

Tidal current turbine demonstration farm in Paimpol-Bréhat (Brittany): tidal characterisation and energy yield evaluation with Telemac

Chi-Tuân Pham¹ and Vanessa A. Martin²

¹EDF Research and Development, National Hydraulics and Environment Laboratory,
6 quai Watier, 78401 CHATOU Cedex, FRANCE,
E-mail: chi-tuan.pham@edf.fr

²EDF Research and Development, National Hydraulics and Environment Laboratory,
6 quai Watier, 78401 CHATOU Cedex, FRANCE,
E-mail: vanessa-audrey.martin@edf.fr

Abstract

On the 15th of July 2008, EDF announced its decision to build the first tidal turbine demonstration farm in France to produce electricity from the energy of tidal currents. Between 2011 and 2012, a few turbines representing several MW will be installed and connected to the grid off Paimpol-Bréhat (Brittany).

EDF R&D has been developing the Telemac-2D software. Over the past twenty years, that allows to model and simulate river and coastal hydrodynamic phenomena. At the Paimpol-Bréhat site, it is used to calculate tidal current characteristics and to assess the tidal energy yield potential produced by turbines exploiting such currents.

The zone where the farm is to be built is characterised with respect to tidal current potential. Data comes from a numerical Telemac-2D model of the Paimpol-Bréhat zone and current measurements from ADCP deployed at sea in 2005 and 2008. The use of realistic data taken from a site appears to be among the crucial technical parameters for site selection and the optimal positioning of the devices within the array.

Different methodologies for tidal resource assessment are described and compared. In particular, the respective strengths and weaknesses of some farm methods used in the Paimpol-Bréhat site study are discussed on the basis of a theoretical nine-turbine farm.

Keywords: Tidal currents, numerical modelling, at-sea measurements, resource assessment

Nomenclature

C = Coefficient including rotor efficiency and other efficiencies [%]
 C_p = Rotor efficiency [%]

E = Energy [GWh]
 h = Water depth [m]
 N = Number of devices [%]
 P_{device} = Mean available power through one device, per annum [kW]
 S_{rotor} = Device swept area [m²]
 T = Time of integration to compute energy from power [h]
 T_{year} = Number of hours in one year [h]
 u = 1st horizontal depth-averaged velocity component [m/s]
 v = 2nd horizontal depth-averaged velocity component [m/s]
 V = Velocity magnitude [m/s]
 $\overline{V^3}$ = Mean annualised cubic velocity [m/s]
 V_{min} = Cut-in speed (below, the device does not work) [m/s]
 ρ = Water density [kg.m⁻³]

1 Introduction

On the 15th of July 2008, after several years' dialogue with the various stakeholders, an announcement was made of the joint decision to build the first tidal turbine demonstration farm in France to produce electricity from the energy of tidal currents. Between 2011 and 2012, a few turbines representing several MW will be installed and connected to the grid off Paimpol-Bréhat (Brittany). On the 17th of October 2008, EDF appointed OpenHydro to develop and build the first tidal current turbines for the Paimpol-Bréhat site.

Section 2 of this paper briefly describes the main features of the Telemac hydro-informatics system that EDF Research and Development (EDF R&D) has been developing for more than twenty years. This system consists of several modules allowing to model and simulate river and coastal hydrodynamic phenomena. Among these, Telemac-2D [1] is used to calculate tidal current characteristics (water depth and velocity) and to assess the tidal energy yield potential produced by turbines exploiting such currents at the Paimpol-Bréhat site.

Section 3 focuses on the tidal characterisation of the zone in which the farm is to be built. Results come from

a numerical Telemac-2D model of the Paimpol-Bréhat zone, built with bought digital bathymetry data and extra bathymetry measurements carried out in 2008, and validated with current measurements from ADCP deployed at sea in 2005 and 2008. Specifically, this paper shows the interesting lessons that can be drawn from the use of realistic data (e.g. ebb/flood asymmetry) taken from a site. This data appears to be one of the crucial technical parameters for site selection. Moreover, once the site is chosen, an accurate knowledge of the site and of the technology is decisive for optimal positioning of the devices within the array.

In the latter sections, different methodologies for tidal resource assessment are described and compared. In particular, we discuss the respective strengths and weaknesses of some farm methods (eg: [2]). used in the Paimpol-Bréhat site study.

The aim of this paper is not to describe precisely the future site with the technology that is to be installed along the Breton coast, but to apply different R&D methodologies to estimate energy yield with tidal conditions of a known site, on the basis of a theoretical nine-turbine farm.

