alignment or guiding onto the foundation, except for the simple operation of the ROV connecting the winch rope to the Support Structure. Once retrieved the turbine is towed to harbour and only lifted once alongside the quay.
- No diver intervention required – no divers are used in either the routine deployment or retrieval operations or in contingency operations (which may require work-class ROV support). Diver intervention would only be considered as a last resort.

5 DEPLOYMENT AND MAINTENANCE SUMMARY

5.1.1 ReDAPT Objectives

In the second year of operation several significant objectives and milestones were achieved within the overall ReDAPT programme objectives:

- Produce performance curve to IEC standards
- Determine turbine C_P
- Determine the load factor at the site
- Produce >1GWh
- Achieve 3 months of continuous operation
- Collect ReDAPT environmental data to support Partner work packages
- Fulfil environmental licence requirements – notably the turbine acoustic survey and mammal impact monitoring.
- Carry out a detailed post-test inspection activity.

5.1.2 Second Year of Operation Overview

This summary starts at Deployment 4, building from the First Year of Operation Report (1). During Deployments 4 – 7 the turbine was operating within operational limits specified by DNVGL as part of their certification approval, the reasons for these limits are explained in the following paragraphs.

During the first year of the test programme new site data was collected and compared to measurements taken prior to the DEEP-Gen IV detailed design phase. The newer data indicated that flow speed at the site was faster than originally modelled. Furthermore, the hydroelastic model and software (DNV-GL's Tidal Bladed) used to design the DEEP-Gen IV turbine had significantly developed since the version used for the original design.

As a result some operating limits were imposed in terms of a cut-out current velocity (3.4m/s) and cut-out wave height (3m H_{max}) in order not to exceed the certified design load margins. Simple and conservative operational limits were used by setting a maximum allowable mean pitch position and by measuring power/pitch fluctuation over typical wave periods: A "high wave shutdown" was triggered by a power transient where power fluctuations were noticeably larger than in normal operation. To set a shutdown on wave height alone would have been difficult to achieve without bespoke wave measurement instruments. This operational limit will have reduced the overall generating output.

Deployment	Days	Availability (%)	Energy Generated (MWh)
First Year			
1	10	10	0
2	28	57.1	0.012
3	58	87.9	9.546
Second Year			
4	58	54.1	128.1
5	60	75.3	163.4
6	59	48.8	161.3
7A	99	72.9	650.3
7B	14	87.7	94.7
TOTAL		**66.8**	**1207.4**

Table 1: Summary of all ReDAPT deployments

Over the series of deployments the energy generated increasing steadily. Deployment 7A achieved the key milestone of 3 months of continuous autonomous operation.

Bottom mounted ADCPs were available on all deployments to provide flow measurement data for the area immediately surrounding the turbine (mostly up and down stream) independent of the sensors on the turbine, which are affected by the flow moving around the turbine and the foundation. Deployment of the ADCPs was not a straightforward process as can be seen by the relative positon of the ADCP compared to the "target zones" shown in Figure 2. The flow data was used to generate performance curves for the turbine, understand the flow around the device and build useful information about the flow at the site.

As well as bottom-mounted ADCPs the turbine carried ADCPs on the buoyant nose (front facing single beam), on top of the nacelle at the rear and on the back of the thruster looking aft. ReDAPT data collection required periods of non-generation with deliberate positioning of the turbine at various orientations to the flow to gather data throughout Deployments 4 – 6 and the data analysis has culminated in the MD3.8 report on the characterisation of near field turbulence (4) and MD1.4 on the CFD simulation and comparison with Tidal Bladed (5).

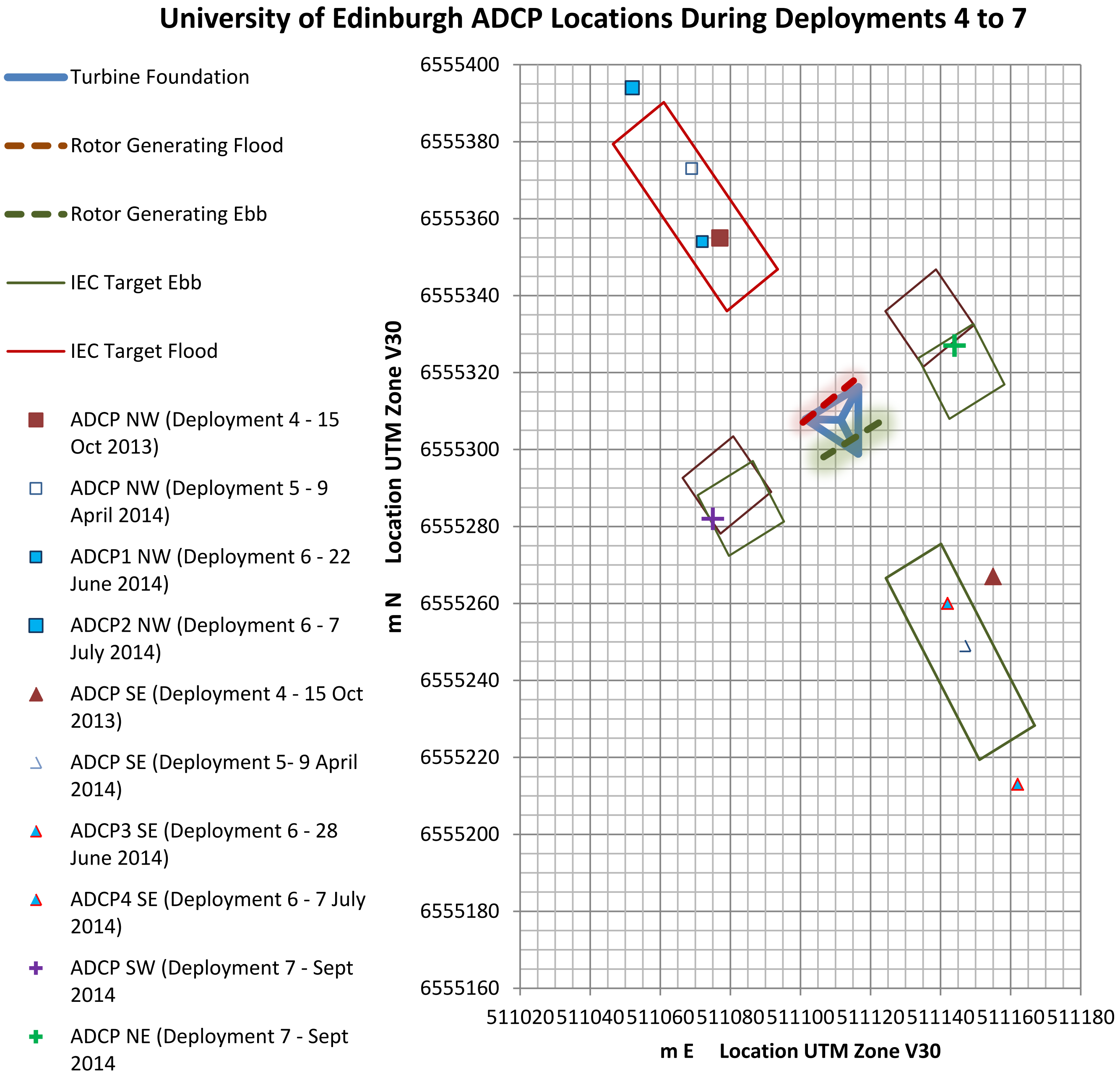

Figure 2: ADCP locations for Deployments 4 to 7 relative to the IEC 62600-200 target zones

5.1.3 Operation and Maintenance Management

Turbine deployments and retrievals were managed by the standard deployment and retrieval processes (method statement and risk analyses). When the turbine was deployed all testing was managed through the use of Test Request Notes (TRNs) as part of Alstom’s internal product verification management processes. These documents described the test that was desired, the value in the test, the methodology and a review of the risks associated with the test. The TRNs were reviewed, accepted amended or rejected, where appropriate, prior to testing on the turbine. Any accepted tests could then be scheduled into the test plan and conducted with the appropriate personnel present. The results from tests were recorded during the test for presentation of the findings at a later date.

During maintenance periods the work to be done was managed through the use of electronic Job Cards defining the task and recording the information/ progress managed by allocated owners. The majority of the jobs were agreed prior to the maintenance period and hence the jobs could be well defined and planned to occur when the appropriately skilled persons were on site. The pre-planned jobs also facilitated more efficient working when parts were required; these could be ordered in advance and the lead times planned into the maintenance activities. Also included in the Job Cards were risk assessments, lifting plans and “5 whys” (root cause analysis) analyses where appropriate.

Once the maintenance period had commenced the Job Cards were updated regularly to reflect the progress with each task. Any arising tasks could be recorded in the Job Card, with the owner ensuring the actions were completed. Throughout the maintenance period as further jobs arose from inspections, further Job Cards were written. Daily calls between the remote operational site in Orkney and the engineering office in Bristol facilitated a detailed transfer of information, feeding into ongoing jobs and generating new Job Cards. Prior to the turbine re-deployment several reviews were held to review all Job Cards, ensure that all tasks had been completed satisfactorily, and ensure that subsequent testing of the system had also been completed. After the maintenance period these Job Cards formed the basis of the record of the work carried out and main events of that period, and were formally approved, issued and lessons learned recorded

5.1.3.1 Deployment 4 and Maintenance Period 4

Deployment 4 achieved the first period of >24 hours of autonomous running of the turbine and facilitated the generation of the first power curve for the turbine. By running consistently for the power curve generation valuable data was collected to baseline the EHM system (6). Other testing throughout this deployment focused on flow data gathering for the ReDAPT project partners use in modelling and validation of tools; this required power generation in various environmental conditions and some periods of non-generation with the nacelle positioned both broadside and aft to the tide to enable the turbine-mounted equipment to monitor the flow conditions. A good proportion of ReDAPT data gathering was completed in this deployment.

This deployment was brought to an end when internal visual monitoring picked up that the slip-ring was loose on its mounting. During the maintenance period that followed the slip-ring was upgraded as a priority. Other work during this maintenance period focused on upgrades and configuration changes to improve the operation of the turbine, based on operational experience to that point.

5.1.3.2 Deployment 5 and Maintenance Period 5

Deployment 5 was affected by a grid loss event early in the deployment, which damaged the pitch battery charging circuit. While the issue was diagnosed fully, the opportunity was taken to gather additional flow data for the ReDAPT project partners. Following diagnosis, the turbine was operated safely in a well-managed, degraded operational mode. The turbine was run in this configuration whilst replacement components were ordered and the maintenance period planned. An acoustic survey using drifting ears (DART) of the site and turbine was undertaken, completing the first part of this survey with baseline non-generating noise assessment and some generating cases.

The turbine was retrieved on the planned date and maintenance upgrades on the pitch battery circuit were carried out. The whole maintenance period, which included many other inspections and enhancements, was completed within two weeks and the turbine deployed in the following neap, demonstrating the rapid maintenance turn-around process.

5.1.3.3 **Deployment 6 and Maintenance Period 6**

Deployment 6 included the final set of ReDAPT flow data collection to support the project partners in flow modelling and tools validation work packages. Following this a 15 day period of continuous testing and data collection for a second power curve was started. Unfortunately, the 15 days period was not completed due to an issue with the HPU. The HPU could not be used to open the clamp for retrieval, so the contingency “hot-stab” hydraulic down-lines deployed and controlled from the installation vessel were used. The contingency method was fully tested, the marine operations carefully planned and the retrieval operations were completed as planned.

In the maintenance period the HPU was stripped, refurbished and rebuilt. The clamp was also inspected and all components were all found to be in good condition. The complete HPU rebuild was accomplished within a month allowing turbine re-deployment 4 weeks after retrieval.

5.1.3.4 **Deployment 7**

Deployment 7 was the longest deployment in the ReDAPT project and included a full 15-day power curve assessment according to the IEC standard and using ADCPs positioned adjacent to the turbine, rather than up and downstream as used in previous deployments. The full power curve (section 5.2) was consistent with previously generated curves and much learning was derived on the importance of ADCP positioning. The test period included numerous Alstom derived tests to feed & support the Oceade™ design, a further acoustic survey to complete the acoustic characterisation study and longer periods of autonomous running: 71.4MWh was generated in one week alone, which is equivalent to more than 42% load factor.

Deployment 7 was interrupted by a control system issue and communication loss with the turbine occurring on 26th December 2014 which meant that diagnosis was delayed due to the holiday period and the batteries were discharged. Testing from shore in the New Year diagnosed the issue and turbine re-energisation was planned. In order to restore power to the turbine the control/power umbilical had to be used from the installation vessel; this operation was completed successfully on the first attempt on 28th January.

Following the re-energisation the turbine was run for another two weeks completing some further Alstom derived tests to feed & support the Oceade™ design, before being retrieved to begin the ReDAPT end of project turbine inspection activity (Section 6).

5.2 Power Curve

The experience gained from generating several power curves within the ReDAPT project is that this is not an easy task, with many variables involved that may cause the data gathered to not meet the IEC/TS 62600-200 requirements (2). Positioning the ADCPs in their target zones is very challenging both in terms of position and orientation, the ADCP hardware is at risk of faults and the turbine availability has to be sufficient through the test period (e.g. storm conditions might cause shut-downs that reduce availability).

The ReDAPT project has demonstrated that a power curve can be generated following the IEC methodology. However, given the complexities of ADCP deployment it has to be questioned as to whether it would ever be viable to use the technique for routine power curve or performance assessment. The IEC method of calculation based on input data is a good one, however to obtain good input data is a real challenge.

A power curve is a turbine’s power shown against flow speed where the data points that make up the curve have been suitably averaged such that they are independent of the tidal variation. The curves are thus created under stringent conditions to ensure they are both accurate and repeatable: all power curve assessments in ReDAPT were made in line with the IEC standard IEC/TS 62600-200.

To calculate a turbine’s power curve the turbine power and flow are measured concurrently. The reference flow that is used is the power-weighted rotor-average (PWRA) velocity. This is the cube of the upstream velocity integrated over the rotor area at a suitable distance upstream such that it is not influenced by the turbine itself. This assumes that the stream-tube expansion (Figure 3) is not such that the upstream area is significantly smaller than the rotor area itself.

The power and velocity measurements contain significant scatter and so averaging is performed to better understand the relationship between the two variables. Once sufficient data has been recorded and averaged over sufficient periods a flood and ebb power curve can be created.

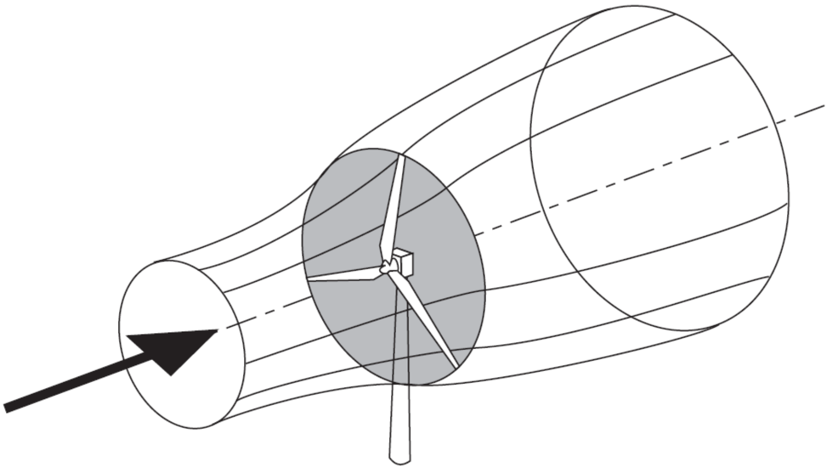

Figure 3: Stream-tube expansion over turbine rotor plane (7)

In MC7.1 (8) initial power curve report a comparison was made between numerical predictions of the performance curve using Tidal Bladed. It was shown that there was strong agreement between the numerical prediction and the measured values: for this report the dynamic numerical predictions from Tidal Bladed are used.

5.2.1 Flow Measurement

IEC/TS 62600-200 (2) details that flow measurement should be performed using a sensor which is able to resolve the three components velocity at discrete intervals along the vertical profile. Constraints on the measurement are that:

- There should be a minimum of ten samples (bins) over the height covered by the vertical profile
- The measured area should cover the whole of the area that is in-line with the rotor plane
- Measurements should be a minimum of 1Hz.

