Currents, Waves and Turbulence Measurement: A view from multiple Industrial-Academic Projects in Tidal Stream Energy

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***Abstract*—Tidal Stream Energy is considered a regular, predictable and dense energy source with potential to make a significant contribution to our future energy needs. Development of the industry, from resource assessment to device design and operation, requires characterisation of the flow environment at a variety of spatial and temporal scales at tidal energy sites. Demand for flow characterisation arises from companies developing, installing and operating tidal turbine prototypes or small arrays in locations from Scotland to France to Canada.**

Flow characterisation for tidal stream applications relies on the measurement of water velocity at the relevant scales, yet given the non-uniformity of the flow field, no single instrument measures all the necessary data inputs required by the sector. This paper provides an overview of a variety of current, surface wave and turbulence metrics of industrial relevance to tidal stream and discusses methods employed to secure these datasets. The use of variants of acoustic current profilers is presented, which have been utilised and developed on previous and ongoing industrial-academic projects, including ReDAPT (ETI, UK), FloWTurb (EPSRC, UK) and RealTide (EC H2020, EU). These variants feature differing numbers of acoustic transducers and varying geometrical configurations with installations at both seabed locations and atop operating tidal stream energy converters.

Ongoing development of advanced sensor configuration is discussed, aiming to achieve resilient, high resolution three-dimensional measurement of mean and turbulent flow tailored for tidal energy applications.

The paper gives practitioners and researchers an overview of tidal stream flow characterisation and practical lessons learnt.

I. INTRODUCTION

Tidal Stream Energy has the potential to make a significant contribution to our future energy needs, indeed by 2050 tidal energy could meet 10 % of European electricity requirements [1]. While tidal stream is considered a reliable and predictable source of dense, renewable and low-carbon energy, the complexity of the associated flow environment poses many challenges for flow characterisation and the development of the sector. Variation in the flow environment occurs at tidal energy sites at spatial scales which range from kilometers (e.g. large scale eddy structures) to blade lengths and smaller (e.g. microscale eddies) and at temporal scales ranging from years (solar/lunar cycle) to seconds (turbulent gusts) [2]. As illustrated in Fig. 1, non-uniformity in the flow field results from a variety of factors such as high shear in the velocity profile, surface waves, turbulence and bathymetric interaction.

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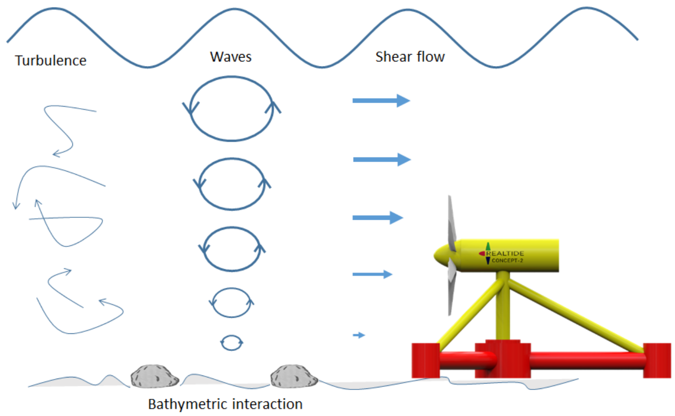


Fig. 1. Factors causing non-uniformity in the flow field around a tidal turbine, after [3]

Flow characterisation for the tidal sector aims to generate input data relevant to engineering models that are used to assess loads and resource availability and to plan on-site activity such as installation and maintenance. To support the industry in its early stage of commercialistion, ultimately leading to cost effective and reliable power production, reductions are required in measurement uncertainty in the highly heterogeneous tidal channel environment. Drawing on the experience of the authors and from the implementation of multiple projects [4] [5] [6], flow characterisation data should not be acquired in isolation. As shown in Fig. 2, data acquisition should be informed by, and inform, multi-scale hydrodynamic models. Data management and processing should reliably allow users outwith the data acquisition team to access, understand and use the data, confident of its quality. Users of engineering tools should also provide feedback to flow measurement campaign designers in order to ensure acquisition of relevant metrics and associated data which can be used to inform and validate tools.

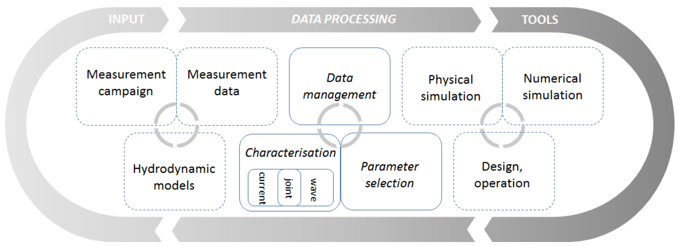


Fig. 2. Feedback between a measurement campaign and the engineering tools utilising the resultant data, developed from [7]

This article is laid out as follows: a brief overview of the tidal industry is provided in Section 2. Section 3 presents an overview of current, wave and turbulence metrics, highlighting aspects of industrial application. Section 4 discusses the instruments used to obtain these industrially relevant metrics and Section 5 reviews several major industrial/academic projects where these instruments have been deployed to obtain these metrics. Section 6 summarises ongoing development of advanced configurations of Tidal Energy Converter (TEC)-associated instruments, based on lessons learned from the industry/academic consortia.