2 The Telemac system, and Telemac-2D

The Telemac hydro-informatics system is a set of computer programs dedicated to the numerical simulation of free surface flows. The system includes the Saint-Venant or shallow water equations (Telemac-2D) and the Navier-Stokes equations in 3 dimensions with a free surface (Telemac-3D) [1]. It is based on finite element techniques and has been developed by EDF and other scientific partners. It is also used externally (more than 200 licences around the world) by many scientific teams, a majority of hydraulic laboratories in Europe, water authorities, universities, and consultants. Telemac-2D is a component of the Telemac system which permits the study of coastal, fluvial, estuarine and lacustrine domains. It can take the following processes into account:

- flows induced by tides, floods, river water intake or dam failure,
- effects of meteorological events: atmospheric pressure and wind,
- propagation of long waves, the non-linear effects being taken into account,
- friction against the bottom,
- influence of the Coriolis force,
- sources and sinks of fluid and momentum within the domain,
- turbulence (various modelling options),
- sub- and super-critical flows, and transition from one of these regimes to another one,

- influence of horizontal temperature or temperature variations on density,
- Cartesian or spherical coordinates for large domains,
- consideration of the tidal generating force for large maritime domains,
- dry areas within the computation domain: tidal flats and flood plains,
- advection and diffusion of a pollutant, with source or sink terms,
- drifters monitoring and Lagrangian drifts,
- sills and submerged dikes.

Telemac-2D solves shallow water equations written in the non-conservative depth-velocity from either primitive equations or pseudo wave equations. Detailed explanations of the numerical algorithm are given in [1].

3 Tidal characterization of the zone

3.1 Presentation of the zone and the site

Paimpol-Bréhat tidal current site is located in the English Channel off the coast of Brittany. The principal port in the zone is Paimpol. Another port is also located in this zone on Bréhat Island. Figure 1 shows the location of a crustacean reserve.

Any type of fishing other than on-line is forbidden in this area. This is one of the main reasons, together with the tidal current resource and the results of a preliminary environmental diagnosis of the zone, why this location was chosen for the tidal current farm. This zone was chosen with the accord of the Local Fisheries Committee of Lannion-Paimpol.

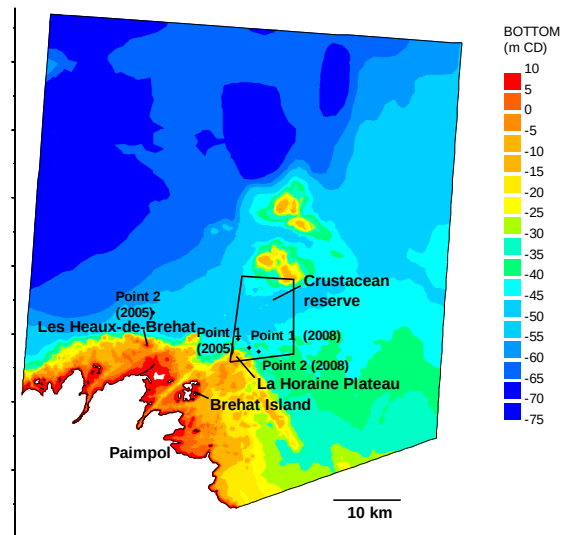


Figure 1: Bathymetry of Paimpol Bréhat zone, location of the site and ADCP deployment.

The future site is located about 10 km from Bréhat Island and about 15 km from the continental coast, near La Horaine Plateau.

3.2 Description of the numerical hydrodynamic model with Telemac-2D

The Telemac-2D software solves shallow water equations in 2D, and is used to model the tide in the Paimpol-Bréhat zone. Results of such simulations are water depth h and horizontal velocities that are depth-averaged u and v . The area covered by the model is almost square, extending 60 km from North to South and from West to East, respectively.

Digital bathymetry data for the zone were bought from the French Navy Hydrographic and Oceanographic Service (© Copyright 2007 SHOM. Realised with the authorisation of SHOM. Contract number 67/2007): they were divided into probes with a minimum distance between each of 25 m and a digital terrain model every 500 m that covers French coastal regions along the English Channel and Atlantic Ocean. Once the location of the future site was determined, an extra bathymetry survey was carried out during spring 2008. On the site, a 3.75 km² area was surveyed (including a 0.75 km² bathymetry with a 1 m resolution). The bathymetry of the zone used in the 2D numerical model is shown in Figure 1.