Two orientations are given for position of the flow sensors:

- In-line – A single flow sensor should be placed upstream of the turbine rotor plane within a target zone measuring 3D in the flow direction and 1D in the direction perpendicular to the flow. The box starts 2D (diameters) upstream of the rotor plane. See Figure 4 for full definition of this. For a bi-directional site, in order to measure both flood and ebb profiles (and thus complete the power curve) two flow sensors will be required.
- Adjacent – Two flow sensors are required in separate target zones which measure 1D by 1D. The zone is positioned centrally over the line extending from the rotor plane and starts 1.5D from the turbine centreline. Again, see Figure 4. Whilst two flow sensors are required it is likely that these may be used to measure both the flood and ebb tides. More profilers may be required for measuring both flood and ebb for sites where the principal flood and ebb flow directions are not close to being inline or for a yawing turbine where the rotor plane extends over 1D from the tower centre. The flow measurement is obtained from an average of the two flow sensors with data discarded if they differ by more than 10%.

For the In-line orientation the position of the flow sensor within the target zones is such that the beam (or beams) spread may not extend outside of the box at a depth equal to the vertical distance taken by the turbine rotor plane, see Figure 5.

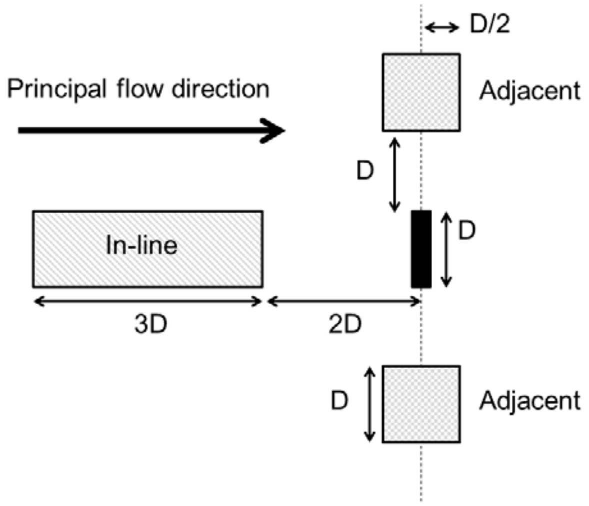

Figure 4: Definition of In-line and Adjacent areas for placement of current profilers

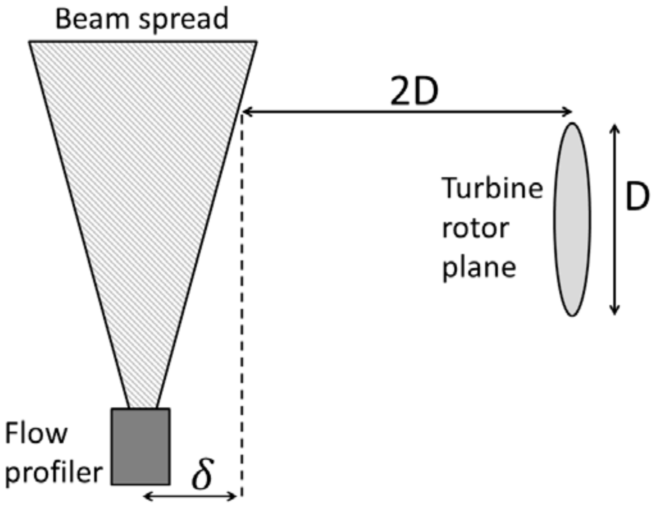

Figure 5: Restriction of flow profiler placement within target zones due to beam spread

There are advantages and disadvantages of both In-line and Adjacent configurations. For the In-line there is confidence that the flow measured by the sensor is that which will interact with the rotor plane. This may not be the case for the adjacent configuration where bathymetry could affect the flow. However, as the Adjacent configuration uses two sensors with a quality check this helps to remove any anomalies in the data which the In-line cannot. Both configurations allow for data to be used for other types of analysis. As the Adjacent configuration measures both flood and ebb directions a flow distribution may be created from either / both sensors; this would not be possible for the In-line configuration unless both flow sensors were combined as it is likely the flow observed by the downstream sensor will be influenced by the turbine wake. Conversely if the wake is of interest the In-line orientation allows for this to be better understood although it is unlikely a single location measurement will be sufficient to truly characterise the wake.

As the velocity profile is measured using discrete bins the PWRA velocity is calculated in respect to this, using the method of bins. The rotor area is split into a series of segments corresponding to the bin heights. Each of these segments is given a weighting coefficient and the cube of the velocity for the associated bin is multiplied by this weighting coefficient. All of these are then summed.

The PWRA velocity, $\underline{\hat{U}}_t$, is calculated as:

$$\underline{\hat{U}}_j = \left[\frac{1}{A}\sum_{k=1}^{S} \underline{U}_{k,j}^3 A_k\right]^{1/3},$$

Where:

$$A = \sum_{k=1}^{S} A_k,$$

And: j is the index of the time instant, k is the index of the ADCP bin, S is the number of ADCP bins over the turbine area, A is the projected rotor area [m^2], A_k is the projected capture area of the turbine corresponding to bin k [m^2], $\underline{U}_{k,j}$ is the velocity vector at time index j and ADCP bin index k [ms^{-1}]. See Figure 6 for definition of these. $\underline{\hat{U}}_j$ is then averaged into bins corresponding to the required sampling period. Note that the complete rotor area is used including the turbine hub.

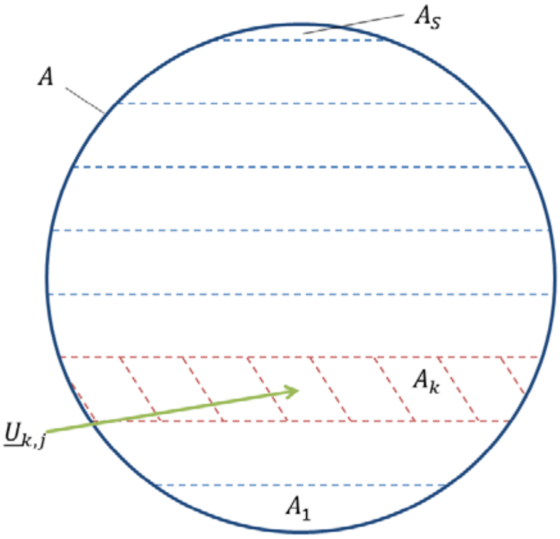

Figure 6: Definition of terms in the method of bins for calculating PWRA velocity

As the bathymetry is of varied depth the ADCPs are placed in locations with a depth different to that of the turbine. This creates difficulty in defining the hub-height location for use in the method of bins. It is decided that the surface is taken as the reference depth with the hub height measured down from this. An additional complication is that the tripod of DEEP-Gen IV has a 2° tilt which results in the turbine being higher in the water column than the assumed hub height during a flood tide and lower during ebb tide. Along with the bathymetry the tilt results in different parts of the flow profiler's beams being sampled which is shown in Figure 7. The degree of tilt is calculated from sudden changes in the external-pressure-sensor-derived depth signal, shown in Figure 8. During each yaw manoeuvre there is a discontinuity of approximately 0.5 m. From the location of the sensor and the geometry of DEEP-Gen IV is then shown that the change in hub-height is a ± 0.24 m offset for flood and ebb respectively.

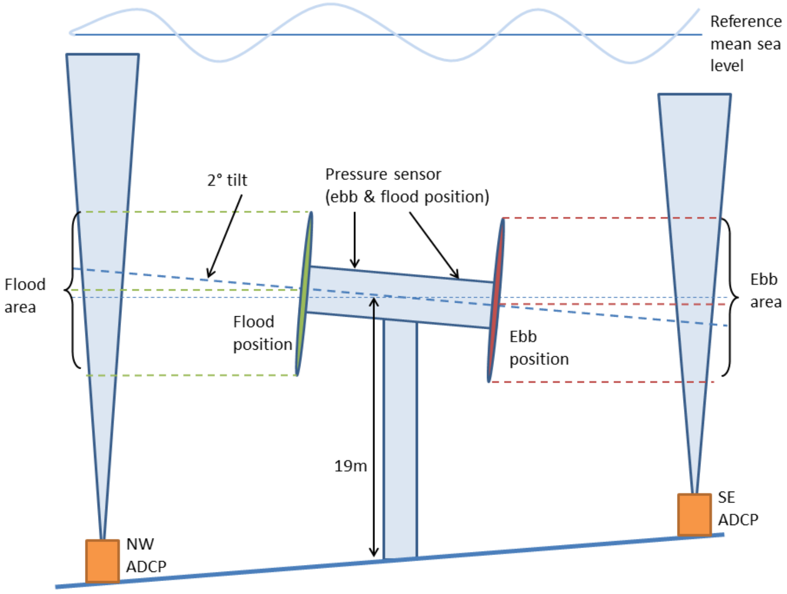

Figure 7: Calculation of hub height from reference surface height and tilt of the turbine

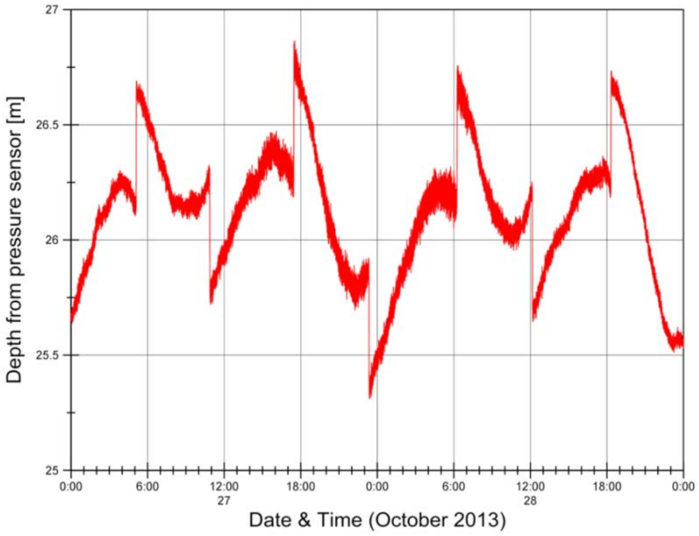

Figure 8: External pressure sensor depth. Jumps are during yaw manoeuvres

5.2.2 Instrumentation

Flow measurement has been performed using Teledyne RDI's 4-beam Workhorse Sentinel 600kHz Acoustic Doppler Current Profilers (ADCPs) positioned in a fixed location on the seabed. These capture the vertical velocity profile in a fixed location for a time period of up to 80 days depending on hardware and firmware settings. The ADCP processing procedure (9) converts the along-beam-velocities into a Cartesian coordinate system referenced to magnetic north providing East, North and Up velocities taking into account the pitch, roll and heading of the ADCP from on-board sensors. This data is then passed through two filters, minimum amplitude and an outlier rejection. Relaxed thresholds were used in the filtering process resulting in few rejected data points. This methodology would make the data sets unsuitable for considering transients but suitable for averaged data as considered here. A description of the ADCP can be found in Table 2.

	ADCP
Sensor name	Teledyne RDI Workhorse Sentinel
No. beams	4
Operating frequency	600 kHz
Sampling frequency	0.5 Hz
Bin size	1 m
Range	50 m

Table 2: Description of flow measurement sensor used

ADCP positioning was a challenging marine operation, to ensure the position was as desired while not being affected by local bathymetry effects. Due to the proximity to the turbine magnetic compasses within ADCP units are often not useful in determining the ADCP orientation; alternative arrangements had to be made to ensure an accurate reference of ADCP position and orientation.

5.2.3 Measurement Campaigns

The data in this report is gathered during three of DEEP-GEN IV's deployments which are described in Table 3; this data is also reported in MD3.15. The layout of the ADCPs and the "view" of the SBD are shown in Figure 9.

Deployment / Date	Flow sensor	Length (days) of ADCP deployment	Orientation	Distance from rotor plane (D)	Depth measured from sensor (m)
4 **Oct – Nov 2013**	SBD	20	Upstream	0.2 – 0.7	
	ADCP01	19	In-line	2.9	46.4
	ADCP02	19	In-line	2.9	43.6
6 **July – Aug 2014**	ADCP03	41	In-line	3.0	45.6
	ADCP04	42	In-line	5.6	46.4
	ADCP05	41	In-line	2.8	43.1
	ADCP06	42	In-line	5.6	NA
7 **Sept – Dec 2014**	ADCP07	43	Adjacent	1.9	NA
	ADCP08	56	Adjacent	1.8	NA

Table 3: Description of flow sensors used in measurement campaigns

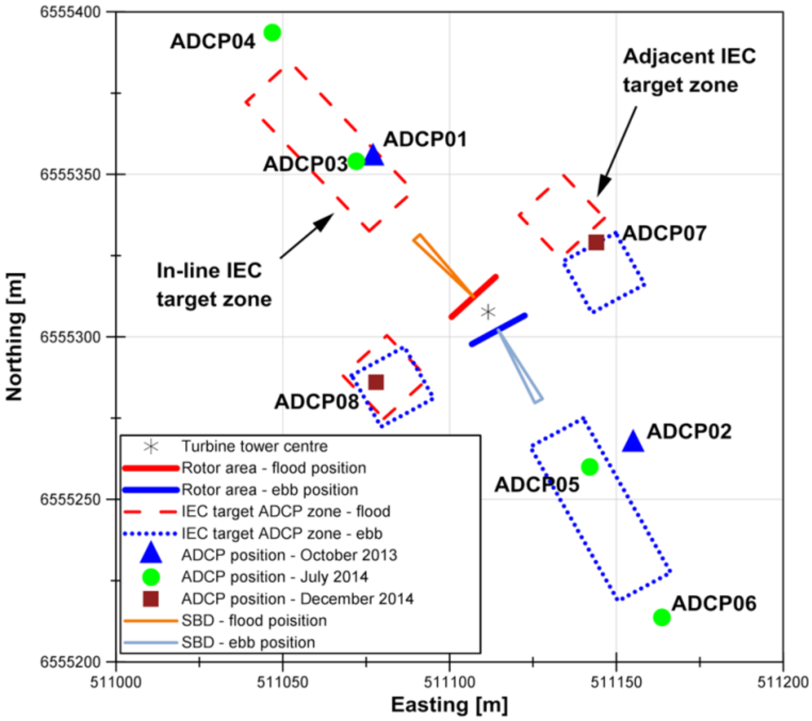

Figure 9: Overview of turbine orientation, ADCP positions, ADCP target locations and SBD positions during measurement campaigns

5.2.4 Turbine Power Measurement

There are several locations in the DEEP-Gen IV power train from which the power may be read. In this report power is measured from the shore power meter; this is the overall turbine power that is generated including all mechanical and electrical losses in the power train:

5.2.5 Power Curve Generation Process

Creation of a power curve follows two averaging steps; one in time and another by velocity. The time averaging period should be between 2 and 10 minutes, and the velocity averaging should be 0.1 ms^{-1} or a smaller integer divisor of this. The process for creation of a power curve is best described by processing steps which are listed below:

1. Turbine data processing.
    a. Read data channels
        i. Time
        ii. Shore power
        iii. Turbine heading
2. Flow data processing. For each ADCP used in the assessment:
    a. Read data channels:
        i. Time
        ii. Velocity (East, North, Up)
        iii. Depth
        iv. Bin heights
    b. Calculate PWRA velocity by method of bins:
        i. Calculate velocity magnitude and direction for each ADCP bin
        ii. Using turbine pressure sensor and ADCP Depth calculate the turbine hub height.
        iii. Calculate area-weighting coefficient for each ADCP bin
        iv. Calculate PWRA velocity by method of bins
    c. Align flow data with turbine controller data:
        i. Select a tide of data for the filtering where rated was not achieved
        ii. Low pass filter turbine power signal and turbine flow signal
        iii. Map filtered signals onto finer time channel
        iv. Perform cross-correlation of turbine and ADCP signals to find offset
3. Time average data. For each Time Interval:
    a. Calculate Min, Mean, Max, Standard Deviation and Number of Data Points for Processed-Turbine-data channels
    b. Calculate Mean for Processed-ADCP-data channels
    c. If using the Adjacent layout for ADCP placement:
        i. Both ADCPs are averaged.
        ii. If the difference between the two ADCPs is less than 90% the Time Interval is ignored.
4. Power curve creation. For each given tide (flood / ebb):
    a. Select data from Turbine and ADCP time-averaged channels based on following criteria:
        i. Turbine heading is the assumed heading for that tide.
        ii. Minimum velocity of a sample is positive when velocity is greater than 1.25m/s. This is to remove samples where there was a shutdown which creates scatter in the final power curve.

    iii. Number of samples is greater than 90% of Time averaging period (seconds) multiplied by Turbine data frequency (Hz). This ensures each ten minute sample has sufficient data to be representative of operating conditions.

b. Reduce by velocity. For each velocity bin of 0.1m/s size in the range 0 – 5m/s:
    i. Calculate the Mean and Number of Samples of the Turbine Data
    ii. If the Number of Samples per velocity bin multiplied by the Time-Average period is less than 30 minutes the data point is classed as invalid. Otherwise the point is valid.
    iii. Linear interpolate the invalid data points. Extrapolation is not allowed and so the curve will not always fill the 0 – 5m/s range.

