



Waddenfonds Texel Tidal Demonstration project

BlueTEC Texel Tidal Project: Environmental measurement and performance analysis

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Abstract

In the context of the BlueTEC project, this report starts by introducing the BlueTEC tidal energy platform and reviewing the patterns of circulation of the Marsdiep inlet. The energy resource assessment and the site selection for the platform's deployment are reported. This document analyses different datasets sampled during the project, including current speeds, wave parameters, turbine power output, platform excursions, and environmental parameters. Most of the data was measured by instruments installed on the platform, with the exception of the wave data, which was sampled by a nearby oceanographic mooring, and except the environmental parameters, which were estimated via satellite and numerical modelling. Preliminary results on the power output and turbine performance are discussed, as well as the effect of the turbine on the water velocity. Finally, discussions on the marine growth, potential environmental impacts and future perspectives are also addressed.

Contents

1	Introduction	3
2	BlueTEC: a floating tidal power plant	4
3	Marsdiep inlet: patterns of circulation	10
4	Energy resource assessment and site selection	11
5	Environmental measurements	12
5.1	Data overview	12
5.2	Currents	14
5.3	Effects of the turbine on the water velocity	17
5.4	Waves	22
5.5	Power output and turbine performance	39
5.5.1	T1 Turbine	39
5.5.2	T2 Turbine	41
5.6	Platform excursions	44
5.7	Temperature, salinity, chlorophyll, dissolved organic matter and suspended sediment	48
6	Marine growth and anti-fouling	52
7	Potential environmental impacts	57
8	Final remarks and future perspectives	58
9	Project team	58
	References	62
	Appendices	64

1. Introduction

In the last decades the utilization of clean and renewable energy has drawn increasing interest due to climate change and limited natural resources. It is a priority direction for the scientific community, policy makers and industry. In this context, the oceans deserve special attention due to their vast potential for providing renewable energy in different ways. Ocean energy is available from salinity gradients, stored heat, waves, ocean currents, tidal range and tidal currents (Uihlein and Magagna, 2016). Although the last two types have the same source, the tides, the production of electricity occurs by different means: conversion from potential and kinetic energy, respectively. In such a classification, tidal currents could also be placed into the ocean currents category.

Amongst these six types, tidal energy holds an interesting advantage: predictability (Cave and Evans, 1984). Due to its predictability, furthering studies of tidal energy potential and relatively accurately forecasting tidal electricity production are feasible tasks, which make it more attractive for potential investors (Waters and Aggidis, 2016a).

Compared to tidal range energy extraction, which started in 1967 (La Rance, France) and is already a reality in different parts of the world (for a comprehensive review of the operating barrages see (Waters and Aggidis, 2016b)), tidal current energy is still at an early stage of development and at the moment there are no purely commercial or large-scale farms (Uihlein and Magagna, 2016; Grabbe et al., 2009). However, energy extraction from tidal currents is not a new idea. For instance, the case of using tidal stream systems as a way of supplying electricity to isolated island communities in the United Kingdom was already speculated back in 1984 (Cave and Evans, 1984).

From the prototypes and/or existing Tidal Energy Converters (TECs), most are mounted on the seabed as rigid structures, which requires large high-end offshore installation vessels and does not allow for easy access for maintenance. Additionally, the installation of seabed-mounted turbines in remote places is a complicated task due to the lack of infrastructure. A challenging and interesting

alternative, still not largely explored, is to operate a turbine in the upper part of the water column, where the velocities are highest, by securing it to a floating platform.

In that direction, BlueTEC is introduced, being a floating tidal energy plant (Fig. 1). BlueTEC is a moored platform which holds a tidal turbine underneath in order to generate renewable electricity from moving water currents. To the knowledge of the authors, this is one of the world's first operational floating tidal plants. It was installed in the Marsdiep inlet, a channel connecting the Wadden and North Seas, between Den Helder and the island of Texel, at the north coast of the Netherlands (Fig. 2).

This report is organized as follows: In Sec. 2, the BlueTEC platform is introduced; Sec. 3 gives an overview of the oceanographic characteristics of the Marsdiep inlet; oceanographic measurements for a preliminary energy resource assessment and the site selection are discussed in Sec. 4; for the period of operation after the platform deployment, Sec. 5 presents the results on currents, waves, effects of the turbine on the velocity field, power output, turbine performance, platform excursions and local environmental conditions; Sec. 6 discusses the biofouling of the oceanographic instruments, as well as the strategy tested to delay the settlement of marine organisms; the potential environmental impacts caused by BlueTEC are debated in Sec. 7; lastly, some final remarks, future perspectives and the project team are presented in Secs. 8–9.

2. BlueTEC: a floating tidal power plant

Installed just south of the Royal Netherlands Institute for Sea Research – NIOZ (Figs. 1c and 2), off the Dutch island of Texel, the BlueTEC tidal energy platform started operating in the Marsdiep inlet on May 11th, 2015 and, apart from a turbine change out, remained in place for testing purposes until August 2016. The project was a collaboration between several partners, being: Bluewater Energy Services, NIOZ, Tocardo International, Damen Shipyards Group/Niron Staal Amsterdam, Van Oord/Acta Marine, Schottel Hydro,

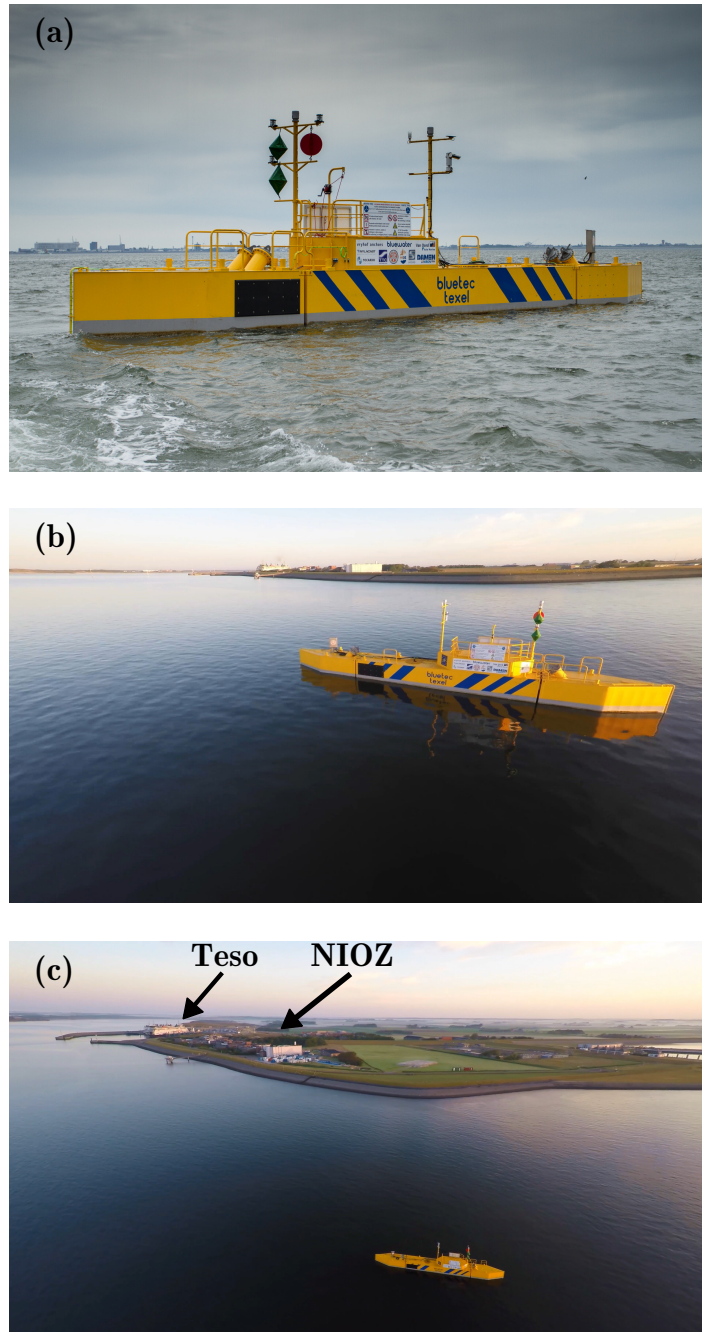


Figure 1: Lateral view (a) and aerial photos (b, c) by drone of the BlueTEC in the Marsdiep inlet. NIOZ and the departure point of the Teso ferry on Texel can be seen in the panel (c). (b, c) Photos credit: John Cluderay.

Twentsche Kabelfabriek (TKF), Global Maritime Vryhof, Nylacast, the Port of Den Helder and the Dutch Marine Energy Centre (DMEC; formerly the Tidal Testing Center (TCC)). Together, they combine extensive experience in coastal sea research and the maritime/offshore industry, covering the fields of design and operation of mooring platforms, shipbuilding, offshore installation, tidal turbines, power cables, anchors and synthetic mooring materials. Designed as a full-scale testing platform serving research and development purposes, the BlueTEC went from the drawing board to a grid-connected operating reality in about 6 months (Bluewater, 2015 (accessed March 29, 2017)).

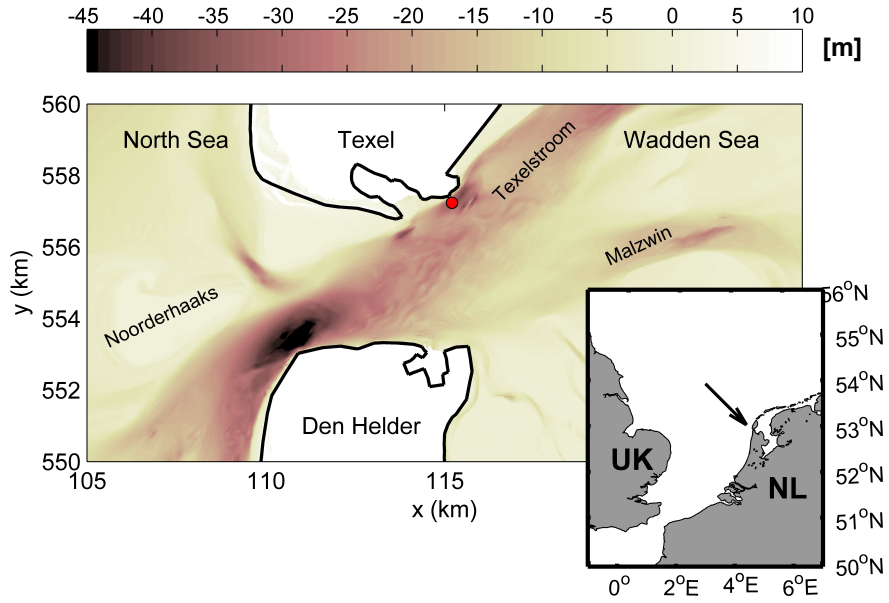


Figure 2: Location of the BlueTEC platform (red dot) installed in the Marsdiep tidal inlet, in the Northern coast of the Netherlands. The background colours represent high resolution bathymetric measurements (elevation from the seabed in meters) sampled using a multibeam system. Notice the Texelstroom, the bathymetric channel where the strongest tidal currents are expected to occur according to the literature.

The BlueTEC was designed as a modular system composed of three modules with the dimensions of standard shipping containers so that it can be easily shipped worldwide at relatively low costs (Figs. 3 and 4). The interior of the

containers allows for easy access for maintenance and dry storage of all critical electrical equipment. The platform was kept in place by four mooring lines, which were under tension, and by four drag anchors; attenuating its movement even under extreme environmental conditions. The platform was connected to the NIOZ electrical grid onshore by a hybrid power and optical fiber cable.

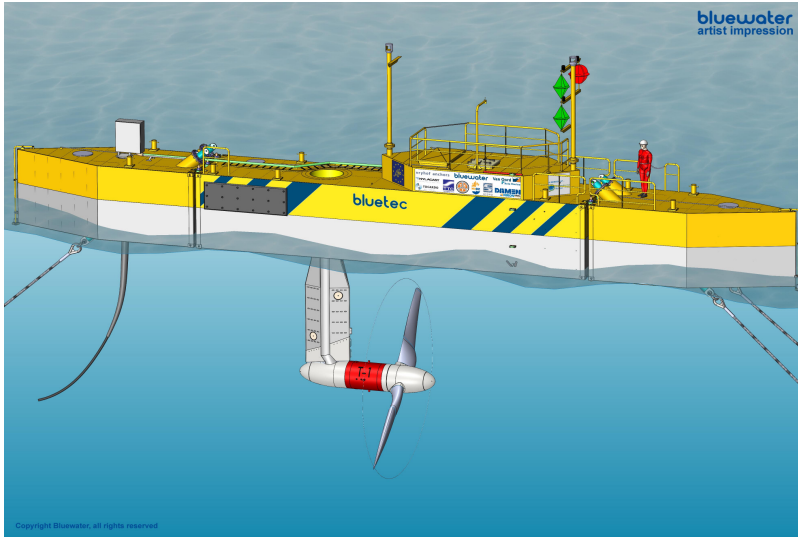


Figure 3: Sketch of the BlueTEC Texel with the T1 turbine, kept in place by the four mooring lines; each attached to an anchor.

The energy extraction took place by means of a free tidal stream turbine, which was installed beneath the floating platform attached to a vertical strut (Fig. 3). At first, the BlueTEC was equipped with a T1 turbine (6.3-m diameter), which was replaced by a T2 model (9.9-m diameter) at the end of 2015 / early 2016. Some compare tidal turbines to wind turbines, however, due to the high density of water compared to air, the underwater blades are smaller and rotate slower. Indeed, the turbines turned relatively slowly, at a maximum frequency of 29 and 23 revolutions per minute for the T1 and T2 turbines, respectively (see Sec.5.5).

To achieve very high availability, the turbine was kept as simple and robust

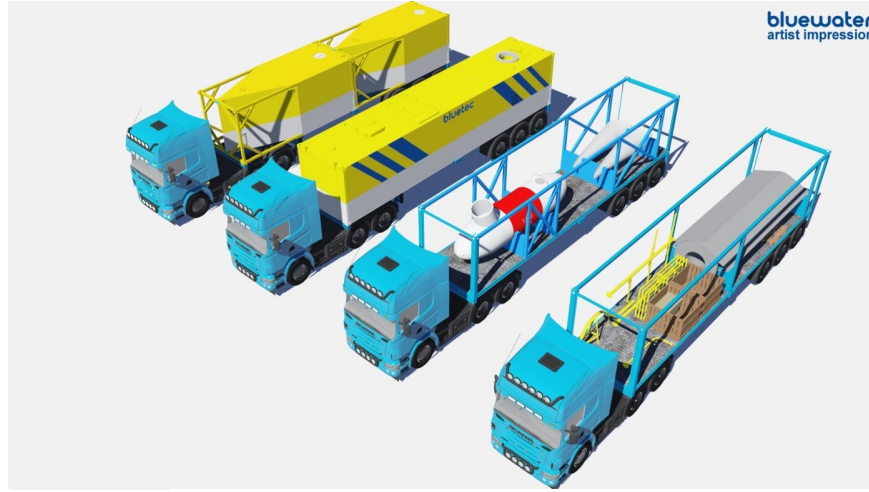


Figure 4: The BlueTEC is designed as a modular system, composed of three modules with the dimensions of standard shipping containers. This allows the platform to be easily shipped worldwide with standard trucks if required.

as possible. This implies no turbine yawing and no blade pitching system, except to rotate the blades according to the flow direction. As the tidal turbines are intended to work with flow coming from both directions (front to tail and reverse), during flood and ebb tidal phases, the orientation of the blades changes according to the flow direction. The bidirectional rotor design makes it possible to turn the two blades 180 degrees simultaneously for reverse flow operation (Fig. 5).

For monitoring the operation and behaviour of the platform and turbine, several instruments were installed on the BlueTEC, such as: a Differential Global Positioning System (DGPS) for tracking the platform's position and heading with high accuracy; motion sensor for measuring the movements of the platform, such as the roll, pitch and heave; strut strain gauges to measure the forces from the turbine; module coupling strain gauges to measure the forces exerted on the rods that connect the three modules; a load pin in the mooring shackles to monitor the forces on the mooring lines; two water sensors were placed to identify leakage in the dry room where the electrical equipment was

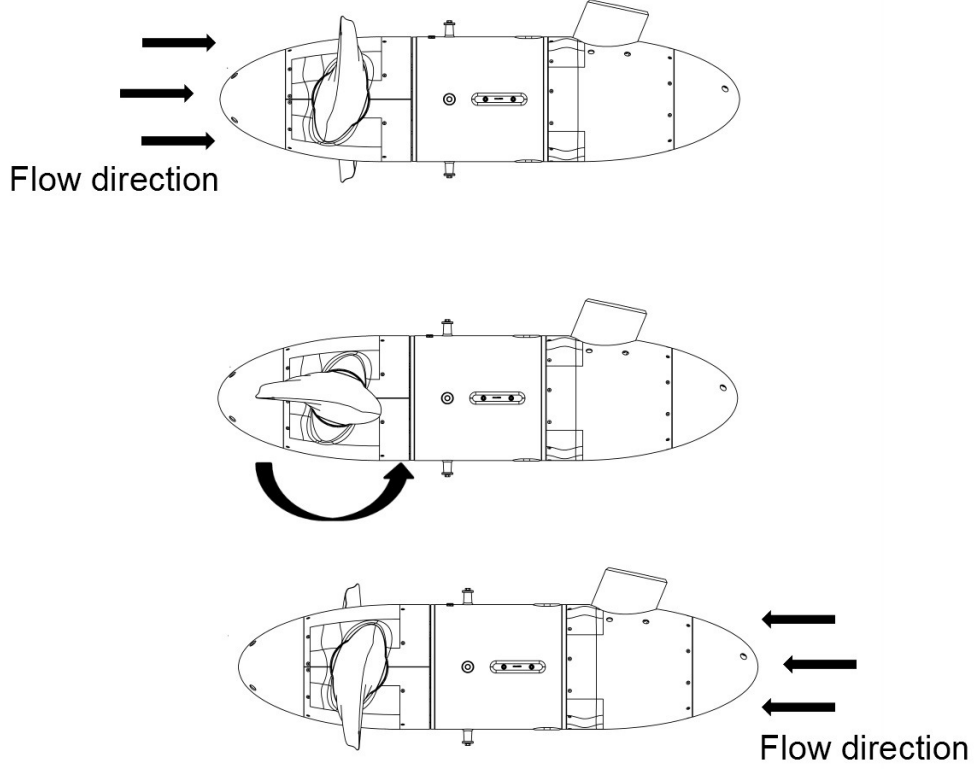


Figure 5: Operation of the bidirectional rotor technology.

stored; and a meteorological station was installed above the floating structure.

For measuring the water velocity during the period when the platform was deployed, the BlueTEC was designed to accommodate four “Acoustic Doppler Current Profilers” (ADCPs), all Nortek “Signature 1000” 5 beams models: (i) sustained by vertical poles, two downward-looking ADCPs were placed underneath the BlueTEC at its extremities (North Sea and Wadden Sea sides), in order to provide vertical profiles of the water velocity. Unfortunately, due to an electrical cable with a poor connection, the data could not be retrieved from the ADCP installed at the Wadden Sea side; (ii) two horizontally-looking ADCPs were deployed to measure the water velocity at the front and back of the

turbine, aiming to evaluate its performance, as well as to understand its impact on the local flow.