The mesh used in this numerical model is a finite element mesh built with Matisse, the mesh generator of the Telemac system. It includes 14 129 nodes and 27 425 triangular elements. The element size varies from 50 m in the interesting zone to 1.6 km where high depths are reached (West and North of the model).

Boundary conditions are generated from an EDF R&D - LNHE model on an area covering the near Atlantic Ocean, English Channel and South of the North Sea. 4 main tidal harmonic components are extracted:

- M2, principal lunar component, semidiurnal (44 714 s = 12 h 25 min 14 s),
- S2, principal solar component, semidiurnal (43 200 s = 12 h),
- N2, larger lunar elliptical component, semidiurnal (45 570 s = 12 h 39 min 30 s),
- M4, first harmonic component of M2, quarter day period (22 357 s = 6 h 12 min 37 s).

Water depths or velocities on the border are imposed using Thompson-type boundary conditions [3].

The results of the model are calibrated with SHOM data (particularly tidal sea levels and mean spring and mean neap tidal roses) and measurements results (see subsection 3.4).

Dissipation by bottom friction is modelled by a constant Strickler coefficient [4] that is set.

No interaction between tidal current turbines and tidal currents are taken into account in this numerical model. In particular, no wake effects are modelled in this paper. To calculate power extraction, the current velocity in the numerical model, is the one without any device and which is then used in equation 7.

3.3 Tidal sea levels

Astronomical tides levels are provided by the French Navy Hydrographic and Oceanographic Service (SHOM) for Paimpol port and are listed in Table 1. The levels are referenced with respect to Chart Datum.

Paimpol	Sea level (m CD)
Mean Sea Level	6.09
Highest Astronomical Tide (HAT)	11.92
Mean High Water Springs (MHWS)	10.80
Mean High Water Neaps (MHWN)	8.35
Mean Low Water Neaps (MLWN)	3.85
Mean Low Water Springs (MLWS)	1.35
Lowest Astronomical Tide (LAT)	0.11

Table 1: Tidal sea levels (©SHOM-2008).

3.4 Description of at-sea measurements

Two measurement campaigns were carried out in this zone by EDF.

The first was a two-week campaign in April 2005. It covered one spring and one neap tide. Two ADCP were deployed to measure velocities (magnitude and direction) along the water column: one was located in the crustacean reserve: point 1 (2005), the other was close to Les Héaux-de-Bréhat: point 2 (2005). These two locations were recommended and requested by the Local Fisheries Committee of Lannion-Paimpol. In particular, the first point in the crustacean reserve was recommended for its tidal current potential.

A second three-month campaign was carried out during spring 2008 (end of March to end of June). It covered four spring tides and six neap tides. Two ADCP were deployed to measure velocities (magnitude and direction) along the water column. The two ADCP (400 kHz and 600 kHz) were located in the crustacean reserve, at a distance of 0.5 to 1.7 km from the future farm (points 1 and 2 (2008)) and around 45 m water depth. In addition, a wave recorder buoy was deployed during a month and a half, together with another ADCP with a high acquisition frequency in order to study wave and current interactions.

Figure 1 shows the location of the deployed ADCP.

3.5 Some results of at-sea measurements

During the two campaigns, in 2005 and 2008, maximum velocity during flood was always a bit higher than during ebb.

During the first campaign in 2005, a 2.6 m/s (resp. 2.4 m/s) maximum *surface velocity* during flood and 2.0 m/s (resp. 1.8 m/s) maximum *surface velocity* during ebb were measured in the crustacean reserve (resp. close to Les Héaux-de-Bréhat). This first deployment showed the asymmetry of the tidal rose on the zone and demonstrated that the crustacean reserve is a better site to install tidal current converters.

The second campaign during spring 2008 was longer than the first. During this period, a 3.0 m/s maximum *surface velocity* during flood and 2.3 m/s during ebb were measured. During the weakest neap tide (resp. a mean neap tide, a mean spring tide, the strongest spring tide), the maximum *depth-averaged velocity* was measured around 0.5 m/s (resp. 1.1 m/s, 2 or 2.2 m/s – ebb/flood –, 2.2 or 2.6 m/s – ebb/flood).

Figure 2 shows the tidal rose of *depth-averaged velocity* during spring 2008 campaign at point 1.