5.2.6 Power Curve Validity

It should be noted that for a power curve to comply with IEC/TS 62600-200 the following conditions should be met:

1. General:
   a. The test data used should be of minimum 15 days duration (maximum 90)
   b. Turbine availability should exceed 80% over the test
   c. Each data set includes a minimum 180 hours sampled data.
   d. The power curve should include a flood and ebb curve.
2. Flow data:
   a. Data points are discarded if the flow profiler cannot capture flow over 90% of the profiler bins.
3. Time averaging:
   a. The period should be between 2 and 10 minutes.
   b. Each time averaged period should contain a minimum of 90% of valid data points.
4. Velocity binning:
   a. The bin size is a maximum 0.1m/s. If less than 0.1m/s is used the bin size should be an integer divisor of 0.1m/s.
   b. Each velocity bin should include at least 30 minutes of time averaged data.
   c. The number of interpolated velocity bins may not exceed 10% of the total number of velocity bins.
   d. There may be no more than two successive interpolated velocity bins.

The experience gained from generating several power curves within the ReDAPT project is that this is not an easy task, with many variables involved that may cause the data gathered to not meet the IEC requirements. Positioning the ADCPs in their target zones is very challenging both in terms of position and orientation, the ADCP hardware is at risk of faults and the turbine availability has to be sufficient through the test period (e.g. storm conditions might cause shut-downs that reduce availability). Further to this, the process to then generate a power curve from this data is complex, as seen in section 5.2.5.

5.2.7 Calculated Power Curves

The power curves calculated using the process in section 5.2.5 are presented in this section. Power curves were generated for the flood and ebb tides, note that the higher velocities were achieved only on the ebb tide. Two IEC standard curves were produced, from Deployment 4 and Deployment 7 data, by averaging the flood and ebb curves for each of these deployments; these are shown in Figure 10. Deployment 4's curve is thought to be less than optimal due to the change in controller parameters during the sampling period. These curves show a very high level of agreement with the steady prediction, verifying the predicted performance of the turbine. There is a rounding of the corner at the rated point (compared to the steady prediction) due to dynamic effects such as waves and turbulence.

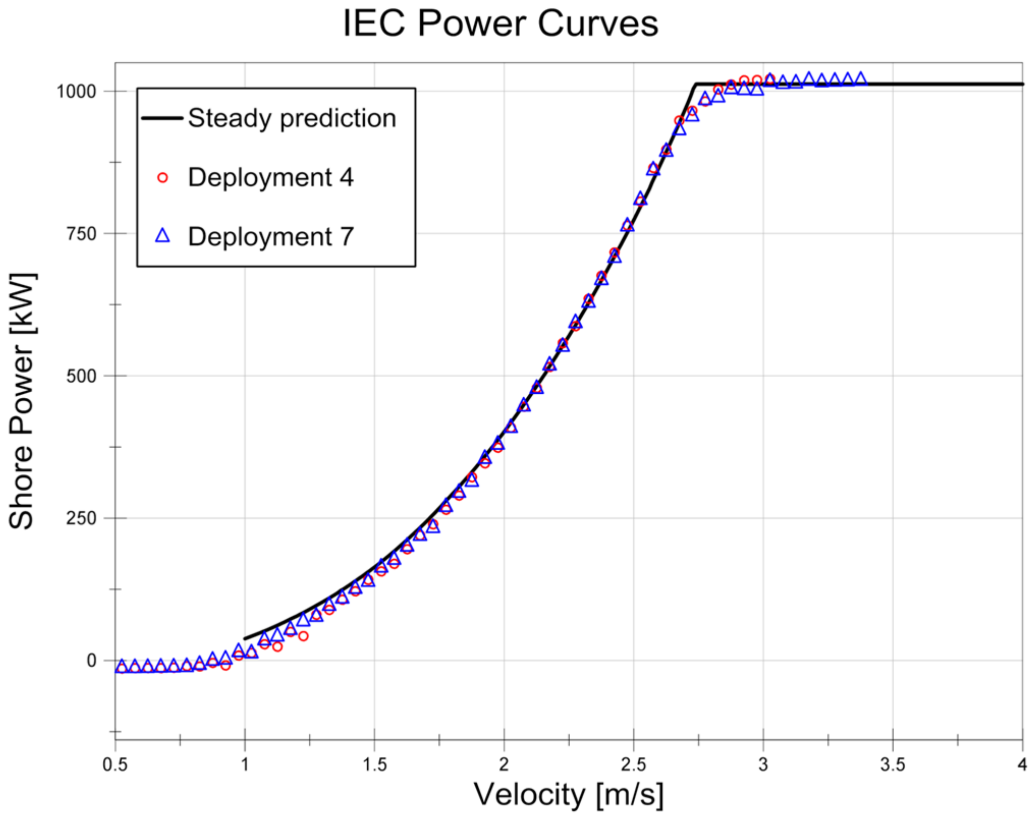

Figure 10: IEC standard power curves produced from Deployment 4 and Deployment 7

Not only is the turbine performance consistent with predictions, but this performance has remained the same over multiple deployments in varying seasons and environmental conditions. Deployment 4 and Deployment 6 made use of in-line ADCPs to monitor flow, while Deployment 7 used an adjacent configuration, but this did not significantly affect the results. The deployed testing has validated the turbine modelling tool, which means that Alstom can predict the performance of their turbines with confidence, provided that the site data is well characterised.

5.2.8 Additional Observations

5.2.8.1 Adjacent vs In-line ADCP Placement

The orientation of flow-sensor placements has been investigated, looking at In-line and Adjacent orientations. Curves created under the same controller settings were not significantly different. However, the no definitive conclusion was possible as the Adjacent and In-line measurements were not performed concurrently.

5.2.8.2 Distance of Upstream ADCPs

The upstream distance of the ADCP in the In-line configuration was shown to have little effect on the results. The closer ADCP showed a slight increase of power measured per velocity bin.

5.2.8.3 Sensitivity to Data Processing Parameters

A study was made of the sensitivity of a 1 m offset to the hub-height and a change in the time-averaging period. It is important to minimise uncertainties associated with the hub-height by understanding well the depth and tilt associated to the turbine and flow sensors. Care must be taken to ensure that the correct relative hub height is used in calculating the PWRA velocity, since the effect of the shear profile can alter results significantly.

The power curves show some sensitivity to the time-averaging period. If the flow and turbine data synchronisation is good it may be desirable to use a smaller averaging period to give a better understanding of the turbine's unsteady performance. A longer time-averaging period reduces the apparent power per velocity bin.

5.2.8.4 Use of Hub Height Velocity as Reference Speed

Comparison of power curves created using the hub-height-ADCP-bin velocity and the PWRA velocity showed, for the cases considered, that there was not much difference in the results. That is not to say that sites with velocity profiles different to that at EMEC would not see an effect.

5.2.8.5 Turbine Mounted Flow Sensors

Nose-mounted flow sensors would allow the flow to be measured before it reaches the rotor plane and at hub height. An investigation into the use of a SBD on DEEP-Gen IV for power curve creation concluded that the SBD selected did not meet the IEC requirements for flow capture. The single-beam sensor can only resolve the flow along the beam and the beam did not measure far enough to not be influenced by the turbine itself. There are also some doubts over the accuracy of the SBD velocity measurement, this is likely to be a calibration issue and easily fixed.

5.3 Efficiency (C_P)

The rotor efficiency assessment uses a large proportion of the process in section 5.2.5, except with a focus on performance prior to reaching rated power and a consideration of power in the flow. For this analysis the strain gauges in the low speed shaft were also required. The main issues to consider are; the strain gauge calibration, drift with temperature and drifting overtime.

To calibrate the strain gauges the manufacturer's efficiency data for the gearbox and generator were taken and compared to the data generated at rated power. The temperature drift was removed by the use of the four-way bridge for torque, however, some drift could still be seen; a temperature correction method was applied. To prevent drifting over time the data was re-zeroed to the slack tide torque before each tide.

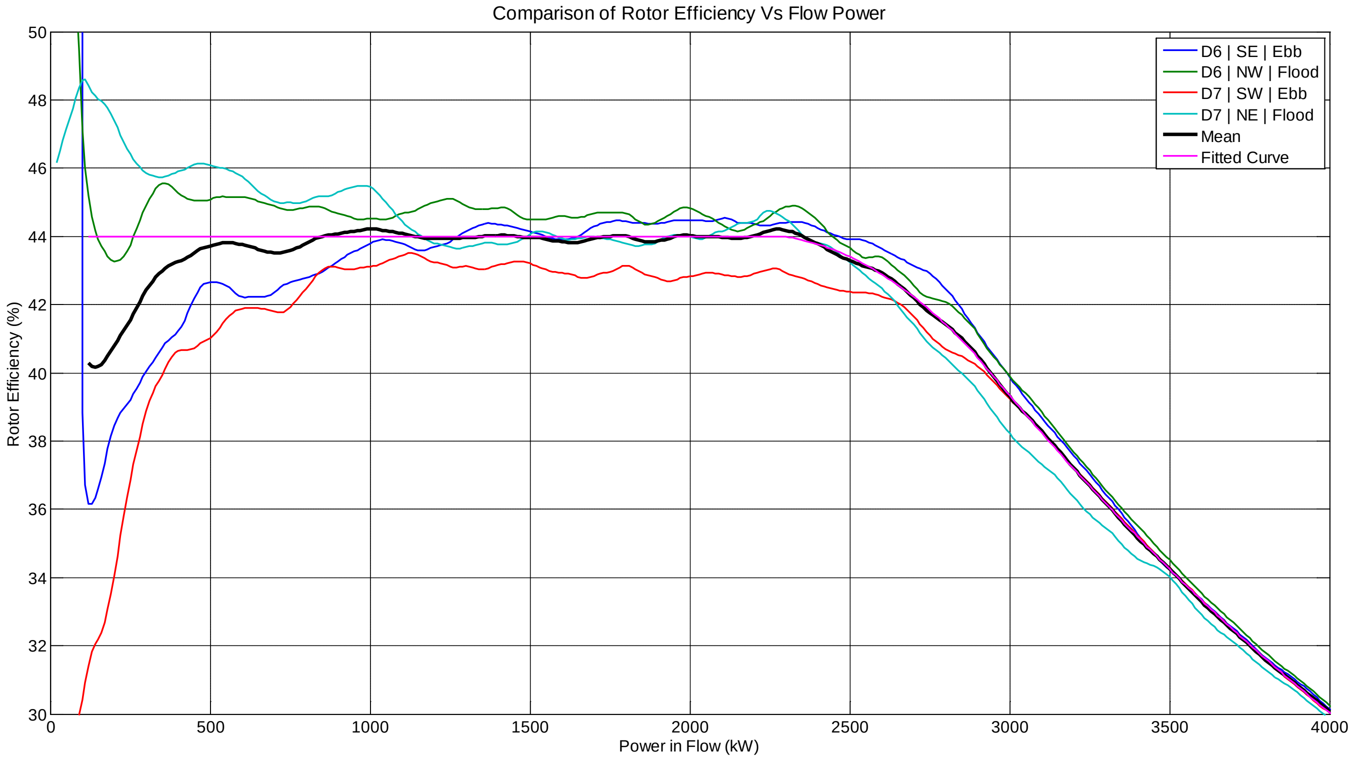

Figure 11 - DEEP-GEN IV Rotor Efficiency Curve

The results for Deployment 6 & 7 separated into Ebb and Flood are presented in Figure 11. There is a large disparity in the measurements on at low flow speeds; this is likely to be a resulted of the poorly developed flow and larger impact of waves and turbulence on the measured flow speed.

At a greater power in the flow (>500kW) there is increased correlation between the four ADCPs studied, probably due to having a more consistent flow speed. In absolute terms the four ADCP studies over Deployments 6 and 7 average out to about 44% efficiency. This holds true up to about 2300kW power in the flow where the efficiency begins to drop due to pitching the blades back away from fine.

At high flows there is even greater correlation between the deployments, as one would expect for highly developed flow. Above about 2900kW power in the flow the data follows a constant power curve as the blades are pitching back to maintain a constant 1MWe. Between 2300-2900kW of power in the flow there is a rounding of the corner due to the influence of waves and turbulence.

The rotor efficiency estimated from these calculations is consistent with the prediction. Below rated the controller attempts to keep a constant TSR to give the best C_P; the predicted peak C_P is about 0.42 which is below the measured value of 0.44. This is not unexpected as the effect of blockage hasn't been taken into account in the simulation and this will produce an increased C_P.

It was noted during this analysis that the spread of data was greater for Deployment 7 where the ADCPs were positioned Adjacent to the turbine. This shows how important it is that the ADCP actually measures the flow entering the turbine rotor; the ADCPs to the side of the turbine did not see the same flow as the turbine.

5.4 Load Factor

The yield and load factor of the DEEP-Gen IV turbine can be calculated using flow predictions for the site and the turbine efficiency curve in Figure 11. Figure 12 - EMEC Flow Distribution Curve shows the calculated flow distribution for the EMEC site during 2010 calculated using tidal harmonic analysis of 4 weeks of ADCP data. The year 2010 is used for this analysis as it is an average year in the 18 year cycle.

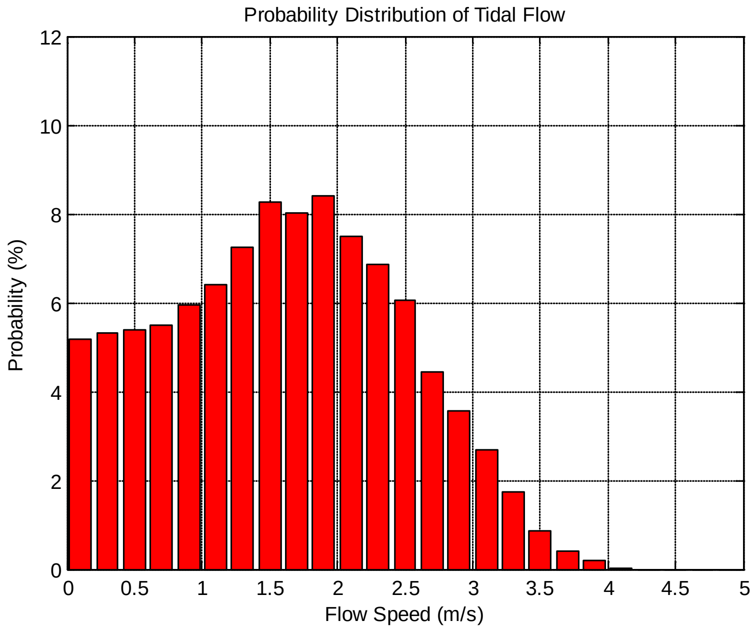

Figure 12 - EMEC Flow Distribution Curve

This flow distribution can be converted to 'Power in the Flow' by using the equation:

$$P_{flow} = \frac{1}{2}\rho v^3 A$$

Where:

ρ = 1027kg/m³

A = Rotor area

V = Flow Speed (m/s)

This results in the plot in Figure 13 - Flow Power Distribution

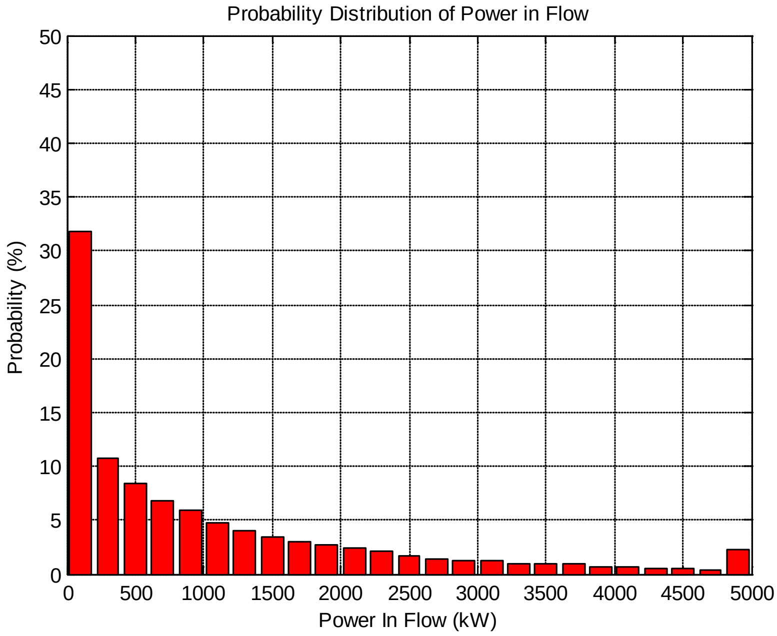

Figure 13 - Flow Power Distribution

This data can then be used to calculate a distribution of the electrical power produced by using the efficiency curve of the turbine shown in Figure 11. The sum of this energy distribution multiplied by the number of hours in a year gives the turbine yield from which the load factor can be derived. This gave a load factor of approx. 33%.