Additionally, still in the context of the BlueTEC project, a subsurface oceanographic buoy equipped with an upward-looking “Acoustic Wave And Current” (AWAC) profiler was deployed during three different time periods, at ~ 5 m from the seabed and ~ 80 m from the tidal plant. This data helps to characterize the wave climate of the region.

3. Marsdiep inlet: patterns of circulation

The Marsdiep inlet is the southern- and westernmost of the connections between the Wadden Sea and the North Sea. This nearly zonal tidal inlet is about 2.5 and 4.5 km wide in its west and east entrances, respectively, and about 5.5 km long. It is bordered to the north by the barrier island of Texel and to the south by the city of Den Helder (Fig. 2). The currents in the inlet are mainly dominated by semi-diurnal tides (M_2 component), which arrive to the Marsdiep from the south as a northward propagating Kelvin wave. This wave enters the inlet from Den Helder and then propagates northward towards Texel and eastward into the Wadden Sea (Zimmerman, 1976; Buijsman and Ridderinkhof, 2007; Buijsman, 2007).

Analysis of long term ferry-mounted ADCP measurements in the Marsdiep inlet showed that the variance in the streamwise and stream-normal currents is maximally 98% and 50%, respectively, explained by the tides (Buijsman and Ridderinkhof, 2007). These authors also revealed that near-surface currents can be as large as 1.8 m s^{-1} during spring tides. Maximum currents are found in the main bathymetric channel within the inlet: the Texelstroom (Fig. 2). Near Den Helder, the mean tidal range is about 1.4 m (Buijsman and Ridderinkhof, 2007; Buijsman, 2007). Wave heights of several meters and wavelengths of 100–200 m have been reported to occur in the region (Sha, 1990).

During flood phase, when the water flows from the North Sea towards the Wadden Sea, the current is characterized by relatively weaker and vertically

stratified velocities; with the current core (maximum velocities) found at subsurface at approximately 15 m depth. On the other hand, ebb phase is marked by a stronger current and homogeneous vertical velocities throughout the water column (de Vries, 2015). The transition from neap to spring tides is distinguished by increasing velocities during ebb, while the flood currents remain nearly constant (de Vries, 2015).

Embedded in the pattern of circulation described above, a net transport between ebb and flood, known as residual circulation, is also reported to occur in the Marsdiep inlet. *In situ* measurements indicated a wind-forced residual component in ebb direction (Buijsman and Ridderinkhof, 2007; Nauw et al., 2014). This residual flow seems to vary strongly from daily to interannual time scales (Nauw et al., 2014; Duran-Matute et al., 2014; Sassi et al., 2016).

4. Energy resource assessment and site selection

The site selection for the deployment of the BlueTEC was determined considering different factors, such as: local oceanographic characteristics, available kinetic energy, proximity to the coast and safe distance from the busy navigation channel. Related to the last item, it is worthwhile to mention that the Marsdiep inlet is the main navigation path between the Dutch Wadden Sea and the North Sea. It is also near the harbor of the Dutch naval fleet and is the pathway for the TESO-ferry, which crosses the inlet connecting Texel and the mainland twice every hour (four times during the high touristic season).

In order to optimize the length of the dynamic export power cable which connects the platform to shore and also to facilitate maintenance activities, the first aspect taken into account for the site selection was the distance from the coast and from NIOZ. In this regard, previous to the BlueTEC installation, NIOZ conducted several oceanographic *in situ* measurements to improve the knowledge of the water velocity structure. Amongst them, a 13-hour mobile survey was conducted on 10/Oct/2008, during a spring tidal cycle. During this survey the RV *Navicula* followed a box-circuit, sampling vertical profiles

of velocity by means of a downward-looking vessel mounted ADCP, in a region near NIOZ, at the northeastern part of the Marsdiep inlet. The tracks of the RV Navicula are represented by the red lines in Fig. 6a.

The box-circuit was divided into small sub-regions (grid in Figs. 6a-b), and the number of passages of the research vessel through each of them is shown in Fig. 6b. The depth-averaged velocity was also estimated for the sub-regions for every Navicula passage. Figs. 6c-f show the depth-averaged velocities over time for four different cells.

Based on these measurements, as well as on a typical tidal period of 12h25min for the region, the best (sum of the errors is smallest) sinusoidal fit was found for the sub-regions. Consequently, an estimation of the tidal energy resource was assessed, being the Energy Tidal Turbine (ETT) calculated as: $ETT = \rho A v^3 t$ (kWh), where ρ is density of the water, A is the cross-section defined by the diameter of the turbine (6.3 m, from the T1 turbine), v is the water velocity and t represents the time of a tidal cycle. Fig. 7 shows the ETT assessed from (a) observed (tidal + residual) velocities, (b) tidal velocities and (c) residual velocities. As expected, in terms of available tidal energy, the ideal region for the deployment is the Texelstroom, the main bathymetric channel within the inlet where tidal currents are strongest. However, due to the site selection factors mentioned above, the platform was deployed in a region closer to NIOZ (Fig. 2).

5. Environmental measurements

5.1. Data overview

In Sec. 4 we described and analyzed the data sampled prior to the BlueTEC deployment. In Sec. 5 we present the data collected during the period when the platform was installed. A graphical representation of the sampled data throughout time is presented in Fig. 8, for the following parameters: velocity measurements from the downward looking ADCP (Sec. 5.2), velocity sampled with the horizontally-looking ADCPs (Secs. 5.3 and 5.5), waves measured with the AWAC instrument (Sec. 5.4), turbine power output (Sec. 5.5), plat-

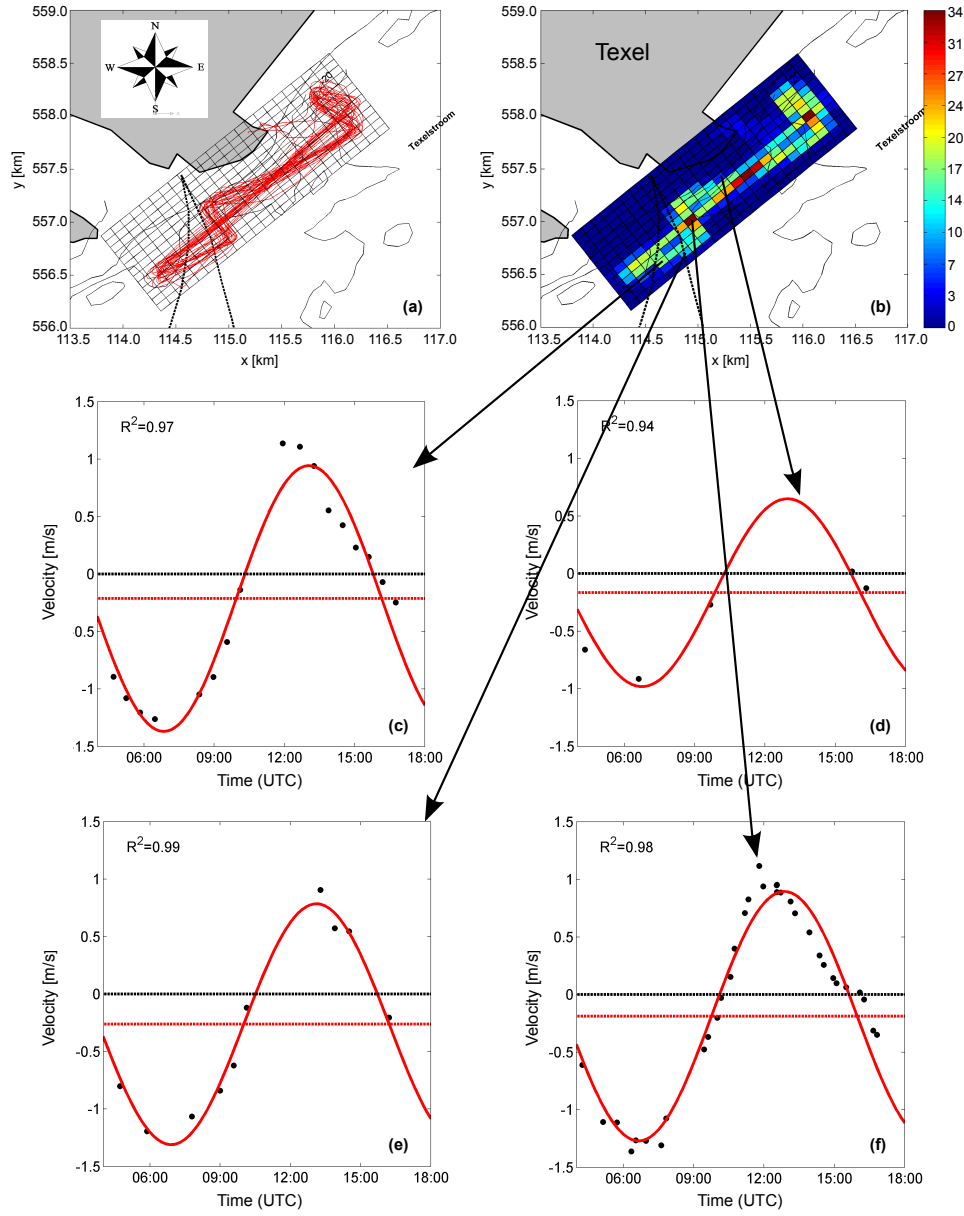


Figure 6: (a) Tracks of the RV Navicula during the 13-hour mobile survey (red line), conducted on 10/Oct/2008. The black dots indicate the main path of the Teso ferry. (b) Number of passages of the RV Navicula by every grid cell. (c–f) Depth-averaged velocities throughout the water column (from surface to bottom), measured from the vessel-mounted ADCP (black points) displayed for 4 different cells. Positive values represent flood currents while negative values indicate ebb currents. The red line represents the best sinusoidal fit for the respective set of measurements.

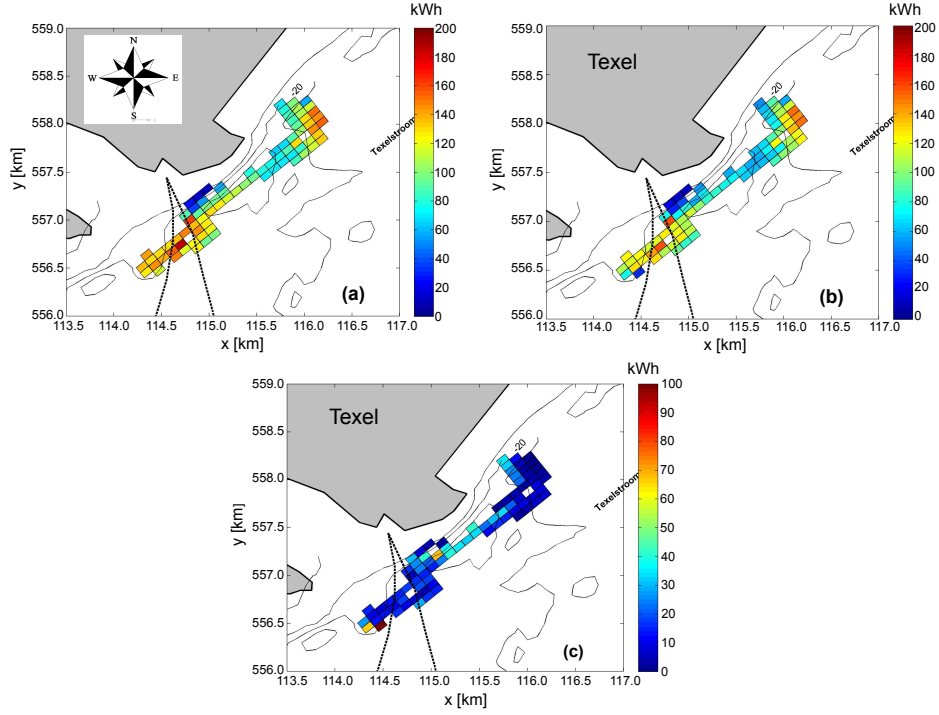


Figure 7: Energy Tidal Turbine (*ETT*) calculated from (a) observed (tidal + residual) velocities, (b) tidal velocities and (c) residual velocities. Values are represented in kWh.

form excursions (Sec. 5.6) and environmental data provided by COPERNICUS (Sec. 5.7). It is worthwhile mentioning that, due to the autonomy of the batteries, the AWAC was deployed three times: Spring/2016 (Deployment #1), Summer/2016 (Deployment #2) and Autumn/2016 (Deployment #3). The periods when the T1 and T2 turbines were operating are highlighted by the vertical yellow and green bars, respectively.

5.2. Currents

The BlueTEC was designed to hold two downward-looking ADCPs, aiming to provide vertical profiles of the horizontal flow at the front and back of the platform. The data was collected with a frequency of 0.2 Hz (period of 5 seconds) and transmitted to land via the optical fiber cable in near real time. As

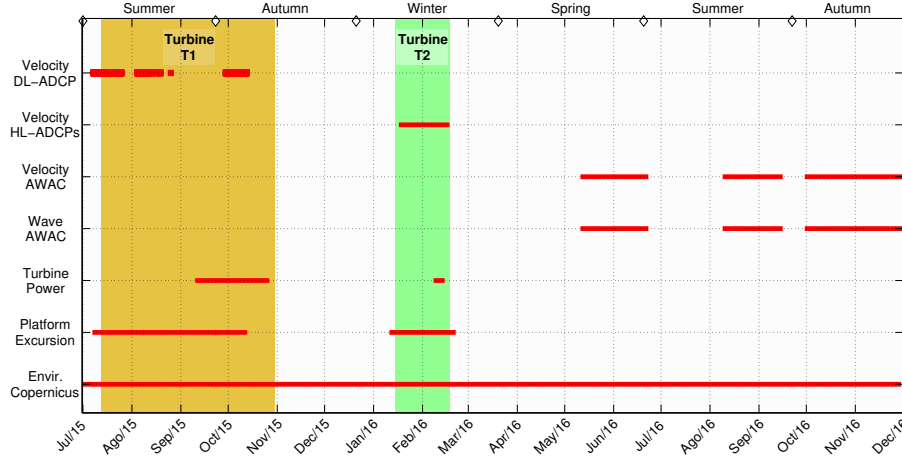


Figure 8: Overview of the sampled data throughout time. The following variable are represented in the y-axis: velocity measurements from the downward looking ADCP (Velocity DL-ADCP), velocity sampled with the horizontally-looking ADCPs (Velocity HL-ADCPs), velocity and waves measured with the AWAC instrument (Velocity AWAC), turbine power output (Turbine Power), platform excursions (Platform Excursions), and environmental data provided by COPENICUS (Envir. Copernicus). The periods when the turbines T1 and T2 were operating are highlighted by the vertical yellow and green bars, respectively. The diamonds at the top indicate the transition between seasons.

mentioned before, the data from the ADCP installed on the Wadden Sea side could not provide data due to problems with the electrical cable.

Fig. 9a shows the raw velocities from the North Sea side ADCP for a period of about two tidal cycles, between 8 July and 9 July 2015, during the T1 turbine testing period. As expected (see Sec. 3), the most striking feature in the time series is the tidal signal, represented by vertical bands of positive (warm colours) and negative velocities (cold colours) in Fig. 9a, with maximum velocities around 1.5 m s^{-1} . Positive velocity values indicate flood phase, while negative velocity values represent ebb phase so that if a single water particle is tracked during flood phase, it will first pass by the region sampled by the ADCP then pass by the turbine. During ebb phase the opposite occurs and the influence of the turbine in the flow is marked by the relatively weaker velocities observed at

~ 7 m depth (black dashed rectangle in Fig. 9a). Vertically, the velocity profiles have the original resolution from the ADCP vertical cells: 0.2 m.

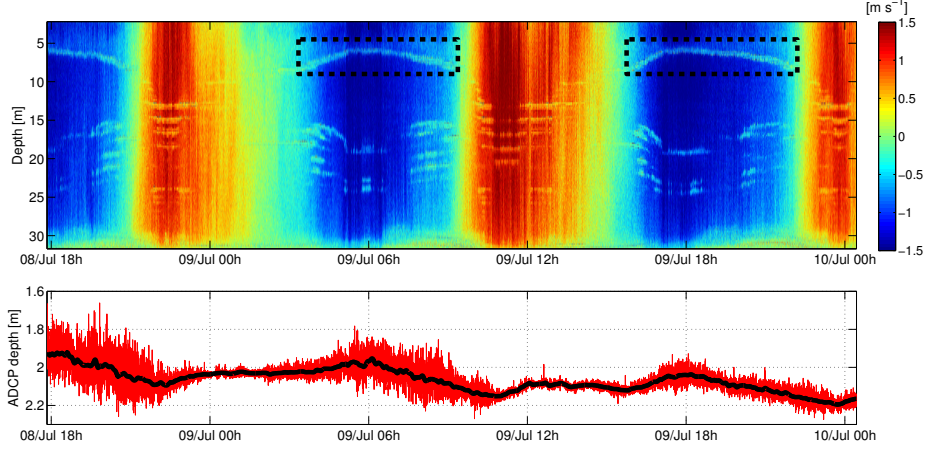


Figure 9: (a) Velocity time series sampled by the North Sea side (downward-looking) ADCP for the period from 8 July (6 pm) to 9 July 2015 (12 pm), during the T1 test period. Positive velocity values indicate flood phase (hot colours), while negative velocity values represent ebb phase (cold colours). Note that if a single water particle is tracked during flood phases, it will first pass by the region sampled by the ADCP then pass by the turbine, while the opposite occurs during ebb phases. Therefore the disturbance in the flow due to the turbine is shown in the ebb phases. The black dashed rectangles highlight these relatively smaller velocities at ~ 7 m depth during ebb phase due to the effect of the turbine in the flow. (b) ADCP depth over time (red line) and its moving average (Hann Window) calculated over a period of 12 hours.

Taking into account that both turbine and ADCP are mounted on a rigid structure, the distance between them are constant over time. However the convex pattern of the disturbed flow observed in the velocity time series (highlighted by the black rectangle in Fig. 9a) suggests that the ADCP depth varies according to the current velocity, being closest to the surface during the peak of ebb phase. The time series of the ADCP depth (Fig. 9b) corroborates this vertical oscillation. However, Fig. 9a shows changes by about 3 m, whereas the ADCP depth in Fig. 9b indicates changes by only a fraction of a meter. The likely ex-

planation for such a flow structure (convex shape) in the disturbed flow lies in the fact that the platform had an angle during high current speeds. This would then angle the turbine and likely therefore the disturbance would also then be angled as the flow passed the turbine. In other words, during strong ebb flow, the Wadden Sea side of the platform had a vertical angle inclined towards the bottom, while the North Sea side of the platform had an angle inclined towards the surface. Such inclination in the platform is also observed in the disturbed flow.

To filter and reduce random noise, the ADCP data was post processed with a weighted moving average by applying a Hann window function (Fig. 10). This methodology takes each data point individually and averages it by also including a number of data points before and after it. Each data point included in the average gets a weighting as per the the Hann windown function. The data point being averaged gets the highest weighting (peak of the function) and the data points before and after it each receive a weight as per the Hann function such that the data points closest to the data point in question get a higher weighting. A window of 61 points was used, corresponding to 30 points before and 30 points after the data point being averaged. The result is that each data point in the set is replaced with an averaged value such that the number of data points remains the same. This methodology retains the main features impressed in the time series.

Fig. 11 shows the post processed velocities from the North Sea side ADCP for the period of 09–27 July 2015 during the T1 turbine testing period. Even after the post processing, the influence of the turbine in ebb flow is marked by the relatively weaker velocities observed at around 7 m depth (black dashed rectangle in Fig. 11). Vertically, the velocity profiles have a resolution of 0.5 m.