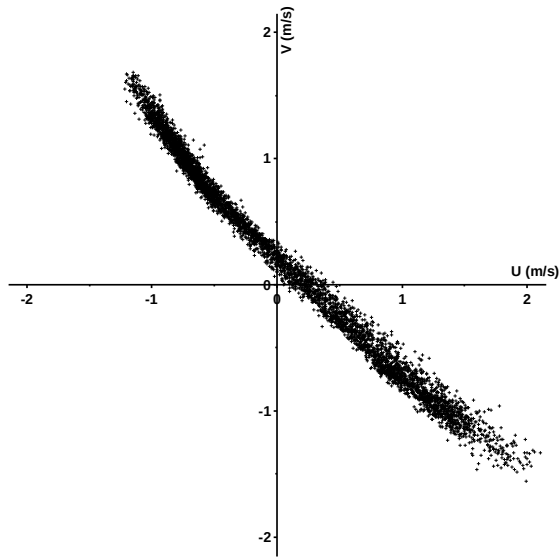


Figure 2: Tidal rose for measured depth-averaged velocity. Point 1 (2008).

The flow is bidirectional with two main directions: around 120° clockwise from North during flood and around 320° during ebb. Ebb and flood are not at opposite angles (around 200°). The tide changes its direction through North. Moreover, directional peak is less spread when water depth increases.

The direction of the tidal current is not sheared along the water column. It is meaningful therefore to consider depth-averaged velocity.

3.6 Some results of the Telemac-2D numerical model on tidal currents

In this subsection, every velocity is *depth-averaged*.

Four characteristic tidal conditions have been simulated:

- one astronomical tide,
- one mean spring tide,
- one “mean” tide,
- one mean neap tide.

Figure 3 shows the maximum magnitude of velocity during a mean spring tide South-West of the crustacean reserve where the farm is to be built a few hundred metres from ADCP point 1 (2008). Velocity can vary significantly on this site.

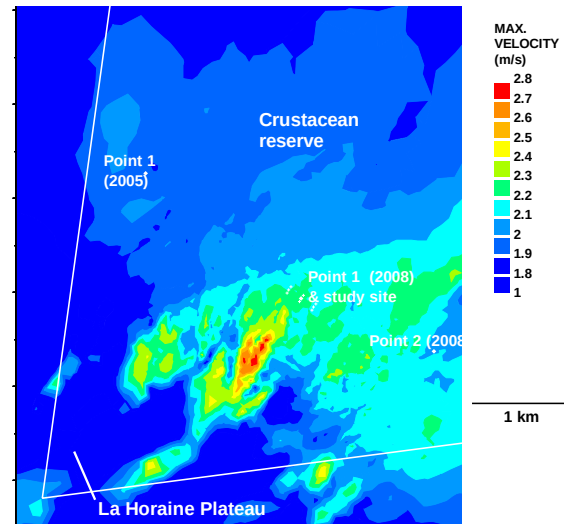


Figure 3: Maximum magnitude of simulated velocity during one mean spring tide.

Figure 4 shows the tidal rose during one mean spring tide computed with Telemac-2D at the first position of the ADCP during spring 2008.

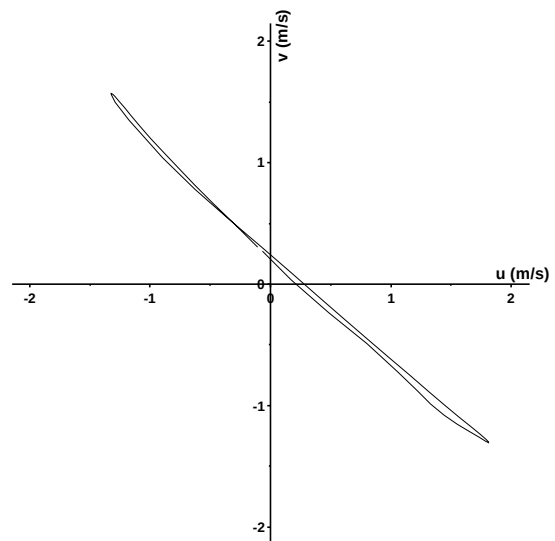


Figure 4: Simulated tidal rose during one mean spring tide. Point 1 (2008)

With this numerical model, mean direction of the tide is North-West to South-East. Ebb direction is towards the North-West (around 320° from North clockwise) whereas flood direction is towards the South-East (around 120° from North clockwise), the tide changing from South-East to North-West directions through North. Ebb and flood are not at opposite angles (around 200°). Moreover, velocities are greater during flood than during ebb.