6 INSPECTION ACTIVITY

The turbine was inspected as part of the completion of the ReDAPT project. The inspection of the turbine produced a significant number of lessons learned some of which are reported here and all have been fed back into the Oceade™ design process.

The detailed pre-planning of this period helped to ensure that all tasks were carried out by the most suitable personnel and in time to allow the scheduled lifting operations. At the end of the inspection activity the DEEP-Gen IV turbine was left in storage on low stands in the corner of the quayside, accompanied by its blades and four containers of equipment, taking up minimal space.

Figure 14: Turbine as positioned for storage on the quayside

Following the inspection the turbine will require some work if it is to be re-deployed. Throughout the turbine there are tags indicating the work that would need to be done to get the turbine ready for re-deployment, as well as a register for all these tasks.

6.1 Inspection Scope

The ReDAPT project defined scope was to inspect:

- The pitch system
- The blades
- The low speed shaft seal
- The brake
- The gearbox
- The generator
- The yaw clamp
- The stab plate
- The nacelle

Alstom added several further inspections to capture as many lessons learned as possible:

- The hub
- The low speed shaft bearing
- The electrical system
- The cooling system
- The strain gauges
- The ballast system
- The thruster
- The winch
- The low speed shaft rear seal

A sample of the inspection findings is given in the following sections.

6.1.1 Pitch System

The pitch sumps were opened up for a direct visual inspection of the crank ring, gear teeth and an inspection of the seal running surface, which were all found to be in excellent condition.

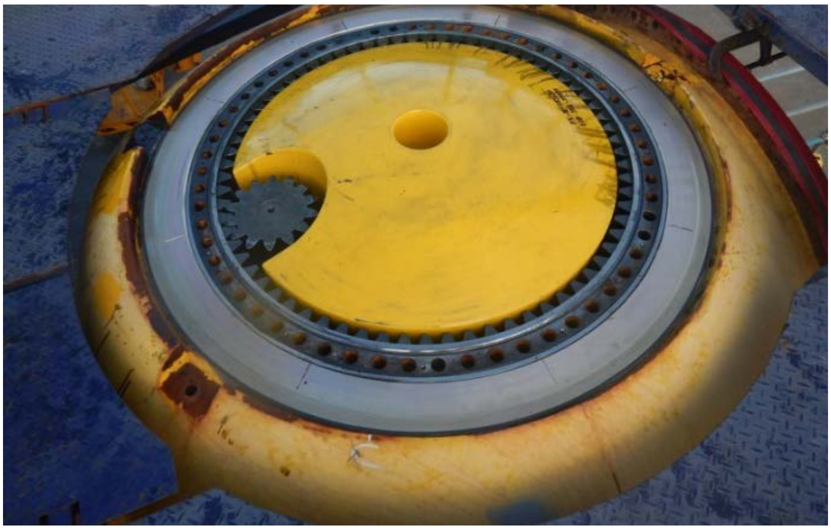

Figure 15 - Blade 3 pitch inspection - overview

Figure 16 -Blade 3 pitch inspection - pinion close-up

6.1.2 Blade Inspection

When the blades were removed the shrouds were dry on the inside and a hiss of air was noted upon removal, showing that the blades had sealed correctly. The nut caps showed some light surface corrosion on the outside, but the coating of bolts and the sealant were all seen to be in good condition.

Figure 17: Blades ready for inspection (Blades 1 to 3, left to right)

Once the blades had been removed and located on their dedicated stands on the quayside, more detailed inspections could take place and be compared to previous inspections. The blades were all in good condition, with very little degradation. The external surfaces showed superficial scratches (the majority of this is believed to of happened during maintenance periods with due to handling & contact with access equipment), which did not go deeper than the antifouling coating. The antifouling coatings worked well, with no growth on the outside surfaces.

A tap test indicated that all the blade skins are well bonded; the blades had not deteriorated during the course of the ReDAPT programme.

6.1.3 Generator Inspection

The generator was inspected for the first time after its 2 years of operation. During operation there had been issues with the encoder signal dropping out (resolved by implementing a change to the control methodology). The detailed inspection revealed that the wires were loose in the terminals in the junction box; these were tightened, resolving the issue.

A polarisation IR test was carried out, which the generator passed, well within limits.

As part of the vibration investigation, an inspection of the bearings was carried out using a borescope. The bearings looked to be in good condition.

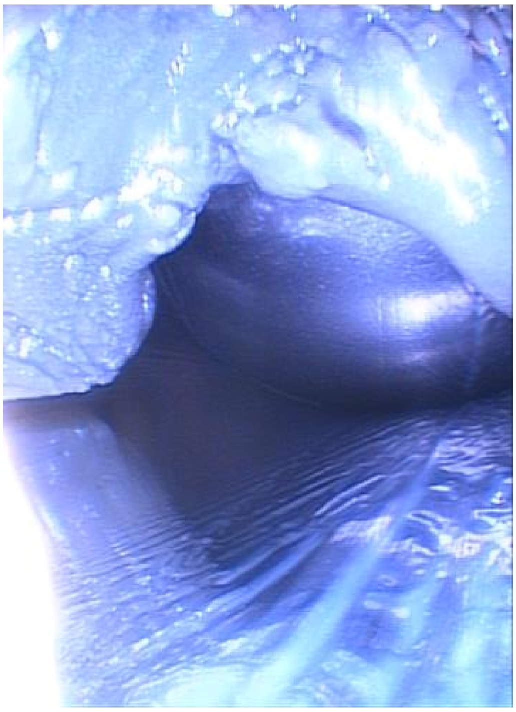

Figure 18: Borescope image of the bearing in the generator

6.1.4 Nacelle Inspection

A photo survey of the anodes on the nacelle was carried out. All the anodes had been active, with the greatest anode depletion taking place in the skirt and thruster areas.

Figure 19 - Turbine Anode (before cleaning)

The turbine was inspected externally. Large areas of the turbine were in good condition with the marine grade epoxy paint was intact. Low levels of biofouling were observed, generally occurring in more sheltered areas. However, where paint had been either chipped or rubbed off (especially at corners and other areas where it may be difficult to adhere) there was surface rust. This was ground back and painted over to ensure the turbine condition didn't deteriorate further during storage.

Figure 20: Nacelle condition after 145 days deployed at Fall of Warness

The whole turbine was steam-cleaned and any damaged paint areas were re-coated.

Figure 21 - Turbine nacelle showing areas before and after steam cleaning

The external fasteners were visually inspected. Stainless steel and xylan bolts looked to be in good condition, with little sign of corrosion. Carbon steel bolts were mixed condition, the ones that had been protected with paint that had bonded were in good condition; however those bolts that had either not been painted or the paint had not bonded correctly were corroded.

A pressure test was carried out on the main seals (between the conical nose and centre section, and between the centre section and aft section) confirming that the seals had not been compromised.

6.2 Planning

The inspection period ran from 26th January 2015 to 20th April 2015 as initially planned. During this time work was carried out on the disposal of Alstom's DEEP-Gen III turbine and the inspections of the DEEP-Gen IV turbine. The intent was to remove the DEEP-Gen III turbine from site at the earliest opportunity, to maximise the available space to work on DEEP-Gen IV, and to organise the storage of DEEP-Gen IV turbine spares and tooling.

The DEEP-Gen IV turbine stands were arranged to allow the turbine to be positioned with the hub & blades over water when it was retrieved. The clamp pallet was set up below the turbine's expected location ready for removing the skirt.

The plan was to remove the blades and skirt, with the hub over the water, as quickly as possible. Once this was carried out, the turbine was to be turned, and lowered down so that it was sitting on its build stands, rather than the higher maintenance stands. The rest of the work would be carried out in this state, allowing easier access to all areas of the turbine.

On 11th February 2015 the DEEP-Gen IV turbine was retrieved, and was lifted onto the quayside that evening. Both the blades and skirt were removed by 21st February 2015. On 4th March 2015 the turbine was lifted and turned and lowered onto the transport stand. Over the next 3 weeks, the majority of inspections were carried out. On 27th March 2015 the turbine was lifted and moved to the end of the quayside where it will be stored until a decision is made regarding its future use.

The turbine was closed up, the containers and blades moved to surround it, a fence erected and the site was left secure. The site was closed up on 20th April 2015; regular inspections of the sites are conducted to ensure safety and security.

7 COST OF ELECTRICITY PREDICTIONS

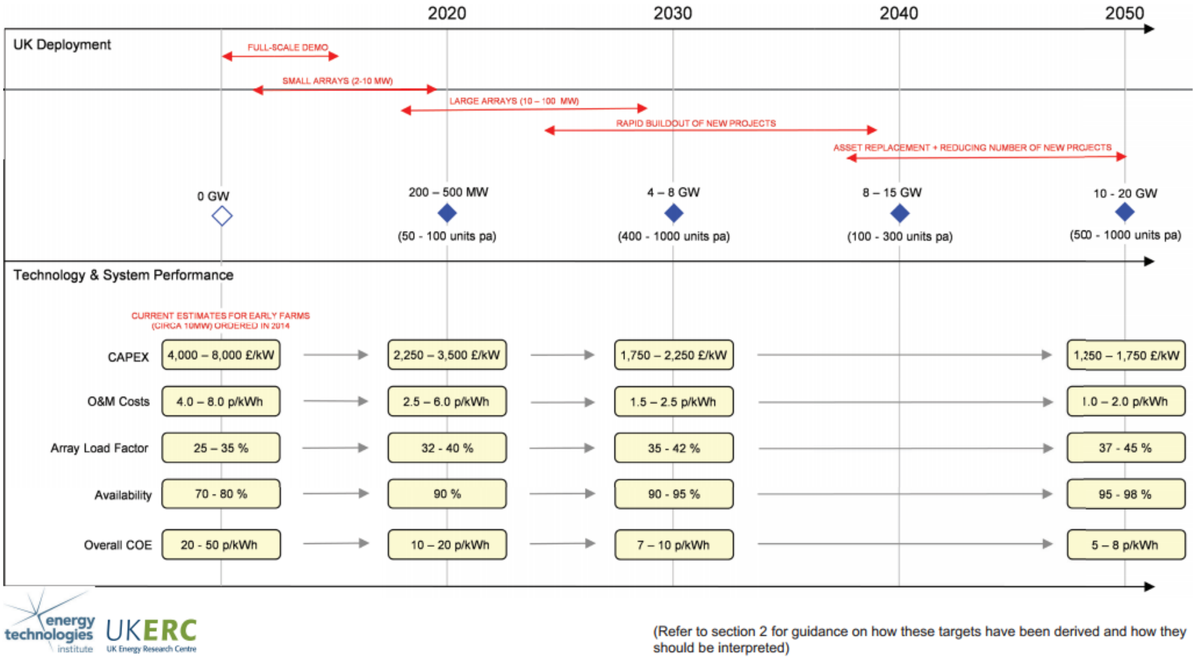

Figure 22: Levelised Cost of Electricity Roadmap – source: ETI (10)

7.1 Background

The ETI target LCOE Roadmap was revised a year ago using input data from the Marine Energy TINA (August 2012), SI Ocean "Ocean Energy: Cost of Energy and Cost Reduction Opportunities" (May 2013) (11) and ETI analysis. Since this work was completed a significant milestone has been reached in the tidal sector: the Meygen project in the Pentland Firth reached financial close. The French administration (Ademe) has also awarded over €100m to two projects in the Raz Blanchard. Revenue will be supported by a €173/MWh feed-in-tariff.

The Meygen project gives a hard data point for the first "small array" in the Roadmap which is higher in CAPEX terms than the Roadmap £4-8m/MW. The Meygen project is £51.3m for 6MW rated power (£8.5m/MW) (12). Note that although the Atlantis and Andritz turbines are rated at 1.5MW, the power conversion is on shore which means that at the shore connection point the power is closer to 1.4MWe, equating to round £9m/MW. Revenue will be supported through the ROC regime for 20 years with 5 ROCs.

The Meygen and French projects are located in sites with a high resource level. This further emphasises that for the early projects work a high level of yield (and therefore revenue) is required: this accords with the ETI view that the sector has to focus on higher energy sites in the first instance (13). These early projects will demonstrate what availability can be achieved.

The ReDAPT programme has delivered some key learning that will help build confidence of project developers and financiers in tidal technology and these are explored in the following sections.

7.2 Power curve and load factor

The real measured power curve of the DEEP-Gen IV 1MWe turbine is in line with the predicted power curve derived through Tidal Bladed taking into account the wave, turbulence and flow environment. This brings confidence that power curves can be derived, provided that a validated data set (flow, waves and turbulence) for the site is established. The power curve can then be used with confidence to establish the load factor and expected yield for a turbine at a single location in a site.

Real load factor in the EMEC site for the DEEP-Gen IV 1MWe turbine is in line with the predictions based on ADCP flow measurement and the predicted power curve. This confirms that the load factor can be predicted with confidence for single-point turbines (and potentially small arrays where array effects are likely to be insignificant).

Load factor is often cited as the main performance characteristic for use in the LCOE modelling. For instance if you take the ReDAPT DEEP-Gen IV machine (18m diameter, rated power 1MWe, rated speed 2.7 m/s) and place it in all the Crown Estates UK Round 1 sites it will achieve load factors of between 15% and >50% (for single turbines), driven by the huge variation in V_{MSP} (mean spring peak velocity) that these sites represent. It is clear is that an 18m-1MWe turbine placed in slower sites with low capacity factors will not work economically as the CAPEX/OPEX for the farm will not be offset by a high enough energy production revenue.

Slower sites will need (provided that depth and environmental limits allow) longer blades. For instance, the Sound of Islay project is considering turbines with 23-24m diameter blades (14). In a high flow site, the challenge is to design a machine that can withstand the forces generated by shallower, wavier and more turbulent conditions AND generate sufficient power. The solution here is to provide machines with smaller rotor diameters (to reduce loads) but higher rated powers to take advantage of more time spent at higher flow speeds. The Meygen project is using 18m-1.5 MW machines and Alstom are developing their Oceade™ 18m-1.4MWe machine for the Raz Blanchard project, both of which are sites with peak flows in excess of 5 m/s. in Alstom's case the 1.4MWe is after power converter.

Furthermore Alstom now offers the Oceade™ platform which is designed to fit the variations in tidal site conditions. The platform concept permits a selection of the most optimal rotor diameter for the site's depth and current conditions to ensure optimum use of the tidal resource. The Alstom Oceade™ platform provides project developers with the possibility of combining variants of the Oceade™ family within a single site to optimise the layout and achieve the best overall yield with capacity factors increased by up to 20% compared to using a single variant.

In order to establish the yield for an array of turbines, detailed site modelling, with careful calibration using bottom-mounted ADCPs, is required. The overall performance (yield) of the array could be reduced compared to isolated turbines due to the energy extraction by the array. Performance of individual turbines within the array will also be influenced by their position in the array (wake effects and localised flow field variations due to topographical features). At present array models rely on simpler bottom drag or energy sink approximations for turbines. It is not clear whether total array yield is under or over-estimated by these methods. This forms a significant risk for the developer as there is a direct link between yield and LCOE, because yield is on the top line of the equation.

The ETI roadmap targets 25%-35% array load factor for the first arrays which is in-line with the experience from EMEC for 1MWe devices deployed in small numbers (therefore minimal array effects) in medium flow sites. To achieve an increasing array load factor up to 45% (by 2050) will require the exploitation of either higher V_{MSP} sites or deeper sites with medium flows but larger rotor diameters. This is technically feasible following the development of these larger devices. The Crown Estates UK Round 1 sites (all except for the Inner Sound) represent medium flow sites akin to EMEC and depth limitations may preclude significant growth in capacity factor (by rotor diameter) for these sites. The development of the Oceade™ platform is aiming to cope with this challenge and offers the possibility to the project developer of addressing the variability of tidal sites.