5.3. Effects of the turbine on the water velocity

In a conventional deployment, the ADCPs are vertically deployed (upward- or downward-looking) so that the four lateral beams are used to estimate the vertical profile of horizontal velocities throughout the water column, while the

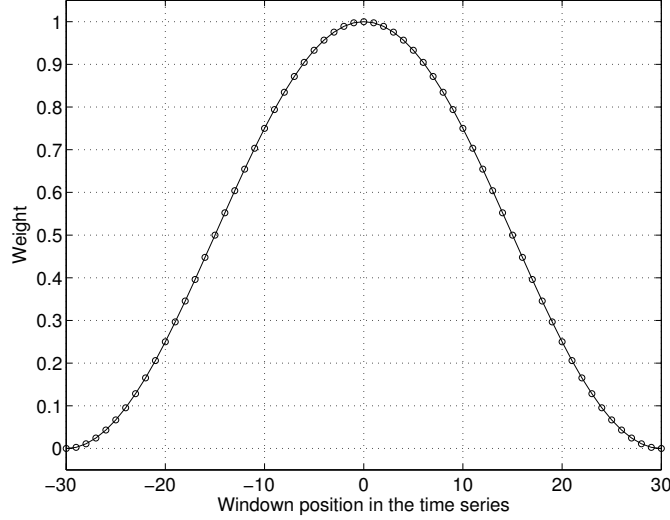


Figure 10: Hann Window used in the moving average and applied to the time series from the downward-looking ADCP. The window width from -30 to 30 points corresponds to a period of 5 minutes, since the original time resolution of the data is 5 seconds.

central beam provides the profile of vertical velocities (see Sec. 5.2). However, the ADCPs installed on and near the T2 turbine were used with a slightly different approach. The instruments were deployed in a horizontally-looking configuration where only the central beam was operating (Fig. 12a). In this way, the instruments provided the velocity of the flow perpendicular to the section defined by the blades of the turbine; the cross-section flow.

The instrument facing the North Sea (ADCP-NS) sampled the flow (Vel_{NS}) at the back of the turbine (hereafter undisturbed flow) during flood phase and the flow after passing the turbine (hereafter disturbed flow) during ebb phase. Conversely, the instrument facing the Wadden Sea (ADCP-WS) inferred the undisturbed and disturbed velocities, both defined as Vel_{WS} , during ebb and flood phases, respectively, when considering the velocities in front of the turbine blades. ADCP-NS was located at an approximate depth of 6.5 m and ADCP-WS was at a depth of approximately 5 m.

In order to compare the flow in front and behind the turbine, the mean values

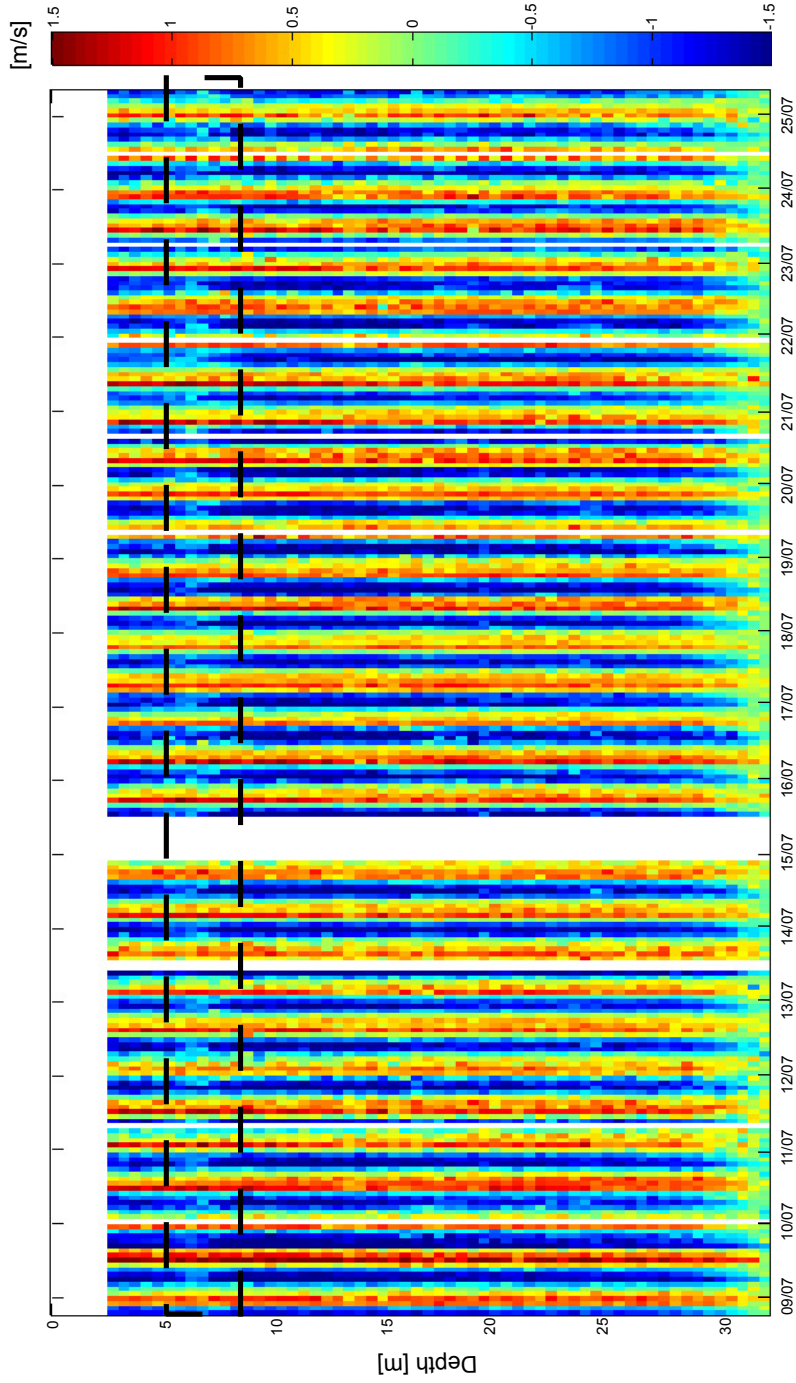


Figure 11: Post processed velocity time series sampled by the North Sea side (downward-looking) ADCP for the period of 09–27 July 2015 (T1 test period). Positive velocity values indicate flood phase (hot colours), while negative velocity values represent ebb phase (cold colours). Note that if a single water particle is tracked during flood phases, it will first pass by the region sampled by the ADCP then pass by the turbine, while the opposite occurs during ebb phases. The black dashed rectangle highlights the relatively smaller velocities at 7 m during ebb phase due to the effect of the turbine in the flow.

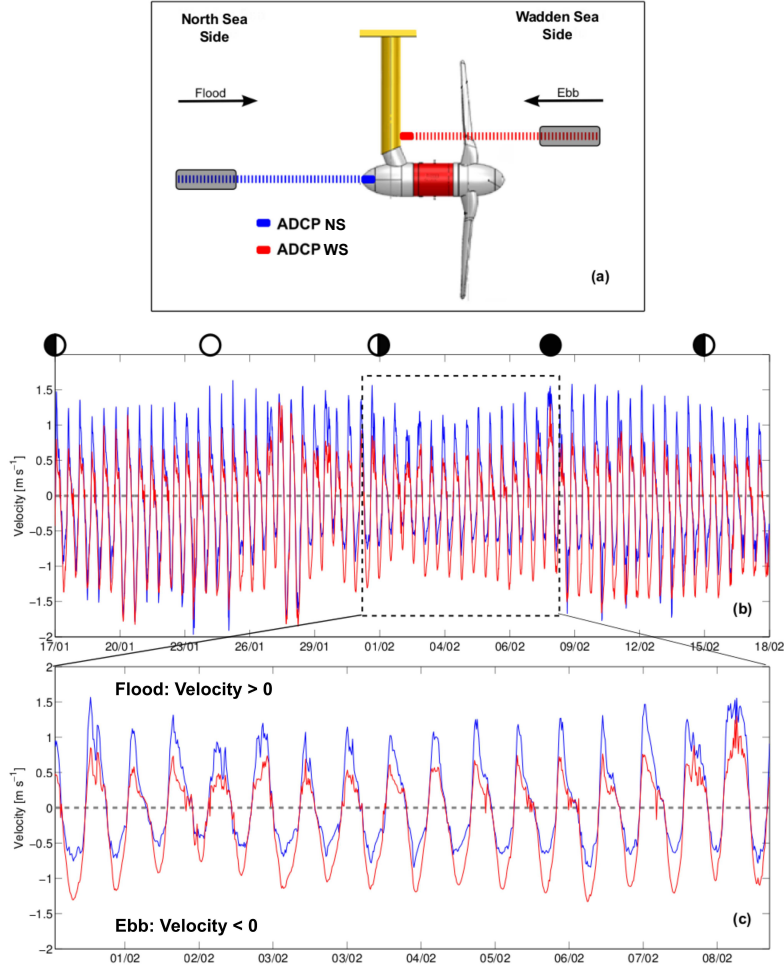


Figure 12: (a) Sketch showing the positions of the horizontally-looking ADCPs mounted on the T2 turbine and the ADCP sampling ranges: ADCP-NS (blue rectangle), facing the North Sea, and ADCP-WS (red rectangle), facing the Wadden Sea. The vertical blue and red bars represent every beam of 50 beams sampled by the ADCPs at every single time span. The black boxes surrounding the furthest 1/3 (35th to 50th) beams from each ADCP highlight the beams used in the time-average presented in panels (b) and (c). Each beam is 50 cm long and, therefore, the 35th beam is about 17.5 m from the ADCP. The black arrows indicate the direction of flood and ebb circulation. (b) 15-minute time-average of the last 16 beams. Positive (negative) values represent flood (ebb) current. The time series from ADCP-NS (blue line) and ADCP-WS (red line) span from 17/Jan/2016 to 18/Feb/2016. The moon phases are indicated at the top, where a full black circle, black-white circle, full white circle and white-black circle represent, respectively, new moon, first quarter moon, full moon and third quarter moon. (c) Same as (b), but for the period from 31/Jan/2016 to 09/Feb/2016. Notice that velocities are positive (negative) towards the Wadden Sea (North Sea).

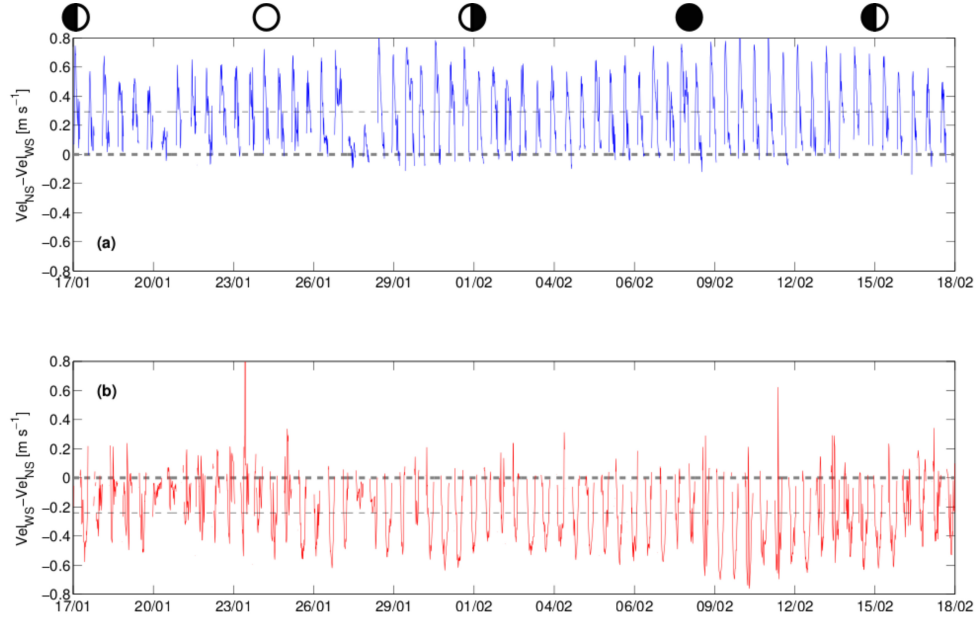


Figure 13: (a) Delta velocity ($\text{Vel}_{\text{NS}} - \text{Vel}_{\text{WS}}$) calculated during flood tidal phase with the T2 turbine. (b) Delta velocity ($\text{Vel}_{\text{WS}} - \text{Vel}_{\text{NS}}$) calculated during ebb tidal phase. Thick dashed lines indicate the reversal on the signal of the delta velocity (change from ebb to flood and vice versa), while the thin dashed lines represent the mean value: (a) 0.30 m s^{-1} and (b) 0.24 m s^{-1} . The delta velocities were calculated during the T2 turbine testing period.

from the furthest 1/3 (35th to 50th) beams (Fig. 12a) were time-averaged for every 15 minutes (Figs. 12b-c). The results show that, on average, the flow is attenuated by 0.30 m s^{-1} and 0.24 m s^{-1} after passing by the turbine during flood and ebb phases, respectively (Fig. 13).

Fig. 14 suggests that the flow is linearly disturbed. In other words, velocity during flood (Vel_{NS}) or ebb (Vel_{WS}) has a linear relation with the delta velocity for flood ($\text{Vel}_{\text{NS}} - \text{Vel}_{\text{WS}}$) or ebb ($\text{Vel}_{\text{WS}} - \text{Vel}_{\text{NS}}$), respectively.

Considering only the data available, the minimum distance from the platform/turbine in which the flow reaches the undisturbed state again could not be determined. This is an important point to be investigated, especially in the case where it is intended to deploy several platforms near each other. It should

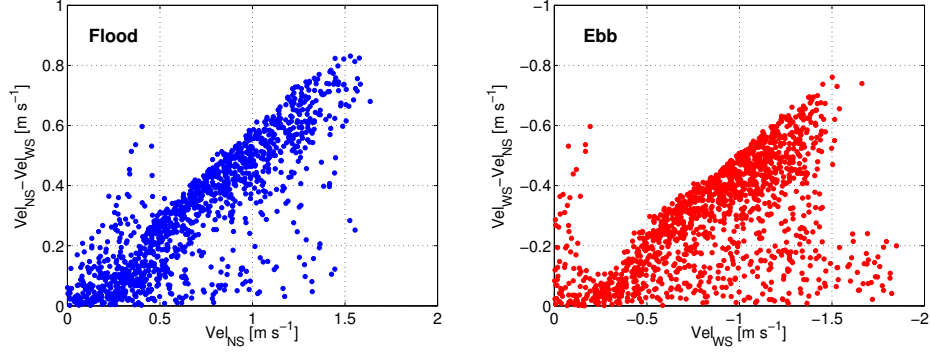


Figure 14: (a) Water velocity before passing the turbine (Vel_{NS}) plotted against the delta velocity ($Vel_{NS}-Vel_{WS}$), during flood currents. (b) Water velocity before passing the turbine (Vel_{WS}) plotted against the delta velocity ($Vel_{WS}-Vel_{NS}$), during ebb currents. To ease the comparison with (a), both the signs of the x-axis and y-axis are reversed in (b).

be noted that horizontally-facing ADCP data could not be collected during the T1 period since the ADCP installed on the strut did not function once the BlueTEC was deployed.

5.4. Waves

Apart from the data sampled with the instruments installed on the platform, a subsurface oceanographic mooring equipped with an upward-looking “Acoustic Wave And Current” (AWAC) profiler was deployed approximately 80 m from the BlueTEC and about 5 m from the seabed. Due to its Acoustic Surface Tracking (AST) system, the AWAC can directly measure wave parameters at high frequencies by echo-ranging the surface with a vertically oriented transducer.

The AWAC was deployed during three different periods: Spring/2016 (Deployment #1), from 11/May to 23/Jun/2016; Summer/2016 (Deployment #2) from 09/Aug to 16/Sep/2016; and Autumn/2016 (Deployment #3), from 30/Sep to 16/Nov/2016. From every deployment, the following parameters were estimated:

- *Significant Wave Height* (H_s): height parameter, estimated as four times the square root of the zeroth-order moment (area) of the wave spectrum.
- *Mean 1/3 Wave Height* (H_3): as the parameter above, this classic parameter intends to provide the significant wave height using the mean of the 1/3 largest waves in a record.
- *Mean 1/10 Wave Height* (H_{10}): the mean of the 1/10 largest waves in a record.
- *Maximum Wave Height* (H_{max}): it represents the largest wave in a record.
- *Mean Wave Height* (H_{mean}): mean value of all waves in a record.
- *Mean Period* (T_{m02}): this is the average period for all the waves in the burst (set of continuous measurements) and it is calculated from the energy spectrum according to the first and second moment of the energy spectrum.
- *Mean Zero-crossing Period* (T_z): mean period estimated from the zero-crossing technique. It is calculated as the mean of all the periods in the wave burst.
- *Mean Zero-crossing Period for H_3* (T_3): mean period associated with the 1/3 largest waves (H_3) in a record, where the period is calculated with the zero-crossing technique.
- *Mean Zero-crossing Period for H_{10}* (T_{10}): mean period associated with the 1/10 largest waves (H_{10}) in a record, where the period is calculated from the zero-crossing technique.
- *Mean Zero-crossing Period for H_{max}* (T_{max}): mean period associated with the largest wave (H_{max}) in a record, where the period is calculated with the zero-crossing technique.
- *Main Direction* (M_{dir}): weighted average of all the directions in the wave spectrum. It is weighted according to the energy at each frequency.

- *Peak Direction* (DirTp): direction of the wave corresponding to the peak (strongest) period. The angle is reported as “from” and in degrees.
- *Unidirectivity Index*: this is a measure of how much of the wave energy over the full spectrum is from a single direction. Values range from 0.0 to 1.0, and a value of 1.0 indicates the energy is from one primary direction. Wave spectra with peak energy at several directions or frequencies will lead to lower values.

Table 1 introduces the basic statistics for the wave parameters. On average, all wave height parameters are larger during Autumn, and smaller in Spring. For instance, for the classical significant wave height estimation of Mean 1/3 Wave Height (H3), the values are 0.29 m (Spring), 0.30 m (Summer) and 0.33 m (Autumn). Regarding the period parameters, the results show longer periods during Spring compared to the other two seasons. For the equivalent mean period associated with the 1/3 largest waves (T3) the periods are 5.04 s (Spring), 3.38 s (Summer) and 3.62 s (Autumn).

Figs. 16, 20 and 24 show the various wave height parameters for all deployments. Mean values are represented by the red dashed lines in the respective panels. The moon phases are also indicated on the top of the figures, where a full black circle, black-white circle, full white circle and white-black circle represent, respectively, new moon, first quarter moon, full moon and third quarter moon.

For the wave period parameter results, the reader is referred to Figs. 17, 21 and 25, which also present the mean and indicate the moon phases.

In terms of wave direction, all deployments showed the waves mainly traveling from the North Sea towards the Wadden Sea, entering the Marsdiep inlet from South-southwest. Calculated from North, the averaged origins of the waves are: 211.9° , 202.7° and 208.2° during spring, summer and autumn, respectively. This preferential direction is explained by the location of the Noorderhaaks (Fig. 15), a sand shoal near the North Sea entrance of the Marsdiep inlet. The Noorderhaaks shelters the inlet from waves from the north and west directions (Buijsman and Ridderinkhof, 2007). Figs. 18, 22 and 26 show the wave direction

represented by histograms where the main direction, peak direction and unidirectivity index are plotted as a function of their respective occurrence. The wave roses combined with the amplitude and occurrence are plotted in Figs. 19, 23 and 27

Table 1: Basic statistics from the AWAC deployments: Spring (Deployment #1, 961 data values), Summer (Deployment #2, 1246 data values) and Autumn (Deployment #3, 1778 data values).