Like at-sea measurement results, this numerical model shows that on Paimpol-Bréhat site, flood and ebb are asymmetric (magnitude and direction). Maximum magnitudes of simulated tidal current *depth-averaged velocity* at ADCP point 1 are:

- 2.6 m/s (resp. 2.3 m/s) during an astronomical tide flood (resp. ebb),
- 2.2 m/s (resp. 2.0 m/s) during a spring tide flood (resp. ebb),
- 1.1 m/s (resp. 1.0 m/s) during a neap tide flood (resp. ebb).

3.7 Comparison between the numerical model and measurements

Tidal ranges are well reproduced by the model for each type of tide. For each tide, the difference between numerical model and measurements for tidal ranges is around 5 cm, with one maximum difference of 10 cm. These differences have to be compared to values of tidal ranges between 4.5 to 11.8 m: there is less than 2.5% relative difference between numerical model and measurements. For mean spring and mean neap tides, the precision of the numerical model for sea levels (high and low) is around 10 cm. Modelled velocities and measurements match rather well over the covered area.

3.8 Interest of the site for installing a tidal current turbine farm

At-sea measurements and numerical modelling show a maximum mean spring current velocity of at least 2 m/s (usual EDF internal criterion on tidal current velocity from which power generation is interesting). This maximum velocity confirms the interest of this site for the installation of a tidal current turbine farm. Moreover, the flow on Paimpol-Bréhat site is bidirectionnal and the tidal rose is rather flat. At-sea measurements also confirm that Paimpol-Bréhat site is rather sheltered from waves.

Nevertheless, both measurements and modelling show the asymmetry of the flow (magnitude and direction). This element may be important for the choice of technology to be installed. Besides, the velocity is not uniform over the zone and it can vary a lot within distances of only hundreds of metres. This will need to be taken into account to optimise the layout with regard to the balance between a close spacing to get a sufficient tidal current velocity and a larger spacing to prevent wake effects, and the minimum security distances for installation or maintenance operations.

4 Different methodologies for energy yield assessment

It should be noted here that the study is limited to energy output assessment and does not deal with economic models. Furthermore, only methods which deal with devices, known as farm methods, are considered, as opposed to flux methods which consider the site cross-area and the potential of the site rather than the energy output of a farm. Both approaches are detailed in [2].

4.1 Method A: Black and Veatch farm method

The first approach is called the farm method, and is detailed in [2]. The input data is the average of the cubic velocity over a year, which can be obtained either by a tide reconstitution from parameters such as the mean spring velocity and flood-ebb and spring-neap ratios and periods, or by at-sea measurements. If at-sea measurements are performed over a period that is not long enough for the purpose of the study, then they can still be used to get the above parameters, and allow the tide reconstitution over the desired period. The mean annualised cubic velocity usually is taken at one location which is supposed to be representative of the area. The power for one device is given by :

$$P_{\text{device}} = \frac{1}{2} \rho S_{\text{rotor}} C_p \overline{V^3} \quad (1)$$

Then, the extractable energy over a year for N devices is :

$$E = N \cdot P_{\text{device}} \cdot T_{\text{year}} \quad (2)$$

4.2 Method B: instantaneous power method

The input data is the velocity distribution at one specific location (always supposed to be representative of the area) over a complete year, which can be obtained by a tide reconstitution from parameters such as the mean spring velocity and flood-ebb and spring-neap ratios and periods, or by at-sea measurements. This method B does take the minimum velocity into account, while method A did not. Results will therefore be closer to reality, as devices do not operate if the flow speed is not important enough. With the device power curve and the reconstituted tide (time discretisation being around 15 minutes), it is possible to estimate the instantaneous device power P_{device} for each device.

$$\begin{aligned} P_{\text{device}} &= 0 & \text{if } V < V_{\min} \\ P_{\text{device}} &= \frac{1}{2} \rho C S_{\text{rotor}} V^3 & \text{if } V > V_{\min} \end{aligned} \quad (3)$$

Then, the extractable energy per quarter hour is:

$$E_{15 \text{ minutes}} = P_{\text{device}} \cdot T \quad (4)$$

Summing these energy outputs for a complete year, and for N devices, gives:

$$E = N \cdot \sum_{1 \text{ year}} E_{15 \text{ minutes}} \quad (5)$$

4.3 Method C: schematic tides method

In this paragraph, we present Remenieras and Smaghe's formula [5]. The method using this formula will be called "method of schematic tides". The energy yield of a tidal current turbine farm is determined for three types of tides:

- one mean spring tide,
- one "mean tide",
- one mean neap tide.