7.3 Availability and OPEX

The second "top line" factor in LCOE is availability. During the final test period of the ReDAPT programme the 1MWe turbine achieved availability levels consistent with the levels in the ETI roadmap (70%-80% availability). Lessons learned from the DEEP-Gen IV turbine have been incorporated into the design of Alstom's Oceade™ 18-1.4MW machines destined for pilot and commercial arrays. Alstom are confident that the ETI roadmap target of 90% availability for first large arrays will be achievable, based on the learning & reliability growth anticipated from pilot arrays and efficient utilisation of marine spreads achieved through deploying a large number of machines.

However, availability does come at a cost in terms of marine operations. Experience from the wind industry suggests that the majority of downtime events that influence availability are issues that can be rectified within 4-8 hours of visiting the turbine. For fully submerged turbines such a "quick-fix" option is not available; the turbine must be retrieved, taken to a suitable working base for rectification and then re-deployed. The Alstom buoyant nacelle concept is seen as a significant advantage over devices that require a heavy lift as the cost and timescale associated with the retrieval and deployment processes are significantly lower.

For larger farms there will be the potential to keep spare turbines; the increase in farm availability will more than pay for the operational spare. Distance to the operations base will also be a key driver – for the Fall of Warness EMEC site, the steaming distance to the O&M base at Kirkwall is 4 hours. Turbine deployment/retrieval operations can only be carried out at slack water in the neap part of the tidal cycle which can be as short as a 3-5 day operating period twice per month. The DEEP-Gen IV 1MWe turbine can be retrieved, lifted, prepared for entry very quickly: 10 hours and similarly for re-deployment. To re-deploy within a single neap period should be the target for the future. Similarly, working on installation and retrieval techniques to maximise the number of slack waters that can be used has to be a priority to improve overall farm availability.

The ReDAPT programme included a long-term charter of the O&M vessel as well as the means of lifting at Kirkwall (which would otherwise only be available at a prohibitive cost due to mobilisation and demobilisation fees on a per-use basis of a suitably sized crane). Such provision allowed the ReDAPT programme to take action on turbine issues very quickly and was a method of de-risking the programme.

The early projects in the UK Round 1 sites will all have to find suitable O&M bases and target the ETI Roadmap figure of 2.5-6.0p/kWh for annual farm OPEX. For the early small arrays, it is likely that support on this front will be required as high fixed costs not being recovered over a large number of turbines and this does not help to reach the right range of p/kWh.

By way of example, assume a pilot array in the Fall of Warness with the following parameters:

Item	Value
Turbine rated power	1MWe
Load Factor	35%
Availability	85%
Annual boat fees	£1m
Annual O&M base running costs	£0.5m

Table 4: FOW Pilot Array Assumptions

The boat fees and O&M base running costs alone contribute the following OPEX costs, based on sharing the costs over 4, 10 or 30 turbines in a pilot array (all other things being equal).

Number of 1MWe turbines	Boat costs	O&M base running costs	Total fixed OPEX costs
4	9.6p/kWh	4.8p/kWh	14.4p/kWh
10	3.8p/kWh	1.9p/kWh	5.7p/kWh
30	1.3p/kWh	0.65p/kWh	1.95p/kWh

Table 5: Farm Size impact on OPEX

And this is before the costs of corrective maintenance activities are included and other farm operating costs.

The challenge of reducing OPEX requires not only the device OEMs to incorporate improvements in its design but through collaboration with marine contractors and site developers as well as the end user/owner. The clear challenge going forward is to develop both cost effective vessels and contracting strategies along with increasing the reliability of the plant and increasing the operating windows for installation and retrieval.

The ability to provide Third Party certification of turbines and foundation structures is essential to give confidence to investors and insurers. Annual insurance fees might be in the range of 1.5-2% of CAPEX value. This becomes a very significant operational expense. It is anticipated that once the first few small-scale arrays have been successfully deployed and operated that insurance fees will drop significantly.

Alstom understand that the ETI Roadmap targets do not include the insurance costs or grid fees (transmission and distribution charges) which in Scotland are an additional burden on the OPEX of the farm. The insurance and grid fees together could contribute as much as 6-10p/kWh to the LCOE requirements.

7.4 Loads

The loads on the turbine structure are in line with predictions from Tidal Bladed, lending to confidence that turbines can be designed and certified provided that a validated data set for the site is established. A key sensitivity is the turbulence levels which strongly drives the fatigue loading on the turbine and foundation structures. Estimations of the levels of turbulence at the EMEC site, based on bottom-mounted ADCPs, have changed significantly over the course of the ReDAPT project as the site data becomes better understood.

The ReDAPT programme has built Alstom's knowledge in the modelling of turbine loads and achieved validation of the DEEP-Gen IV 1MWe machine loads against real site and loads data. With this validated modelling, Alstom are able to design their Oceade™ turbine with confidence that the loads are well understood.

Achieving a clear, validated, view of the site data (wave, flow and turbulence) is essential to designing a cost-effective turbine and foundation structure. Uncertainty in the site conditions drives the need for margin in the design which in turn increases cost. The active involvement of DNV GL with regards to the certification guidelines, within the ReDAPT programme should help to limit the conservatism in design margins as well as providing the reassurance to customers, investors and insurers that the technology will both perform and survive in the environment.

7.5 CAPEX costs for early pilot arrays

Alstom have modelled the overall LCOE based on the following assumptions:

Parameter	Value
Location	Scotland, Fall of Warness
Farm size	10 units
Turbine rated power	1MWe
Losses to grid	2%
Electrical connection	Single cables to shore
Array load factor	35%
Farm availability	85%
Turbine CAPEX	Based on ReDAPT machine with learning at 8-11%, based on typical wind industry learning rates
Foundation CAPEX	Based on revised tripod design for 25 year life
Foundation installation	Based on Alstom drilled pin pile solution from DP CSV
Turbine installation	Assumed covered in long-term charter of an O&M vessel
Insurance	1.5% of CAPEX
Duos/TnUos	North Scotland figures
O&M base	Kirkwall infrastructure improved and capable of handling 2 turbines
Lifting means	Assumed available at the O&M base on a per use basis
O&M vessel	Based on the ReDAPT long term charter and per use fee for retrieval and installation
O&M costs	Based on 2 operations per turbine per year and assumptions on components likely to be replaced derived from FMECA and wind return on experience

Table 6: FOW 10MW array LCOE assumptions

For a 10MW pre-commercial array the CAPEX breakdown (Figure 23) is derived including all site development costs and this is in-line with Renewables UK’s most recent analysis. The CAPEX is in line with ETI Roadmap target. Whilst turbine and foundation supply represent around 53% of the CAPEX there are considerable costs associated with the installation of foundation and cables, construction of the substation and grid connection. As with the fixed costs for the O&M base, the “per MW” cost of these items will reduce significantly as the size of the farm increases (e.g. mobilisation and demobilisation costs which can be a significant proportion of an offshore campaign if it is only a short campaign and volume manufacture will reduce component and assembly costs).

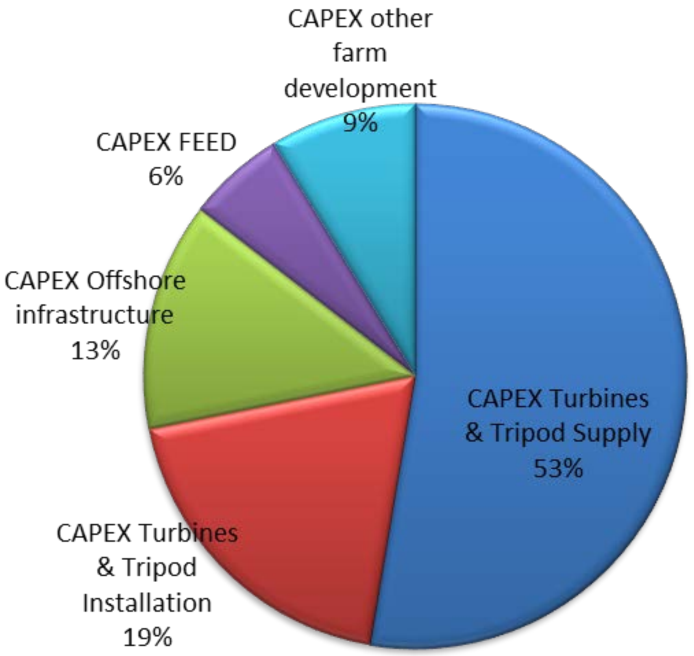

Figure 23: CAPEX Breakdown

The model uses the assumption that both on capital grant support and the tariff support (£305/MWh in the UK) is available.

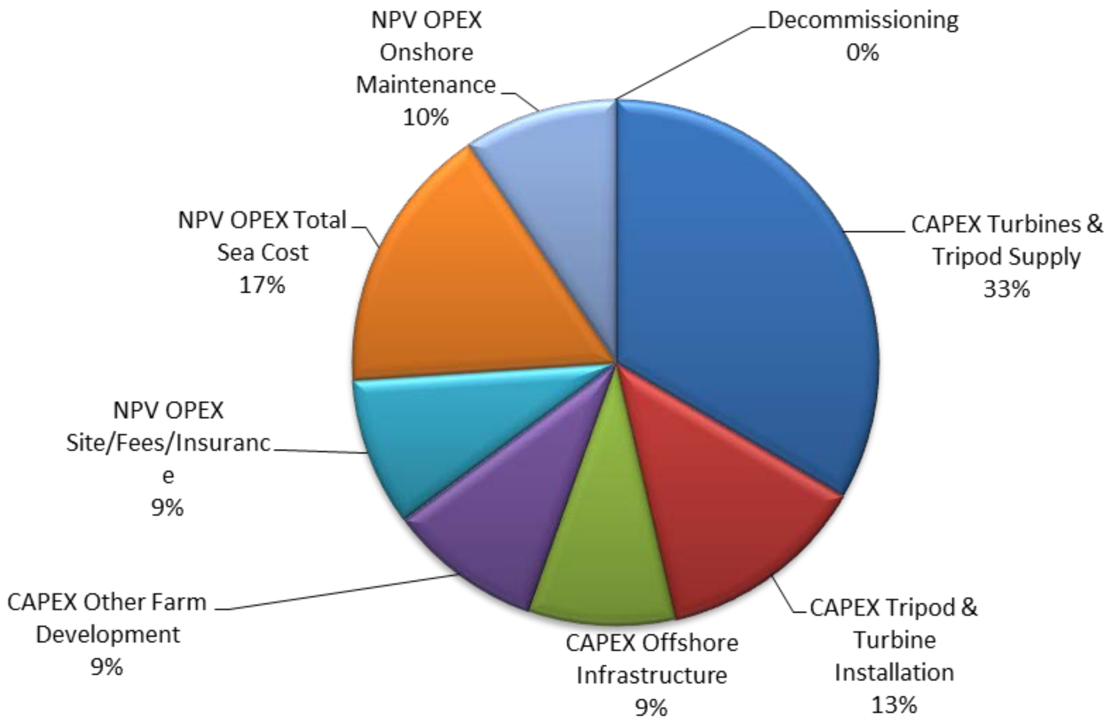

Figure 24: Levelised Cost of Electricity Division

CAPEX represents approximately 64% of the LCOE, site fees (licence), grid fees and insurance represent 9%, sea costs 17% and onshore maintenance activities 10%. In this model, the OPEX includes all site fees, insurance and O&M operations.

7.6 LCOE Conclusions

DECC are currently consulting on the level of CfD strike price for the last two years of the first EMR period (to 2021). The Low Carbon Innovation Group is updating their Technology Innovation Needs Assessment (15) and ORE Catapult published a view on funding needs (16). Both ORE Catapult and LCIG agree that early small arrays still require significant capital support and/or risk mitigation support mechanisms. Once the sector has delivered several small arrays, the level of capital support can decrease but the level of tariff support will need to remain substantial the first commercial projects have been installed in early markets (for example, in the UK, £305/MWh). Further innovation funding will bring forward new solutions in the light of learning from the early arrays.

There is clearly great opportunity to reduce LCOE through improved offshore operations, volume manufacture and technology innovation driven supported by learning from early array installation. The ReDAPT programme has provided the sector with validated tools to design and certify tidal turbines and support structures. Early arrays will build on this learning and will be able to reach financial close if accompanied by the right level of grant funding and tariff support. These arrays will build project developer, OEM and investor confidence and enable larger commercial arrays to be planned and deployed achieving LCOE in the range of £100-200/MWh in the medium term.

8 RECORD OF GRID OUTAGES

This section was provided by EMEC (italicised) and provides a summary of outages and export restrictions at Eday Berth 2, for 1 January 2013 to 11 February 2015. (17)

The Alstom DEEP-Gen IV 1MW turbine was deployed on seven occasions between January 2013 and February 2015, as summarised in section 0. This note describes interruptions to the main high voltage supply during this period arising from outages of the EMEC network and from the external grid.

The Alstom plant is fed from the EMEC 11kV berth 2 feeder breaker, D02. The 11kV supply may be interrupted either by planned switching at D02 or by the "G59" loss of mains protection which is intended to disconnect generation in the event of loss of mains.

8.1 11kV Berth Feeder Breaker Status

CB Open

From	To	Duration (hrs)	Remarks
12/03/2013 13:12	17/03/2013 08:34	115.37	To allow investigation/repair of Alstom 6.6kV CB actuator. (During Deployment 2)
06/03/2014 13:19	06/03/2014 16:34	3.24	Not recorded (turbine not deployed)
18/06/2014 09:29	18/06/2014 19:01	9.53	Alstom onshore switchgear & transformer maintenance (Turbine not deployed)
05/08/2014 16:23	06/08/2014 20:32	27.95	EMEC planned maintenance
27/01/2015 16:27	28/01/2015 08:58	16.52	Note 1

Table 7: 11kW D02 circuit breaker open times

Note 1: the Alstom 6.6kV CB tripped on 26-Dec-14 and was not reclosed until 28-Jan-15 after connection of a vessel auxiliary supply. This outage of D02 was associated with these works.

8.2 G59 Loss of Mains Interruptions

The G59 protection senses voltage at the EMEC 11kV busbar and acts to open the Alstom onshore 6.6kV circuit breaker. The settings used are:

Function	Setting
Over-voltage (1)	13.20 kV 1s
Over-voltage (2)	Not used
Under-voltage (1)	8.8kV 2.5s
Under-voltage (2)	Not used
Over-frequency (1)	51.5Hz 90s
Over-frequency (2)	52Hz 0.5s
Under-frequency (1)	47.5Hz 20s

Under-frequency (2)	47.0Hz 0.5s
Loss-of-mains (1)	Vector shift 12°

Table 8: G59 protection settings

These settings are those originally advised by the DNO at the time of connection of the previous DEEP-Gen III 500kW turbine and differ from the G59/3 settings now required for new connections.

The loss of mains protection will automatically reclose the 6.6kV circuit breaker 11 minutes after restoration of healthy 11kV supplies.

Status of the Alstom 6.6kV circuit breaker is not available to the EMEC SCADA system. The table below gives the time of initiation of a G59 event and an indication of the length of the disturbance at the EMEC 11kV busbar.

Two outages in 2013 are worthy of note. Electricity supplies around the Northern isles are provided by a 33kV ring consisting of submarine cables between and overhead lines across the isles. On 4th March, the 33kV submarine cable between Eday and Westray failed. The open point on the ring was moved to restore supplies to the EMEC facility. A replacement subsea cable was at the time under manufacture, so SSE did not attempt fault location and repair. On 26th July, the cable at the opposite end of the ring, between Shapinsay and the mainland, failed, leaving four islands (including Eday) with no supply. Portable generators were rapidly mobilised but all embedded generation was constrained off until the fault was located (fortunately in an onshore section) and repaired on 31st July.

There were an unusually high number of loss of supply incidents in summer 2014. Several are believed to be related to grid upgrade works on the Scottish mainland, including replacement of grid transformers at Thurso and replacement of the 132kV Beauly-Denny line with a new 400kV line. These both required short-or medium-term reconfiguration of the network to maintain supplies, with less resilience during the periods of reconfiguration.

Orkney experienced severe lightning over several days in December 2014, with significant disruption to supplies.

