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1 SUMMARY

The Reliable Data Acquisition Platform for Tidal (ReDAPT) programme gives the opportunity to develop tidal technology and also highlight the key issues and difficulties associated with the operation and maintenance of a tidal turbine through testing the DEEP-Gen IV in real tidal conditions. The turbine performance appears as expected with the power curve and the load factor close to prediction. Metocean studies and sea life interactions are ongoing with no indication to date of contact with marine mammals.

Voltage step changes were assessed and are within prescribed limits. Detailed voltage flicker records have yet to be assessed in detail but early indications suggest that these will also be within limits. Current harmonics were assessed from the Alstom connection and are within the limits prescribed by Engineering Recommendation G5/4 (Reference 4). The power factor has been shown to be within the limits of the connection agreement at active power levels above 200 kW, or 20% of turbine rating. The turbine exhibits a high capacitive reactive power between periods of generation.

The predicted Levelised Cost of Energy (LCOE) derived using Capital Expenditure (CAPEX) figures provides a modest IRR for the early farm developer relies on capital grant support which is in line with the tariff support provided by the 5 Renewable Obligation Certificate (ROC) regime (including all site fees, insurance and Operation and Maintenance (O&M) operations). There is clearly great opportunity to reduce LCOE though improved offshore operations and volume manufacture however tariff support will be required for many years until these improvements are delivered.

2 INTRODUCTION


The ReDAPT project is intended to provide information to the Tidal Industry to facilitate rapid growth and help achieve the ETI's objectives.

- Accelerate development of tidal energy industry
- Install and test a commercial scale, horizontal flow, tidal turbine
- Develop analytical and environmental assessments
- Progress certification guidelines
- Increase confidence in tidal turbine technologies
- Three year programme

Various industry leaders are involved in the project:

- Alstom
- EDF
- E.ON
- European Marine Energy Centre (EMEC)
- DNV GL
- Plymouth Marine Laboratory (PML)
- University of Edinburgh

This document provides an overview of the first year of operation at the EMEC test site, Fall of Warness tidal test site (Berth 2) of the DEEP-Gen IV tidal turbine as part of the ReDAPT programme. The behaviour of the DEEP-Gen IV is assessed based on the data available and the implication this has for future LCOE is discussed.

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3 TURBINE PERFORMANCE

3.1 Power Curve

The electric power output performance of the DEEP-Gen IV, 1 MW tidal stream turbine was calculated, where possible, using the process stated in IEC guidelines (reference 1). There are a number of areas where this was not possible. The most significant is lack of sufficient tidal flow data. The data available, however, suggests that there is good agreement between the predicted and measured power curve.

3.1.1 Flow Measurement

Accurate flow data is essential for the creation of a tidal turbine power curve. An error in velocity makes a significant change in calculated efficiency as the power available in the flow is proportional to the flow speed cubed.

Two Acoustic Doppler Current Profilers (ADCP) were located on the sea bed upstream of the turbine, one in the flood (North West) (ADCPNW) and one in the ebb (South East) (ADCPSE) direction. The target location for both ADCPs was within the area recommended in the IEC guideline (reference 1).

3.1.2 Power Measurement

Power is recorded using a meter at the shore station. This power therefore includes cable transmission and transformer losses. These losses are 25 kW at a turbine power of 1 MW. Future power curves will be derived taking account of these losses.

Measurements shows that the residual power draw is approximately 14 kW when not generating and varies depending on which systems are active.

3.1.3 Calculation Method

1. Identify a suitable test period where the turbine was generating in representative conditions.
2. Find the minimum, mean and maximum shore side power for 10 minute bins.
3. Calculate flow magnitude by taking the vector sum of north and east velocities.
4. Apply the method below to find a "rotor area average velocity".
5. Align the two datasets.
6. Populate power curve with points.

3.1.4 Assumptions and Possible Errors

Sufficient generating time with concurrent ADCP data was not available at the end of the first year of operation. This meant that few data points were used to calculate this initial power curve; the IEC guidelines recommend at least 15 days of operations with concurrent ADCP data. Additionally 10 minute data bins are recommended but due to the small sample size 3 minute 20 second bins were used.

The turbine heading was aligned to historic measurements of flow directions due to the failure of the flow instrument on the turbine. Later turbine deployments have a more complete set of instrumentation so the optimum heading will be corroborated from several measurements.

