Assessing the impact of ADCP resolution and sampling rate on tidal current energy project economics

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Abstract - **This research examines the impact of accuracy in tidal current energy resource assessment on the likely economics of a tidal array project, ultimately estimating the impact of resource uncertainty on overall lifetime project economics. The analysis utilises field data gathered at 3 key locations at the European Marine Energy Centre (EMEC) tidal test-site in the Fall of Warness, Orkney. Data analysis techniques appropriate for application to tidal current energy projects are presented and the results obtained interpreted. The widely adopted Matlab code *t_tide* is then used to conduct harmonic analysis of the tidal current velocity data records. The adjacent ADCP records enable analysis of the spatial variability of the tidal resource at the EMEC site. Electricity generation potential and project revenue estimates are generated using simple and clear assumptions regarding typical tidal turbine topology and array layout. The impact of resource uncertainty on the prediction of Annual Energy Production (AEP) of the idealised array is calculated by varying the temporal and spatial resolution of the ADCP data utilised as input to the analysis, and similarly by using various lengths of the measured tidal records. These scenario based predictions are analysed in a simple financial model to examine the effect resource estimate uncertainty has on the projected returns on investment. Overall, the results suggest one clear conclusion: the range of impacts on project economics of uncertainties introduced by the resource estimation process warrant greater investment of time and money by project and technology developers at an early stage of development.**

Index Terms — **Renewable Energy, Marine Technology, Tides.**

I. INTRODUCTION

In the wind energy industry there are established tools, techniques and procedures for resource assessment enabling project developers and their lenders to agree on the 'certainty' of their project return estimates. Characterising the resource is a critical part of estimating project revenues and is a key risk for project finance. No equivalent tools or techniques have been established for the nascent tidal energy industry. This will hinder deployment of commercial scale arrays and hence industry development.

Though appropriate technologies exist to measure the tidal resource, much less is understood about how to make cost-effective use of the technology to produce 'bankable' estimates. This research draws on the historic database of tidal resource measurements from the European Marine Energy Centre (EMEC) in Orkney to make recommendations on how to optimise tidal resource assessments.

A. Background

Across Europe, challenging targets have been set for the reduction of overall Greenhouse Gas (GHG) emissions. A key foundation of achieving these targets is the rapid de-carbonisation of the energy industry. In many European states, electricity generation is primarily derived from centralised coal and gas burning power stations. For example, the major electricity supply providers by resource type in the UK for 2010 can be broken down as 47.4% gas, 28.4% coal, nuclear 15.6%, and 6.9% renewable [1]. Hence, displacing carbon intensive fossil-fuel electricity generation plants with renewable energy generation solutions has become a cornerstone of 21st Century energy policy. Development and application of renewable energy approaches and technologies has rapidly become established as a major industrial activity (e.g. total renewable electricity capacity increased by 12% in the UK between 2009 and 2010 [1]).

Tidal current energy resources around the UK coastline are among the most energetic in Europe, created by tidal propagation through straits, resonant systems and around headlands linking the Atlantic and North Sea [2]. These energy resources are variable but largely predictable as the underlying tide generating forces are the product of gravitational attraction between the combined Earth-Sun-Moon system. Hence, tidal energy has the potential to offer complementary availability in a future energy mix with other variable renewable energy sources such as on- and off-shore wind, wave and solar energy. Tidal current energy research, development and demonstration have been gathering momentum in the UK over the last decade, in no small part due to financial support from UK government organisations [3]. Development of pioneering tidal current energy converter (TEC) technologies has now reached pre-commercialisation demonstration of full-scale devices in the open sea. Nonetheless, there is still much to learn about technology optimisation, the tidal energy resource, its conversion and economic delivery, and the operating environment for TEC technologies on the way to development of a mature industry.

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B. Learning from the experience of the wind industry

There are high-level similarities between the emerging tidal industry and the more mature wind industry. Hence, given the immaturity of TEC technology development and the lack of experience of utility scale generation of electricity from TEC devices, the emerging tidal sector often looks to the more established wind industry for knowledge transfer. This can be seen at a technology development level, in terms of the necessary infrastructure at a project and industry scale, and in terms of policy support mechanisms. The focus of the research being reported herein is in understanding the impact of tidal resource uncertainty on utility scale project economics. This is an area where it is possible for tidal industry development to benefit from the experiences of the wind industry by assessing the potential for adoption and adaptation of existing methodologies underpinning wind energy resource characterisation tools and procedures.

II. AN INVESTOR'S PERSPECTIVE ON TIDAL ENERGY ECONOMICS

Aside from the obvious technological, and operational developments that are required to deliver commercial scale marine energy projects (e.g. scaling up the technology, demonstrating reliability, development of the installation and maintenance supply chain), it is critical that the finance community considers marine energy projects a sound investment offering returns at least as good as those available elsewhere in the energy market. The role of 'project finance' has been instrumental in the commercial deployment of wind power, both on and off- shore; it is likely to be similarly vital in the marine energy sector.

Potential investors in energy projects (tidal or otherwise) will consider a wide range of risk factors; typical considerations are listed in table I. Many of the risks in a project can be appropriately managed through time. For instance failing contracts can be terminated (and new suppliers found) or renegotiated, and Government agencies seldom apply new legislation in retrospect. Where then do resource estimates sit in the consideration of project risk? The role of resource estimation is informing decisions to ensure correct sizing of the plant and enable accurate forecasting of the revenues from generation.

TABLE I: Typical risk considerations in energy projects

Category	Risk Consideration
Regulatory	How is the electricity market structured and regulated? Can cost increases be passed on to consumers through price increases?
Regulatory	How stable and long-lived are revenue support mechanisms for renewable electricity (e.g. ROCs in the UK)
Merchant/ Market	What are the anticipated price variations for electricity? What proportion of the project's output should/ can be sold forward in a Power Purchase Agreement?
Project execution	What are the supply Chain risks? What is the ability of sub-contractors to deliver against the requirements of their contracts? How competitive is the market for supply if alternatives are required?
Revenue	What is the confidence in the plant's reliability?
Revenue	What is the confidence in the estimate of the available resource for electricity generation? Has the plant been sized correctly given the available resource?