G59 Event

From	Duration at EMEC 11kV busbar	Remarks
30/01/2013 02:20:56	< 15 sec	
04/03/2013 03:20:39	1 hour 20 mins	Failure of Eday – Westray 33kV subsea cable.
27/03/2013 22:29:57	< 15 sec	
27/03/2013 23:10:35	< 15 sec	
26/07/2013 03:02:05	134.33 hours	Failure of Shapinsay-Mainland 33kV subsea cable. No supply until fault located (onshore section) and repaired
31/07/2013 19:01:36	< 15 sec	
07/08/2013 14:56:09	< 15 sec	
04/09/2013 23:03:43	< 15 sec	
11/09/2013 14:22:48	< 15 sec	
16/09/2013 13:02:19	57 minutes 42 secs	
23/10/2013 23:15:45	< 15 sec	
19/11/2013 22:25:19	< 15 sec	
19/11/2013 23:53:50	1 hour 36 minutes	
05/12/2013 04:22:18	< 15 sec	
05/12/2013 05:14:31	< 15 sec	
05/12/2013 08:20:45	< 15 sec	

17/02/2014 07:16:25	< 15 sec	Total loss of supply
28/03/2014 04:58:37	< 15 sec	Total loss of supply
29/03/2014 09:57:01	< 15 sec	Transient caused by client activity (torque demand error during power converter commissioning)
31/03/2014 10:10:39	< 15 sec	Transient caused by client activity (torque demand error during power converter commissioning)
16/04/2014 19:35:52	12 hours 58 mins	Major grid loss affecting North of Scotland.
22/06/2014 04:15:14	< 15 sec	Total loss of supply
14/07/2014 02:34:26	20 sec	Total loss of supply. Fault on Scottish mainland.
23/07/2014 12:08:05	20 mins 21 sec	Fault at Eday substation (SSE Eday distribution substation, not associated with the tidal test site).
25/07/2014 00:53:16	< 15 sec	Total loss of supply. Fault on Scottish mainland.
25/07/2014 11:15:57	< 15 sec	Total loss of supply. Fault on 33kV system, Orkney West mainland
06/08/2014 08:34:18	6 hrs 56 mins	EMEC planned 11kV busbar outage
12/08/2014 20:36:32	19 mins 57 secs	Total loss of supply. Localised within Orkney
06/09/2014 14:54:58	< 15 sec	Total loss of supply. Localised within Orkney
07/10/2014 05:59:36	41 mins 41 secs	Severe gales
07/10/2014 10:38:48	51 mins 33 secs	Severe gales
07/11/2014 08:57:39	2 mins 6 secs	
07/12/2014 20:50:45	< 15 sec	
10/12/2014 15:36:38	< 15 sec	Lightning affecting external network
10/12/2014 15:48:48	< 15 sec	Lightning
11/12/2014 01:01:49	< 15 sec	Lightning affecting external network
11/12/2014 01:20:31	< 15 sec	
11/12/2014 02:24:40	< 15 sec	
11/12/2014 02:38:07	< 15 sec	
11/12/2014 03:17:16	7 mins 41 secs	
11/12/2014 03:49:10	20 mins 53 sec	
11/12/2014 10:23:12	13 mins 10 sec	
11/12/2014 14:49:33	3 mins 31 sec	
11/12/2014 15:13:47	10 mins 40 sec	
12/12/2014 12:18:45	< 15 sec	
14/12/2014 18:50:22	< 15 sec	
09/01/2015 06:47:21	< 15 sec	
09/01/2015 07:50:16	< 15 sec	

Table 9: summary of G59 events (48 in total)

9 ELECTRICAL POWER QUALITY

The following section reviews the power quality and is an extract from a report supplied by EMEC in August 2015 (18). The extracted summary (italicised) has been agreed with the author.

9.1 Introduction

The DEEP-Gen IV 1MW turbine was deployed a total of seven times between the first deployment in January 2013 and final retrieval in February 2015 and underwent a series of commissioning and development tests during which operating modes and control parameters were changed as required by the test regime. The analysis in this report is based on data from October 2014 during which time Alstom advise that the mode of operation was sensibly constant and representative of normal operation. Data within this period has been further selected to exclude periods in which other tidal turbines were active.

9.2 Scope of Study

The power quality issues examined are:

- *Voltage*
- *Voltage flicker*
- *Power factor and reactive power*
- *Harmonics*

9.3 Measurement Systems

Power quality analysis is for the most part an assessment of the impact on system voltage. Voltage at the EMEC 11kV busbar was sensed by a set of three single-phase voltage transformers conforming to IEC 60044-2 measurement class 1. Current at berth 2 was measured by current transformers to IEC 60044-1 measurement class 0.1, using a two-phase configuration.

Voltage and current signals are fed to a Schneider ION7650 multi-function power transducer which combines these inputs to derive a range of signals including active power, reactive power, power factor, voltage flicker, total harmonic distortion and individual voltage harmonics up to the 48th.

The ION7650 provides 1-second or 5-second sample values (1-second for voltage, current and power and 5-second for other values) to the EMEC SCADA system. It also calculates short- and long-term voltage flicker over the standard intervals of 10 minutes and 2 hours and aggregates individual harmonics over 10 minute intervals. Flicker and harmonics are logged by proprietary ION Enterprise software. The ION meters, ION Enterprise system and EMEC SCADA share the same network and are synchronised via NTP.

9.4 Data Used

Alstom advise that data from October 2014 is expected to be representative of normal operation of the turbine. Seven periods in which there was no other generation on site for at least eight hours have been identified. Ten-minute average data was first examined but it was evident that substantial changes in mean power in response to tidal conditions can take place on a shorter timescale, particularly at spring tides. One-minute data was therefore used except for flicker and harmonic analysis, where the ION7650 meters process data using a ten-minute period as specified by international standards.

The one-second maximum and minimum voltage (i.e. the maximum and minimum values of one-second mean voltage) was checked against the statutory voltage limits for an 11kV supply of ±6% to detect and exclude samples where the external grid was out of limits. No out-of-limits data was found when measured against these criteria. However, the analysis of voltage flicker described in section 9.6 found a small number of lesser transients believed to be of external origin. These have been retained in the analysis.

9.5 Voltage

The magnitude of voltage change in response to a change in power is determined by the current injected into the network and the network impedance. The current injected for a given power is influenced by the generator characteristics (the generator power factor) whereas the network impedance is an external parameter and (barring network reconfiguration) varies between fairly narrow limits determined mainly by the extent of local generation. Section 8 of this report shows that the Alstom turbine power factor is close to unity when generating. The voltage changes seen are therefore as low as can reasonably be achieved for this point of connection.

9.6 Voltage Flicker

Permissible limits for voltage flicker are defined in ER P28 (19). *This allows plant giving rise to short-term flicker less than 0.5 to be connected without further assessment. Plant giving rise to higher levels of flicker may be connected provided the long-term flicker (calculated over 2 hours) does not exceed 0.8 and the maximum short-term flicker does not exceed 1. For connection to the EMEC facilities, where several machines may operate simultaneously, the lower limit of 0.5 is appropriate, as required by SOP-069* (20).

The period for long-term flicker assessment (2 hours, aligned to round clock boundaries) does not fit well with the relatively short tidal cycle and the analysis presented here is limited to short-term flicker, which is based on a 10-minute interval. Long-term flicker need only be examined if short-term flicker frequently approaches the value 0.5.

A small number of cases with flicker in the range 0.5 – 1.0 can be seen. Only one of these triggered a disturbance record. This record shows a voltage notch affecting two phases. The turbine was in operation at mid-power throughout this ten-minute period and the maximum and minimum values do not suggest any significant power excursion. The origin is thought to be external.

It is concluded that flicker attributable to the Alstom turbine during normal operation and during starting and stopping is well within the required limits.

9.7 Reactive Power and Power Factor

The EMEC connection agreement requires power factor to be maintained "at or as near to unity as practicable", with limits "unity to 0.95 lead". It does not have explicit requirements for reactive power other than those implied by the power factor.

9.7.1 Reactive Power

Above approximately 50 kW, reactive power is a linear function of active power with moderate scatter, implying a constant power factor. The value of reactive power at 50kW active power is roughly 10 kVAR. With decreasing active power, reactive power rises quickly towards a near-constant value in the region of 65 kVAR. EMEC understand this is due to capacitors in the grid side filter of the power converter being left in circuit when the turbine is not generating.

9.7.2 Power Factor

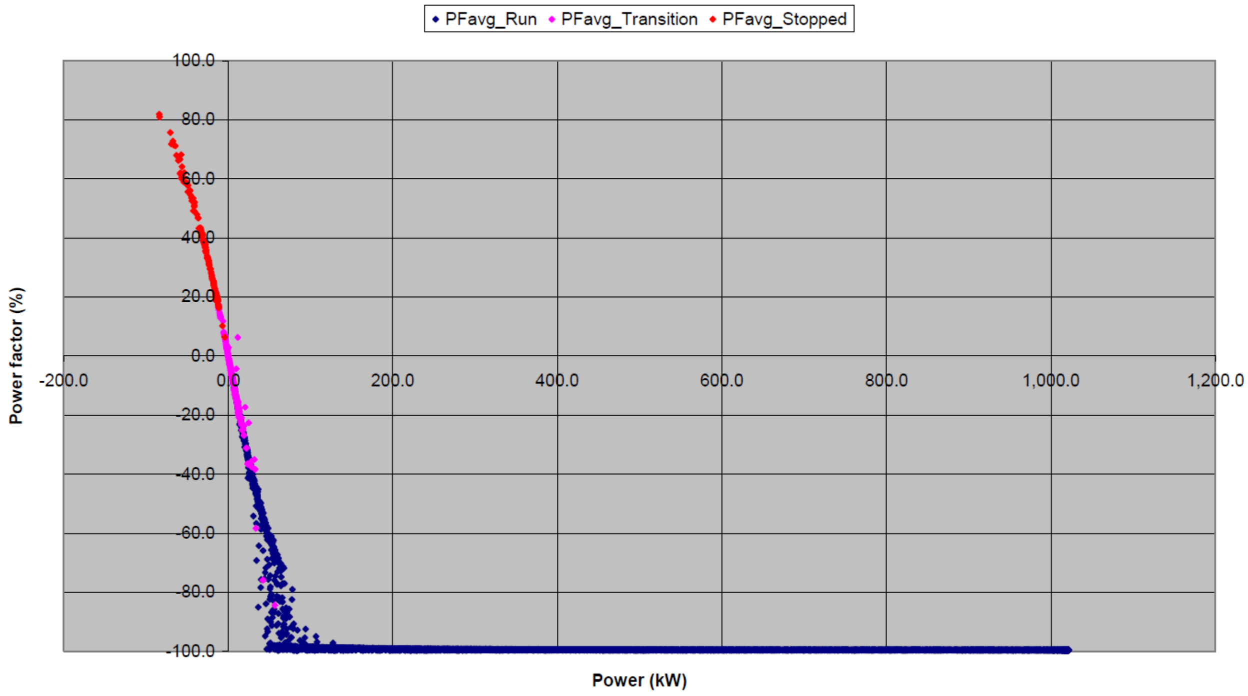

Figure 25: Power factor vs active power

Power factor (as measured at the point of connection to the EMEC 11kV busbar) is plotted against active power in Figure 25*, with points where the turbine was running for the full one-minute period (minimum power >0), was stopped (maximum power <0) or was in transition separately identified. The ION7650 expresses power factor as a percentage which thus takes the range -100 to +100. The IEEE sign convention is used as described below.*

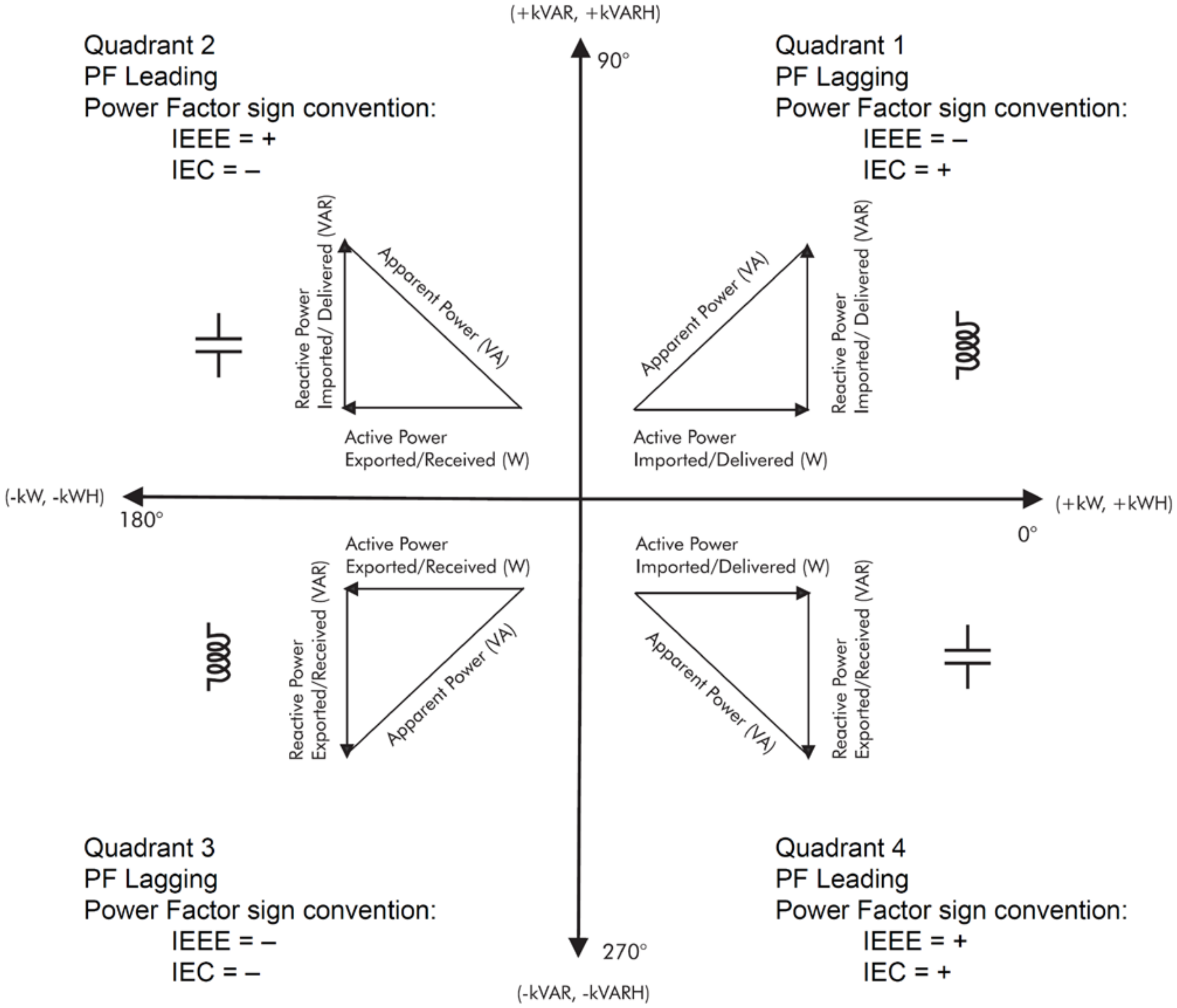

Figure 26: IEEE sign convention

9.7.3 Discussion

The power factor when generating at medium and high power is constant and very close to unity. The abrupt transition at about 50kW suggests that an active power factor control mode drops out below this power level.

The behaviour at low powers is unusual as a consequence of the reactive power contributed by the filter capacitors.

For the general case of a tidal turbine connected via a transformer and subsea cable, it is expected that the power factor measured at the onshore point of grid connection will drop off at low power as the effect of static components (principally the submarine cable capacitance and transformer inductance) begin to dominate the generator characteristics. As active power falls to zero or goes slightly negative to supply small auxiliary loads, there is usually a small and roughly constant reactive component which represents the effect of the vector sum of the transformer magnetising current and the cable charging current. The power factor can be quite poor (perhaps only 0.2) although the *magnitude of reactive power is low. In this case, however, the additional filter capacitance results in appreciable reactive power.*

This discussion shows that it is not practicable to maintain a high power factor at the point of connection to the grid as active power falls towards zero and generation ceases. The practical issue is not the power factor itself, but the magnitude of reactive power – the compliance requirements would be better stated as a working area on a P-Q diagram rather than as a simple power factor. In a different context, the DNO was able to give consent for up to 100kVAR in quadrants 2 and 3 for the EMEC Eday facility as a whole, for a limited period for a particular trial, indicating that a moderate level of reactive power irrespective of active power can be tolerated. This lack of clarity makes assessment subjective. Power factor control above 50kW is clearly very effective and meets the requirements of the connection agreement. As power drops to zero the reactive power supplied by the filter capacitors quickly becomes dominant and persists when the turbine is not generating. The magnitude of reactive power (about 65 kVAR) is rather high and is judged to be at the limits of acceptability for connection at the Eday facility.