The ADCP data was not quality controlled (QC) but visual inspection showed no obvious anomalies. The 2 ADCPs are deployed at different depths; therefore a different depth bin is used for a reference hub height velocity. This vertical offset between the ADCPs is approximately 3 m however there is potential for error in the height.

The upstream flow is measured before the same volume of water meets the turbine. This is equivalent to approximately 3 turbine rotor blade diameters i.e. between 54 s and 14 s depending on flow speed. Accounting for this will add much

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complexity to the analysis, due to the impact of wave action and turbulence. It may be best to assume a simple offset based on a mean speed in later studies.

3.1.5 Power Curve Results

Initial Measured Power Curve

min/mean/max per 200 sec bin

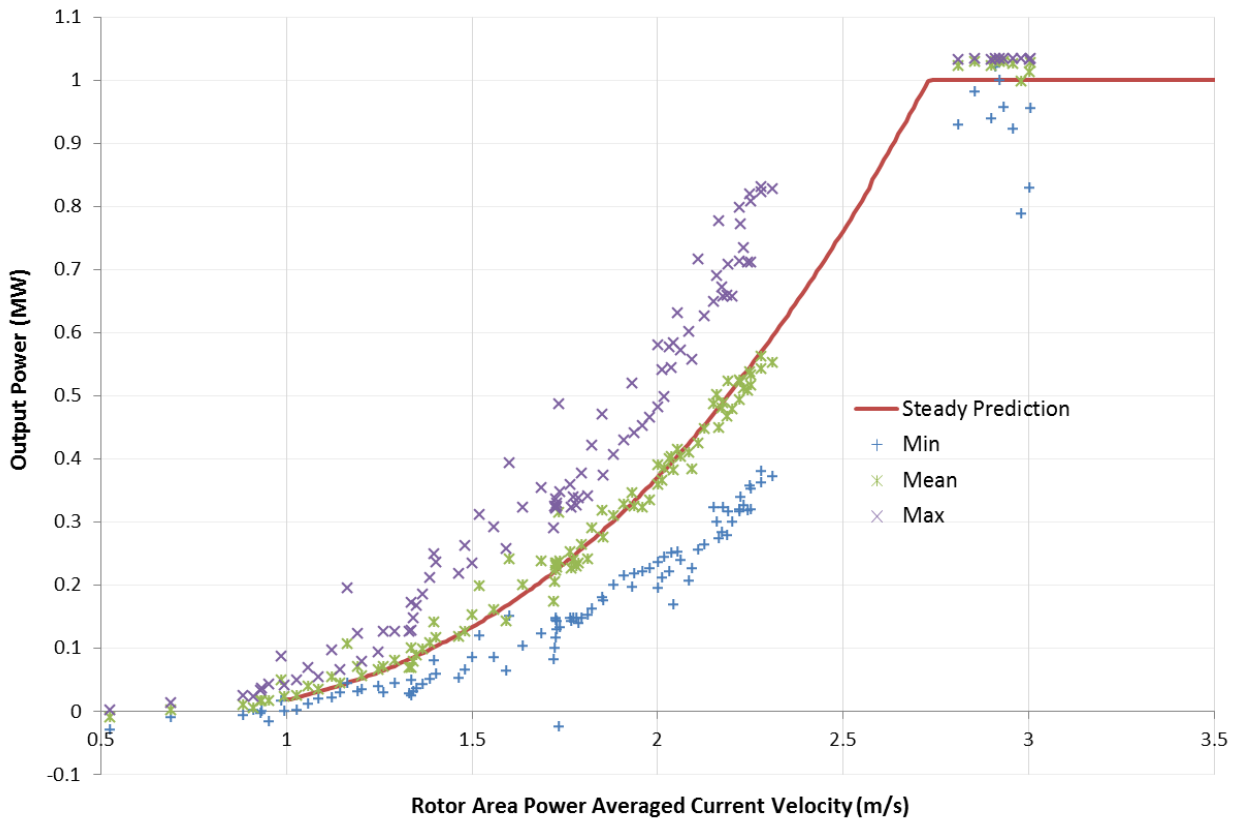


Figure 1 Initial Measured Shore Power Curve

Figure 1 was compiled using 3 days operation with both flood and ebb data sets. One complete tidal cycle is included (although the mean peak flow was insufficient to reach rated power).

The large range between minimum and maximum electrical power in a given data bin is typical for this site and was witnessed on Alstom’s previous DEEP-Gen III 500 kW turbine. These deviations are caused by turbulence and wave effects.