An important metric of the economic effectiveness of any energy project is the capacity factor – the ratio of the potential output of the plant over a period, to the maximum theoretical 'nameplate' output delivered over the same period (which itself is a function of the reliability of the plant, its power curve characteristic and the distribution of the resource (wind/ tide speed) over the period of interest). The higher the capacity factor, the more quickly the plant will recover the capital invested. More importantly, if the cost curve for installed capacity (in terms of £/MW installed capacity versus rated plant output) is known for an array of devices, then the optimum array size (and hence investment) for the given resource can be derived. For these considerations to work effectively, the resource availability at the site of interest must be accurately forecast. Hence, accurate resource estimates have a significant part to play in successful financing of tidal energy projects. It is clear then that resource prediction is potentially a substantial risk for the economics of tidal energy projects. Looking instead at the opportunity, it should follow that accurate resource estimates hold the promise of reducing the risk of tidal energy projects: increasing the likelihood that they will attract investment and reducing the cost of the project. Even in the more established wind industry, there is evidence that better wind forecasting is reducing the cost of finance for projects. The Economist magazine recently reported [4]:

> "[project] developers use a statistical model to obtain a 'P90' wind value - the average wind speed in which they can be 90% confident. The closer the P90 reading is to the measured average speed, the more attractive the site becomes to investors. If the P90 wind-speed is within 12-15% of the average, banks are usually happy to stump up. But a difference of 20% or higher renders a wind farm "un-financeable". …Conversely, reducing the error margin to 7-10% can reduce a project's cost of funds by 0.5-0.75 percentage points, resulting in higher investor returns."

In case this seems insignificant, a basic hypothetical example will illustrate the potential impact on overall project economics: Suppose an offshore marine energy plant project with a lifetime of 20 years is proposed with an installed capacity of 100MW at a capital cost of £1.5M per MW of installed capacity. The project capital requirement is £150M. If the split between debt and equity is 66/33, the bank loan required is approximately £100M. Assuming the cost of the debt is 7.75% in the 'high' case (where the resource estimate error is in the range 12-15%) and 7% in the 'low' case (with a more accurate resource estimate), then, applying an approach outlined in [5], the capital cost of the project is reduced by more than £11M in current cash terms (or if a discount rate of 15% is applied, capital cost is reduced by more than £4M when considering Net Present Value).

III. ENERGY RESOURCE MEASUREMENT AND PREDICTION

There are broad analogies, for resource estimation, between the wind and tidal energy markets. Principles for resource assessment and prediction in the wind industry are well established with many engineering consultancies offering appropriate services to project developers and operators. Similarly, device performance assessment is documented in appropriate international standard documentation [6]. The existence of this institutional experience and know-how gives lenders and potential investors confidence. Development of similar technology performance assessment approaches have been proposed for tidal energy application [7, 8], and separate 'Technical Specification' documents are now under development for tidal energy resource characterisation and TEC device performance assessment under the stewardship of the IEC. However it must be recognised that at heart, the wind and tide are different natural process: the variation of wind is stochastic, but tidal variation is deterministic. As such the tide lends itself to harmonic analysis, based on a least squares decomposition of a measured record of tidal velocity [9]. The industry standard for measuring tidal velocities is an Acoustic Doppler Current Profiler (ADCP). When a tidal prediction is subsequently generated from harmonic analysis, the estimation of Annual Energy Prediction (AEP*)* from the velocity probability distribution is theoretically straightforward.

A. Wind Energy Approach

The IEC International Standard document [6] lays out agreed procedures for measuring and predicting the wind resource at a given site and for forecasting the AEP for a given design of turbine. The Standard requires that actual wind velocity measurements are taken at the site of interest for a period of sufficient length to generate a representative sample of the long-term average wind velocity and its distribution around the mean. Measurements are typically made using a mast mounted cup anemometer and wind vane (the measurement of wind speed and direction is conducted at, at least 1Hz or higher and reported as averaged over 10 minutes). Equipment set-up and measurement procedures are closely prescribed by the Standard, as are methods for quantifying measurement uncertainty. When the wind speed distribution at a given site has been established a 'method of bins' is used to segment the data to give a probability of occurrence of a wind speed within a defined range over a representative year. If the variation of turbine power output with wind speed is also characterised by measurement, then the Annual Energy Production can be estimated from summing the power output across each 'bin' multiplied by the total number of hours for which that wind speed occurs in a given year.

Accurate characterisation of the mean wind speed at a given site requires many years of continuous measurement; other important characteristics (e.g. wind shear and turbulence intensity) require 6-12 months of data. To shorten project timescales, the wind industry typically applies a 'Measure – Correlate – Predict' technique, where shorter-term measurements (e.g. over 6 months) at the project site are correlated with a known long-term data series from a nearby location (e.g. data from a nearby airfield). Long-term predictions for the project site are then derived assuming that the distribution of wind speeds around the mean are the same as at the reference site. For detailed site design ('micro-siting', in the industry jargon), numerical models are validated against local site measurements to determine the wake effects of terrain and other turbines in the array. A wide range of proprietary software tools supports this market (e.g. WAsP, GH WindFarmer). Additionally, processes for application of detailed bespoke CFD numerical simulations exist for application to particularly complex projects (e.g. complex terrain) where the extra investment in ensuring accurate understanding of wind resource variability is deemed beneficial.

B. Tidal Energy Approach

The principles of tidal and wind resource assessment are common, in so far as, actual measurement of the resource variation with time combined with an accurate description of the energy extraction device performance characteristics can deliver long term estimates of energy production over the life of the project. However, the long-term variation of wind speed is a stochastic process, whereas tidal variability is deterministic. Hence the detailed analysis of the variation of tidal velocity over time has some critical differences. In particular the use of the measured record is different. Typically, a wind resource assessment uses the measured record to determine the mean wind speed and a Weibull or Rayleigh distribution is assumed to describe the parametric variation of wind speed around the mean for future prediction [10]. In contrast, for tidal energy, the analysis of the measured record requires a different approach. Harmonic analysis is used to determine tidal constituents representative of that exact location that can then be used for future prediction, again using harmonic analysis techniques. Harmonic analysis uses a least squares approximation to 'fit' the measured tidal record to the known forcing frequencies and seeks to determine the phase and amplitude of those dynamic constituents at the site of interest. In both the wind and tidal cases, the predictions extrapolated from real world measurements can be used to validate numerical models representing the detailed characteristics of the project site, which in turn enable informed decisions to be made regarding the optimal installed capacity and siting, which, finally, allows economic calculations based on Annual Energy Production from the whole site and return on capital to be projected.