II. THE INDUSTRY

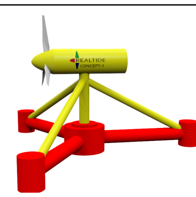
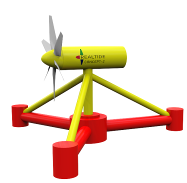
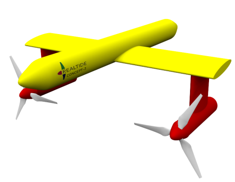
Sites suitable for tidal stream TEC deployment are typically those which, as a minimum, have a water depth of 25 to 45 m, which can be connected to an electrical grid and which have a peak spring tide velocity of at least 3 m/s [8]. Three generic designs of TEC and associated deployment locations are identified in Table I. In each, a horizontal axis turbine utilises one of a variety of designs (e.g. number of blades, ability to pitch and yaw, complexity), sizes (e.g. rotor diameter, rated power capacity) and modes of operation (floating or gravity based).

The tidal industry faces many challenges, epitomised by the recent liquidation of tidal energy company OpenHydro and near bankruptcy of developer, Tocardo. Nevertheless, there remains considerable activity globally. In the UK, SIMEC Atlantis Energy in the Pentland Firth are operating 4 x 1.5 MW grid-connected turbines with plans to extend this array with another two turbines and a regulatory lease in place for the installation of up to 398 MW. Orbital Marine Power operated a 2 MW prototype floating turbine for 2 years in Orkney, generating over 3,000 MWh of electricity and are now developing a floating 2 MW commercial demonstrator. Nova Innovation are operating a 3 x 100 kW turbine array in Shetland with plans to extend this array by a further 3 turbines to enable field investigation of array interaction. Magallanes Renovables, from Spain, are building on previous ocean testing of a tenth scale prototype with the deployment of a 2MW tidal platform in Orkney. In France, Sabella are operating a 1 MW turbine in the Fromveur Strait, following which the installation of 2 x 500 kW turbines is planned in the same area. In Nova Scotia, Canada, Sustainable Marine Energy are operating a floating platform hosting 4 x 250 kW turbines, focussing on community scale systems. [1]

Current, wave and turbulence metrics - and the interaction between these processes - are used to predict available resource, to determine power quality fluctuations and to assess fatigue and extreme loading of TECs [2]. Required both for individual TECs and interactions between arrays of TECs, incorporation of these metrics into engineering tools informs design. This contributes to the reliable and predictable production of grid quality power at costs competitive with other forms of energy generation - paramount for the future growth and development of the tidal industry [9].

[1]Information in paragraph sourced from web searches

TABLE I
GENERIC TYPES OF TIDAL ENERGY CONVERTER (CREDIT: REALTIDE/ENEROCEAN)

Generic classification	**Key features**	**Image**	**Example companies, deployment location**
Complex bottom fixed tidal turbine	Horizontal axis Open rotor 3 blades Bottom fixed Pitch control Yaw mechanism Gearbox drive		*SIMEC Atlantis Energy* Pentland Firth, Scotland https://simecatlantis.com/
Simple bottom fixed tidal turbine	Horizontal axis Open rotor Multi blade Bottom fixed No pitch control No yaw mechanism Direct drive		*Sabella* Fromveur Strait, France https://www.sabella.bzh/en *Nova Innovation* Bluemull Sound, Shetland, Scotland https://www.novainnovation.com/
Floating multi-rotor tidal turbine	Horizontal axis Open rotor Multi blade Floating No active pitch mechanism No active yaw mechanism Gearbox drive		*Orbital Marine Power* Falls of Warness, Orkney, Scotland (prototype, removed Sept 2018) https://orbitalmarine.com/ *Sustainable Marine Energy* Grand Passage, Nova Scotia, Canada https://sustainablemarine.com/

III. METRICS OF INDUSTRIAL RELEVANCE

In the literature a wide range of metrics exist to describe currents, waves and turbulence and may be directly measured, derived from time or frequency domain analysis or derived statistically [16], [17]. From this range of potential metrics, a subset are in frequent use by the tidal industry throughout design, planning and operation, a range of which are referenced in Table II (NB. wind metrics, which drive waves and local wave-current interactions, are excluded from this paper)

In the following, the application of these metrics to the tidal sector is considered, noting that evaluation of the effect of tidal stream energy extraction on the marine environment is outwith the scope of this paper (see e.g. [9] and [18] for review).