The torque and pitch controller (Variable Speed and Pitch Regulated, VSPR) was tuned based on predictions from DNV GL’s Tidal Bladed software and a small quantity of test data. Power fluctuations around 1 MW may be minimised after a further retuning of the controller.

The mean points match closely to the predicted performance, unfortunately there was insufficient data to populate the complete flow speed range.

These initial results build confidence in the performance of the turbine. Also the fact that the calculated efficiencies/performance from the earlier (DEEP-Gen III) turbine can be used to accurately predict the performance of a new machine give confidence in the design process.

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3.2 Load Factor

Figure 2 shows the flow speed frequency distribution (DNV GL harmonic analysis) for the EMEC site. It also shows the resulting power per speed bin for the DEEP-Gen IV turbine.

The value of power per bin can be summed to give the mean power available and from this an estimated load factor. For this environment and turbine combination the estimated load factor is 34.2%.

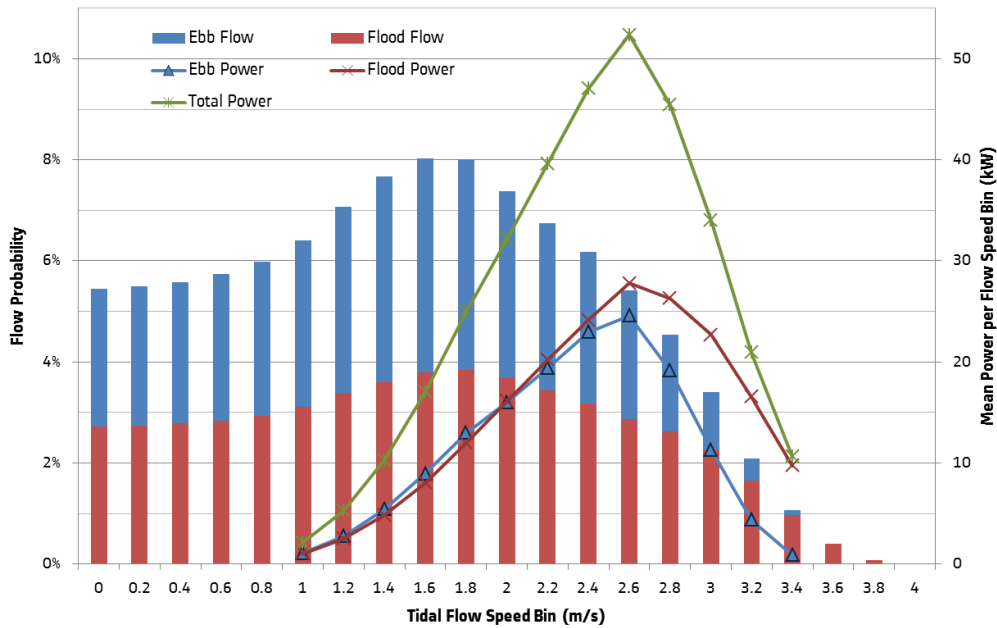


Figure 2 Mean Power per Bin for DEEP-Gen IV at the EMEC site

4 COST OF ENERGY PREDICTIONS BASED ON PERFORMANCE

This section reviews the Levelised Cost of Electricity (LCOE) targets give in the ETI roadmap based on the performance of the ReDAPT 1 MWe turbine to date and highlights challenges for the industry to achieving the targets going forward.