	Spring		Summer		Autumn	
Parameter	Mean	STD	Mean	STD	Mean	STD
Hs [m]	0.29	0.18	0.30	0.24	0.33	0.21
H3 [m]	0.29	0.19	0.31	0.24	0.34	0.22
H10 [m]	0.38	0.25	0.40	0.31	0.44	0.28
Hmax [m]	0.55	0.38	0.55	0.42	0.61	0.38
Hmean [m]	0.18	0.11	0.19	0.15	0.21	0.13
Tm02 [s]	4.12	0.78	3.75	0.59	3.92	0.72
T3 [s]	5.04	1.73	3.38	0.89	3.62	0.93
T10 [s]	5.56	2.10	3.71	0.99	4.04	1.14
Tmax [s]	6.15	4.87	4.10	1.95	4.37	2.00
Tz [s]	3.70	1.02	2.45	0.63	2.54	0.56
Mdir [degrees]	211.9	74.2	202.7	64.1	208.2	77.6
DirTp [degrees]	193.6	82.1	193.0	76.6	192.4	86.2

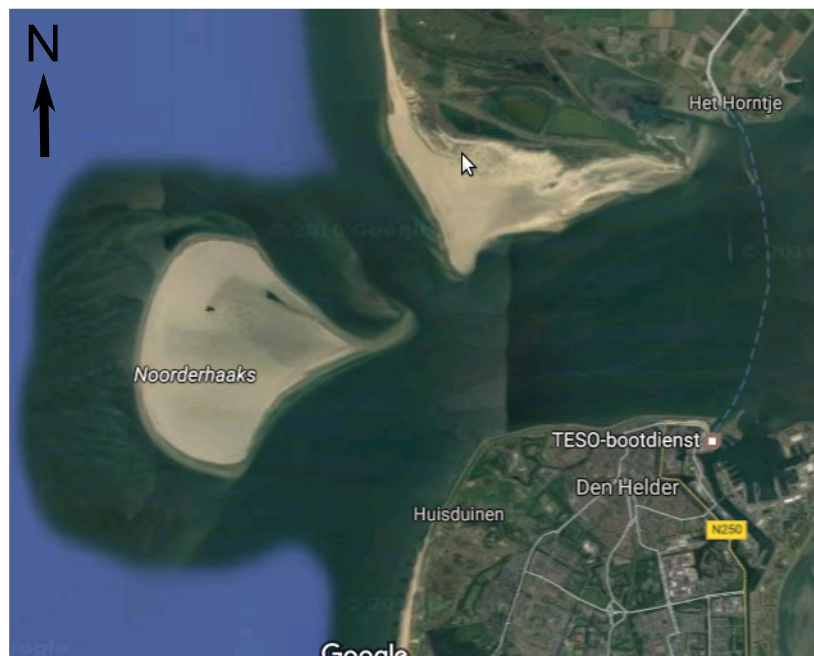


Figure 15: (a) Aerial image from Google Maps showing the location of the sand shoal Noorderhaaks in the west entrance of the Marsdiep inlet.

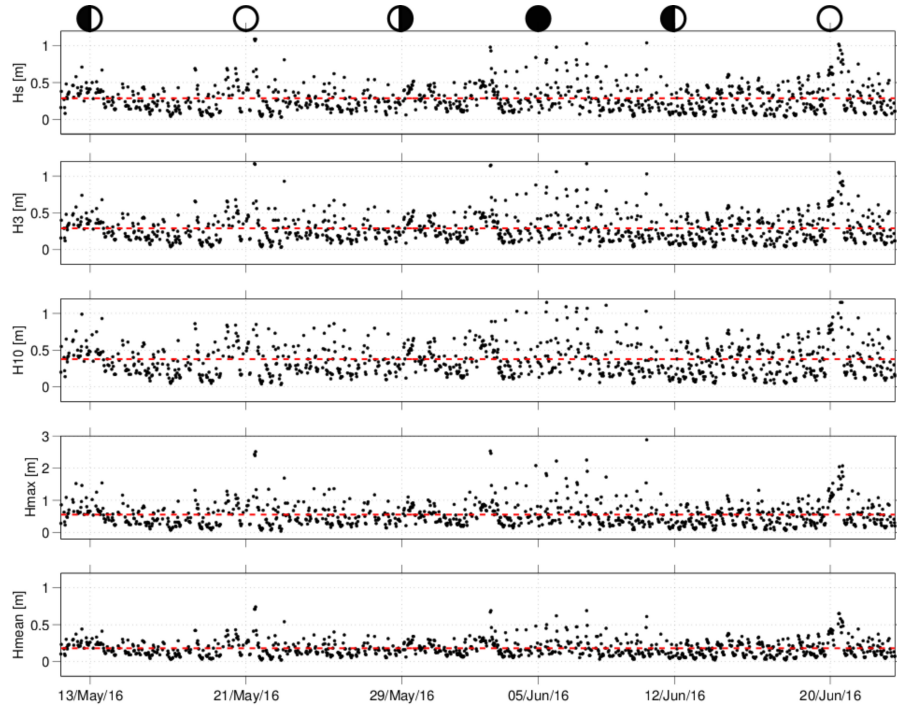


Figure 16: Wave parameters (Height) from Deployment #1 (Spring): Significant Wave Height (H_s), Mean 1/3 Wave Height (H_3), Mean 1/10 Wave Height (H_{10}), Maximum Wave Height (H_{max}) and Mean Wave Height (H_{mean}). Wave bursts were sampled for every 40 min period, with 2048 samples per burst sampled at a frequency of 1 Hz. Every burst is represented by a single black point being the associated wave parameter value within the burst. Total number of bursts: 961.

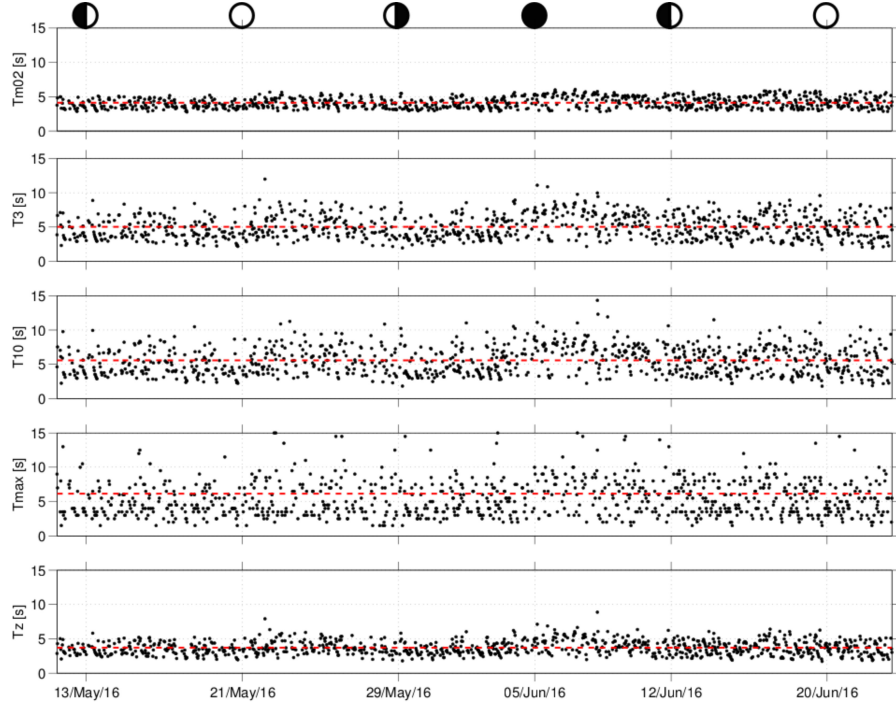


Figure 17: Wave parameters (Period) from Deployment #1 (Spring): Mean Period (T_{m02}), Mean Zero-crossing Period for H3 (T_3), Mean Zero-crossing Period for H10 (T_{10}), Mean Zero-crossing Period for Hmax (T_{max}) and Mean Zero-crossing Period (T_z). Wave bursts were sampled for every 40 min period, with 2048 samples per burst sampled at a frequency of 1 Hz. Every burst is represented by a single black point being the associated wave parameter value within the burst. Total number of bursts: 961.

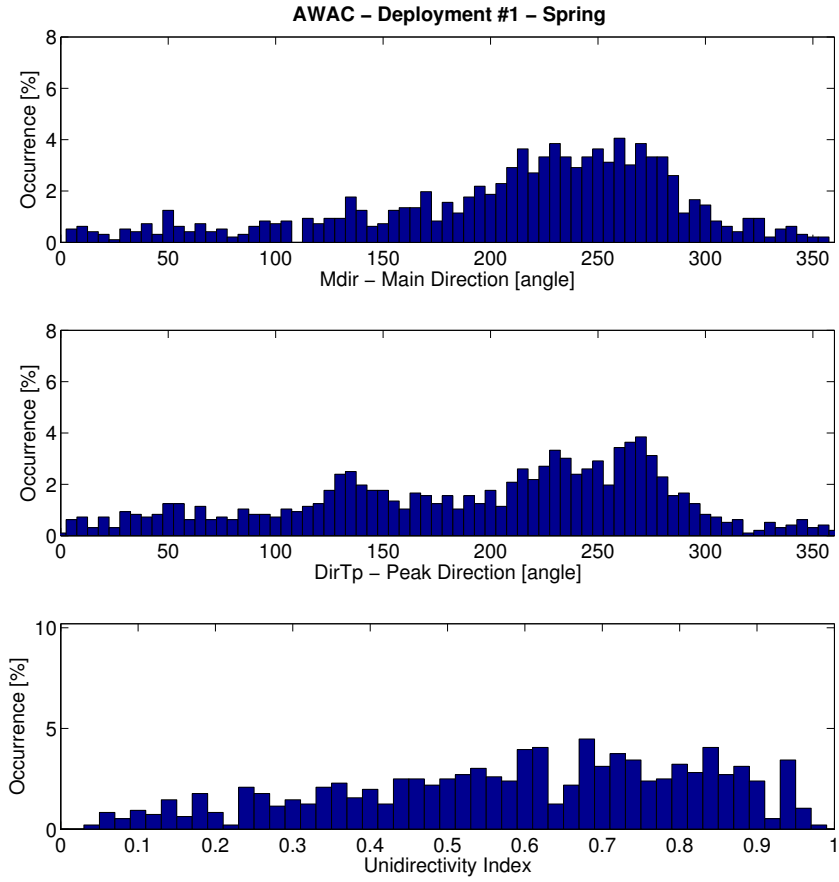


Figure 18: Wave parameters (Direction) from Deployment #1 (Spring): Main Direction (Mdir), Peak Direction (DirTp) and Unidirectivity Index. Wave bursts were sampled for every 40 min period, with a number of 2048 samples per burst sampled at a frequency of 1 Hz. Total number of bursts: 961.

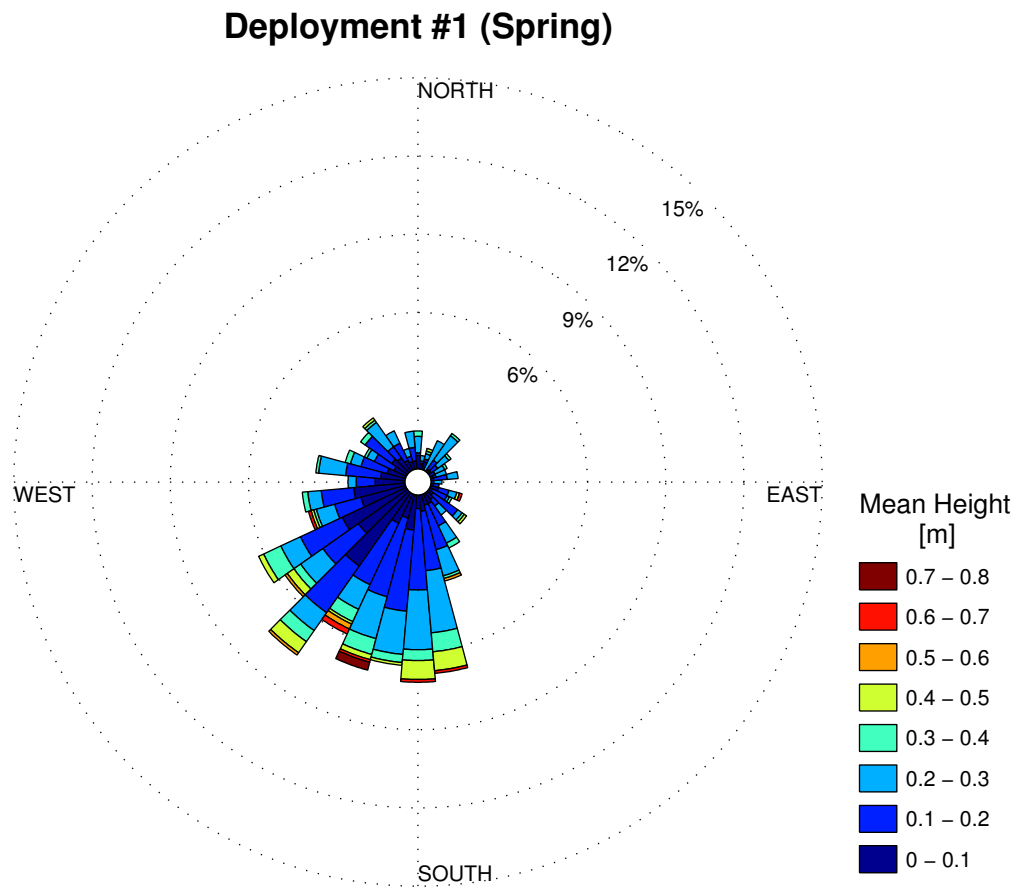


Figure 19: Wave rose displaying the Mean Height (Hmean), direction interpreted “as from” and the percentage of occurrence for Deployment #1 (Spring). Wave bursts were sampled for every 40 min period, with 2048 samples per burst sampled at a frequency of 1 Hz. Total number of bursts: 961.

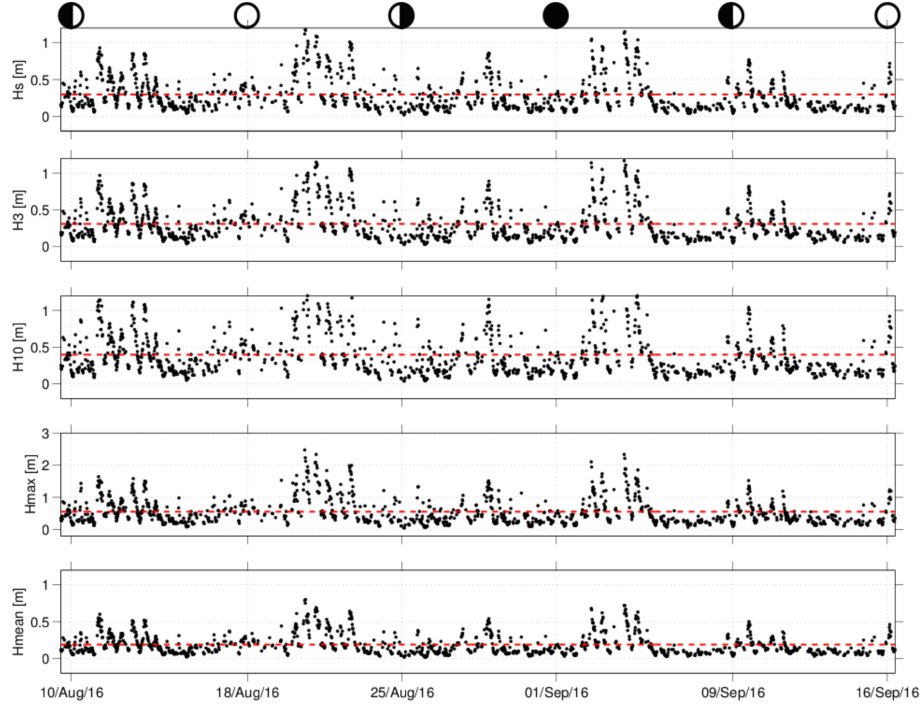


Figure 20: Wave parameters (Height) from Deployment #2 (Summer): Significant Wave Height (H_s), Mean 1/3 Wave Height (H_3), Mean 1/10 Wave Height (H_{10}), Maximum Wave Height (H_{max}) and Mean Wave Height (H_{mean}). Wave bursts were sampled for every 20.8 min period, with 2048 samples per burst sampled at a frequency of 2 Hz. Every burst is represented by a single black point being the associated wave parameter value within the burst. Total number of bursts: 1246.

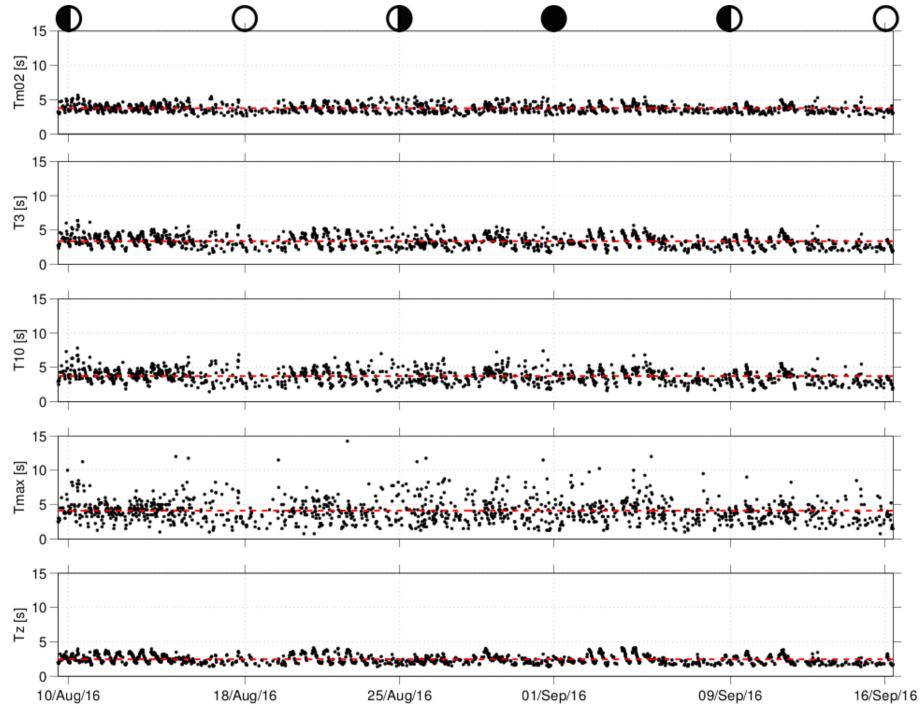


Figure 21: Wave parameters (Period) from Deployment #2 (Summer): Mean Period (T_{m02}), Mean Zero-crossing Period for H3 (T_3), Mean Zero-crossing Period for H10 (T_{10}), Mean Zero-crossing Period for Hmax (T_{max}) and Mean Zero-crossing Period (T_z). Wave bursts were sampled for every 20.8 min period, with 2048 samples per burst sampled at a frequency of 2 Hz. Every burst is represented by a single black point being the associated wave parameter value within the burst. Total number of bursts: 1246.