C. Difficulties associated with the tidal energy approach

Typically harmonic analysis has been the preserve of oceanographers studying the long-term variation of the seas. Engineering interest has generally been reserved for shoreline interactions and navigational safety – the purpose of utilising harmonic analysis for tidal energy prediction is distinct.

If a tidal measurement record is visualised in the frequency domain (a plot of spectral density against frequency), then the tidal energy elements will appear as peaks around the discrete forcing frequencies of the harmonic constituents. Non-tidal energy will be evident as broadband noise (or long period seasonal effects may appear at discrete frequencies). By their nature, these non-tidal phenomena are longer-term processes with lower temporal variability. A tidal current measurement for energy extraction is concerned primarily with the tidal element of the measured signal and hence will require a relatively short sample period. One of the purposes of this research effort is to examine the sensitivity of resource estimates to measured resource data characteristics (e.g. sample periods). Another potentially significant part of the measured record will be instrument error and noise and shorter-term wave and wind effects, which will have an influence in coastal regions at limited depth. It is important to be able to separate and analyse both tidal and non-tidal elements of the record to understand their impact on TEC device performance.

Potentially the most significant determinant for the quality of the measured record and the subsequent resource prediction is the total length of the record and the sample interval. The length of the measurement record directly impacts the number of tidal constituents that can be derived from the harmonic analysis. The longer the record length, the easier it becomes to resolve between constituents of similar frequency. To develop confidence in the resource estimate derived from harmonic analysis, it is important to understand what the key determinants of the quality of the measured record are.

IV. METHODOLOGICAL APPROACH

A tidal energy resource assessment should most appropriately be based on a harmonic analysis prediction for the location of interest assuming a suitable ADCP record is available. The most complete understanding of the impact on project economics is made possible by taking account of the characteristics of typical tidal turbines. It is then possible to derive simplified predictions of AEP following [7] (which itself broadly follows [6]). This approach has the advantage of super-imposing the limitations of the selected TEC turbines in extracting energy from the flow. The first step of the analysis is to generate a velocity probability distribution based on the tidal resource characteristics generated from the harmonic prediction (in this case the bin width is set at 100mm/s). When the velocity distribution is known the AEP is calculated from equation (1):

$$AEP = 8760.A_v.\sum_{i=1}^{i=N_B} P_i.f_i \qquad (1)$$

Where 8760 is the number of hours in the year, and A_V is the mechanical availability of the machine as a percentage (assumed to be 100% in this study - though this is far from realistic, as long as the value is maintained as a constant throughout the comparisons, the absolute value is not important). P_i is the power output of the machine in the i^{th} velocity bin, and f_i is the probability that the velocity (the average of the velocity bin range) of the i^{th} bin will occur. Finally, N_B is the total number of velocity bins. The power output of the turbine in any given bin, i, is then:

$$P_t = 0.5.\rho.A.C_p.U_i^3 \qquad (2)$$

Assuming a typical horizontal axis TEC configuration of turbine diameter 16 metres (to assess the swept area, A), in water of uniform density (ρ) 1025 kg/m^3, we only have to estimate the machine's C_p and rated speed to generate a 'typical' power curve to give P_i and then an AEP prediction. If the machine operates on the principle of variable speed/ controllable pitch, it is a reasonable approximation to assume that it achieves a relatively constant C_p up to its rated speed. Assuming a C_p of 0.42 and a rated speed of 2.4 m/s gives a power curve as shown in fig. 1 (rated power of 600kW). All of the assumed turbine characteristics have basis in proven existing operating device performance. The results of the AEP analysis can then be used to understand the performance of an idealised turbine. For this analysis, the assumption of uniform inflow conditions across the rotor swept area with flow consistently perpendicular to the plane of the rotor disc has been applied. Clearly this is a substantial simplification over the real world scenario where the velocity shear across the turbine swept area should be modelled, but is adequate for consistent comparisons of AEP based on different approaches to measuring and predicting the tidal currents in an area of interest. An estimate of annual revenue generated by a hypothetical project is possible after making some further assumptions. An array of approximately 50MW is taken to represent a typical early stage commercial project (at 0.6MW rated output per machine this gives a total of 83 turbines). The wholesale electricity price is assumed to be £30/ MWh and the Renewable Obligation Certificates received by the project owner for each MWh generated are assumed to have a buy-out price of £30 each (a conservative approximation of the value set by Ofgem of £36.99/ MWh for 2010-2011 [11]). Under the assumption of a project based in Scottish waters, the venture would benefit from government support of 3 ROC payments for early stage tidal energy projects. This basic scenario will in later sections provide a means of comparing the revenue generation of various simulated development scenarios.

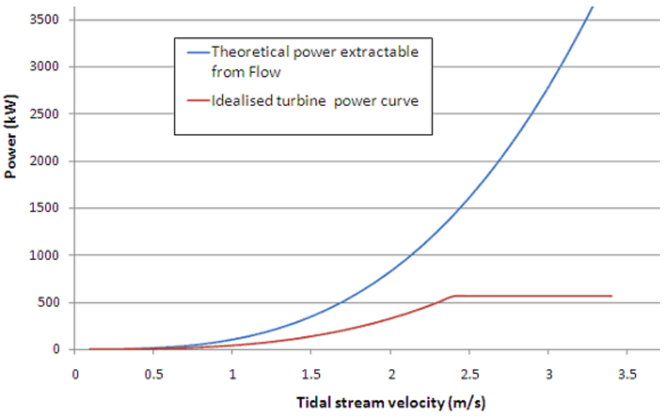

Figure 1: Idealised TEC device power curve used in the analysis.

The principles of operation of an ADCP device are straight forward, but it is important to understand the errors and uncertainty that they introduce to any resource prediction. Hence, a brief description of key ADCP operational and quality control measures follows. Interested readers can address a more comprehensive treatment by one of the available device manufacturers (upon which this description is based), in [12].