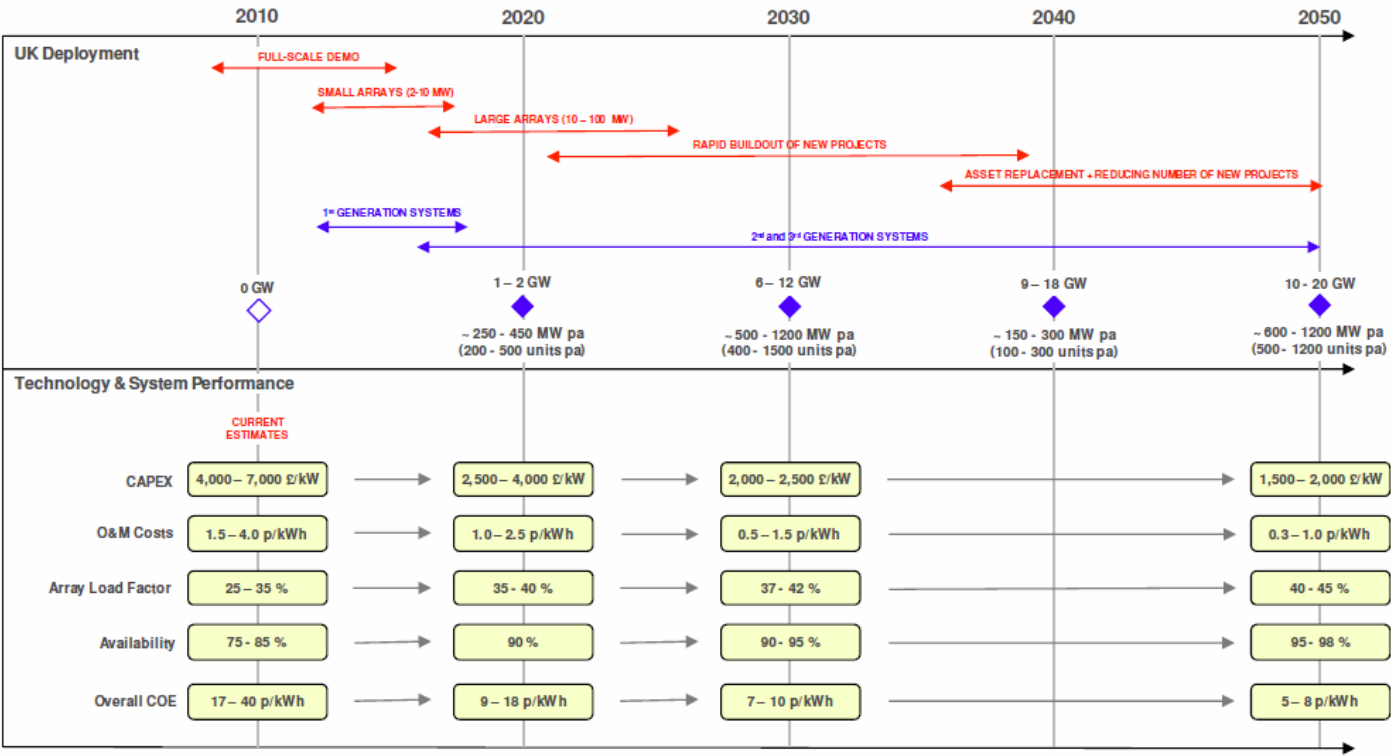


Figure 3 ETI Levelised Cost Of Electricity Targets

4.1 Input assumption

The ETI model was created 4 years ago and at the ReDAPT Stage Gate C review changes to the input assumptions were discussed and it was agreed that the ETI model needs to be updated to reflect the delays to the time schedule that have occurred across the industry. These are specifically the delays of the demonstration and pilot arrays with subsequent impact on large commercial array timescales and the cost savings associated with higher volumes.

This slower build up will delay the improvement in CAPEX, load factor and availability that will naturally come from turbine improvements and 2nd generation machines. Furthermore, the current estimates of total CAPEX for pilot farms are significantly lower than the industry is clearly experiencing – influenced not by device costs but the considerable challenges associated with foundation installation, cable procurement and installation and high grid connection costs (projects are remote from the transmission grid and required to fully fund grid upgrades to their substation, a fixed cost that cannot be spread over large numbers of turbines when in a pilot farm). This is evidenced by the fact that the three projects that have secured NER300, MEAD and MRCF funding have not yet managed to reach financial close.

Another significant area of variance between Alstom’s view and the ETI roadmap is the O&M cost which, combined with the delays to the other improvements, will drive a much slower reduction in the LCOE.

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4.2 CAPEX costs for early pilot arrays

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

Parameter	Value
Location	Scotland
Farm size	10 units
Turbine rated power	1 MWe
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
Foundation CAPEX	Based on revised design for 25 year life
Foundation installation	Based on 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 a corrective and preventative maintenance schedule which is improved compared to ReDAPT experience. Current assumptions on components likely to be replaced derived from FMECA and experience

Table 1 LCOE assumptions

For the first 10MW pre-commercial array the CAPEX is in-line with Renewables UK's most recent analysis, but a little higher than the original 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).