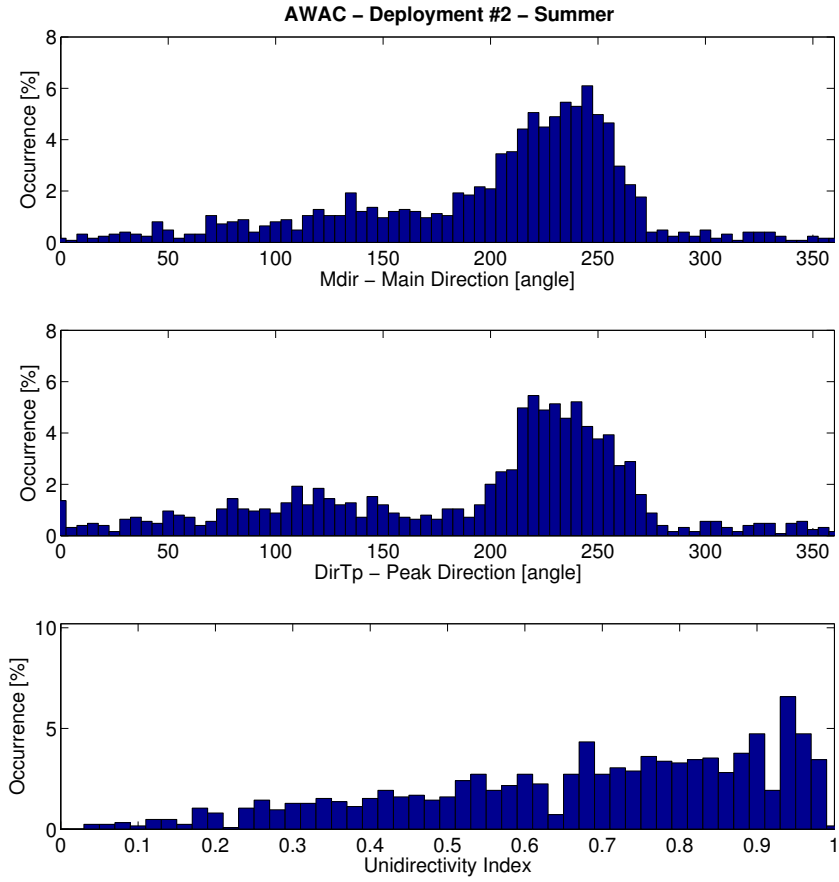


Figure 22: Wave parameters (Direction) from Deployment #2 (Summer): Main Direction (Mdir), Peak Direction (DirTp) and Unidirectivity Index. Wave bursts were sampled for every 20.8 min period, with 2048 samples per burst sampled at a frequency of 2 Hz. Total number of bursts: 1246.

Deployment #2 (Summer)

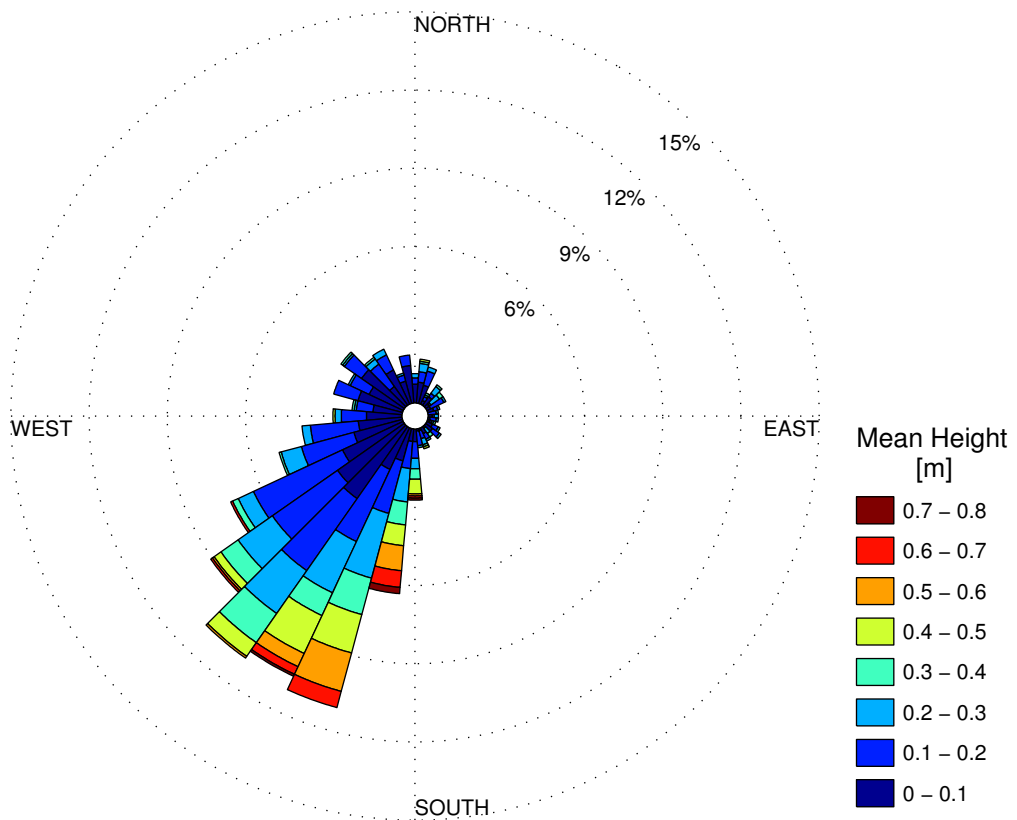


Figure 23: Wave rose displaying the Mean Height (H_{mean}), direction interpreted “as from” and the percentage of occurrence for Deployment #2 (Summer). Wave bursts were sampled for every 20.8 min period, with 2048 samples per burst sampled at a frequency of 2 Hz. Total number of bursts: 1246.

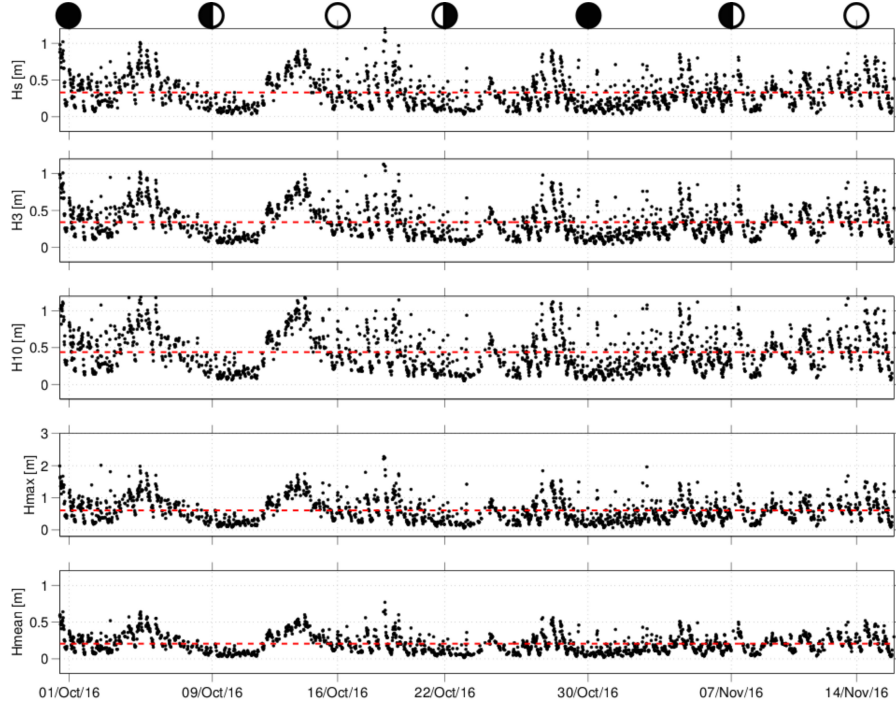


Figure 24: Wave parameters (Height) from Deployment #3 (Autumn): Significant Wave Height (H_s), Mean 1/3 Wave Height (H_3), Mean 1/10 Wave Height (H_{10}), Maximum Wave Height (H_{max}) and Mean Wave Height (H_{mean}). Wave bursts were sampled for every 20.8 min period, with 2048 samples per burst sampled at a frequency of 2 Hz. Every burst is represented by a single black point being the associated wave parameter value within the burst. Total number of bursts: 1778.

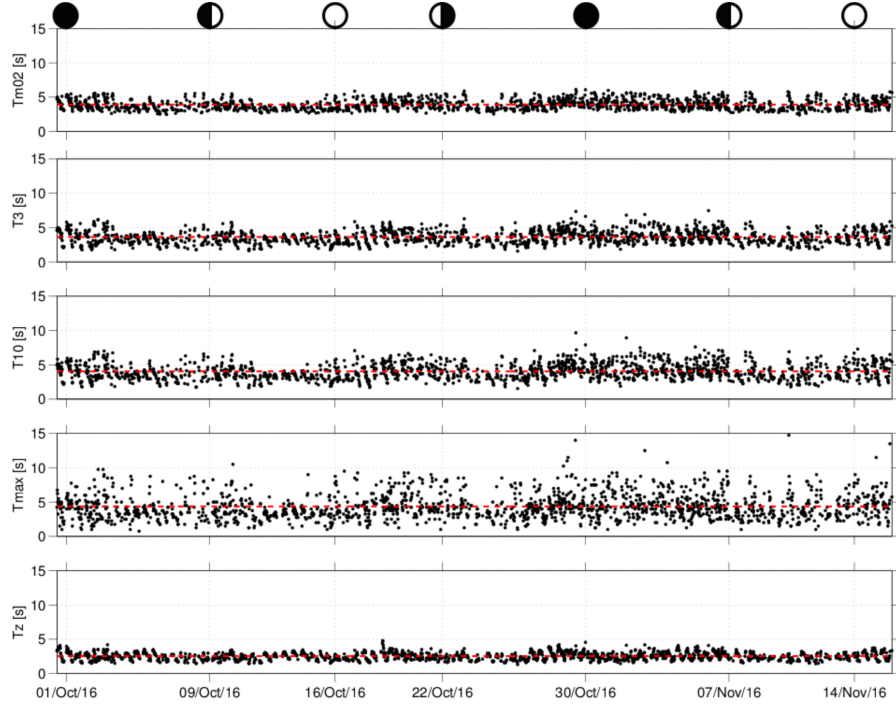


Figure 25: Wave parameters (Period) from Deployment #3 (Autumn): Mean Period (T_{m02}), Mean Zero-crossing Period for H3 (T_3), Mean Zero-crossing Period for H10 (T_{10}), Mean Zero-crossing Period for Hmax (T_{max}) and Mean Zero-crossing Period (T_z). Wave bursts were sampled for every 20.8 min period, with 2048 samples per burst sampled at a frequency of 2 Hz. Every burst is represented by a single black point being the associated wave parameter value within the burst. Total number of bursts: 1778.

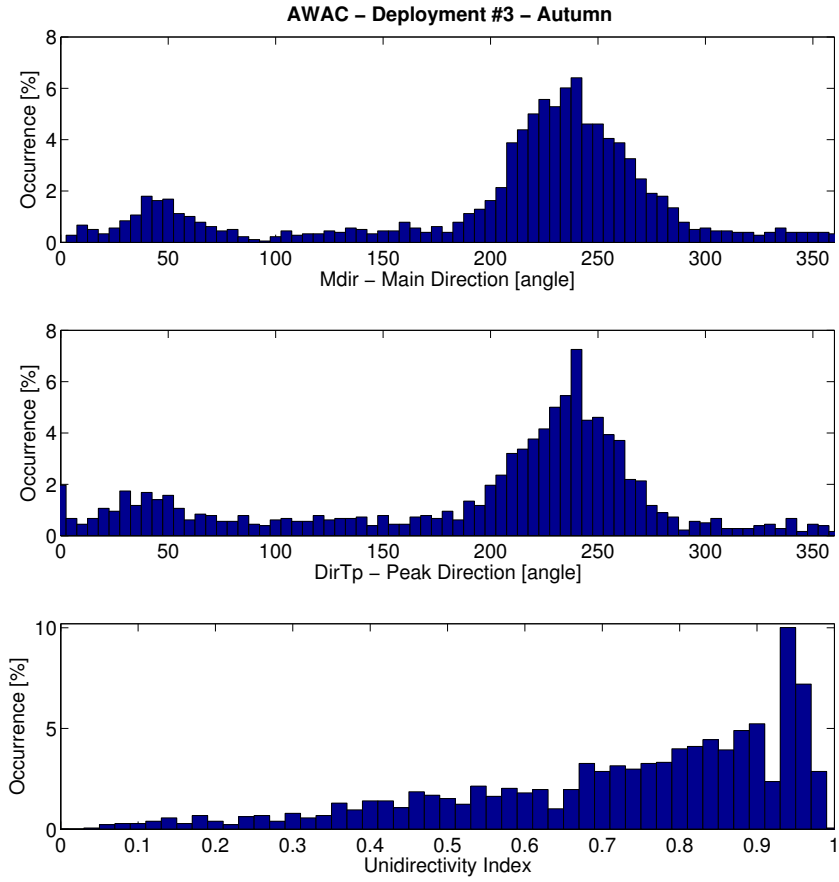


Figure 26: Wave parameters (Direction) from Deployment #3 (Autumn): Main Direction (Mdir), Peak Direction (DirTp) and Unidirectivity Index. Wave bursts were sampled for every 20.8 min period, with 2048 samples per burst sampled at a frequency of 2 Hz. Total number of bursts: 1778.

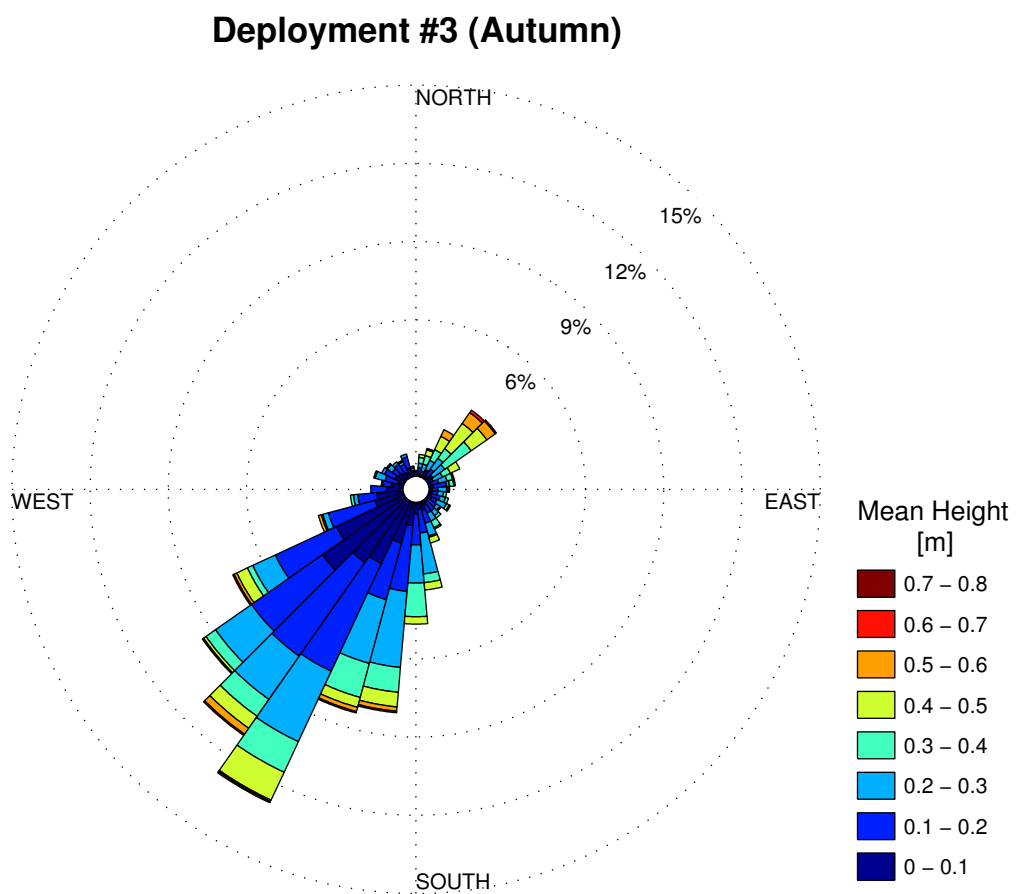


Figure 27: Wave rose displaying the Mean Height (H_{mean}), direction interpreted “as from” and the percentage of occurrence for Deployment #3 (Autumn). Wave bursts were sampled for every 20.8 min period, with 2048 samples per burst sampled at a frequency of 2 Hz. Total number of bursts: 1778.

5.5. Power output and turbine performance

The performances of the turbines were evaluated in terms of rotations per minute (RPM) and produced electrical power during two test periods: from 10/Sep/2015 to 27/Oct/2015 for the T1 turbine, and from 08/Feb/2016 to 14/Feb/2016 for the T2 turbine. Additionally, during the T2 period the water velocity passing through the blade cross-section was also measured so that the efficiency of the system could be tested. The RPM and electrical power were straightforwardly measured at the exit of the cabinet via current transformers and voltage terminals, while the water velocities were sampled by the horizontally-looking ADCPs installed on the front (Wadden Sea facing) and back (North Sea facing) of the T2 turbine.

5.5.1. T1 Turbine

Fig. 28a shows the time series of RPM (blue lines) and produced electrical power (black lines) corresponding to the test period for the T1 turbine. This turbine has a diameter of 6.3 m, a rated capacity of 40 kW for this site, and spun up to 28 revolutions per minute (RPM) under high velocity conditions during spring tides. Generally, for an RPM rate higher than 25, the produced electrical power was within the range of 20–35 kW. Fig. 28b displays a zoom-in of the time series on a single day: 30/Sep/2015. Notice that RPM and power increase from zero in slack tide to maximum values during the peak of tidal velocities. On average, for the period from 10/Sep/2015 to 14/Oct/2015 (period when the turbine was operating with no interruption), the energy produced by the T1 turbine reached the averaged amount of 58 kWh day⁻¹, with maxima up to 100 kWh day⁻¹ during the high peak of energy production (Fig. 29), taking into account the self consumption of the system.