9.8 Harmonics

Total harmonic distortion is shown as a function of power in Figure 27*, with running, stopped and transition separately identified. The range of values in all three categories is broadly similar. Statistics for the three groups are given in table 6 and show no significant difference in THD between the groups. All values are well below the 4% limit imposed by G5/4.*

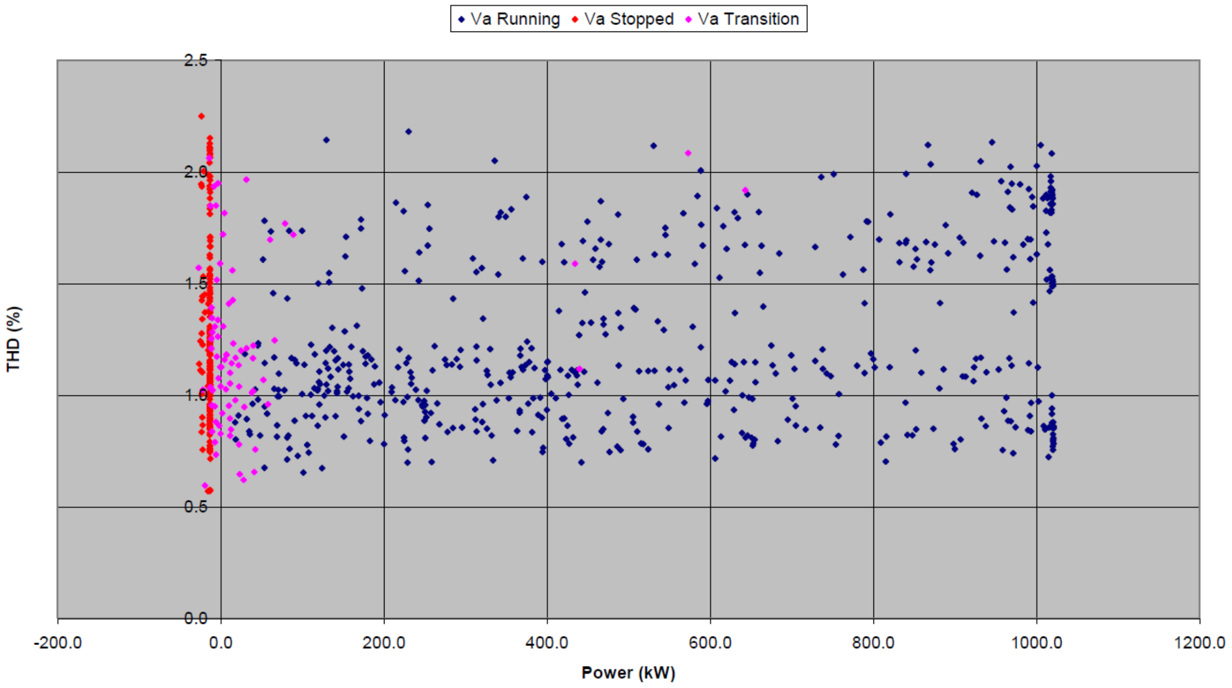

Figure 27: Total harmonic distortion as a function of power

Voltage THD (%)			
Running	Va	Vb	Vc
Count	529	529	529
Mean	1.232	1.221	1.242
Max	2.18	2.067	2.231

Min	0.653	0.677	0.706
95th %ile	1.908	1.88	1.931
Stopped	Va	Vb	Vc
Count	180	180	180
Mean	1.273	1.297	1.29
Max	2.249	2.12	2.295
Min	0.57	0.643	0.633
95th %ile	2.065	1.869	2.008
Transition	Va	Vb	Vc
Count	79	79	79
Mean	1.217	1.224	1.234
Max	2.084	1.928	2.058
Min	0.595	0.615	0.655
95th %ile	1.937	1.82	1.974

Table 10: Total harmonic distortion

9.9 Conclusions

Power quality for the Alstom DEEP-Gen IV 1MW tidal turbine has been examined using data from October 2014, during which time the turbine was reported to be in normal operational mode with no significant changes to control parameters. The data was collected at the point of connection to the EMEC 11kV busbar and was screened to exclude periods when other tidal generators were in operation, leaving a total of 131.7 hours of data for analysis.

The scope of the survey covered voltage, voltage flicker, power factor, reactive power and harmonics.

Steady-state operation at full load (1 MW) was found to raise voltage at the EMEC 11kV busbar by approximately 1%. This is acceptable when compared to the statutory supply limits of ±6% and is less than the normal background variation in voltage which spanned a range of approximately 3.2% over all data.

The drop in voltage during a shutdown from full load is similarly about 1%. In the example illustrated, the shutdown takes the form of a steep ramp over several seconds and is therefore a less severe voltage disturbance than a step change. Applying the guidelines in ER P28 (19)*, the impact of such a full-load shutdown on voltage flicker was predicted not to be significant. The worst case would be a trip which caused immediate electrical disconnection and therefore a step-change in voltage. For this case, the maximum repetition period estimated from P28 is in the region of 30 seconds. This is sufficiently short that there is no need to consider controlling the time between turbine shutdown and re-start.*

The turbine was found to have very little effect on voltage flicker. When isolated cases due to external grid disturbance were excluded, the mean and 95th percentile values for short-term flicker of the worst phase for the three cases turbine stopped, turbine running and transitions between running and stopped were:

	Stopped	Running	Transition
Mean	0.244	0.25	0.259
95th percentile	0.363	0.372	0.387

The worst phase short-term flicker value for the full-load shutdown used to illustrate voltage step-changes was found to be 0.344. These values are all comfortably within the permitted limit of 0.5.

Flicker did not show any evident correlation with mean power, but was shown to be a weak function of the standard deviation of power which can be taken as an indicator of the mean rate of change of power.

Power factor when generating is very close to unity for power levels down to approximately 50 kW and reactive power is correspondingly low. Below this value, reactive power rises rapidly to a value of around 65 kVAR when the turbine is stopped. This high value is reportedly due to filter capacitors which remain in circuit. Although strict compliance with the connection agreement requirement for power factor is often not practicable at very low power, when the effects of cables and transformers become dominant and are usually acceptable, the elevated reactive power due to the filter capacitors is judged to be at the margin of acceptability.

The turbine was found to have little impact on voltage harmonics. Comparing harmonics with the turbine in operation and turbine stopped, the most noticeable findings were:

- All phases show a modest reduction in 3rd to 7th inclusive when the turbine is running;

- All phases show a slight increase in harmonics above 10th when running

- All phases show an increase in 2nd harmonic when running

- There is a general increase in mid-range even harmonics when running in phases Vb and Vc, and a less pronounced increase for Va.

The background levels of the 5th and 7th harmonic were appreciable and were slightly improved by turbine operation. All other harmonics were within compliance levels. The presence of even harmonics may indicate slight asymmetry in turn-on or turn-off the positive and negative arms of the power converter inverter bridge.

10 ENVIRONMENTAL CONDITIONS

The report on the work carried out by DNV GL's (formally Garrad Hassan) in support of MD6.1 analysis (21) concludes the following (excerpt italicised).

Analysis of existing site data was undertaken to develop an environmental characterisation for a design basis for loading and performance calculations.

The definition of a design basis was discussed along with the requirements for site characterisation in order to gain certification for a tidal device. For certification it is necessary to undertake load calculations to ensure the structural integrity of the device over its lifetime. During that time a device will experience continual cyclic loading (fatigue) as well as potential extreme loads, thus the environmental conditions driving long term and extreme effects must be characterised.

The long term mean and extreme conditions for tidal flow, tidal elevation, wave and wind activity at the European Marine Energy Centre (EMEC) site have been evaluated, specifically at the location of the Alstom device.

Tidal flow and elevation data was available from an Acoustic Doppler Current Profiler (ADCP) survey carried out by Alstom, recording one month's worth of flow and elevation data at 1Hz. Wave climate data was obtained from the Royal Haskoning Report (22) *and from post-processing the ADCP data. The wind data available was taken from EMEC's local meteorological station.*

The tidal flow and elevation data was analysed using GH's tidal site data analysis software. The data underwent quality control, before being analysed for principal directions, depth flow profiles and turbulence intensity. Particular attention was paid to turbulence characterisation as it is a key parameter in evaluating fatigue loads. The magnitude and directional components of turbulence intensity are calculated, as well as the variation with flow speed, flow direction and depth bin to give a full image throughout the water column. Corrections for ADCP measurement noise are applied to attempt to best represent the turbulence conditions.

The wave data is taken from the Royal Haskoning report and turned into an inshore wave scatter table from the data provided for the long term wave climate. The extreme sea states are also converted into design values for extreme wave height and period. Both the long term and extreme wave results were compared against the post-processed ADCP data, however both the report and the ADCP data have their limitations, so results should be treated with caution.

The wind data available for the EMEC site was correlated against nearby long term reference sites to generate the long term mean wind speed and the 1 and 50 year extreme wind speed. These results should be treated with caution as GH were unable to verify that the mast set up meets IEC recommendations and that the close location of the anemometer to the ground means it is likely that there is interference due to the local topography and nearby obstacles. These wind speeds are translated into wind induced current profiles using assumptions taken from certification guidelines.

The results for these analyses which constitute the site definition aspect of a design basis are reported in the following table.

		Value	**Unit**
Long term tidal flow conditions			
$Ur_{\_rms}$	Long term mean current	1.804	m/s
$Urf_{\_rms}$	Long term mean flood current	1.701	m/s
$Ure_{\_rms}$	Long term mean ebb current	1.896	m/s
U_{msp}	Mean spring peak current	3.079	m/s
U_{mnp}	Mean neap peak current	1.744	m/s
$Ur_{\_max}$	Maximum current on a mean day	2.42	m/s
$Ur_{\_min}$	Minimum current on a mean day	0	m/s
	Variation between maximum and minimum current on a mean day	2.42	m/s
	Principal flood direction	322	°
	Principal ebb direction	137	°
	Flood / ebb ratio	0.897	
	Spring / neap ratio	1.765	
ρ_{water}	Sea water density	1027	kg/m3
Extreme tidal flow conditions			
Ur-1	Regular current with a recurrence period of 1 year	3.911	m/s
Ur-50	Regular current with a recurrence period of 50 years	4.212	m/s
$Uw_{, 1-yr}$	1-year return wind-generated surface current velocity	0.766	m/s
$Uw_{, 50-yr}$	50-year return wind-generated surface current velocity	0.574	m/s
Long term tidal elevation levels			
MSL	Mean sea level (relative to Chart Datum)	1.51	m

Requester : James HARRISON | Reviewer : David DOBSON | Approver : Paul CHESMAN | Rev : A | 12/08/2015

HAT	Highest astronomical tide (relative to Chart Datum)	2.97	m
LAT (Chart Datum)	Lowest astronomical tide and Chart Datum from seabed	41.57	m
Extreme tidal elevation levels			
HSWL1	Highest still water level with a recurrence period of 1 year (relative to Chart Datum)	2.88	m
LSWL1	Lowest still water level with a recurrence period of 1 year (relative to Chart Datum)	0.11	m
HSWL50	Highest still water level with a recurrence period of 50 year (relative to Chart Datum)	2.97	m
LSWL50	Lowest still water level with a recurrence period of 50 year (relative to Chart Datum)	0	m
Long term wave conditions			
E[Hs|Vhub]	Significant wave height, conditioned on mean wind speed and mean wind direction*	1.11	m
E[Tp|Vhub]	Spectral period, conditioned on mean wind speed and mean wind direction*	4.2	s
Γ	Peakedness parameter for Jonswap spectrum	1	-
Extreme wave conditions			
Hs1	1-year significant wave height	3.9	m
Tp1	1-year peak spectral period	9.1	s
H1	1-year individual wave height	7.25	m
T1	1-year individual wave period (range of possible values)	7.00 – 9.02	s
Hs50	50-year significant wave height	5.2	m
Tp50	50-year peak spectral period	10.4	s
H50	50-year individual wave height	9.67	m
T50	50-year individual wave period (range of possible values)	8.08 – 10.4	s

Table 11: Table from (21)

This report (21) *has developed a description of the environment which can be used to set-up representative Tidal Bladed simulations for the purpose of undertaking load calculations. The next step will be the construction of Tidal Bladed simulations with representative inflow conditions. These will be used and developed in MD6.2 to better represent the inflow conditions, with particular focus on flow turbulence and wave and current interaction. The design basis* *description of the environmental conditions will be used to construct a set of load calculations which will be reviewed after the validation exercise in MD6.5 in order to assess the suitability of the initial design loads.*

11 ENVIRONMENTAL INTERACTION

Information on the environmental monitoring summarised in this section has been provided to Marine Scotland as part of the marine licence requirements.

11.1 Deck Plate Mounted Camera

Although there was a deck mounted camera that could be monitored intermittently, no data was continually recorded (although limited data has been captured) and both the refresh rate and resolution were low. The poor lighting levels and turbid flow meant that the camera was not a viable monitoring tool. In addition several issues were encountered with camera operation.

During Deployment 7 the camera system, which had previously struggled to operate, was removed and replaced with a simpler camera system. Unfortunately the replacement camera was active for less than 5 minutes with only ~15s of footage captured (image in Figure 28), before the camera failed. The image quality from the camera was good; however, the cable connection was not robust enough for the environment and signal was lost. The lack of success with rotor monitoring cameras is a key lesson learned as opposed to the comparatively good reliability of the strain gauge analysis.

Figure 28: Typical image from footage captured by the camera (23)

11.2 Strain Gauge Monitoring

An off-line algorithm was used to monitor spikes in the values recoded by the turbine blade and Low Speed Shaft (LSS) strain gauges. Such a spike may indicate a collision with a large object in the water such as a marine mammal. This algorithm was developed for the 500kW DEEP-Gen III turbine marine licence and was updated for the DEEP-Gen IV turbine.

When data was provided for mammal activity by Marine Scotland (from EMEC MMOs), there was very little activity in the area of the turbine (that could be spotted); the only time a mammal was reported in the immediate vicinity was a time when the turbine had been shut-down for a number of hours. This and other studies suggest that marine mammals tend to avoid horizontal axis tidal turbines.

11.2.1 Instrumentation used

The Low Speed Shaft (LSS) torsion strain gauges were the preferred monitoring method because any impact will temporarily reduce the torque as a result of a reduction in the inertial energy of the rotor. This would manifest as a short term reduction of LSS torsion detectable from the four torsional strain gauges located on the shaft. The analysis in Deployment 5 was performed without the LSS strain gauges, while the analysis in Deployment 7 did use these strain gauges.

Blade and shaft loads were analysed by assessing bending moments and rates of change (ROC) to detect any potential impact. Through impact analysis and published marine mammal data, thresholds were determined for use in the monitoring algorithm.

11.2.2 Strain Gauge Monitoring Results

The clearest results from this algorithm came in Deployment 7 when the LSS strain gauges could be incorporated into the analysis. The analysis has been carried out for specific dates provided by Marine Scotland and thresholds were not breached. There were no sharp reductions in torque throughout this period. Where a large drop in torque did occur this was associated with a shutdown event.

No evidence of marine mammal interaction has been found; events that breach thresholds have been related to brake events and momentary signal losses.

11.3 Biofouling

Only superficial algal growth and crustaceans have been noted on DEEP-Gen IV on the turbine retrievals. During the turbine inspection activity a detailed study of biofouling was undertaken, very little biofouling was noted overall. There were higher concentrations in more sheltered and/or intricate areas of the turbine. All the biofouling could be easily removed when pressure washing the turbine. No biofouling was found to be significant or affecting operation.

Further to this the turbine was used to house specific material panels for PML; the results of their findings are presented in ME8.4 (24) and ME8.5 (25).

Figure 29 - Biofouling on the University of Edinburgh's thruster mounted instrumentation rack

11.4 Acoustics

During both Deployment 5 and 7 acoustic surveys were carried out. Within these surveys the turbine would be set up in a pre-determined state (i.e. generating, yawing, idling etc.) and the noise could be measured using drifting hydrophones that were submerged just below the surface. The work was undertaken by EMEC, who produced a report detailing the acoustic study of the turbine (italicised) (26).

The EMEC tidal energy test site is located at the Fall of Warness between the islands of Eday and Muckle Green Holm in Orkney. Tidal currents can reach 7 knots at spring tides. The area has a hard seabed and is likely to be a low-loss acoustic environment. In 2012, EMEC undertook acoustic surveys to characterise the baseline underwater noise signature at the test site (Harland, 2012), and this is used as a reference when characterising the underwater acoustic output from the DEEP-GEN IV device.