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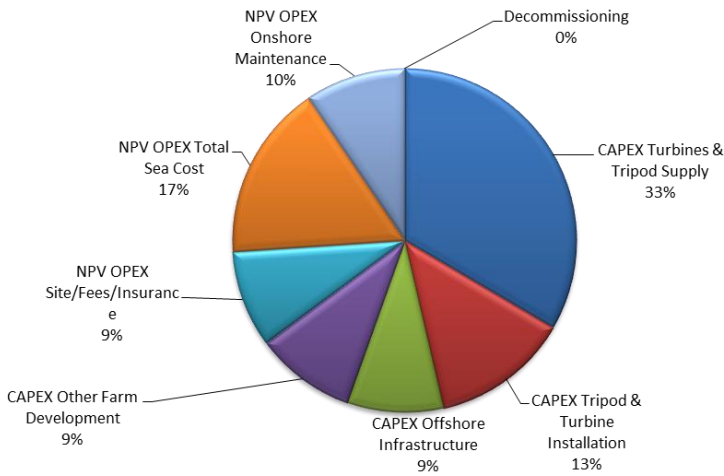


Figure 4 Levelised Cost of Electricity Division

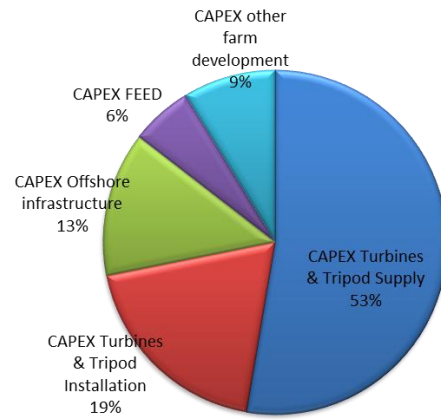


Figure 5 CAPEX Breakdown

4.3 LCOE Conclusions

The LCOE derived using these CAPEX figures which provides a modest IRR for the early farm developer and relies on capital grant support which is in line with the tariff support provided by the 5 ROC regime (including all site fees, insurance and O&M operations).

CAPEX represents approximately 64% of the LCOE, site fees (licence), grid fees and insurance represent 9%, sea costs 17% and onshore maintenance activities 10%.

There is clearly great opportunity to reduce LCOE though improved offshore operations and volume manufacture however tariff support will be required for many years until these improvements are delivered.

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5 SEA LIFE INTERACTION

5.1 Deck Plate Mounted Camera

The view from this camera could be observed from the turbine control room and was checked periodically with the turbine operating, idling and parked. No marine life was identified on these occasions.

5.2 Strain Gauge Monitoring

An algorithm is used to monitor spikes in the turbine blade and low speed shaft (LSS) instrumentation. 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 500 kW DEEP-Gen III turbine and was updated for the DEEP-Gen IV turbine.

Following a review of the test data alarm threshold value was exceeded on three occasions. All of these were caused by issues confirmed to be other than mammal interaction. The threshold values selected will be revised based on the results noted as testing progresses.

5.3 Bio-fouling

Only superficial algal growth and crustaceans have been noted on DEEP-Gen IV on the turbine retrievals.

The PML Benthic Pods have been deployed at the Alstom test site and the first ROV survey has indicated they are fit for purpose and performing well. The experimental design used on both the Pods and the turbine appears to be suitable to generate reliable data required. However, the image quality from the ROV surveys is only suitable to provide a high level check of experimental progress and detailed time point analysis will not be possible.

Collaboration with other scientists studying settlement biology in the area has proved very fruitful. Examination of the navigation buoys provides a good indication of the extent and type of fouling that can be expected on the turbine itself.

Studies of the fouling on the other structures deployed in the vicinity of the Alstom turbine have shown that aggressive fouling occurs in short timescales, some times in a matter of weeks. The most obvious macrofouling organism to settle on the turbine in significant numbers is likely to be barnacles, probably of the species *Balanus crenatus*, although further identification is required to confirm this identification. Barnacles are showing settlement preferences in terms of hydrodynamics but are readily settling on a variety of materials, including those which are traditionally considered to be reasonably resistant to fouling such as marine grade stainless steel.

To-date, the majority of the fouling on the other ReDAPT structures deployed near the turbine test site has been attributed to barnacles. However, this is probably because most of the surfaces have only been deployed for about 6 to 8 weeks. As ReDAPT deployment times increase we anticipate that the fouling communities will mature, become more diverse and architecturally complex.

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6 RECORD OF GRID OUTAGES

This section is a summary of outages and export restrictions at Eday Berth 2 from 1st January 2013 to 1st December 2013.