The operator sets the ADCP device 'ensemble period' and returns from each 'ping' are averaged across the ensemble. As random measurement errors are normally distributed about the mean, increasing the number of pings per ensemble reduces the standard deviation of the error (in proportion to the square of the number of pings). This is useful to the point where the random error is less than the bias of the machine, which cannot be corrected ([12] reports bias of the order of 10mm/s velocity as typical). In general, the ADCP unit does both depth and ensemble averaging before transmitting results to the data collection system (this can be over-ridden by the user, however, it has the advantage of reducing the data volume needing transmission, and the ADCP automatically corrects velocity vectors to earth co-ordinates and corrects for beam pointing angle errors). However, external errors (from turbulence in the water column, for example) tend to dominate ADCP error. These can be estimated by computing the standard deviation of the reported velocity errors. In addition the ADCP reports 3 other quality control measures to enable judgement of measurement quality (summarised in table II). Neither sound speed variation with depth or thermoclines substantially effect data quality. However strong echoes from the sea surface (for bottom mounted units) must be removed from the data record.

TABLE II: Quality control measures for ADCP operation (source [12]).

Quality Control Measure	Detail
Echo intensity	Data output in units proportional to decibels (dB) and are a measure of the proportion of the energy in the return echo to the energy sent out by the ping. The stronger the echo intensity, the more reliable the data.
Correlation	A measure of data quality (ping/ echo signal correlation for detecting small phase changes - well correlated ping/ echo signals look similar). Output is scaled in units such that the expected correlation (given high signal/noise ratio) is 128.
Percent-good	Data tell you what fraction of data passed a variety of criteria. Rejection criteria include low correlation, large error velocity and fish detection (false target threshold).

V. SOURCE DATA

The data set informing this research utilises a range of surveys conducted by the European Marine Energy Centre (EMEC) in the period 2005 -2007 at the tidal test-site located in the Fall of Warness, Orkney. A number of criteria were applied to identify those surveys most suitable for this analysis from the suite of surveys made available by EMEC – these were:

- Record length – a record of greater than 30 days duration is desirable, for better constituent resolution and to allow the effect of record length on resource prediction to be analysed.
- Temporal resolution – short ensemble periods are desirable to allow post measurement ‘down-sampling’ of the record to examine the effect of temporal resolution on resource predictions.
- Spatial resolution – surveys that are well separated around the location are desirable to develop an understanding of the impact of channel bathymetry on the optimal spatial resolution of samples.

For these reasons, surveys 7, 10 and 13 were selected as a baseline for further investigation and comparison. The approximate locations of these survey measurements are shown in Fig. 2 (page 10). Alongside the data sets, EMEC issue separate quality control reports on each of the surveys against the criteria outlined in table II and limits defined by the ADCP Original Equipment Manufacturer (OEM). They conclude that, all three surveys represent good quality data.

The ADCP data provided comprise text files that represent north, east, vertical and error velocities (units mm/s) against ensemble number and time across the full range of depth bins. Having removed the ancillary data from the record, the following procedures were applied:

- Where necessary, remove the start and end of the time series when the instrument is deployed but no measurements are made.
- Replace identified ‘bad’ data in the record with NaN entries (which are then ignored by Matlab during analysis).
- Remove the top and bottom of the water column record from the dataset. At the water surface the top 5m of the record is removed to take account of:
  - Surface reflection/ side-lobe suppression (see [12]);
  - The variability of water depth through the tidal cycle;
  - The envisaged practical limit of the top of a TEC device’s swept area for navigational safety clearance and to avoid excessive cavitation;
- At the bottom of the water column, the record from the lower 25% of the total depth is removed, because in a realistic turbine deployment project:
  - The resource close to the seabed tends to be of limited economic value for harvesting - strongest flow characteristics are experienced in the upper half of the water column.
  - Additionally, this minimises shear loading on the turbine due to the strength of the boundary layer near the sea-bed;
- Depth-average the East and North velocities across the remaining depth bins for every ensemble sample in the record, giving a single column velocity vector for both components.
- Where the temporal resolution of the record is to be investigated, sample the depth averaged velocity vector at the user specified resolution according to one of two approaches: discrete sampling or period averaging. At the same time the time series vector is ‘down-sampled’ so that the ensemble number corresponds with the new temporal resolution of the velocity record.

The data presented for harmonic analysis is therefore representative of an idealised water column with no velocity variation with depth. The harmonic analysis is conducted using *t_tide*; a suite of programmes implemented in Matlab code [13]. In order to validate the *t_tide* results the authors conducted some basic comparisons with model output against the model described in [14] (not shown). The two models were in excellent agreement in terms of harmonic analysis outputs, often in agreement to the level of insignificant decimal places. Output from subsequent harmonic predictions were also in generally excellent agreement, although the more refined selection of harmonic constituents for inclusion in the analysis provided by *t_tide* did in certain cases lead to some divergence in the predictions generated.

Before conducting harmonic analysis, the properties of the raw survey datasets were analysed. Table III summarises the key characteristics following adoption and adaptation of a methodology presented in [15]. Following a common approach to data presentation allows comparisons to be made between the data presented here and data from other location in the future. To aid understanding and interpretation in a tidal energy context, the metrics are presented representing the entire dataset, and additionally separated into flood and ebb, with tidal velocities below 0.5 m/s considered as slack. In terms of energy generation, velocities of 0.5 m/s or less are of limited significance, as a typical TEC device will not operate under such conditions. This is because a TEC turbine requires significant input thrust to provide enough rotational torque to overcome friction in the turbine system. Ebb and flood regimes are determined using principal axis decomposition. Presenting the flood and ebb tides separately highlights that the two regions have specific characteristics. The mean power density figures presented have been assessed for an assumed