The diagram RPM *versus* Power for the time series shown in Fig. 28 is presented in Fig. 30. As a predictor of Power as a function of RPM, we estimated the best 2nd-order polynomial fit for such a distribution of points as follows:

$$Power(RPM) = 0.067RPM^2 - 1.08RPM + 4.209. \quad (1)$$

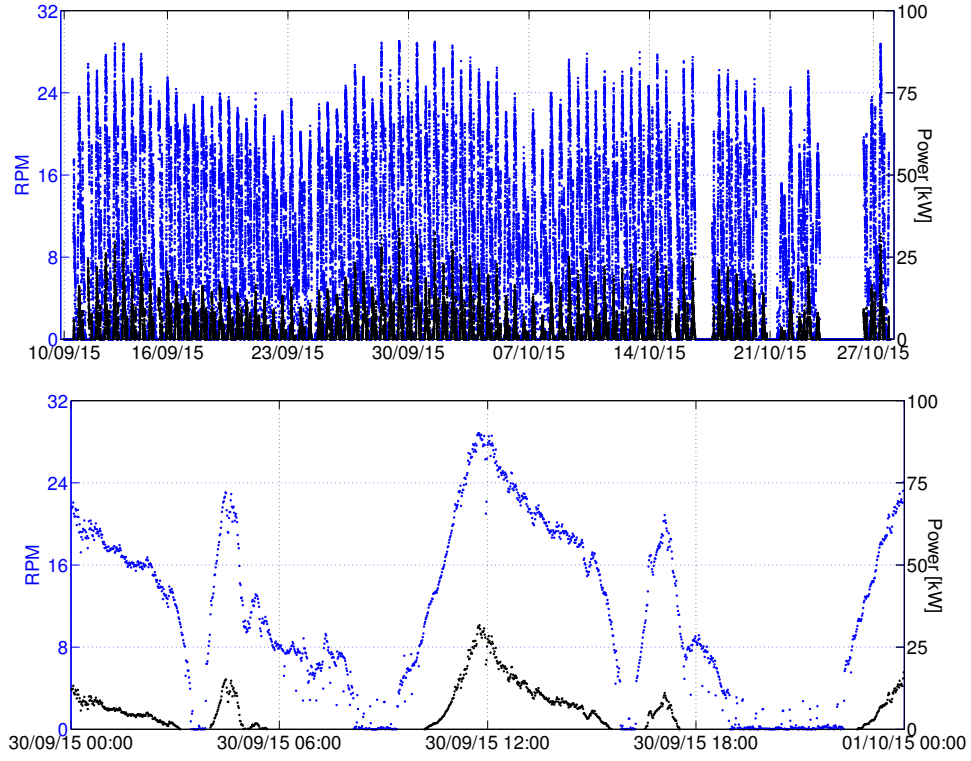


Figure 28: (a) Time series of RPM (blue, left hand y-axis) and produced electrical power (black, right hand y-axis) corresponding to the test period for the T1 turbine, spanning from 10/Sep/2015 to 27/Oct/2015. (b) Same as (a) but for a 1-day period (30/Sep/2015).

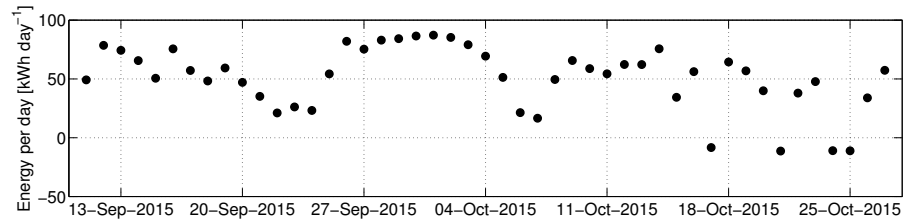


Figure 29: Energy production per day [kWh day⁻¹] during the T1 test period.

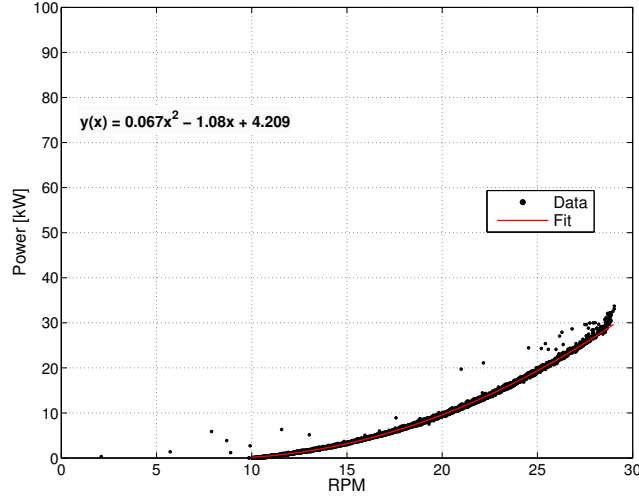


Figure 30: Diagram RPM *versus* Power for the time series presented in Fig. 28a (black dots) for the T1 turbine. The red line represents the best 2nd-order polynomial fit, which is defined by the equation displayed in the figure.

5.5.2. T2 Turbine

The T2 turbine has a diameter of 9.9 m and a rated capacity of 103 kW for this site. Compared with the T1, it rotated at a slower rate per minute (Fig. 31). On the other hand, due to the larger radius of the blade cross-section, the electrical power production presented higher levels. For instance, 14–17 RPM were required for a power production of 20–35 kW, while the T1 turbine produced similar amounts of electrical power with an RPM rate higher than 25. On average, for the 7-day period (08/Feb/2016 to 14/Feb/2016), the energy produced by the T2 turbine reached the averaged amount of 362.3 kWh day⁻¹, with maxima up to 430 kWh day⁻¹, taking into account the self consumption of the system (Fig. 32).

The larger efficiency of the T2 is also noticed by the RPM–Power curve (Fig. 33), which is more inclined compared to the same curve from the T1 (Fig. 30). As a predictor of Power as a function of RPM, the best 2nd-order polynomial fit is given by the following equation:

$$Power(RPM) = 0.321RPM^2 - 3.724RPM + 10.587. \quad (2)$$

As mentioned before in Section 5.3, the water velocity was sampled by the horizontally-looking ADCPs installed on the front and back of the turbine during the T2 test period. The front ADCP (Wadden Sea-facing) was used during ebb tides (south-westward velocities), while the back ADCP (North Sea-facing) was used during flood tides (north-eastward velocities). In order to filter the interference of the turbine blades in the flow, the median over one minute was calculated from the data that was sampled at a frequency of 16 Hz. Also, the

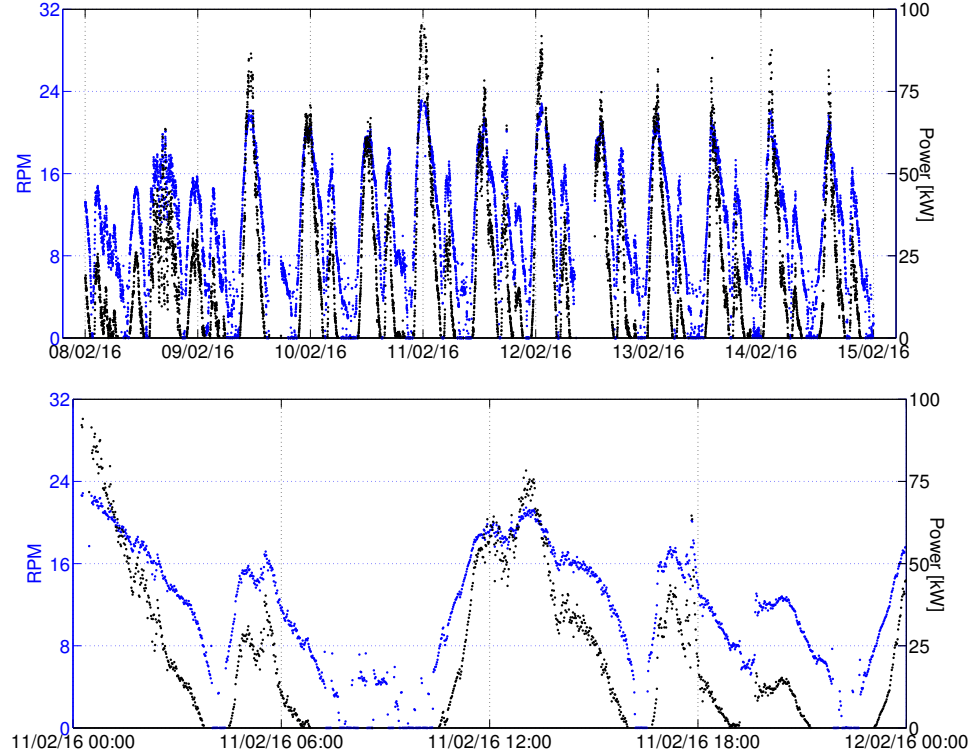


Figure 31: (a) Time series of RPM (blue, left hand y-axis) and produced electrical power (black, right hand y-axis) corresponding to the test period for the T2 turbine, spanning from 08/Feb/2016 to 14/Feb/2016. (b) Same as (a) but for a 1-day period (11/Feb/2016).

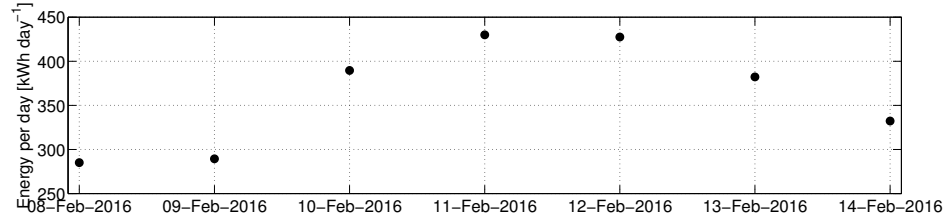


Figure 32: Energy production per day [kWh day⁻¹] during the T2 test period.

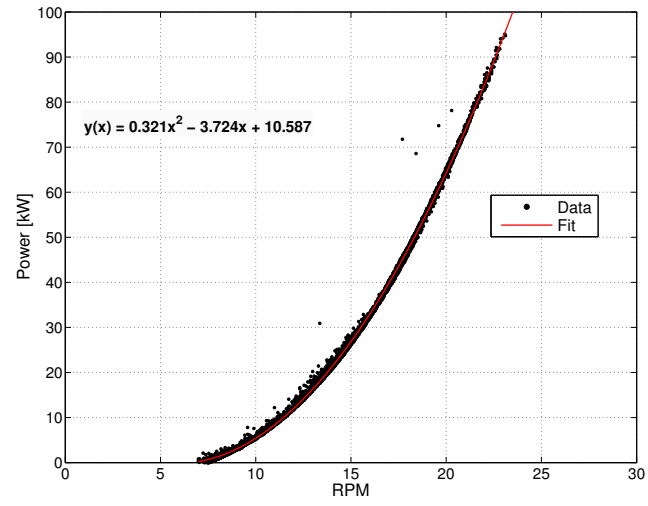


Figure 33: Diagram RPM *versus* Power for the time series presented in Fig. 31a (black dots) for the T2 turbine. The red line represents the best 2nd-order polynomial fit, which is defined by the equation displayed in the figure.

farthest beams of both ADCPs were used to minimize the shadow effect of the turbine.

The efficiency of the system (η factor) could be calculated by comparing the produced electrical power (P) measured at the exit of the cabinet with the power available in the water flow (P_{water}),

$$P_{water} = \frac{1}{2} \rho \pi r^2 v^3, \quad (3)$$

where ρ is the water density, r the radius of the blade cross-section and v the ADCP's velocities. The η factor is given by:

$$\eta = \frac{P}{P_{water}}, \quad (4)$$

and the results show a mean value of $\eta \approx 0.31$. It is worth mentioning that the T2 turbine was not specifically designed for the BlueTEC's location, explaining its non-optimum performance.

Fig. 34 shows the velocity-power diagram from the *in situ* data (black dots), which has a good agreement with the predicted power (P_{pred} , red dots) estimated from the water velocity and corrected by the η factor, as follows:

$$P_{pred} = \frac{1}{2} \rho \pi r^2 v^3 \eta. \quad (5)$$

Negative values in Fig. 34 are due to the self consumption of the system (≈ 4.2 kW). Notice that electrical power production reaches higher values during ebb, since the currents are also stronger during this phase.

5.6. Platform excursions

From 07/Jul/2015 to 12/Oct/2015 (during the T1 test period) and from 11/Jan/2016 to 22/Fev/2016 (during the T2 test period) a Differential Global Positioning System (DGPS) continuously recorded the BlueTEC's geographical position. Measurements were made at a frequency of 1 Hz. The instrument reveals excursions of the platform up to 8.5 m from its mean position, calculated

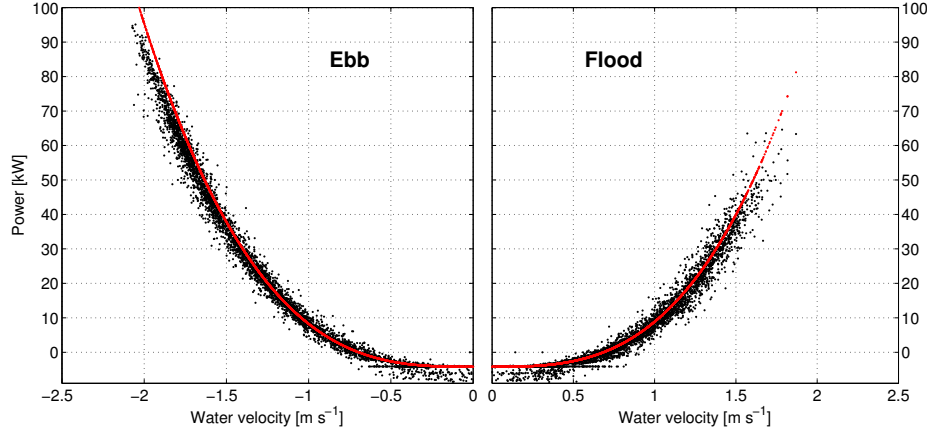


Figure 34: The black dots represent the velocity-power diagram measured during ebb (left) and flood (right) tidal phases during the T2 tidal period. The red dots indicate the estimated power calculated with Eq. 5.

as $4^{\circ}47.664'$ °W and $57^{\circ}0.075'$ °N, during the T1 period (Fig. 35a). The excursions performed during the T2 period resemble the previous period, however they are shorter in distance (Fig. 35b). The explanation lies in the fact that, for the T2 test period modifications were made to the platform which made the pull-in of the mooring lines easier. The mooring lines on one side of the platform were pulled-in with a winch onboard, instead of using the winch on the installation vessel. This allowed the lines to be tensioned at a higher tension, which in turn helped reduce the platform excursions.

Hereafter, the discussion of the results focus on the T1 period, in which the platform experimented the largest excursions. Table 2 shows the excursions of the platform, in meters, for different excursions ranges (column 1). The percentages of measurements within every range, taking into account a total of 7.4×10^6 samples, are shown in columns 2–4. Notice that for most of the East-West excursions (x-Direction), about 85.1% are shorter than 1 m, while 13.3% of the excursions are within the range of 1–2 m. Excursions longer than 3 m are rarely observed in the x-Direction. On the other hand, North-South excursions (y-Distance) were more recurrent and for longer distances (Fig. 35 and 36). For

instance, 61%, 25.5%, 8.4%, 3.2% and 1.9% of the samples are within the ranges of <1, 1–2, 2–3, 3–4 and >4 m, respectively. In terms of absolute excursions, 52.5%, 30.7%, 10.3%, 3.8% and 2.6% fall within the five previously mentioned ranges.

Table 2: BlueTEC excursions measured from a Differential Global Positioning System (DGPS) for the period from 07/Jul/2015 to 12/Oct/2015 with the T1 turbine. Columns 2–4 show the percentage of measurements found within the respective excursion ranges displayed in column 1. Excursions in the East-West direction are shown in column 2, North-South excursions are shown in column 3, and the absolute distances from the mean position ($4^{\circ}47.664'$ °W, $57^{\circ}0.075'$ °N) are given in column 4. Percentages were calculated based on a sampling frequency of 1 Hz, for a total of 7419006 samples.

Excursion	x-Distance [%]	y-Distance [%]	Abs. Distance [%]
<1 m	85.14	60.98	52.49
1–2 m	13.35	25.49	30.70
2–3 m	1.45	8.43	10.34
3–4 m	0.06	3.20	3.85
>4 m	0.00	1.9	2.63

From Fig. 35, it can be seen that the movement of the platform was mainly from side-to-side when considering the heading of the platform. Due to the mooring lines being under tension in the direction of front-to-back, it was as expected that there would be less motion in that direction and more side-to-side excursions.

The water velocity did not play a clear role in the platform’s position, at least for the period of the DGPS recording. The DGPS output was plotted against the ADCP velocity data in Fig. 37. Notice that there is not a good correlation between these two datasets. On the other hand, the excursions seem to be more influenced by the waves impinging on the lateral of the platform based on the comparison of the platform excursions and hindcast wave and wind data. Unfortunately, a direct comparison is not possible since the wave measurements (Sec. 5.4) do not coincide in time with the DGPS measurements.

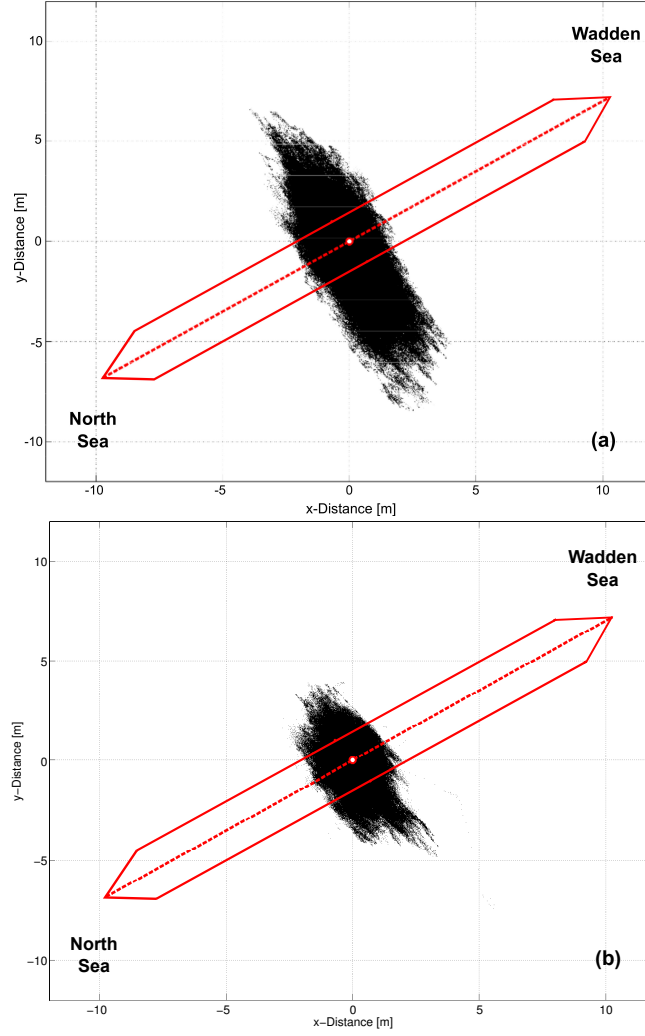


Figure 35: (a) DGPS data (black dots) representing the platform excursion (in meters) from the mean position ($[0, 0]$, red dot) during the T1 test period. (b) Same as (a), but for the T2 test period. In geographical coordinates, the mean position for both deployments is: $4^{\circ}47.664'$ °W and $57^{\circ}0.075'$ °N. The BlueTEC is represented in real scale by the red lines: 24.480 m length and 2.438 m width. The position of the DGPS in the platform is also placed at the mean position.

However, it is understood that this is an important point to be investigated in a later stage, by means of additional wave data (e.g., modelling outputs), and/or a future project.

5.7. *Temperature, salinity, chlorophyll, dissolved organic matter and suspended sediment*

In addition to the variables measured *in situ* by the instruments installed on the platform and on the nearby mooring (for an overview see Section 5.1), other environmental parameters such as sea surface temperature, sea surface salinity, chlorophyll, coloured dissolved and detrital organic materials absorption coefficient (CDM) and Secchi disk depth estimate (ZDS) were systematically monitored by means of open source global datasets provided by COPERNICUS, the European Union (EU) Earth Observation programme (COPERNICUS, 2016 (accessed December 01, 2016)). The near real time (NRT) data was initially provided but after the procedure of quality control applied by COPERNICUS, the data was replaced by the gridded delayed time (DT) version. All parameters were interpolated to the platform’s position using a bilinear interpolation between the 4 nearest grid points.