6.1 EMEC 11kV Supply to Alstom

This data is provided by EMEC from the EMEC 11kV Circuit Breaker D02 status

D02 open from:	To:	Reason
16-Jan-13 17:35:58	17-Jan-13 11:33:17	Power transducer upgrade (M301 replaced by ION7650)
12-Mar-13 13:12:27	17-Mar-13 08:34:50	To isolate for work on Alstom 6.6kV CB

6.2 G59 Events

This data is provided by EMEC from the SCADA records of G59 operation. G59 protection is triggered by voltage excursions, frequency excursions or "loss of mains" (detected by vector shift) and usually operates in response to grid loss or in response to an external grid disturbance. G59 is sensed by the EMEC protection system but operates the Alstom 6.6kV circuit breaker. The times below indicate periods when the G59 protection was set, indicating an abnormal grid condition. The Alstom 6.6kV breaker would normally automatically reclose 11 minutes after the grid returns to normal

From	To	Remarks
16-Jan-13 15:53:26	16-Jan-13 15:58:03	
30-Jan-13 02:20:56	30-Jan-13 02:21:08	
04-Mar-13 03:20:39	04-Mar-13 04:41:16	SSE Eday-Westray submarine cable failure. Network reconfigured.
27-Mar-13 22:29:57	27-Mar-13 22:30:16	
27-Mar-13 23:10:35	27-Mar-13 23:10:54	
26-Jul-13 03:02:05	31-Jul-13 17:22:11	SSE mainland - Shapinsay cable failure. No HV supply to Eday.
31-Jul-13 19:01:36	31-Jul-13 19:01:53	
07-Aug-13 14:56:09	07-Aug-13 14:56:15	
04-Sep-13 23:03:43	04-Sep-13 23:03:56	
11-Sep-13 14:22:48	11-Sep-13 14:23:02	
16-Sep-13 13:02:19	16-Sep-13 14:00:02	
23-Oct-13 23:15:45	23-Oct-13 23:16:02	

6.3 Export Restrictions

From	To	Remarks
05-Mar-13	04-Sep-13	EMEC site restricted to 1.5MW export pending repair of Eday-Westray cable
05-Nov-13 10:00	07-Nov-13 18:00	EMEC site restricted to 1.5MW export for SSE mainland-Rousay cable connection
11-Nov-13 08:00	14-Nov-13 10:30	EMEC site restricted to 1.5MW export for SSE Westray transformer replacement

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7 METOCEAN CONDITIONS

Analysis of existing site data was undertaken by DNV GL (formerly GL Garrad Hassan) 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 1 Hz. Wave climate data was obtained from the Royal Haskoning Report (Reference 2) 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 DNV GL'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 DNV GL 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 Table 2.

This analysis 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 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 a later validation exercise in order to assess the suitability of the initial design loads.

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		Value	unit
Long term tidal flow conditions			
U_{r_rms}	Long term mean current	1.804	m/s
U_{rf_rms}	Long term mean flood current	1.701	m/s
U_{re_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
U_{r_max}	Maximum current on a mean day	2.42	m/s
U_{r_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/m ³
Extreme tidal flow conditions			
U_{r-1}	Regular current with a recurrence period of 1 year	3.911	m/s
U_{r-50}	Regular current with a recurrence period of 50 years	4.212	m/s
$U_{w, 1-yr}$	1-year return wind-generated surface current velocity	0.766	m/s
$U_{w, 50-yr}$	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
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			
HSWL ₁	Highest still water level with a recurrence period of 1 year (relative to Chart Datum)	2.88	m
LSWL ₁	Lowest still water level with a recurrence period of 1 year (relative to Chart Datum)	0.11	m
HSWL ₅₀	Highest still water level with a recurrence period of 50 year (relative to Chart Datum)	2.97	m
LSWL ₅₀	Lowest still water level with a recurrence period of 50 year (relative to Chart Datum)	0	m

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		Value	unit
Long term wave conditions			
$E[H_s V_{hub}]$	Significant wave height, conditioned on mean wind speed and mean wind direction*	1.11	m
$E[T_p V_{hub}]$	Spectral period, conditioned on mean wind speed and mean wind direction*	4.2	s
Γ	Peakedness parameter for Jonswap spectrum	1	-
Extreme wave conditions			
H_{s1}	1-year significant wave height	3.9	m
T_{p1}	1-year peak spectral period	9.1	s
H_1	1-year individual wave height	7.25	m
T_1	1-year individual wave period (range of possible values)	7.00 – 9.02	s
H_{s50}	50-year significant wave height	5.2	m
T_{p50}	50-year peak spectral period	10.4	s
H_{50}	50-year individual wave height	9.67	m
T_{50}	50-year individual wave period (range of possible values)	8.08 – 10.4	s
Long term wind conditions			
V_{ave}	Annual average wind speed at hub height	5.5	m/s
I_{15}	Characteristic turbulence intensity as function of wind speed	Speed dependant	%
ρ_{air}	Air density	1.225	kg/m ³

Table 2 Summary of results

A comparison of measured tidal data with commercially available software predictions will be conducted at a later date.