- *Current speed and direction:* TECs have a rated, cut-in and cut-out current speed. Knowing the relationship between current speed and TEC power output generates a power curve which can be applied to measured/determined current speeds for a specific location to forecast energy yield [19]. Tides may not be rectilinear or symmetrical and if a TEC does not yaw, current direction is key to installation to ensure the TEC is oriented to maximise power capture during all tidal conditions. Real time control of the TEC, seeking to maximise power output while minimising loads, depends on a feedback loop between measured and/or expected current speed and operation of the TEC [20].
- *Turbulence:* Generated by shear instabilities, turbulence is part of the velocity field in an area and has multiple scales from vortices the width of a tidal channel to microscale eddies, millimeters in size [2]. Understanding is required of the level (turbulence intensity) and nature (length-scale) of both ambient turbulence (i.e. natural turbulence before TECs are installed and which will occur upstream of the TECs) and also turbulence post installation [21]. This influences the understanding of TEC wake formation and dissipation, interaction between TEC wakes in an array and fluctuations in load across a swept rotor area - informing TEC design to withstand fatigue and TEC siting within an array [22]. Research continues into application to the tidal industry of turbulence theory and models which have been validated for the wind industry, given the influence of the free surface (air/sea boundary) and seabed bathymetry including bounding channels [2].

TABLE II
EXAMPLE METRICS IN USE IN THE TIDAL INDUSTRY

Metric	**Typical data requirement** [10] [11] [12] [13]	**Measurement considerations**
	Current	
Flow velocity (u,v,w)	Mean current: long term, flood and ebb current; spring and neap peak currents; Maximum and minimum current on mean day; Return periods of 1 and 50 years	1) Duration & siting of measurement campaign informed by temporal and spatial variation e.g effects of headlands, islands, sudden bathymetric changes
Velocity profile (U_z)	Typical assumption made in relation to 1/7th power law and fully developed boundary layer which may not apply at tidal sites [3]	2) To fully characterise tidal energy site, measurements complemented by dynamically coupled wind-wave-tide model [14]
Water level	Mean sea level, Highest Astronomical Tide, Lowest Astronomical Tide, highest and lowest still water level with recurrence periods of 1 year and 50 year [12]	3) Reference to common datum for e.g. water depth, position of instruments, time
	Waves*	
Significant wave height $(H_s\, or\, H_{m0})$	Determined from a time series (H_s) or a spectrum (H_{m0}). Typically required for long term and 1, 5 and 50 year return periods	1) Need to consider data requirements to adequately determine wave spectrum e.g. maximum frequency to be resolved and therefore measurement sampling frequency;
Period e.g. zero crossing $(\bar{T}_0)$	For given wave heights, the corresponding periods which result in the highest loads	2) Selection of the probability distribution function (e.g. Rayleigh, Weibull or log-normal) to estimate likelihood of extreme values is a qualitative decision.
Spectral peak period (T_p)	Long term given mean wind speed and direction 1 year and 50 year return period	
Mean wave direction (θ_m)	Overall characteristic, determined from spectra. Challenging to quantify and validate, may use assumption of unidirectional sea state [13]	3) Measurement data extrapolated to obtain extreme wave metrics
Wave spectra $(S(f))$	Multiple potential models, including Pierson Moskowitz and JONSWAP. In offshore engineering, spectra typically defined by H_{m0} & T_p [13]	
	Turbulence	
Turbulence Intensity (I_u)	If turbulence is anisotropic, measurements are required in u,v and w directions	1) May be over-estimated in wave-current environment given the comparable magnitude of wave & larger turbulence length scales.
Turbulent Kinetic Energy (TKE)	Measurement required in u,v and w directions	
Length scale (ℓ_x)	From measurement of u,v and w, spectra are generated to calculate length scales via e.g. autocorrelation or von Karman fitting	2) Not industry standard requirement in resource [10] or annual energy production assessment [11].
Reynolds Stress Tensor $(\bar{R})$	Full tensor can't be obtained at hub height by single instrument. Currently 5 of 6 components can be obtained via 5-beam D-ADP [15]	3) Turbulence metrics are an input to CFD for TEC and used in loading assessment [13].

*deep/intermediate/shallow water equations to be applied accordingly

- *Waves:* To assess irregular sea states for TEC and component loading analysis, characterisation of waves is required by obtaining significant wave height, peak period, wave spectrum and wave direction. A simpler, yet less comprehensive methodology is to use regular waves, characterised by maximum wave height, period and direction. As waves can penetrate to significant depths in the water column, estimated to be approximately 50 % of their wavelength [23], turbine blade loading can be affected, even at considerable depths.
- *Wave/current interactions:* While investigation of this interaction has typically been limited/neglected in field measurements, there is growing recognition of its impact on TEC loading and power capture. Waves are predicted to influence turbine power output due to the cubic relationship between power and flow velocity [24]. Waves acting on floating TECs cause them to yaw and pitch, changing their orientation in the tidal current and thus affecting the blade angle of attack. Assuming that wave and current can be added together using particle velocity vectors is too simplistic and may under or over estimate loading because [23], [24]:
  - Wave-current interaction is non-linear
  - There is high spatial variation in velocity (shear), introduced by e.g. the decay of the effect of wave energy with depth
  - There is turbulence and surface waves
  - The direction of wave and current may be following, opposing or oblique
  - Forces applied to blades from waves will have circular components

  Tank studies [25], [26] have demonstrated that understanding of wave-current interaction is required for TEC design so that

Current, wave and turbulence metrics are incorporated into tools which are used in engineering design and validation.