Fig. 38 displays the five mentioned parameters, extracted from three different databases: (i) Temperature and salinity are outputs from a 3D global numerical model, with $1/12^\circ$ degree of spacial resolution and calculated daily. The data is available as “Global Ocean $1/12^\circ$ Physics Analysis and Forecast updated Daily” from the COPERNICUS online catalogue; (ii) Chlorophyll A concentration is derived from satellite observations (MODIS/AQUA, MERIS, VIIRS and SeaWiFs) and listed as “OCEANCOLOUR GLO CHL L4 NRT OBSERVATIONS 009 033” on the catalogue. Spatial and temporal resolution are 4 km and daily, respectively; (iii) CDM and ZDS, also derived from satellite and organized at daily and 4 km resolutions, are found under the product identified as “OCEANCOLOUR GLO OPTICS L3 NRT OBSERVATIONS 009 030”.

The basic statistics (mean, standard deviation, minimum and maximum val-

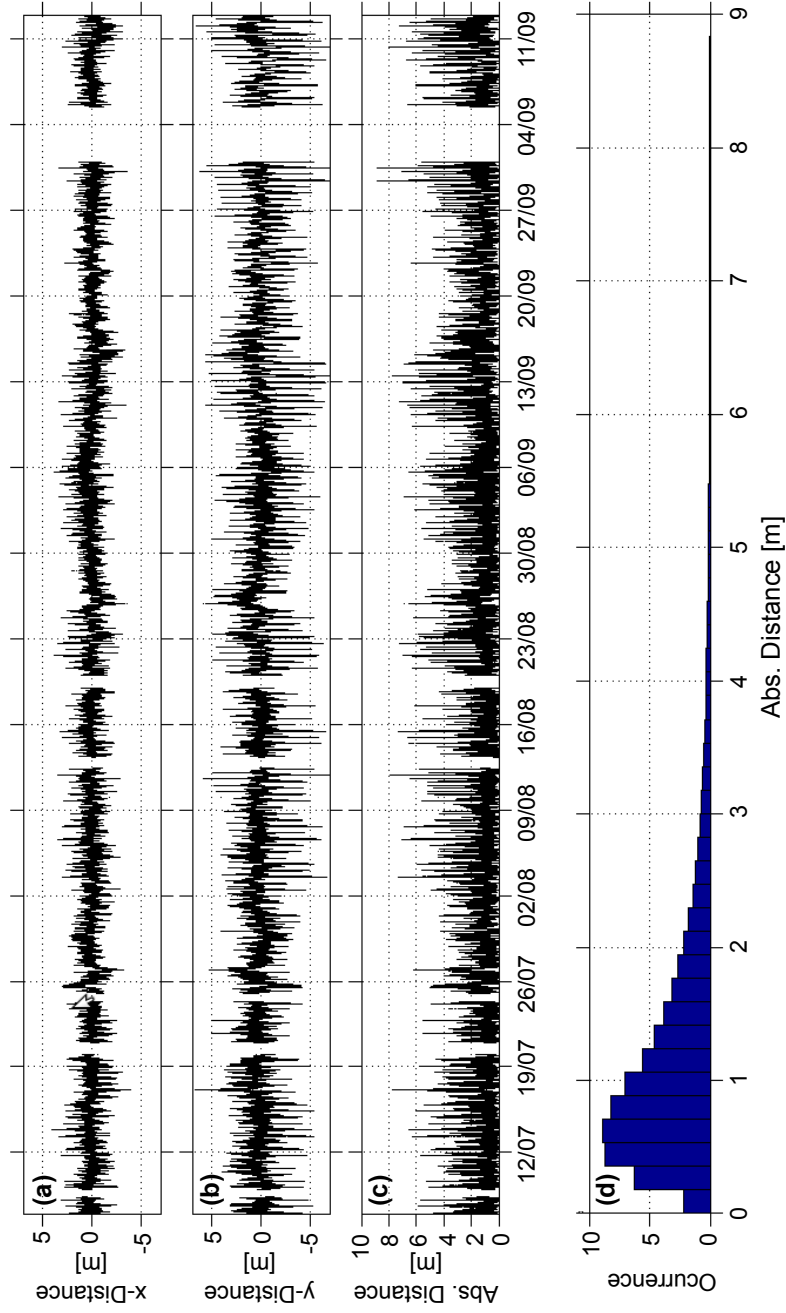


Figure 36: (a) East-West, (b) North-South and (c) Absolute excursion of the platform from its mean location during the T1 test period. (d) Histogram of the absolute excursion of the platform. The excursion is displayed in meters in all panels.

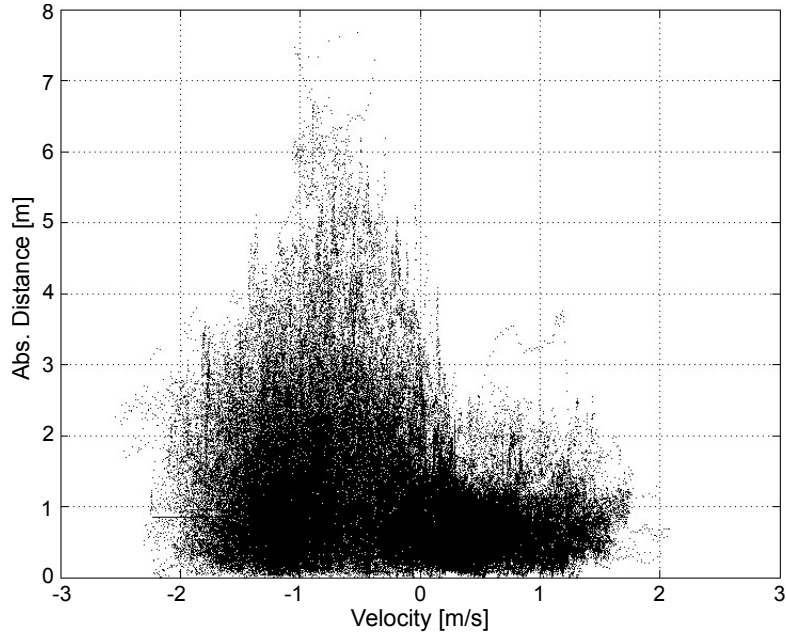


Figure 37: Absolute platform excursion *versus* water velocity measured from the downward-looking ADCP during the T1 test period.

ues) from all time series, spanning from 31/Mar/2014 to 30/Nov/2016, are found in Table 3. For instance, the temperature time series had a mean and standard deviation of 12.75 °C and 4.39 °C, respectively. As expected, Fig. 38a shows that this parameter is strongly marked by a seasonal signal, with amplitude from about 5 to 20 °C. Seasonal averages are: 11.01 °C in spring, 17.77 °C in summer, 13.16 °C in autumn and 6.87 °C in winter.

Fig. 38b also suggests a seasonal signal in salinity, however it appears weaker than in temperature. Maximum salinities are observed in winter and minimum during summer months. Seasonal averages are 31.23 psu in spring, 31.11 psu in summer, 31.94 psu in autumn and 32.51 psu in winter, while for the whole time period the average (standard deviation) is 31.61 psu (1.00 psu).

The curve of chlorophyll concentrations shows the typical spring bloom, with peak biomass around May (Fig. 38c). This pulse of biomass in spring occurs due

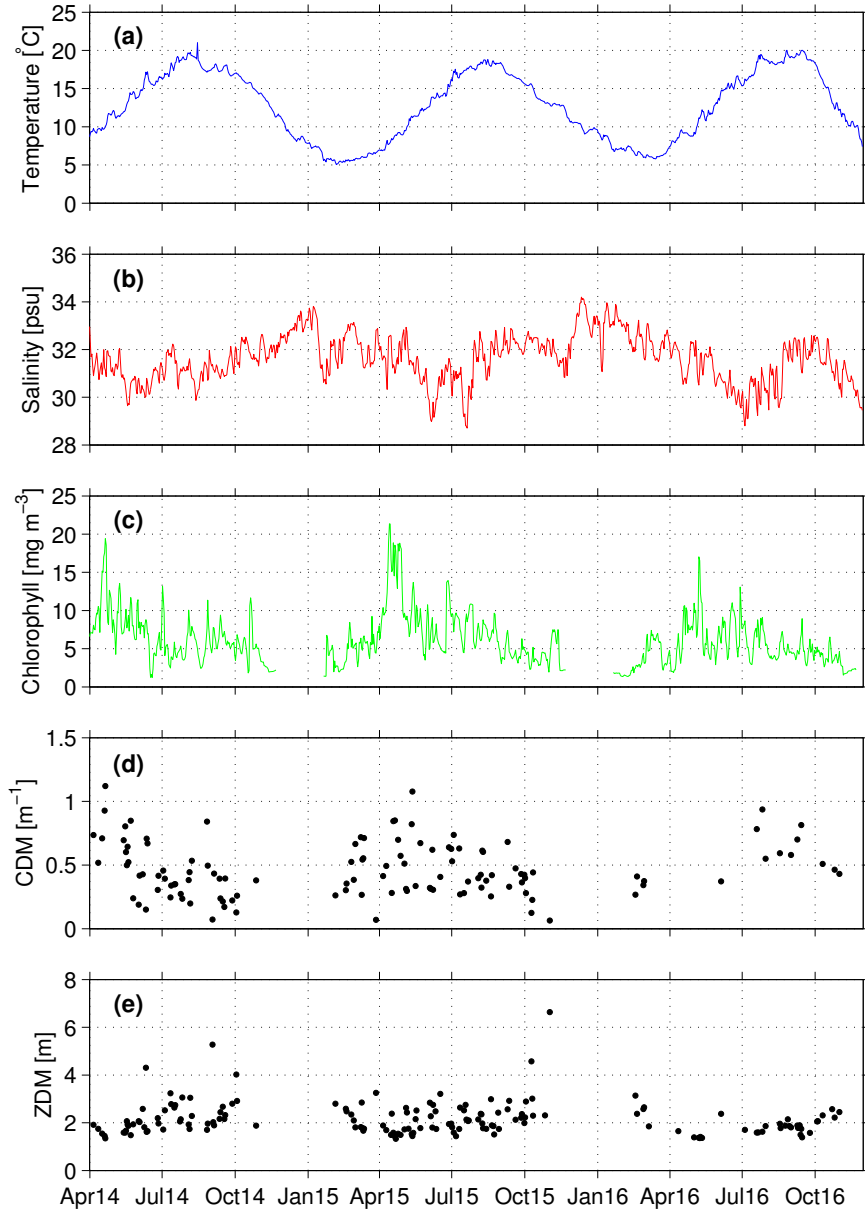


Figure 38: Oceanographic parameters provided by COPERNICUS (see Sec. 7) for a point (53.00°N, 4.79°S) near the BlueTEC platform: (a) Sea Surface Temperature [°C]; (b) Sea Surface Salinity [psu]; (c) Chlorophyll [mg m^{-3}]; (d) Coloured dissolved and detrital organic materials absorption coefficient (CDM) [m^{-1}]; (e) Secchi disk depth estimate (ZDS) [m].

Table 3: Basic statistics (mean, standard deviation, maximum and minimum values) from the environmental data provided by COPERNICUS for the period from 31/Mar/2014 to 30/Nov/2016. The following parameters are represented: temperature [$^{\circ}\text{C}$], salinity [psu], chlorophyll-a [mg m^{-3}], coloured dissolved and detrital organic materials absorption coefficient (CDM) [m^{-1}] and Secchi disk depth estimate (ZDS) [m].

Parameter	Mean	STD	Max	Min
Temperature [$^{\circ}\text{C}$]	12.75	4.39	21.00	5.06
Salinity [psu]	31.61	1.00	34.20	28.70
Chlorophyll [mg m^{-3}]	6.03	3.31	21.36	1.22
CDM [m^{-1}]	0.47	0.22	1.12	0.06
ZDS [m]	2.16	0.71	6.64	1.33

to the increasing sunlight and availability of nutrients stored during winter, since sunlight is a photosynthesis limiting factor. This variability pattern was already reported in the Wadden Sea and Marsdiep inlet (Winder and Cloern, 2010) and it has important consequences to the biofouling observed on underwater structures of the platform, as well as on the oceanographic mooring. The reader is referred to Sec. 6 for an extended discussion on this point.

Finally, CDM and ZDS present averages of 0.47 m^{-1} and 2.16 m , respectively. A good anti-correlation is observed between these two parameters (Fig. 39, black dots). In other words, a low transparency in the water column (ZDS) suggests a high concentration of suspended organic matter, of which CDM is an indicator. We applied a Single-Term Exponential Model, $f(x) = a * \exp^{b*x}$, in order to quantify the relation between these two variables. According to the polynomial fit the coefficients (with 95% confidence bounds) are $a = 2.744$ (2.139, 3.349) and $b = -0.845$ (-0.962, -0.729) (Fig. 39, red line).

6. Marine growth and anti-fouling

Marine growth is a common challenge to be faced when deploying underwater structures and oceanographic instruments. Especially at sites with high

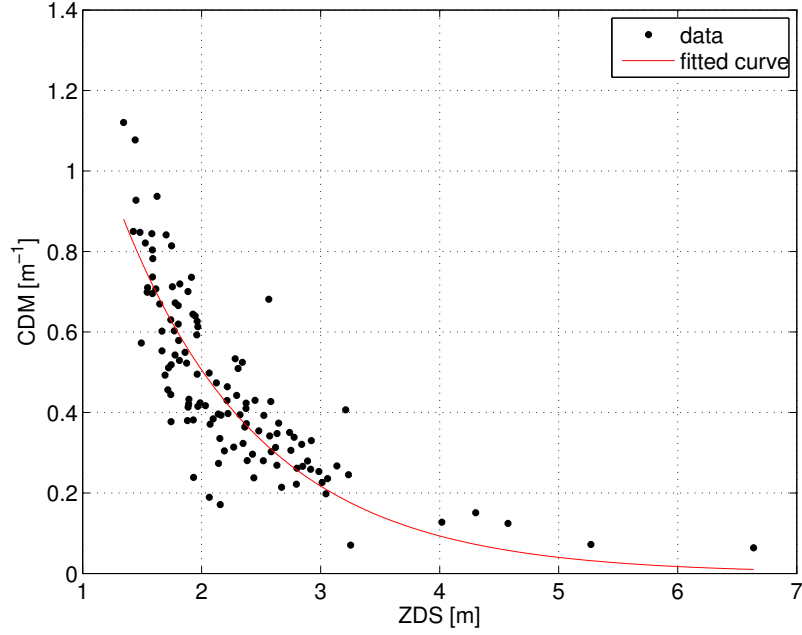


Figure 39: The black points represent the Secchi disk depth estimate (ZDS) [m] *versus* the coloured dissolved and detritol organic materials absorption coefficient (CDM) [m^{-1}], while the red line represents the fit of the data using a single-term exponential.

biological productivity, such as the Marsdiep inlet and the Wadden Sea. As discussed in Section 5.7, this challenge is more evident during summer and mainly during the typical spring biomass bloom, when the availability of sunlight and nutrients generates the right combination for increasing primary production.

Marine growth, particularly from spring and summer blooms, was found in mass quantities on several areas of the BlueTEC system and equipment which was not coated with an anti-fouling coating. The platform hull was coated and only saw small amounts of growth, however the mooring lines and umbilical power cable for instance were at least double their size due to the presence of mussels and other organisms. For more information on the marine growth on the BlueTEC platform, see the report by Bluewater Energy Services titled “BlueTEC Texel Project, Waddenfonds Report”.

In terms of the instrumentation, the effect of seasonal biomass blooms was observed during the AWAC deployments. After the first deployment, which remained at sea during May and June 2016, the AWAC mooring (both mooring buoy and instrument) was covered by marine animals and algae (Fig. 40a). However, the instrument was recovered much cleaner after the second deployment (August and September 2016), with reduced biofouling (Fig. 40b). An increased amount of fouling could potentially affect the buoyancy of the underwater buoy, and its dragging by the local currents. Since the quality of the acoustic surface tracking measurements is sensitive to inclinations of the upward-looking instrument (quality data is provided when the AWAC inclination is smaller than about 10 degrees), a large amount of fouling could, therefore, impact the measurements of the wave parameters. In addition, specific tests have to be directed in order to understand the effects of the biofouling on the acoustic signal (emitted and received) itself.

In order to try to inhibit the settlement of marine organisms, a mixture of udder cream and cayenne pepper was applied on the AWAC (Fig. 41a) and downward-looking ADCPs. The mixture was kept in place by a pantyhose fabric (Fig. 41b). A conclusive answer as to whether this mixture minimized the biofouling could not be determined, but based on the previous experience of NIOZ deploying oceanographic instruments in the Wadden Sea, apparently the settlement and growth of organisms were indeed minimized. However, specific studies have to be conducted to prove the efficacy of this mixture.

In general, the type, amount, and seasonal fluctuations of marine growth at a tidal project site should be investigated well in advance so as to ensure proper anti-fouling coatings and preventative measures are selected and implemented, if possible. Anti-fouling solutions for subsea equipment and surfaces such as mooring lines and power cables either do not exist or need to be improved; therefore more research into specific solutions are needed.

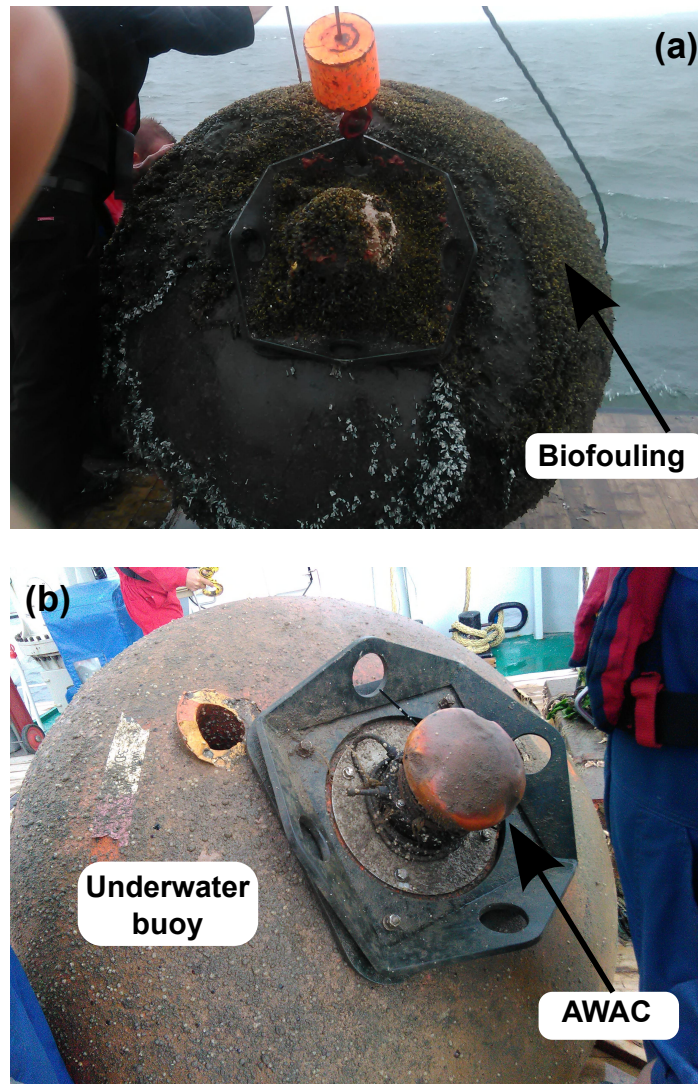


Figure 40: AWAC frame right after the (a) first (Spring) and (b) second (Summer) deployments.