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8 ELECTRICAL POWER QUALITY

This section is an initial assessment of power quality conducted by EMEC on 2 December 2013 for the Alstom DEEP-Gen IV turbine connected to berth 2 at the EMEC Eday tidal test facility.

The largest voltage step-changes during normal turbine operations are expected to arise from shut down from full load. This has been shown to comply with the requirements of P28. Although voltage flicker data has not yet been examined, it can be argued by comparison of the magnitude of second-by-second power changes with the full load shut down case that flicker during normal operation is likely to comply with P28.

The onshore transformer is known to cause a voltage depression in excess of P28 limits on energisation and an operational restriction on transformer switching remains in place.

Power factor has been shown to be within the limits of the connection agreement at active power levels above 200 kW, or 20% of turbine rating. At lower powers the power factor falls below the specified limit. Although this is inevitable at very low powers (where the magnitude of reactive power is more important than the power factor), the point at which strict compliance is lost is a little high: a value of 10 – 15% of rated power would be expected.

The turbine exhibits a high capacitive reactive power in between episodes of generation. This is unusual and is not strictly in accordance with the connection agreement. EMEC are aware that the terms in which reactive power and power factor are specified in the connection agreement do not match what is realistically achievable at low powers and intend to discuss this with the network operator to obtain guidance on acceptable limits.

Voltage harmonics have not been assessed due to the difficulties in obtaining a data set free from contributions from other clients. Current harmonics have therefore been examined in an attempt to isolate the impact of the DEEP-Gen IV turbine from other clients. However, a step-change in current harmonic behaviour was noted around 22-23rd October which appears to be related to other equipment connected to the 11 kV busbar. This suggests that mutual interactions are more significant than expected and the harmonic analysis is therefore presented as provisional only, pending further investigation.

The mutual interactions noted above were present for the greater part of the data examined and had the effect of increasing the most prominent harmonics. Berth 2 current harmonics were compared to the stage 2 limits in G5/4 and found to be acceptable. It is therefore likely that berth 2 harmonics in isolation from other influences will also be acceptable.

The requirements of G5/4 apply at the point at which EMEC is connected to the DNO and therefore must allow for contributions from all connected clients. The assessment of berth 2 as yet makes no allowance for headroom for other clients at EMEC.

The harmonic spectra show distinctly different profiles when generating and when in standby or “quiescent” mode of operation. Quiescent mode exhibits high levels of 11th and 13th current harmonics.

The harmonics in standby mode are thought to be related to the high reactive power in this mode. Neither of these traits is wholly desirable from the grid perspective and it is recommended that consideration be given to whether they are essential and if so whether any mitigation is possible.

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9 REFERENCE DOCUMENTS

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2. Royal Haskoning, 9P3878-03, M Davin, "Orkney Tidal Energy Assessment; Wave Modelling Report", 2006
3. Engineering Recommendation P28 "Planning limits for voltage fluctuations caused by industrial, commercial and domestic equipment in the UK" Energy Networks Association 1989
4. Engineering Recommendation G5/4, "Planning levels for harmonic voltage distortion and the connection of non-linear equipment to transmission systems and distribution networks in the UK", Energy Networks Association 2005.

10 ACROYNMS

ADCP	Acoustic Doppler Current Profiler
CAPEX	Capital Expenditure
DP	Directional Positioning
DEEP-Gen	Deep-water Efficient Economic Prototype Generator
ETI	Energy Technologies Institute
LCOE	Levelised Cost Of Electricity
LSS	Low Speed Shaft
NW	North West
O&M	Operation and Maintenance
PML	Plymouth Marine Laboratory
QC	Quality Control
ReDAPT	Reliable Data Acquisition Platform for Tidal
ROC	Renewable Obligation Certificate
SE	South East
VSPR	Variable Speed and Pitch Regulated