As an example, the metrics are used as input into high resolution, coupled wave and current hydrodynamic models which complement field measurement campaigns being lower cost (and risk) than field data acquisition which will always produce relatively sparse and localised data in comparison. Hydrodynamic models can generate representative site conditions (normal conditions used to determine fatigue loading) and be used to evaluate the impact of extreme conditions (infrequent conditions which occur with a statistical probability that can lead to extreme loading on the TEC e.g. 50 year return period). The limitations to modelling are however recognised: the challenges of model validation given the lack of available field data across regional scale models and at open boundaries; assessment and quantification of model uncertainty; model grid size and input data (e.g. bathymetric resolution) limiting the spatial and temporal scales of analysis which can be conducted.

Other tools using flow characterisation data include fully coupled tide to wire models (e.g. Fig. 4) which use CFD models such as Tidal Bladed, a Blade Element Momentum Theory (BEMT) code developed by DNV GL. The model uses input data such as flow speed and direction in the water column, flow shear, turbulence intensity and turbulent length scales to determine the hydrodynamic forces of thrust and torque acting on a TECs blades and rotors. The torque component is subsequently used as input into an electrical generator model which generates electrical power and controls the rotational speed of the rotor which is used as input to the BEMT turbine. The fully-controlled, fully-rated power electronics allow the electrical generator to operate in variable speed and to maximise power capture from the resource by altering the power take off electromechanical torque of the generator. This feedback process depends on the accuracy and availability of measurements such as tidal current speed, mechanical torque and mechanical power.

Validated tide to wire models enable examination of the effect of changing flow conditions on power output, of the effect of extreme metocean conditions and of the effects of fluctuating loads on components within/elements of the rotor and blades during variable speed operation. On the grid side, the effect of grid faults on the operation of the system as well as the quality of exported power to the grid under different realistic scenario can be investigated. These coupled models are in early stages of development see [6], [27].

A further, albeit not mutually exclusive, use of current, wave and turbulent metrics by the tidal industry is to fulfill industrial standards. These standards (outlined in Table III) specify

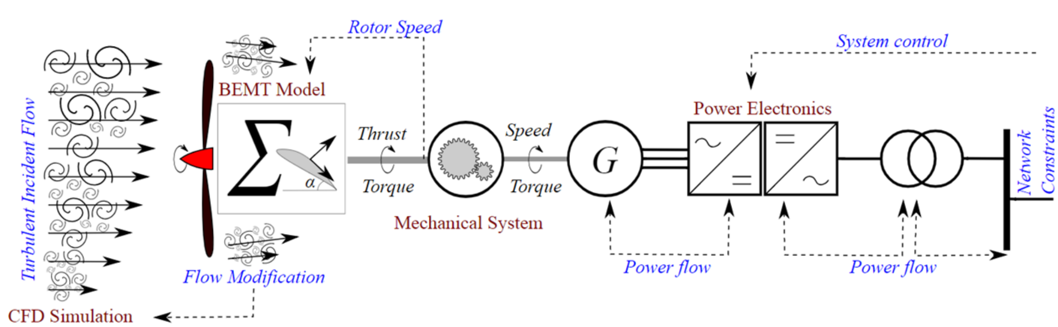


Fig. 4. Tide to wire model: overview schematic (*Reproduced with permission from D. Ingram)*

required metrics and provide guidelines for their acquisition and application. The standards seek to ensure consistency in approach across the sector, capturing best practice and enhancing confidence in the emerging industry via verification and certification against the requirements.

IV. Instruments used to obtain these metrics

It is inherently challenging to undertake flow characterisation for application to the tidal industry as measurement is required at turbine hub height rather than in close proximity to the sea floor, flows are fast and instruments can invalidate results by disrupting the flow. Further, a compromise must be made between the range of spatial and temporal scales over which measurements would ideally be made and the time, cost and number and type of instruments that must be deployed to achieve this [28].

Significant developments have been achieved in wave, current, and turbulence measurement by the application of acoustic current profilers which measure current using the Doppler shift of backscattered acoustic signals from suspended particulate material moving at the same speed as water particles and whose motion are a proxy for the speed of the local fluid flow. Such instruments are inherently drift free and do not require routine calibration. These instruments sample ranges of the water column remotely without interference in the fluid flow (see Table IV for instruments used by UEdin).

Historically, wave measurements were made using wave rider buoys [29]. In fast flowing tidal sites, their use is limited, being pulled under by the flow although they can provide useful boundary condition inputs into coupled wave/current site models. Where acoustic devices can be used to obtain estimates of wave height and direction, the requirement is removed to deploy multiple sensors to measure waves and currents. As water depths increase, limits are encountered on the frequency, period and height of wave which can be detected via diverging acoustic current profilers, requiring the use of alternative sensors [29].

Acoustic Doppler Velocimeters are a modification of profilers which have been developed to make point measurements of velocity and turbulence in close proximity to boundaries. Up-scaling of this concept to make measurements remote from boundaries is discussed further in Section VI.

Challenges in field deployment and retrieval of acoustic current profilers are exacerbated in tidal stream flow characterisation, for example the levelling of a frame/structure at a tidal site where seabed scouring can result in uneven, rocky surfaces. Similarly, frame retrieval is challenging in high flow, acoustically noisy environments where available time for deployment and retrieval activity is typically limited to short (e.g. 15 to 30 min) periods of slack water during neap tides.