TABLE III: Characteristics of the 3 survey records

		Survey 7	Survey 10	Survey 13
	SITE			
	1 Measurement duration (days)	32. 93	40.74	32
	2 Vertical resolution (m)	1	0.75	1
	3 Sampling interval (min)	10	20	0.5
	4 Mean depth (m)	48	26	36
	5 Assumed hub height(m)	Mid depth	Mid depth	Mid depth
	VELOCITY			
	6 Mean velocity magnitude (m/s)	1.58	1.66	1.69
	7 Neap Spring Ratio	0.34	0.38	0.41
	8 Max sustained velocity (m/s)	3.57 *	3.38 *	4.05 **
	9 Flood/ Ebb asymmetry	-0.24	0.19	-0.26
	10 AvgVertical shear (m/s per m)	0.014	0.017	0.024
	11 Max Vertical shear (m/s per m)	0.075	0.131	0.326
	DIRECTION			
	12 Principal axis direction (deg)	158	145	146
	13 Standard deviation (deg)	34.71	31.58	36.01
	14 Flood/ Ebb assymetry (deg)	-3.65	-19.75	-5.84
	POWER			
	15 Mean power density (kW/m sq)	3.74	4.04	4.70
	16 Flood/ Ebb asymmetry	0.63	1.30	0.69
	VERTICAL PROFILE			
	17 Power law exponent 1/(α)	5.4	10.5	11.3
	18 R -squared (α)	0.999	0.991	0.992
EBB	**VELOCITY**			
	19 Mean velocity magnitude (m/s)	1.85	1.72	1.96
	20 Max sustained velocity (m/s)	3.49 *	3.30 *	4.05**
	21 Avg Vertical shear (m/s per m)	0.013	0.014	0.029
	22 Max Vertical shear (m/s per m)	0.062	0.099	0.326
	DIRECTION			
	23 Principal axis direction (deg)	341.19	311.05	317.78
	24 Standard deviation	6.87	20.28	10.38
	VERTICAL PROFILE			
	25 Power law exponent 1/(α)	6.2	14.7	10.5
	26 R -squared (α)	0.998	0.991	0.963
	POWER			
	27 Mean power density (kW/m sq)	5.08	3.96	6.16
FLOOD	**VELOCITY**			
	28 Mean velocity magnitude (m/s)	1.61	1.91	1.70
	29 Max sustained velocity (m/s)	2.95 *	3.38 *	3.65**
	30 Avg Vertical shear (m/s per m)	0.016	0.021	0.022
	31 Max Vertical shear (m/s per m)	0.075	0.131	0.161
	DIRECTION			
	32 Principal axis direction (deg)	155.56	150.80	143.62
	33 Standard deviation	7.34	11.71	14.79
	VERTICAL PROFILE			
	34 Power law exponent 1/(α)	4.6	8.0	11.8
	35 R -squared (α)	0.999	0.994	0.994
	POWER			
	36 Mean power density (kW/m sq)	3.22	5.14	4.27

* For survey 7 & 10, max sustained velocity in an hour.

** For survey 13, max sustained velocity in 5 minutes.

device hub height at mid depth. No further assumptions are necessary. There are important similarities and differences between the three surveys. The reader must keep in mind that the data presented in table III relates to 3 different time-periods. The main variations are in flow direction and vertical profile. The significant variation in vertical profile is potentially of major significance from a tidal current energy perspective (and general interest relating to properties of extreme tidal regimes), but is beyond the scope of this paper – it is mentioned in passing to highlight an area requiring further research effort.

VI. IMPACT OF DATA VARIABILITY ON RESOURCE ESTIMATES

This section describes the results of the tidal analyses using *t_tide*, examining the effect on resource estimates of varying:

- The temporal resolution of samples at survey site 13;
- The overall record length at survey site 13;
- Spatial resolution across survey sites 7, 10 and 13;
- Signal to Noise Ratio (SNR) at survey site 7.

As a basic measure of the quality of the prediction, *t_tide*, reports the variance of the predicted tidal velocities as a proportion of the variance of the measured velocities. Clearly the higher the ratio, the better the prediction is considered to be. In all of the following results, the proportion "variance predicted to variance measured" was greater than 90%.

A. The impact of temporal resolution

Survey 13 was selected to examine the effect of temporal resolution of resource estimation because it spanned more than 30 days and had a basic ensemble period of 30 seconds, allowing 'down-sampling' to simulate the effect of a range of sample intervals. Initially both discrete sampling at different time periods and period averaging were investigated. But the results for period averaging only are presented because it is considered more closely representative of the actual measurement process of an ADCP deployed with longer ensemble periods. As described in section IV, the standard ADCP process averages returns from all pings within a given ensemble to reduce measurement error; in effect period averaging a record with a short temporal resolution best simulates the effect of a longer ensemble period. Initially the record was analysed at the recorded ensemble period of 30 seconds. Then the measured record was period averaged to simulate a record measured at ensemble periods of 5, 20 and 60 minutes. *T_tide* was then used to generate predictions over the full length of the original time series from constituents based on a harmonic analysis of each of these records (including only those constituents with a calculated SNR greater than 2 as recommended by [13]). Brief inspection shows that there is effectively no variation in the predicted constituents for sample periods 30 seconds and 5 minutes. At a simulated sample interval of 60 minutes, 2MN6 is not significant, but the harmonic analysis picks up the long period (around 28 days) constituent MM at a frequency of 0.0015 cph; at a magnitude which is unlikely to materially affect the predicted currents. Plotting overlapping scatter diagrams using the measured and predicted velocity based harmonic analyses conducted at temporal resolutions of 30 seconds and 60 minutes clearly indicates that the temporal resolution of the sample has limited impact on the predicted velocity pattern (not shown).

To examine the impact, not just on the statistical distribution of the predicted tidal currents but on project economics, a simple analysis of likely AEP was conducted. The results of this analysis are presented in table IV. Again it is clear that there is very little difference in the predictions based on sample intervals in the range 30 seconds to 20 minutes. Only at an interval of 60 minutes are substantial differences in the predicted velocity distribution evident. Probably the most significant indicator here is the predicted Capacity Factor (a measure of the cost effectiveness of the investment in turbines as a function of the revenue generated from the available tidal current). With details of the potential impact on AEP in hand, the impact of the difference in tidal velocity predictions in terms of project economics (on the basis of the simple assumptions set out in section IV) can now be considered. If we assume that the most accurate forecast of the total revenue available from the project should be based on the prediction from the highest resolution tidal record at 30s sample interval (the original measurement record), then the total annual project revenue would be £22, 230, 170 and the maximum 'delta' caused by lengthening the sample interval to as much as 60 minutes would represent as much as 1.56% of the overall projected annual revenue.

TABLE IV: Survey 13 – Impact of temporal resolution on AEP predictions.