Acoustic data was collected using the Drifting Acoustic Recorder and Tracker (DART) system developed by EMEC. Full details of the DART system, including the deployment and recovery method used, are provided in (26)*.*

The noise produced by the turbine was predominantly lower frequency noise <500Hz and there was little noise associated with high frequencies. It was also noted that the noise of the tidal flow passing through the site was quite significant. The report is now being reviewed by Marine Scotland.

12 LESSONS LEARNED

Throughout the ReDAPT programme, periodic lessons learned reviews have taken place, both internally within Alstom and externally with the ReDAPT partners. The lessons learned have been at many levels and have come from a multitude of different sources.

At the programme level, Alstom has collated feedback from several of the partners based on their experiences throughout ReDAPT.

At an operational level, Alstom has carried out lessons learned sessions following each maintenance period and marine operation; the latter often including marine operations contractors.

At the technical level, lessons have been captured though internal engineering design and development processes, including design reviews, maintenance documentation and reports (Job Cards etc.), and specific technical lessons learned sessions. A major output of the ReDAPT programme within Alstom Ocean has been the collation of all lessons learned into a log, with over 700 entries. The log has been used to ensure that all lessons learned are incorporated into the design of the Oceade™ turbine, by implementing mandatory reviews of the log being in the Alstom Ocean Design Review Process.

The following sections outline the main lessons learned from the ReDAPT programme at the various levels.

12.1 Programme Lessons Learned

The ReDAPT partners felt that the ReDAPT programme was not flexible enough in terms of commitments to deliverable dates and inclusion of budget contingency, particularly at the start of the programme. This meant that the ReDAPT partners found it difficult to react to emerging risks and take account of more up-to-date information as the programme evolved. The overall level of bureaucracy seemed excessively high for such a small programme, again reducing flexibility and consuming a disproportionate amount of time and resource. This detracted from the progression of technical objectives, particularly within the minor partners.

The contract itself was particularly complex, with structure changes during multiple contract amendments only serving to compound this issue. The milestone nature of the project was enforced rigorously, which led to inevitable compromises in technical and operation decisions, the outcome of which could be argued caused longer term delays and cost increases.

Despite the above issues causing concern during the early phases of the programme, lessons were learned around these points and changes were implemented; in the second half of the programme an improved and more pragmatic approach to collaboration was taken by all.

Another positive aspect of ReDAPT was the implementation of the structured Design Process of a large industrial group throughout the ReDAPT partners. Although some partners were more experienced with this type of process, for others it was a steep learning curve initially; however, most partners agreed that it had long term benefits in terms of improving the technical content and quality of their designs.

12.2 Operations Lessons Learned

Throughout ReDAPT there have been many site operations conducted by the ReDAPT partners, during assembly, testing, maintenance, deployment and retrievals. These operations have primarily taken place on Hatston Quay, Kirkwall and on marine contractors' vessels in and around the Fall of Warness. These operations have included turbine equipment maintenance, ADCP deployments, paint panel deployments, sub-sea inspections and of course turbine deployments and retrievals.

One of the difficulties faced regarding operations was the application of CDM regulations for all marine operations. Albeit necessary, this created an additional layer of auditing and protection that was not fully understood by all ReDAPT partners, which caused delays. During marine operations in particular, communication between vessel- and shore-based engineers was hampered by inconsistent mobile phone reception. In hindsight, this should have been mitigated early on through investment in a satellite phone (or similar), which although expensive would have provided opportunity to reduce marine operations uncertainty and even remove the need for some (expensive) travel.

Alstom's primary marine contractor (Keynvor Morlift Ltd) was very flexible throughout the ReDAPT programme. Having an integrated vessel (deployment/retrieval) and barge (turbine lifting) contract was also beneficial as it reduced paperwork and contract related complexity involved in planning and executing marine operations.

12.3 Technical Lessons Learned

12.3.1 Deployment & Retrieval

Through the marine operations over the last four deployments and retrievals (deployments 4 to 7) several events have led to lessons being learned for future operations. Two elements of the marine operations that have been a risk throughout the ReDAPT programme are the reliance on the ROV and the use of umbilicals. There are many benefits to the use of the ROV, especially in performing inspections and removing the need for divers during simple submarine "work". However, each ROV operation carries with it several risks, including the potential for umbilical entanglement and the susceptibility to changeable weather and tide conditions.

The skill of the ROV pilots also plays a huge role in the success or otherwise of the ROV operations. Umbilicals are also very useful, allowing direct communication and control of the submerged system (ROV / turbine / winch) and the provision of ship's power, which removes the reliance on batteries. However, umbilical handling can be challenging, especially in a tidal site, and the use of multiple umbilicals at one time can very easily lead to entanglement, which can result to equipment damage and an increased EHS risk for umbilical handlers. Umbilicals are also susceptible to damage and are expensive and time consuming to repair or replace.

There have been several occasions where the limitations of the ROV and umbilicals have been realised. These and other experiences have served to reinforce the lesson that **the use of ROVs and umbilicals for normal operations should be limited as much as possible by design**. It can also be said that **the addition of a dedicated launch and recovery system (LARS) with umbilical management for the ROV would de-risk the ROV operations significantly**.

Deployment 6 ended with the turbine being recovered through the use of hydraulic hot stabs. This was a complex operation for which detailed planning had not been completed prior to the failure that led to its implementation. The procedure was developed, along with the hardware modifications, in the few weeks leading up to the retrieval. Use of divers, multiple vessels, an ROV, and hydraulic and electrical umbilicals meant that this operation had to be planned thoroughly. In the event, all aspects of the operation went to plan, including the use of a pre-planned contingency for one element of the operation. This operation was a great success and highlighted **the importance of good planning and simple, robust processes in complex marine operations,** as well as underlining the reliance upon good weather.

12.3.2 Maintenance

During the ReDAPT project, communication with Orkney Harbours regarding our circumstances and the priority given to cruise ships (during summer months) impeded operations. This was not only disappointing, given Orkney's position in renewable energy development, but led to delays and increased costs for ReDAPT. It should be noted that in the latter few months of operations at the quayside, the relationship with Orkney Harbours improved significantly. However, the lesson to take from our overall experience is that **for a tidal developer to function effectively at any site**

they need to build a trusting relationship with the owner of the site and ensure that all potential conflicts of interest are discussed and agreed upon prior to signing a contract.

Throughout the early part of this project the resource planning for maintenance tasks was not optimised. The use of engineers for the “hands-on” roles reduced the resource available to plan, design and record the work. During the last year of maintenance activities, there was a shift towards the use of trained mechanical and electrical fitters for the “hands-on” work, freeing the engineers to plan, supervise and record the work. This setup led to more efficient maintenance periods and more thorough records of work undertaken. The lesson learned is that **the correct resource type should be used for planning, supervising and executing maintenance tasks**. However; it should be noted that **having design engineers on site allowed for immediate feedback of onsite issues and the designer’s experiences have been fed back into the design of the Oceade™ turbine**.

Many maintenance tasks involved accessing fluid systems to take samples and to drain, fill, and bleed them. Many of the fluid systems had not been designed with this work in mind so did not have fill and bleed points in accessible positions. This compromised the quality of the oil system work that was undertaken and also added delays to the programme of work. Inadequate drain points also increased EHS hazards since poor location of, or failure to provide drain points could result in workers being contaminated with oil or coolant. For future designs **the provision of adequate and accessible fill, drain and bleed ports for all fluid systems must be a requirement and should be considered from the design stage**.

The turbine work at the Hatston Quay maintenance site was managed and supervised on a daily basis by one of several Alstom ocean engineers who spent a week at a time on site, away from the Bristol or Nantes office, on a rotation basis. One of the hardest elements of this role was keeping track of the work that was being undertaken on site. During the last maintenance periods, a CCTV network was set up on the quayside to monitor activity in and around the turbine, which allowed the site supervisor to view all activity in the turbine and at key points on the quayside from one location. This improved the efficiency of this role as well as reducing EHS risks relating to the turbine’s confined space hazards. It is suggested that **future maintenance should consider use of a CCTV setup to monitor workers inside the turbine and around the site as well as ensuring turbine ventilation, primarily from an EHS point of view**.

12.3.3 Biofouling

Biofouling is certainly a concern for tidal turbines and during ReDAPT Alstom has tried to learn as much as possible about its effects and how to remove and prevent it. During the inspection of the blades it was noted that the drainage holes in the blade had attracted barnacles. Further investigation revealed a very small amount of biofouling inside the drainage passage within the blade structure. The main lesson from these findings is that **future designs, particularly those employing flooded blade sections, should consider the effect of biofouling on their operation and try to minimise its growth and will be able tolerate appropriate levels of fouling**.

During the last few maintenance periods the turbine has been washed to remove biofouling. Initial attempts were undertaken once the turbine had been on the quayside for several days, but these proved difficult with the hard barnacle shells being hard to remove. However, on advice from PML, subsequent cleaning activities were undertaken within 4 days of removal from the water; the biofouling was removed much more easily. In all cases the turbine was washed using a steam cleaner. Only water was used (no detergent). The lesson learned is that **all biofouling removal activities should happen as soon as possible after retrieval of the turbine to achieve the best results, ideally within 4 days**.

12.3.4 Design

Several issues arose from fasteners becoming loose, including the buoyant nose bolts and electrical components within turbine cabinets. Many of these fasteners were affected by vibration, but some suffered with assembly quality issues. Although the root causes of these issues varied, the lessons to take away are that **the selection of fasteners at the design phase should consider the propensity for working loose during operation and provide suitable mitigation (threadlock, lock wire, tab washers etc.)**, and that **the assembly of fasteners should be properly prescribed, controlled and quality-checked during all assembly and maintenance activities**.

One significant issue during the final year of ReDAPT testing was the failure of the HPU. This was due ultimately to a control logic error that caused the HPU to run continuously. . The lesson learned from this incident is that **control logic and alarm levels need to be thoroughly validated and tested on land before deployment**.

Some issues during the testing and commissioning phases of the ReDAPT programme were related to circuit breakers opening. These circuit breakers were not always remotely resettable and in some cases required manual intervention. Although circuit breakers are designed to open as part of an appropriate response to a damaging or dangerous condition, some of the CB opening events during ReDAPT were not as a result of these conditions. In some cases the root cause of the inappropriate CB openings was an extremely brief and non-damaging over-current event caused by macro electrical effects, such as phase combination. These events caused inappropriate CB opening because their settings were not robust. Therefore, one of the lessons learned was the requirement to **have a robustly designed electrical protection system consisting of circuit breakers that can be set according to their specific requirements, which, if opened by a minor event, can be remotely reset; if possible this system should be tested to full power and the CB opening settings tested prior to deployment**.

12.3.5 Testing and Operation

Following the commissioning of the DEEP-Gen IV turbine, the majority of its operation during the ReDAPT programme was focused on completing test objectives. These test requirements came from a variety of sources, which initially made the tests difficult to develop. However, during the second year of operation the Alstom turbine operations team engaged well with the test stakeholders to collate test requirements and develop the test schedules. The main lesson learned was to **engage with all test stakeholders as early as possible in the test programme to determine test requirements and to develop test schedules**.

The test planning was also a difficult task given the multitude of factors affecting each test. Many tests were dependent upon weather conditions, tidal flow conditions, instrumentation health, personnel availability and the completion of other tests. In addition, some tests were to be executed mutually exclusively from other tests that required the same conditions. As the testing phase progressed, the turbine operations team developed a better understanding of the factors that could affect test execution and this experience helped to prioritise tests and develop contingency tests into the plan. The lesson to take forward regarding the test planning is that **you cannot plan weather and tide dependent tests with a great level of certainty and it is therefore prudent to plan contingency tests and to use "time-windows" rather than tying the tests down to a particular tide**.

A valuable lesson was learned throughout this project regarding the best practices to implement in order to generate a turbine performance curve. As detailed in the power curve section, valuable information in terms of ADCP deployment and positioning has been yielded, especially **the importance of understanding the positioning of the ADCP and the local bathymetry**. This feeds into another lesson learned that **any time spent understanding the environment is time well spent**; this encompasses the resource, the slack water periods and the wave environment.

The ReDAPT project has demonstrated that a power curve can be generated following the IEC methodology. However, given the complexities of ADCP deployment **it has to be questioned as to whether it would ever be viable to use the technique for routine power curve or performance assessment**; rather the focus should be on validating modelling tools, such that the difficult, often costly and time consuming process of generating an IEC standard power curve can be minimised.

12.3.6 External Factors

Throughout the ReDAPT programme there have been a number of external factors that have influenced the work being undertaken during maintenance and deployed periods. This has included: internal and external audits; product demonstrations; site visits by customers, partners and government officials; and television film crew visits. These external factors did cause delays to the operations and in some cases work was postponed. In some cases, the scope of the external task was not agreed upon prior to it taking place (such as a TV crew who progressed from filming activities from a distance, to conducting interviews and “directing” tasks for multiple cuts). The main lesson to take from this experience is that **external factors will always play a part in turbine operation and maintenance activities; the best way to limit their disruption is to plan them well in advance and clarify and agree the scope and ground rules upfront**.

13 IMPLICATIONS FOR INDUSTRY

In the timeframe of the ReDAPT project the industry has moved to the next level – pilot arrays of multiple turbines. ReDAPT has contributed to this confidence in the tidal sector by demonstrating the viability of horizontal axis tidal turbines in the tidal environment and the ability to operate and maintain the turbines in a cost effective manner. Moreover, the knowledge base supporting the industry has been vastly improved through the ReDAPT project, with many published papers and ground-breaking studies.

The ReDAPT project has played in major role in shaping the certification guidelines for future development and has enabled the reduction of safety factors through the elimination of uncertainty in modelling and predictions. This progress facilitates more economically efficient designs helping to reduce the Levelised Cost of Electricity.

A major reduction in uncertainty has come about through the validation of modelling tools: the industry now has a full suite of validated and updated tools for future progression. The modelled power curve of the DEEP-Gen IV turbine was validated through the production of measured power curves. However this process also highlighted to the industry the difficulties of collecting the data in order to produce a power curve in accordance with IEC standards.

The data gathered from the ReDAPT project provides a multi-terabyte database of quality controlled environmental data and associated device data in the public domain to enable many PhDs and further studies to be carried out.

Through the data collection process included in the project, guidance on how to collect, characterise and analyse site data is now available, aiding future studies. This is an important step since an accurate definition of the conditions on site is fundamental to efficient turbine design. An understanding of the necessary instrumentation has been established for near field measurements, particularly concerning turbulent length scales. Further to this, the data collected has aided the understanding of the required data acquisition systems and quality checking processes.

The data has been used within the project to assess the accuracy of CFD modelling in realistic unsteady tidal conditions. These models allowed the development of a detailed study of transient flow and loading effects due to waves and turbulence, which is an important area of knowledge growth for the industry. Modelling of the far field and channel flow has made use of the data gathered to help develop and validate large scale resource modelling which will support the industry as it moves from single devices toward larger multi-turbine farms.

Finally the ReDAPT project has demonstrated turbine performance in the marine environment and the interactions with that environment have been observed and monitored, such that the marine licence is satisfied. An understanding of the behaviour of various materials in the marine environment has been gained, with important information gathered regarding the effects and impacts of biofouling. Acoustic surveys were carried out to begin to understand the noise produced under various operational conditions and the background noise in a tidal site.

13.1 Public Domain Reports

Deliverable ID	Deliverable Title
MC7.1	Public domain report - initial operation/power curve
MC7.2	Public domain report - first year

MC7.3	Public domain report - final (inc strip report)
MC8.27	Draft certification standards available
MC9.1	Report - Method for tidal turbine CO2 payback calculation
MC9.5	Report – Recommendation for declaring specification and testing of a tidal turbine
MD1.1	3D CFD model development - Step 1 - Report: demonstrate feasibility
MD1.2	3D CFD model development - step 2 - Report: assess influence of turbulence
MD1.3	3D CFD model development - step 3 - Report: assess influence of waves
MD1.4	3D CFD model development - step 4 - Report : formulations, assumptions, results of validation and comparison with results of GH‟s Tidal Bladed.
MD1.5	Turbulence characteristics of EMEC flow for input to numerical models
MD3.15	First, second, and third measurement campaign completed
MD3.4	Report: Interim Parametric Model
MD3.8	Report: Characterisation of near field turbulence
	Partial validation of tidal bladed - EWTEC paper arising from MD6.5
ME 8.5	Interpretation of biofouling and development of decision tool protocol; results of micro-scale environmental impact assessment and development of guidance
ME8.2	Final experimental design, blind controls deployed / arrays planned /treatments for TGL device developed
MP3.2	Develop and distribute course material based on the ReDAPT outputs

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