As in any acoustic current measurement campaign, but particularly when measuring turbulence for incorporation into TEC design, correction is required for Doppler noise. Doppler noise, the standard error resulting from the estimation of the Doppler shift of finite length acoustic pulses, depends on the sample rate and on bin size (via pulse length) [30]. Without correction for noise, the resultant calculations of turbulence leads to design incorporating unnecessarily conservative safety factors, introducing extra cost into the design, impacting levelised costs of energy [31].

TABLE III
Overview of standards

Standard	Stated purpose	Comment
IEC/TS 62600-200:2013 Electricity producing tidal energy converters-Power performance assessment	Systematic methodology for evaluating the power performance of tidal current energy converters that produce electricity for utility scale and localised grids	Defines - TEC rated power - Rated water velocity - Power curve production - - Results reporting
IEC/TS 62600-2:2016 Marine energy-Wave, tidal and other water current converters	Provide primary design criteria to ensure engineering integrity throughout the defined design life of marine energy converters such as wave and tidal	Site-specific conditions /environmental loads; Safety factors; External load cases (extreme, normal); Failure probability and consequence; Redundancy
IEC/TS 62600-201:2015 Marine energy-Wave, tidal and other water current converters. Tidal energy resource assessment and characterisation	System for analysing and reporting, through estimation or direct measurement, the theoretical tidal current energy resource in oceanic area...that may be suitable for the installation of arrays of TECs	Staged approach to calculation of resource assessment with increasing level of detail from feasibility stage to design layout. Outlines data collection for calibration and validation of hydrodynamic models.
DNVGL-ST-0164 Tidal turbines	Principles, technical requirements and guidance for design, construction and in-service inspection of tidal turbines.	Requirements for site characterisation; Limit state approach to design; Addresses design loads and associated return periods (e.g. 1 and 50 year); Load effects and load combination analysis
DNVGL-RP-C205 Environmental conditions and environmental loads	Guidance for modelling, analysis and prediction of environmental conditions as well guidance for calculating environmental loads acting on structures	Specific to wind, wave, current loading on a range of structures. Outlines metrics, their statistical derivation and the methodology for load calculation on e.g. slender members and large volume structures

TABLE IV
EXAMPLE ACOUSTIC CURRENT PROFILERS DEPLOYED IN FLOW CHARACTERISATION

		Beam configuration	**Range from sensor (m)**	**Maximum sample frequency (Hz)**	**Pulse frequency (MHz)**	**No. operating beams**	**Minimum bin length**
D-ADP	Nortek AWAC	Divergent	35	1	1	3-5	1.0 m
D-ADP	RDI ADCP	Divergent	50	2	0.6	4	0.5 m
D-ADP	Nortek ADCP	Divergent	60	8	0.5	5	0.5 m
SB-ADP	Nortek ADCP	Single	20	4	1	1	0.4 m
ADV*	Nortek ADV	Convergent	0.15	64	0.1-0.25	3	5 mm
C-ADP	Nortek ADCP	Convergent	4	4	1	4	0.4 m

*point measurement
D-ADP Divergent Acoustic Doppler Profiler; ADV Acoustic Doppler Velocimeter; SB-ADP Single Beam ADP; C-ADP Converging ADP

V. INDUSTRY-ACADEMIC PROJECTS

A range of significant industry/academic projects have been funded by pan-European and national entities to facilitate and accelerate the exploitation of marine renewable energy (MRE) which includes tidal energy. This includes projects such as Equimar (2008-2011) developing protocols to standardise assessment of different MRE technologies; SI Ocean (2012-2014) identifying gaps and barriers/opportunities to adoption of MRE; DTOcean (2013-2016) and DTOcean plus (2018-2020) developing design tools to support option selection, development and deployment in the MRE sector.

To further understand the flow environment in which TECs operate and derive industrially relevant metrics, a range of European and UK projects have, or are, being run with a variety of certification bodies, academic and industrial partners (Table V). From these projects, a number of lessons can be drawn that are being incorporated into subsequent TEC/flow characteriation projects and which also have wider applicability. These include:

- *Scheduling:* When a flow characterisation campaign is associated with an industrial partner operating a TEC, the measurement campaign timeline and intervention opportunities are driven by TEC installation and maintenance plans. This interaction influences the time available to develop instrument packages and affects when the instruments can be accessed in addition to weather and tidal constraints to access. This occurred on ReDAPT (Table V) which involved the deployment of a range of acoustic current profilers over 36 months on and around the Alstom DEEPGen IV TEC and RealTide (Table V) which involves the deployment of a range of acoustic current profilers on and around the Sabella TEC.
- *Communication:* Close co-operation with the operator of the device is paramount to the success of the measurement campaign. Potential seabed instrument locations may be rendered unusable by vessel mooring positions or cable laying routes, constraints which should be understood early in the campaign's planning phase. To mount instruments on the TEC, upfront agreement is required on location, particularly where additional complexity is introduced with, for example, instruments mounted on a rotating hub (see Section VI). Any penetrations required to mount instruments should be incorporated into TEC structural design and any material incompatibilities identified and designed out or mitigated. To understand the measurements being made by the instruments, the instrument operator needs information about the TEC, such as the operational status of the turbine, the rotational direction of the blade, the yaw of the turbine (if applicable), power generation and blade loading. To protect their company and assets in an emerging yet competitive industry, TEC developers can be particularly sensitive about data and information confidentiality. Confidentiality agreements are required to clearly establish any limitations on the use and the dissemmination of data obtained.
- *Reference datum:* In order to ensure data acquired from instrumentation can be utilised to draw conclusions between instruments and across measurement campaigns, a number of datum must be established:
  A period of stationarity must be determined, over which there is a stable mean and variation. For wave characterisation, periods of 3 hours are typically used, over which a constant significant wave height and spectral peak period are assumed [17]. For turbulence calculations from field data, periods of pseudo-stationarity of 5 or 10 min have been used, over which mean velocity and its variation (i.e. turbulence) are assumed constant [36].
  The hub height of the turbine may typically be used as the reference (z) location within the water column, although alternative reference locations may exist, e.g. the swept area of the turbine blade or the mean water level. The reference velocity will be measured from a specific x, y location by a particular instrument.
  The measurement scale can range from localised measurement at hub height, to the swept area of the rotor, to the validation of hydrodynamic models which typically have areas of higher resolution around the areas of interest e.g. TEC location. The target scale must be agreed at the outset of the measurement campaign design given the objective of the campaign.

TABLE V
SELECTED INDUSTRIAL ACADEMIC PARTNERSHIPS FURTHERING FLOW CHARACTERIATION FOR THE TIDAL SECTOR

Project (abbreviation) Funder, duration, value (US $ million), *partners*	**Key objectives**	**Key flow characterisation outputs *(anticipated)***
Reliable Data Acquisition Platform for Tidal (ReDAPT) project [4] ETI, UK; 2010 to 2015; $16.2 m *Alstom; E.ON; EDF; DNV GL; Plymouth Marine Laboratory; European Marine Energy Centre (EMEC); University of Edinburgh (UEdin)*	Design, installation, operation of a 1 MW horizontal axis turbine, Orkney Multi year field measurement campaign for tidal energy resource characterisation	Calibration & validation data for BEMT Tidal Bladed model tool [32] Site-wide hydrodynamic model (MIKE 3) Long term, multi instrument dataset with application to model validation Effect of wave climate on turbulence characteristics [33]
Flows, Waves and Turbulence (FloWTurb) project [5] EPSRC, UK; 2017 to 2019; $1.1 m *Cape Breton University; DNV GL (UK); Marine Scotland Science; Marine Alliance for Science and Technology for Scotland; National Institute of Ocean Tech; Nova Innovation Ltd; Partrac Ltd; Scotrenewables Ltd; UEdin*	Database of field scale measurements from Pentland Firth, Orkney and Shetland Measurements from UEdin wave-current facility to determine hydrodynamic loads on a TEC	Farm scale estimates of mean flow and turbulence variability Methodology to calculate turbulence intensity from site measurements Validated, coupled wave and tidal current model for Fall of Warness ReDAPT data re-analysis
Advanced monitoring, simulation and control of tidal devices in unsteady, highly turbulent realistic tidal environments (RealTide) [6] H2020, EU; 2018 to 2020; $5.7 m *Sabella; Bureau Veritas; Institut Francais de Recerche pour l'Exploitation de la MER (IFREMER); 1-Tech; Ingeteam Power Technology S.A.; EnerOcean S.L.; UEdin*	Combine flow measurement, condition monitoring and turbine components with tide-to-wire modelling to design reliable power take off and control systems delivering grid compliant energy	*Detailed tide to wire simulator incorporating environmental and machine models* *Site flow characterisation with and without waves* *Validated hydrodynamic model to complement and extrapolate field data*
Resource Characterisation to Reduce the Cost of Energy through Coordinated Data Enterprise (RESOURCECODE) [34] Oceaneranet EU; 2019 to 2021; $2.3m *EMEC; IFREMER; University College Dublin; Ecoles Centrale Nantes; UEdin; Innosea; OceanData Lab; SmartBay Ireland*	Creation of marine data toolbox to facilitate decision making. Open data platform Cross validation of models	*Accessible metocean data* *Tools to utilise metocean data in design* *Validated high resolution hydrodynamic model of French, Irish and UK waters*
Enabling Future Arrays in Tidal (ENFAIT) project [35] EC H2020, EU; 2017 to 2022; $23 m *Nova Innovation Ltd; Offshore Renewable Energy Catapult; ELSA; SKF; Mojo Maritime Ltd; UEdin; Wood Group; RSK Environment; HMK Technical Services Ltd*	Develop, operate, decommission 6-turbine, grid connected array over 5 years to prove cost-competitiveness of tidal energy	*Array model validation* *In-situ measurement and characterisation of tidal array wake interactions*

A common time stamp is required between the TEC, its ancilliary equipment and the instruments. Any drift in time stamping over the duration of the measurement campaign must be understood in order to be addressed in the post processing of data.