Sample interval	AEP (kWh)	AEP (MWh)	Capacity factor
30 seconds	2231945	2231.94	42.46%
5 minutes	2231652	2231.65	42.46%
20 minutes	2228365	2228.36	42.40%
60 minutes	2197145	2197.15	41.80%

B. The impact of record length

The survey 13 measurement record was also chosen to examine the impact of record length on the accuracy of prediction and the uncertainty of the resulting AEP estimate. The original record length of the full survey is 31.92 days. To examine the impact of shortening the record length on the harmonic analysis and subsequent prediction, the original data was split into 2 half records, each 15.96 days long. Importantly, each half record is still longer than the Spring/Neap cycle, suggesting that it should be possible to resolve the major constituents. Table V details the predicted significant major axis constituents for each case, and the data is alternatively presented in fig. 3 (page 10). Only 4 constituents are common to all 3 analyses: the principle semi-diurnal lunar and solar constituents M2 and S2; and then M6 (a higher shallow water overtide of the principal lunar constituent M2) and 2MS6 of period around 4 hours. Surprisingly, the harmonic analysis of the second half of the record returns two constituents that are not significant in the full record analysis: the approximately fortnightly Luni-solar synodic, MSF and the3MK7 constituent of period 3.53 hours. It should be noted that both these constituents are resolved in the full record, but they are not deemed 'significant' for use in the prediction because their SNR is below the user-defined threshold of 2. This emphasises the importance of improving the understanding of the error estimation technique employed by *t_tide* for tidal current energy application. In both cases, the shorter records significantly under predict the peak tidal velocities. Detailed analysis highlights that the largest reduction of peak velocity between the full and half records is 309 and 405 mm/s (East and North components respectively). This represents the introduction of what is considered significant potential error into the analysis dependent upon the selection of ADCP measurement record length for tidal current energy projects. The impact on projected AEP is detailed in table VI as for the preceding case. The impact on project economics represents a variation of as much as 14.92% of annual project revenue in the worst-case scenario (the difference in capacity factor can be seen as a simple indication of the potential economic impact). This is now indicative of resource uncertainty having a significant potential impact on project economics, even on the basis of 'judgement' rather than more detailed analysis.

TABLE V: Impact of data record length on harmonic analysis outputs.

Constituent	**Frequency (cph)**	**Major axis constituent amplitude (mm/s)**		
		1st half	**2nd half**	**Full record**
MSF	0.00282		61.855	
Q1	0.03722			49.208
O1	0.03873		85.663	100.882
K1	0.04178		61.593	66.544
EPS2	0.07618			127.911
MU2	0.07769			278.712
N2	0.079			520.203
M2	0.08051	2667.682	2326.934	2485.788
L2	0.08202			221.001
S2	0.08333	1007.398	1250.212	1141.182
MO3	0.11924			14.732
M3	0.12077	52.013		28.341
MK3	0.12229			13.689
SK3	0.12511	21.926		
M4	0.16102		59.704	61.785
MS4	0.16384		66.995	43.396
2MK5	0.2028			11.589
M6	0.24153	82.623	36.94	61.318
2MS6	0.24436	94.176	95.526	92.48
2SM6	0.24718		45.403	32.599
3MK7	0.28331		7.351	
# significant constituents:		***6***	***11***	***18***

TABLE VI: Survey 13 - Predicted AEP using various record lengths

Record length	AEP (kWh)	AEP (MWh)	Capacity factor
First half	2300413	2300.41	43.77%
Second half	1967361	1967.36	37.43%
Full record	2231945	2231.94	42.46%

C. The impact of spatial resolution

Surveys 7, 10 and 13 were selected to examine the impact of spatial resolution of resource estimates because: they all have record lengths in excess of 30 days; they are well separated with some differences in the local bathymetry; and the range of ensemble sample intervals (at 30 seconds to 20 minutes) had already been demonstrated to have limited potential impact on subsequent predictions. Fig. 2 (page 10) indicates the actual locations of each survey and table VII reports the latitudes and longitudes of each site and their physical separation in terms of distance and bearing.

TABLE VII: Position and spatial separation of surveys 7, 10 and13.

	Position		***Spatial separation***		
	Latitude	Longitude		Distance	Bearing
7	59° 08' 27"	02° 48' 59"	7 - 10	1,684 m	342°
10	59° 09' 09"	02° 49' 31"	7 - 13	797 m	134°
13	59° 08' 09"	02° 48' 23"	10 - 13	2,416 m	153°

The measured record data for surveys 7 and 13 were 'down-sampled', using the approach to 'period averaging' described earlier, such that all 3 records had effective measurement period ensemble intervals of 20 minutes. Harmonic analyses of each record (at the common ensemble interval) were conducted at a common threshold SNR of 2 against their original time base (start times range from March 2005 to March 2007). To assess the impact of spatial resolution, harmonic predictions were then generated from each set of constituents for a common start time and period length (19 Mar 2005 10:47:37, for 33.15 days, the start and duration of survey). As a result, the predictions based on surveys from all 3 sites can be compared directly. Figure 4 displays a scatter plot of the predicted velocity vector tips based on harmonic analyses of the measured records at survey sites 7, 10 and 13, with predictions to a common time base. Substantial variations are evident. All of the plots correspond well with the orientation of the bathymetry local to the survey locations. The most northerly dataset, survey 10, displays rotary aspects, although the plot is still substantially bi-directional. Site 10 also shows lower peak velocities than are predicted from the harmonic analyses of the records at sites 7 and 13. The prediction based on the record at site 7 shows an almost perfectly bi-directional tidal pattern with the highest peak velocities – which is consistent with its mid channel position at the point of greatest ‘constriction’. If the flood tide is considered to be flow from NW to SE, then the prediction at 7 shows modestly greater velocities on the ebb. The prediction at site 13 is a little less linearly bi-directional, a minor East – West rotary element is indicated.

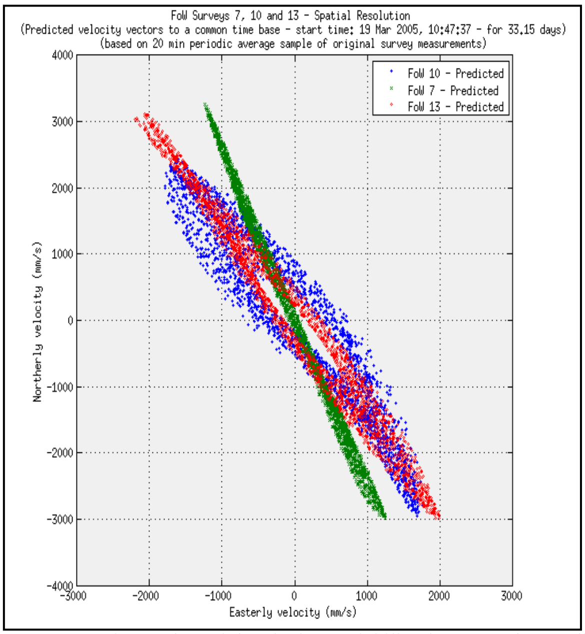

Figure 4: Comparison of spatial velocity variability between three adjacent ADCP records (maximum linear separation less than 2.5km – see table VII).