Figure 41: (a) AWAC frame covered with the mixture of udder cream and cayenne pepper.
(b) Same as (a), but the mixture is now protected by a pantyhose fabric.

7. Potential environmental impacts

As with every human development activity in the seas and oceans, the energy conversion from tidal streams also brings some impacts to the environment. The deployment of floating platforms and/or underwater turbines potentially affects the water transport by disturbing the water velocity (see Sec. 5.3) and, consequently, may impact the sediment and larval dispersion. Additionally, an increase in the biomass of part of the local fauna is expected due to the fouling on the floating platform and turbine.

Taking into account that the turbines typically operate with low speeds, noise is expected to be minimal. Also, with the low turbine rotation speeds compared to the ability of fish and marine mammals to swim, one could speculate that the physical impact of the turbine's blades on the passing marine animals would be quite limited and minimal. Aiming to better understand this potential impact, the research project "Tidal Energy Fish Impact" involving NIOZ, Wageningen Marine Research, Tocardo, Bluewater, the Dutch Marine Energy Centre (DMEC), Deltares and Nederlandse Organisatie voor Toegepast Natuurwetenschappelijk Onderzoek (TNO) is evaluating this risk by means of a DIDSON acoustic camera. The camera records and monitors the behaviour of marine animals approaching an underwater turbine installed in the Den Oever tidal outlet sluice. This project is partly funded by Nederland Maritiem Land (NML) and Maritime Innovation Impulse Projects (MIIP).

However, all the potential impacts mentioned above could be considered minimal when compared to most other ways of producing electrical energy. For instance, tidal barrages, which also take advantage of renewable tidal energy, require civil engineering works for building dams and large reservoirs and, therefore, represent a larger impact on the local and surrounding ecosystems (Grabbe et al., 2009).

8. Final remarks and future perspectives

Testing at the Wadden Sea site has resulted in much learning in various areas; including platform design; platform and mooring installation; platform motions; operations and maintenance; sensor selection and placement; data collection; marine growth; umbilical design, etc.

Bluewater has decided to focus on “medium” level sites in terms of current speed and environmental conditions. Thus, the aim is to eventually design a larger, “medium-sized” BlueTEC device (roughly 0.5–1.0 MW capacity). Although the Wadden Sea site is considered a “low” level tidal site when compared to other sites (due to its lower current speeds and sheltered wave regime), further learning at the site is intended using the present BlueTEC device, as this allows for further learning at an acceptable cost level.

Some improvements being considered for the present BlueTEC aim to ease the installation of the mooring system and platform, improve sensor reliability, repair the umbilical cable, redesign the umbilical seabed frame, and potentially redesign the layout of the dynamic section of the umbilical cable (the part running from the seabed into the platform). Future platform designs are expected to focus on allowing for offshore turbine access for maintenance, easing installation of the mooring system and platform, and withstanding harsher environmental conditions. Future platforms will likely have different mooring and anchor configurations, depending on the environmental and local site conditions.

9. Project team

The data included in this report, as well as its content, were collected, processed and analyzed by Bluewater, Tocardo and NIOZ. The team members are mentioned below:

NIOZ

Leandro Ponsoni is an oceanographer graduated from the University of São Paulo, where he also completed his master thesis. He has a PhD in physical

oceanography from Utrecht University. His main research interests are the climate, ocean circulation and sustainable energy. Leandro was hired as a PostDoc in the BlueTEC project from April to November/2016. He is now an assistant researcher at the *Université Catholique de Louvain* (UCL).

Janine Nauw completed her masters in meteorology and physical oceanography at the University of Utrecht. There she also obtained her PhD in physical oceanography. Janine has vast experience in estuarine hydrodynamics, sediment and fish larvae transport, as well as in methane dispersion in a marine environment. She designed the monitoring programme on and near the BlueTec Tidal energy platform to investigate it's effect on the physical environment and vice versa. Janine now teaches physics at CSG Dingstede in Meppel.

Sven Ober has a degree in Applied Physics and works as a senior research-engineer at NIOZ. He participated since 1986 in numerous oceanographic cruises including 5 cruises to the Polar Regions. Today he is the first responsible for the NIOZ-CTD-systems and most of the moored instruments at NIOZ including ADCP's.

Marck Smit is graduated in Maritime Technology from the Delft University of Technology. For more than a decade he was responsible for the NIOZ Marine Technology Department. This department has vast experience with innovations in measuring, monitoring and sampling in the sea. Marck is now business development manager and manager technology of The Netherlands Deep Sea Science and Technology Centre.

Bluewater

Carly Nichols works at Bluewater Energy Services as a Solutions Development Engineer working on renewable energy projects. She acted as the Interface Engineer for the development of the BlueTEC where she worked with all of the partners, ensuring all partner scopes were well defined and that the proper in-

formation was exchanged for the various interfaces. Carly has a Bachelor degree in Mathematics and (Mechanical) Engineering and a MSc degree in Renewable Energy. She also has four years of work experience as a manager of Sustainable Design Services for sustainable building projects.

Jan Kenkhuis has fourteen years of experience within Bluewater in conducting offshore installation works in combination with mooring design and procurement of mooring components. As Technical Manager, Jan is responsible for developing installation procedures in cooperation with offshore installation contractors, including the supervision during execution of the work. On the BlueTEC project, Jan was involved during all offshore installation and operational activities required. Jan has a Bachelor degree in Civil Engineering and a Master degree in Offshore Geotechnics and is currently a Principal Engineer in the Mooring & Subsea Department of Bluewater.

Caspar Schmidt is working for Bluewater within the Floating Production department and has been actively involved in the operation of FPSO's (Floating, Production, Storage and Offloading unit) since 2002. First as engineering coordinator, later as Asset Manager of various FPSO's including the Bluetec since halfway 2015. Currently, he is responsible for the development of Asset Controls (operational/financial) and FPSO Tenders. He has a Master degree in Business Economics and a Bachelor degree in Naval Architecture.

Tocado Turbines

Aymeric Buatois is a SCADA development engineer at Tocardo, where he is in charge of the development of the software tools to communicate with the turbines and analyse the data to evaluate the reliability and status of the turbines in the field. Aymeric has an MSc in sustainable energy technology from Delft University of Technology.

Pieter de Haas is an entrepreneur with a naval engineering background and in-

ternational experience in ship building, business development and change management. Actively involved in the project development and commercialization of Tocardo since 2006, he is now responsible for the development of the Tocardo technology.

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Appendices

List of Appendices:

A: Note on the BlueTEC Texel project published in the Hydro International magazine: <http://www.hydro-international.com/content/article/bluetec-texel>

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SEPTEMBER 2016 | VOLUME 20 NUMBER 6



INERTIAL NAVIGATION SYSTEMS

Bridging the Positioning Gap

COASTAL RISK ASSESSMENT

BlueTEC Texel

A FLOATING TIDAL ENERGY PLATFORM
PROTOTYPE

A Floating Tidal Energy Platform Prototype

BlueTEC Texel

Traditional solutions for generating electricity from the tides, where tidal turbines are installed on the seabed, require high-end offshore installation vessels and do not allow for easy access for maintenance. The BlueTEC floating tidal energy platform has a different approach. It is a permanently moored platform which generates renewable electricity from tidal currents by holding a tidal turbine underneath. The BlueTEC Texel is the first prototype and serves as a demonstration platform and is being used for R&D testing purposes.

The project was realised through a partnership between companies active in the maritime and offshore industry: Bluewater, Damen Shipyards, Van Oord/Acta Marine, Tocado, Schottel Hydro, TKF, Vryhof Anchors, Tidal Testing Centre and the Port of Den Helder, with scientific support from the Royal Netherlands Institute for Sea Research (NIOZ). The platform was installed off the Dutch island of Texel in the Wadden Sea in the summer of 2015, initially equipped with a Tocado T1 tidal turbine and in early 2016, re-installed with a larger T2 turbine.

The BlueTEC Platform

The platform consists of three modules of standard 20" and 40" shipping container dimensions, allowing the system to be shipped at low cost to ports worldwide. The platform allows for easily assessed, dry storage of all

critical electrical equipment. The strut holds the turbine underneath the platform, and a dynamic export power cable transports the generated electricity to shore. The platform is kept in place

measurements to better understand the patterns of circulation near the Marsdiep inlet as well as to select an optimal deployment location. The results show that the region is

Turbines are kept as simple and robust as possible to achieve very high availability

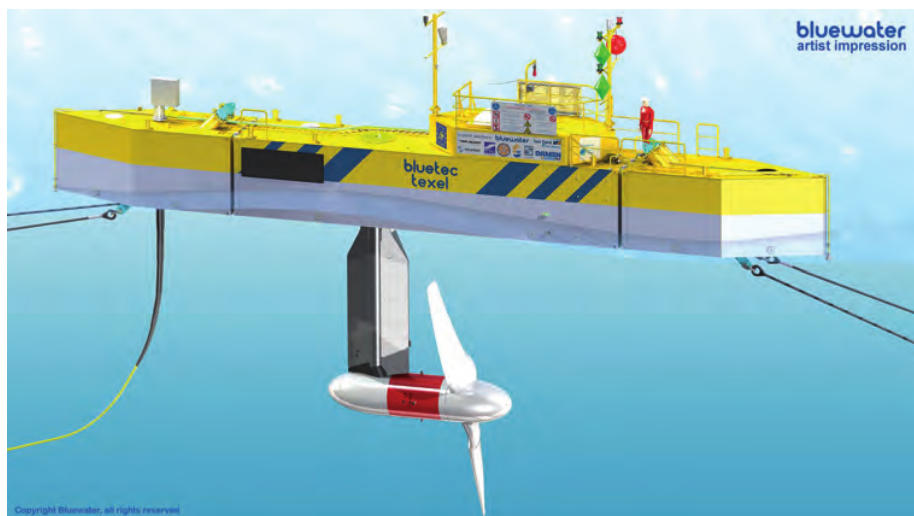
by four mooring lines, which are under tension with four drag anchors, allowing the platform to stay in place under all-weather circumstances, including storms (Figure 1).

Pre-operational Phase

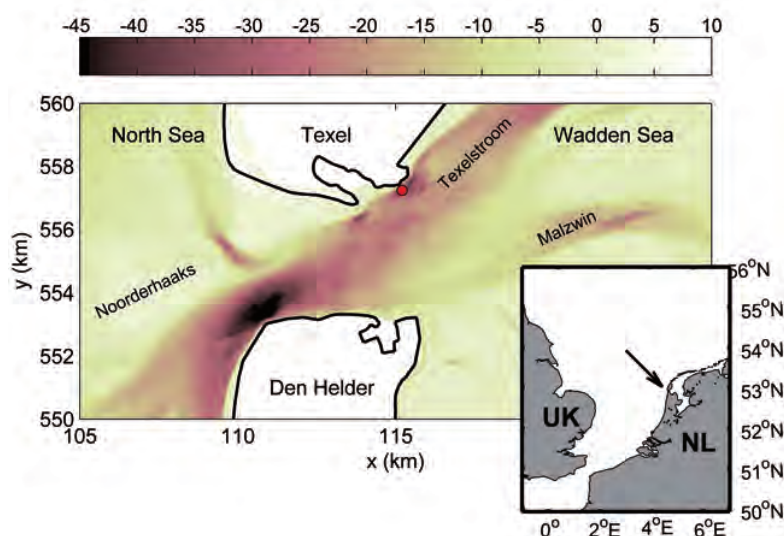
Prior to the installation of BlueTEC, NIOZ conducted several oceanographic

mainly dominated by tidal currents. However, a wind-forced residual component in ebb direction was also identified. During ebb phase, i.e. during the period when the water flows from the Wadden Sea towards the North Sea, the circulation is marked by a strong current, which results in homogeneous vertical velocities. On the other hand, the flood phase is characterised by weaker and vertically sheared velocities, with the core of the tidal current found at subsurface, at approximately 15 metres depth. This peculiarity is particularly interesting, since the turbine is placed close to this depth of maximum velocities.

The transition from neap to spring tides is distinguished by increasing velocities during ebb, while the flood currents remain nearly constant. Spatially, the distribution of velocities depends on the interaction with the bathymetry, being stronger in the Texelstroom, the main tidal channel in the Marsdiep inlet. The BlueTEC location was selected (Figure 2) based on in-situ observations of the local currents, and also taking into account other factors such as, for instance, a safe distance from the navigation channel and proximity to the Royal NIOZ on Texel.



▲ Figure 1: Artist's impression of BlueTEC Texel holding a T2 turbine.



▲ Figure 2: Location of the BlueTEC platform (red dot) in the Marsdiep tidal inlet in the Northern part of the Netherlands.



▲ Figure 3: BlueTEC Texel hoist into water.



▲ Figure 4: Offshore installation of BlueTEC Texel.

Offshore Installation

Prior to the first offshore installation, the turbine was fitted underneath the mid-module of the platform on the quayside. The module was then lifted into the water by a crane and connected to the two end modules while in the water. Meanwhile, offshore, the drag anchors were embedded in the sand at the site using a multi-cat vessel. Hereafter, the platform was towed to the site and hooked up to the mooring lines and tensioned using the multi-cat vessel's on-board winch. Next, the power cable was lifted through an opening in the platform and connected to the platform. The remainder of the cable was laid on the seabed with weights to hold it in place, and its end connected to the grid onshore (Figure 3).

The offshore vessel used was a 37-metre-long multi-cat with dynamic positioning class 1 (DP1). Compared to other ocean energy installations, this is a relatively simple vessel (Figure 4). The offshore installation work required attention to the times of the tides and their direction. The weather window adhered to for the offshore installation was three full days of waves with significant wave height (Hs) lower than 1.0 metre, and wind speeds of maximum 5 Beaufort.

During the turbine change-out, improvements to the platform were made to ease the offshore installation.

Monitoring Programme

The monitoring programme involves a suite of instruments mounted on and in the platform (Table 1), as well as on the turbine. The Royal NIOZ investigates the impact of the tidal energy

extraction on the local flow and sediment balance using two downward looking ADCPs on either end of the platform. They measure the incoming flow and the flow just behind the turbine and can be used to observe local bathymetric changes. Moreover, also the efficiency of the turbine is examined under various hydrodynamic conditions, varying from neap to spring tide; high and low discharge

conditions and thus strength of the stratification, and under various wave conditions as measured with the AWAC, which is moored on the seafloor next to the platform.

Turbines and Performance

To achieve very high availability, Tocardo's turbines are kept as simple and robust as possible. It implies no yawing and no pitching

DGPS	The Differential Global Positioning System measures the platform's geographical location and its heading with high accuracy.
Downward-looking ADCPs (x2)	Acoustic Doppler Current Profiles measure the velocity profile throughout the water column in Eastward, Northward and Upward direction using pings.
Horizontally-looking ADCPs (x2)	Acoustic Doppler Current Profilers measure the water velocity at the front and the back of the turbine.
AWAC wave profiler	Uses the same technology as ADCPs to measure wave height, speed and direction.
Weather monitor	The weather monitor records the meteorological data at the site, such as wind speed, wind direction, rain fall and temperature.
Motion sensor	The motion sensor measures the movements of the platform such as the roll, pitch and heave.
Strut strain gauges	Strain gauges were mounted onto the strut to measure the forces from the turbine.
Module coupling strain gauges	The platform consists of three modules inter-connected by six rods. Strain gauges were mounted onto the rods to measure the forces exerted on these rods.
Mooring line load shackles	The mooring lines include a shackle near the platform which measures the forces (loads) on the mooring lines.
Water sensor (x2)	Two water sensors inside the local equipment room detect if there is water within the module.

▲ Table 1: Monitoring equipment installed on BlueTEC Texel.

More Information

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Website BlueTEC: <http://www.bluewater.com/new-energy/bluetec-phil/>



Carly Nichols works at Bluewater Energy Services, assisting the project engineer and asset manager and often acts as interface engineer between the 10+ Partners within the BlueTEC Texel Tidal project. She has an MSc in Renewable Energy and four years of work experience as a manager of Sustainable Design Services for sustainable building projects.



Bram Pek works at Bluewater Energy Services, concentrating on business development activities for Bluewater's new energy business. He has a systems engineering degree from Delft University of Technology, specialised in energy & industry systems and finance. Before joining Bluewater he gained experience in working on liquid gas storage, biomass supply chains and sustainable housing.



Janine Nauw is a researcher working at the Coastal System Sciences at NIOZ. She has vast experience in estuarine hydrodynamics, sediment and fish larvae transport, as well as in methane dispersion in a marine environment. Janine has a PhD in physical oceanography from Utrecht University.

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Leandro Ponsoni is an oceanographer graduate from the University of São Paulo, where he also completed his master thesis. He has a PhD in physical oceanography from Utrecht University. Leandro has extensive experience processing oceanographic data sampled both in-situ and from satellites. His main research interests are ocean circulation and sustainable energy. He has been working at NIOZ since 2013.



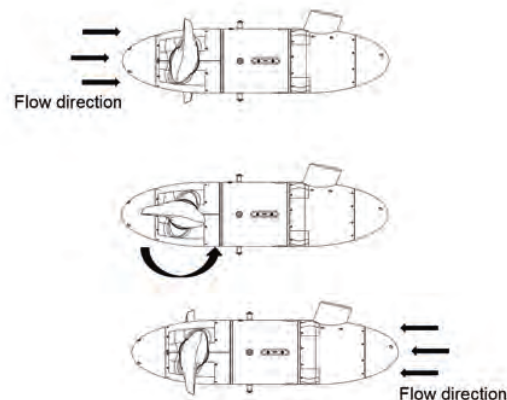
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Pieter de Haas is an entrepreneur with a naval engineering background and international experience in ship building, business development and change management. Actively involved in the project development and commercialisation of Tocardo since 2006, he is now responsible for the development of the Tocardo technology.



▲ Figure 5: Functioning of the bidirectional rotor technology

system. Because tidal turbines are intended to work with flow coming from both directions (front to tail and reverse), the blades need to be orientated according to the direction of the flow. The bidirectional rotor design makes it possible to turn the two blades 180 degrees simultaneously for reverse flow operation (Figure 5).

To evaluate the performances of the T2 turbine, two horizontally-looking ADCPs were installed to measure the water velocity at the front and the back of the turbine. The ADCPs only use the central (forward-looking) beam and measure the velocity at 16Hz. Each cell is 50cm long and the last cell centre is 25m ahead of the ADCP. One ADCP is mounted on the strut behind the rotor blades; observations at instances when the blades are in the path of the acoustic beam are discarded.

To measure the undisturbed water velocity, it is necessary to measure it at least two rotor diameters ahead of the 9 metres diameter rotor plane, explaining the need to have a 25 metres measurement range. Preliminary results show that the turbine efficiency is in line with the expectation.

Marine Growth

The platform was coated with anti-fouling on all subsea surfaces, which was provided through the Seafront project. Although these coatings notably prevented marine growth on the platform, significant marine growth in the form of mussels was found on the mooring lines and subsea power cable auxiliary equipment. Marine growth on these systems can significantly impact the system's dynamic behaviour and potentially the lifespan of the equipment. This experience revealed that marine growth in the local area should be well researched or tested far in advance of a project such that it can be properly accounted for in designs, anti-fouling plans, and operation and maintenance regimes.

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Thanks are due to Walther Lenting, Belén Blanco and the crew of the *Navicula*. ◀

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