- *Instrument controller:* If a TEC's power and communications systems are used by the measurement campaign, there are multiple interfaces with the operators systems to understand, manage and test. Such interfacing may also generate the requirement for external enclosures housing additional instrument control, fusing and remote diagnostic equipment. The ability to receive real time data from instruments and remotely change their settings, despite the additional complexity associated with TEC interfacing, represents significant benefits over stand-alone deployments of acoustic current profilers where no information can be recovered from the system until retrieval days to weeks after deployment.
- *Heterogeneity of location:* the spatial and temporal heterogeneity at tidal stream sites must inform the design and duration of measurement campaigns and subsequent use of the data. The site topography can e.g. constrain local flow and lead to the shedding of eddy structures, affecting current velocity. This heterogeneity can be seen in the ReDAPT project data, where two D-ADPs were deployed approximately 80 m apart at points 6a and 6b (Fig. 5a), for 85 and 71 days respectively from 17/09/2014. The depth profile of streamwise velocity is shown for the ebb tide at both D-ADP locations with the data being plotted against reference velocity bins from 0.6 m/s to 3.8 m/s using bin widths of 0.4 m/s (Fig. 5b). The flow profiles measured by sensor 6b (circles) resemble those characterised by the power law [14]. A distortion of this profile occurs at 6b, visible in the upper half of the water column. This distortion is present only on the ebb tide [36] and may be due to the influence of a nearby headland.

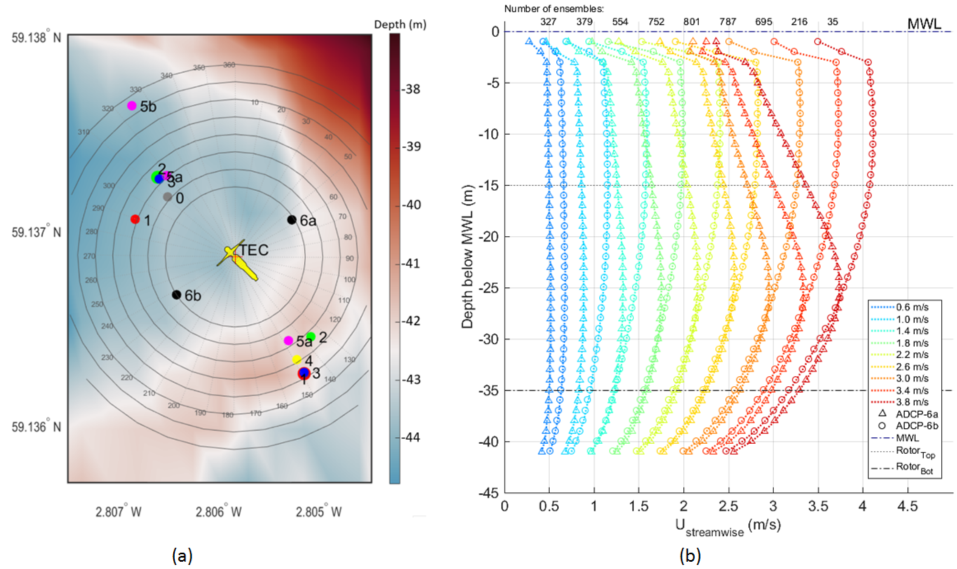


Fig. 5. Vertical variation in current velocity at ReDAPT locations 6a & 6b, 80 m apart a) Locations of D-ADP [36] b) Streamwise velocity depth profiles

- *Distortion of compass readings:* guidance such as the IEC standard [10] provides recommendations for mitigation of compass distortion e.g. use of non-ferrous frames and associated components and compass calibration occurring in the deployment frame away from any sources of magnetism. Where in-situ calibration or re-calibration is not achievable, alternative methods of instrument alignment can be used, e.g., via ROVs as performed in ReDAPT.

Data management and quality control (QC) /assurance (QA) is key to ensuring the validity of the data captured by instruments and subsequent data dissemination and utilisation. Briefly considered here, this complex subject is covered in detail in manuals such as [37]:

- *Quality assurance (hardware checks):* QA includes the checking of hardware, for example ensuring that instruments are checked and calibrated pre-deployment, that corrosion and bio-fouling are mitigated and that timely maintenance is conducted.
- *Quality control (data checks):* QC processes check both data integrity i.e. that the expected volume of data has arrived in the expected format, and also the validity of the data. Data validity checks involve the identification and management of unrepresentative or anomalous data. This requires the selection of QC parameters associated with e.g. sensor health, signal quality, current velocity and the overall profile. When these checks are applied to the data, flags are inserted based on defined thresholds, providing subsequent users with an indication of data quality. Given the quantity of data generated in a multi-instrument campaign over a period of weeks to months, automation of QC processes should be targeted.
- *Data storage:* Data which has been quality controlled must be held securely while being accessible and searchable to the target audience. This typically involves the use of a relational database. Geo-referencing of the data facilitates its integration with other geospatial measurements and geographical information system (GIS) querying/presentation. Metadata (information about the data, its acquisition and processing) is recorded and stored in line with relevant standards such as the Marine Environmental Data and Information Network ISO19139 discovery metadata profile
- *Uncertainties*: Uncertainties should be identified and quantified both for models e.g. amount of energy lost by seabed friction and instruments e.g. ADCP error velocity increasing with distance from the instrument. Albeit it is recognised [11] that there is a paucity of field and model data to obtain statistical significance.
- *Clustering:* Unlike data collected in the lab, field data obtained over a period of time under a variety of conditions requires filtering and clustering to statistically characterise the tidal energy site. Clustering occurs on a variety of parameters: those associated with instruments e.g. configuration, availability, location, orientation; those associated with the project e.g. turbine installed, turbine operational; those associated with flow characteristics e.g. maximum wave height, wave period. During the data acquisition campaign, there may be periods of time of instrument non-availability. It was found, for example, on ReDAPT that despite data being collected over a period of 3 years, once data is filtered for particular set of conditions e.g. no waves, ebb tide, turbine operational and current speed between cut in and cut out speed, only a limited number of samples remain. This re-inforces the need for a calibrated, validated, coupled wave-tidal hydrodynamic model which generates data to complement direct measurements [14].