Continuing with the previous assumptions regarding typical turbine topology and the numbers required for a tidal array with installed capacity 50MW (16 metre diameter; and 83 turbines respectively) and further assuming that each machine is separated by 15 diameters downstream and 2.5 diameters perpendicular to the flow, the area of seabed required to accommodate the array can be assessed. At a ‘per turbine’ footprint of approximately 240m (length) by 40m (width), a 50MW array is likely to occupy an area of around 2000 metres by 400 metres if bathymetry variability enables a uniform distribution of devices in an array. Comparing this estimate with the linear separation of the survey sites listed in table VII, it is evident that the variation of predicted velocities presented here is a reasonable representation of what might be experienced across an array.

Fig. 5 (page 10) presents the significant constituents (at SNR threshold of 2, major axis amplitude only) generated by harmonic analyses for each of the survey records. It is evident that there is reasonable agreement in both frequency and amplitude for surveys 7 and 13, located relatively closely in mid-channel. The prediction for site 10 shows significant variation, mainly in that different constituents at shorter periods are evident. Constituents clustered around the semi-diurnal frequencies dominate all the harmonic analyses. The resulting velocity probability distributions are plotted in fig. 6 (page 10). The lower probability of peak velocities for survey 10 is evident, and lower prediction of AEP for this location is therefore expected (table VIII), despite a higher probability of lower velocities in the approximate range 250 – 1000 mm/s (which are of limited use for energy generation as a typical turbine will not ‘cut-in’ until around 0.7 m/s).

TABLE VIII: AEP predictions based on different spatial representations

Input data	AEP (kWh)	AEP (MWh)	Capacity factor
Survey 7	2038619	2038.62	38.79%
Survey 10	1917435	1917.44	36.48%
Survey 13	2133190	2133.19	40.59%

Based on these predictions, the maximum total revenue from an array (assuming the flow conditions across the array are uniform and best described by the prediction at site 13) for a given year is £21,246,575. The largest simulated variation (based on an assumption that flow conditions are uniformly as at site 10) is 10.1% of this revenue – which is obviously a significant impact on project economics. A point of relevance should be considered here. In the development of a larger scale tidal array, it is very likely that tidal hydrodynamic numerical models will be developed to optimise the array design and take full account of the local bathymetry. An important question arises: how many ADCP surveys are required and in what locations to validate the numerical modelling? A high-level assessment of these results suggests that – where the channel geometry is reasonably constant, i.e. in the region of survey sites 7 and 13, then reasonable agreement is obtained for surveys separated by nearly 800m (at least for absolute velocity, if not for direction of flow). However, in regions characterised by varying local topography, like survey site 10, a greater density of surveys may be required to ensure the model in question is representing the local flow conditions effectively.

D. The impact of spatial signal to noise ratio

Given the significance in the *t_tide* code of the method of estimating errors and the subsequent calculation of the Signal to Noise Ratio, a brief study was conducted on the sensitivity of resource estimates to the SNR limit. In the notes accompanying *t_tide*, it is suggested that the range techniques applied to error estimation give reasonable results in the range SNR 10 to SNR 1 (see [13], for a more detailed discussion). Fig. 7 (page 10) shows the significant constituents calculated from the harmonic analysis with varying SNR thresholds from 1 to 10. To interpret this figure: look first for the highest SNR limit 10 (in cyan), these are the only constituents included in a prediction based on this limit. As the SNR threshold is reduced, so the other colours show which constituents are included in the prediction (so for an SNR threshold of 4, both the constituents coloured cyan and red are included). At all threshold levels, the principal lunar and solar semi-diurnal constituents that dominate the tidal response at this site are included in the prediction.

Table IX summarises the simulated AEP in each case, and the impact on project economics of the variation between the resource estimates. Taking the case where the SNR threshold is set to 1, the maximum possible annual revenue that the project could deliver is £20,643,293. The largest possible delta from setting another SNR threshold represents 3.36% of this total. This relatively small variation is mainly due to the predominance in this location of the main lunar and solar semi-diurnal constituents. In other locations where shallow water over-tides are particularly important or where non-tidal process dominate the observed record, the choice of SNR may be far more significant in the energy yield assessment.

TABLE IX: Survey 7 - annual energy production at various SNR.

Signal to Noise Ration	AEP (kWh)	AEP (MWh)	Capacity factor
SNR1	2072620	2072.62	39.43%
SNR2	2058107	2058.11	39.16%
SNR4	2003053	2003.05	38.11%

VII. CONCLUSION

The results demonstrate that the following variables (listed in order of decreasing significance) impact accuracy of energy resource assessments: total record length; spatial resolution (in relation to the total area covered by a projected array); the user selected signal to noise ratio (which is particular to *t_tide* and determines the number of constituents which are carried forward from the harmonic analysis to the subsequent prediction); and, finally, the temporal resolution (or sample interval) of the recorded survey. The relatively low significance of the temporal resolution of the survey is an unexpected result. If this trend can be confirmed by analysis of data from other tidal sites suitable for energy extraction, it would suggest a clear recommendation could then be made that tidal surveys should be conducted with a sample interval less than or equal to 20 minutes (results indicate that the change in the resource estimate below this level is insignificant for the purpose of AEP assessment). This has advantages for project and technology developers who are currently utilising much higher resolution sampling - it would allow a better trade-off, within the constraints of ADCP battery life and data storage capacity, between the total survey length (shown to be of key importance), the sample interval and the number of pings per ensemble (which reduces the instrument measurement error). On the other hand, significant increases in temporal resolution are required to inform certain key TEC device design (e.g. turbulence characteristics of a particular site). Given the conflicting requirements of high resolution, short recording periods to suit device design, and (relatively) low resolution and long recording periods for energy yield assessment, the authors recommend that data gathering for the two purposes is conducted separately.