VI. Advanced Sensor Configuration

From Section V, flow characterisation research challenges in relation to TEC mounted/associated instruments are highlighted as: a) measuring turbulence at TEC relevant locations b) mounting instruments at TEC-relevant locations c) mitigating accelerated failure. Fig. 6 illustrates this via an idealised configuration of TEC mounted/associated instruments but doesn't address the differences in measurement locations required by different TEC concepts (e.g. fixed/floating, Table I) which would inform measurement campaign specification.

Measuring turbulence at TEC relevant locations: Initial development of a convergent beam ADP has been presented in [38] and [39] with this work aiming to overcome the limitations of acoustic current profilers in quantifying turbulence, including the assumption of flow homogeneity between D-ADP beams. While valid for larger eddies, coherent turbulent structures smaller than beam separation cannot be resolved, an inaccuracy which increases away from the instrument due to beam divergence. Further, the full Reynolds stress tensor cannot be resolved with a single four or five beam instrument (Table II). In currently available convergent instruments (ADV), the proximity of the sample volume to the instrument means it cannot readily be used to profile turbulence in the water column. The C-ADP instrument uses convergent beams to achieve high resolution, three-dimensional measurements of mean and turbulent flow, thereby obtaining higher resolution information on the spatial coherence of velocity fields. Initial verification of concept as part of the ReDAPT deployment [38] demonstrated close agreement in the velocity measurements made by the C-ADP and an D-ADP, as well as comparable vertical velocity measurement between the C-ADP and a single beam ADP. Instrument development and testing continues, including focal point scanning.

Mounting instruments at TEC relevant locations: Mounting standard acoustic current profilers at hub height involves instrument integration with the TEC to obtain measurement of flow velocity and turbulence with lower uncertainty and direct measurement of inflow/wake lengthscales. Such integration on a rotating hub can involve the use of a bespoke slip ring although the introduction of additional complexity and potential failure modes may not be acceptable to a TEC developer, necessitating novel power and communication solutions. Other potential solutions include the compliant mooring of instruments tethered at the relevant depth in the water column with correction for platform motion [28] [40].

Mitigating accelerated failures During the ReDAPT project, multiple wet-mateable connector failures shortened the duration of the measurement campaign. Potential failure causes include the highly oxygenated environment accelerating failure and pressure oscillations in rubber casing due to tidal and wave cycles. While minimising the cost of solutions, greater resilience is required along with remote diagnostics. Instruments and their ancilliaries should be included in system-wide inspection and maintenance procedures, addressing e.g.biofouling removal.

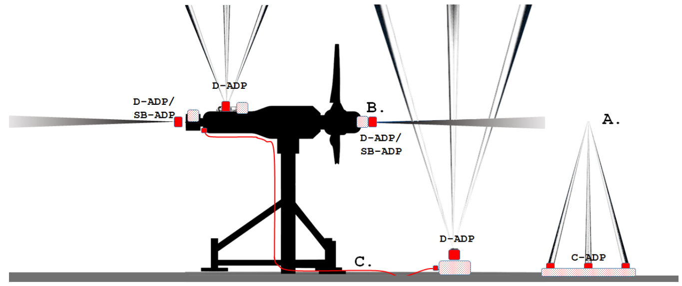


Fig. 6. Multi-instrument deployment around fixed bottom TEC illustrating research challenges A. Measurement at TEC relevant location B. Mounting instruments at TEC relevant location C. Mitigating accelerated failures

VII. Conclusion

This paper has given examples of the types of tidal stream devices currently in operation and outlined the application of current, wave and turbulence metrics in use by the tidal industry. It has reviewed the instruments deployed to capture these current, wave and turbulence metrics and their use in a number of projects. Gaps identified have led to the ongoing development of advanced sensor configuration seeking to advance measurement of turbulence with direct application to the design and development of TECs and their array configuration. Field measurement data is key to the validation of models which are used to understand and predict a site's hydrodynamics and the resultant loading on TECs. Model validation, coupled with uncertainty assessment throughout the chain of data acquisition, data processing and data utilisation generates confidence in design tools. As the tidal stream industry continues to develop, and an increasing number and size of tidal arrays are deployed, engineering tools supported by field-validated models are key to ensuring the industry reliably produces power which is competitive with other forms of energy, notably wind.

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