The results assessing the impact of spatial resolution suggest that project developers will need to give careful consideration to the number and geographical distribution of in-situ measurements utilised to characterise a tidal energy development, particularly as the industry moves towards deployments of arrays of multiple devices. As projects increase in scale, it is likely that there will be a tendency to rely on 3D hydrodynamic numerical models as the basis for detailed large-scale resource assessment. Validation of the model results from in-situ tidal survey data will remain key to ensuring confidence in the resulting resource estimates. The number and length of surveys required for these purpose will remain a matter of judgment for some time, but it should be possible to develop effective best practice guidance once data from a larger sample of locations become available in the public domain.

The motivation for conducting this analysis has been to raise awareness of the potential detrimental longer-term economic impact on project returns of failing to appropriately invest in assessing the specific tidal current energy site characteristics. This is currently an area where tidal energy project developers are minimising cost expenditure. Evidence of the potential impact on project returns have been highlighted. The research presented has also been conducted with the intention of informing the recently initiated moves to develop International Standard documentation for the tidal current energy industry under the auspices of the IEC TC114.

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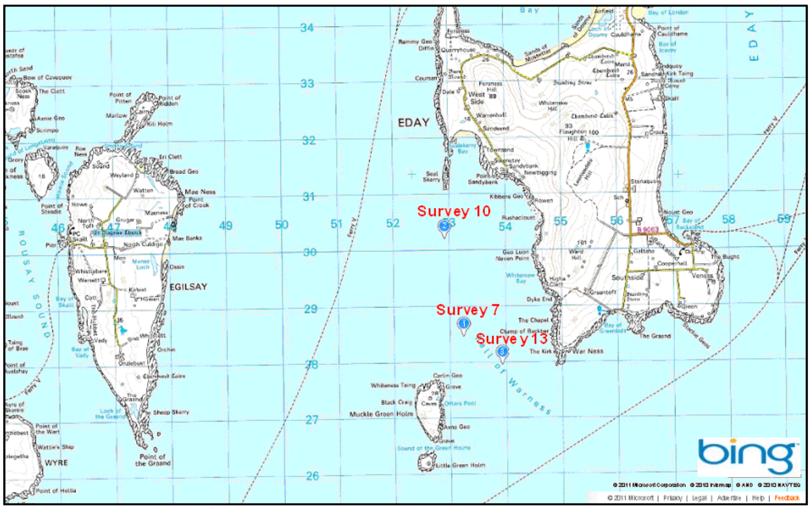

Figure 2: Relative position of the three ADCP data surveys use in the analysis (EMEC tidal test-site).

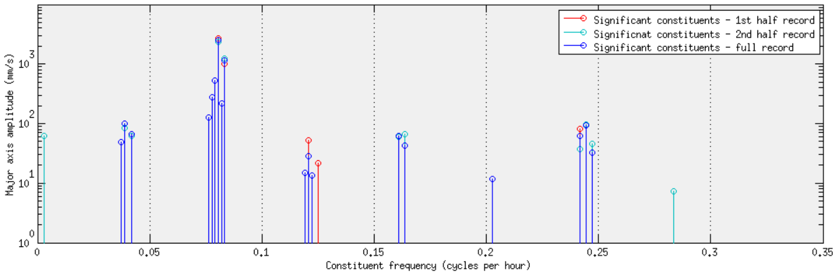

Figure 3: Comparison of constituents predicted with a SNR > 2 for the 1st and 2nd half of the overall measurement record and from the full record.

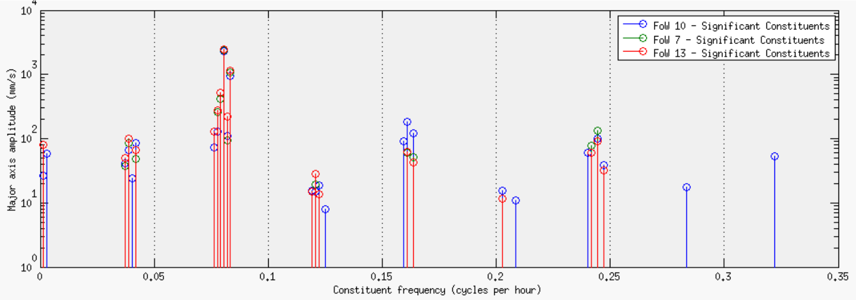

Figure 5: Comparison of constituents wih a SNR > 2 for predictions at a common time basis for surveys 7, 10 and 13.

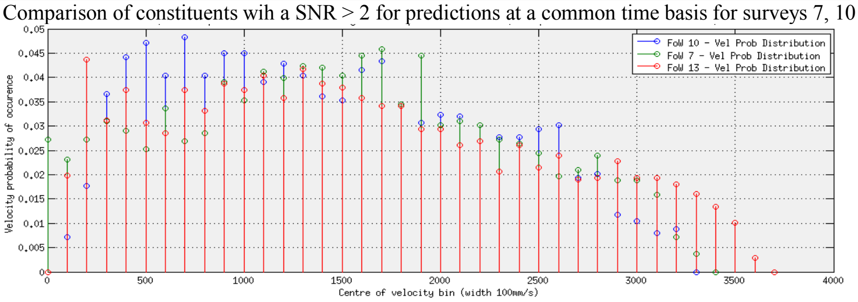

Figure 6: Comparison of velocity distributions based on predictions at a common time basis for surveys 7, 10 and 13.

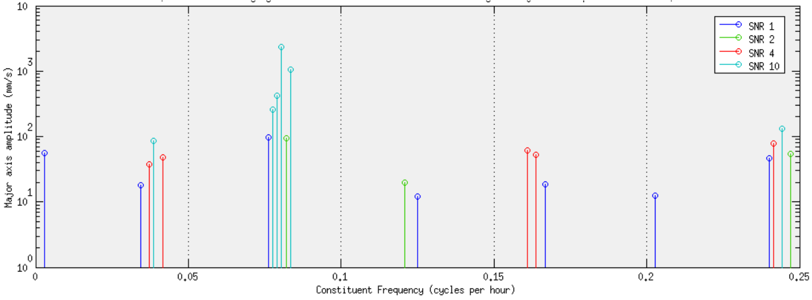

Figure 7: Survey 7 - major axis amplitude constituents obtained from harmonic analysis utilising various signal to noise ration for a single measured record.