For each type of tide, the energy yield for each tidal current turbine is computed as follow:

- during the computation, at each time step and for each tidal current turbine, the instantaneous power transmitted to the rotors is computed with (3). For each tidal current turbine, the energy yield transmitted to the rotors is deduced by multiplying instantaneous power by the duration of one time step,
- by adding the energies generated at each time step during the considered tide for each tidal current turbine the energy yield of the whole tidal farm is computed.

The energy yield E generated during one year can be estimated using the energies generated during one mean spring tide, one “mean” tide and one mean neap tide, using Remenieras and Smagghe’s formula [5]:

$$E = 0.3E_{\text{spring}} + 0.4E_{\text{mean}} + 0.3E_{\text{neap}}, \quad (6)$$

with:

- E_{spring} being the energy yield which would be generated during one year if every tide was a mean spring tide,
- E_{mean} being the energy yield which would be generated during one year if every tide was a “mean” tide,
- E_{neap} being the energy yield which would be generated during one year if every tide was a mean neap tide.

The computations are carried out using formula (6) and on the basis that there are 705.8 tides during one year.

4.4 Method D: real tides method

A last method to estimate energy yield accurately is described. The theory is to use a whole year simulation of tides over the whole geographic area. In practice, year 1992 is a mean year of energy generation with tidal currents. The energy yield for each tidal current turbine during the simulated whole year is computed as follow:

- during the computation, at each time step and for each tidal current turbine, the instantaneous power transmitted to the rotors is computed by applying the relation (3). For each tidal current turbine, the energy yield transmitted to the rotors is deduced by multiplying instantaneous power by the duration of one time step,
- by adding the energies generated at each time step during the simulated year, the annual energy yield transmitted to the rotors is computed.

This method differs from the previous one in the way the tide is reconstituted: the schematic tides method which models schematic tides and uses Remenieras and Smagghe’s formula [5] to estimate the annual energy yield is

simple and quick to carry out. The main drawback of this method is that velocity variations during one year are schematic through Remenieras and Smagghe’s formula. The real tides method models a whole year of tides. The main advantage of this method compared to the former is that it represents correctly the velocity variations throughout the modelled year. However CPU time is greater than the previous method (only a few hour physical time simulation). Nevertheless, the two methods give results which are quite similar.

5 Comparison of energy outputs for a tidal farm of nine turbines in Paimpol-Brehat

The main interest in comparing the previous methodologies lies in the estimation of the energy yield error which is derived using a simplified method (A, B, or C) originally designed for resource assessment, and not for energy output assessment. Method D results will serve as a reference.

5.1 Description of the ideal turbine model

In order to compare methodologies, we will assume that the energy output we are looking at stands just behind the rotor. Therefore, in the next paragraph we will only consider rotor efficiency.

Moreover, the characteristics of the ideal turbine model that are used here are public ¹. Data of the device considered are taken from an EPRI technical report [6], and the power output can be expressed by:

$$\begin{aligned} P &= 0 & \text{if } V < V_{\min} \\ P &= \frac{1}{2} \rho C S_{\text{rotor}} V^3 & \text{if } V > V_{\min} \end{aligned} \quad (7)$$

with:

$$\begin{aligned} \rho &= 1\,025 \text{ kg.m}^{-3}, \\ C &= 0.557, \text{ coefficient which includes various efficiencies, derived from } 1\,520 \text{ kW rated power at } 2.57 \text{ m/s speed in [6],} \\ S_{\text{rotor}} &= 313.8 \text{ m}^2, \\ D &= 16 \text{ m inlet outer rim diameter,} \\ V_{\min} &= 0.7 \text{ m/s cut-in speed.} \end{aligned}$$

The farm considered is a nine-turbine farm, divided into 3 rows of 3 devices (Figure 5, 1 to 3, 4 to 6 and 7 to 9). The 3 rows are perpendicular to the flood direction. The spacing between the devices is given by the following rule [2]: 10 rotor diameter spacing down current, and 2.5 diameter spacing cross-current. The longitudinal space between two rows is equal to $10D = 160 \text{ m}$ whereas the transversal space is equal to $2.5D = 40 \text{ m}$. The central point of the farm is located where the first ADCP was deployed during spring 2008 (point number 5 in the study farm) ².

¹Due to confidentiality reasons, these characteristics are different from the characteristics of the technology that is to be installed in the future at Paimpol Bréhat.

²The location of this farm is not where the first turbines are to be installed in 2012. A site with better natural tidal conditions exists in this zone with constraints of bathymetry and distance to the coast, and the first turbines will be installed there.

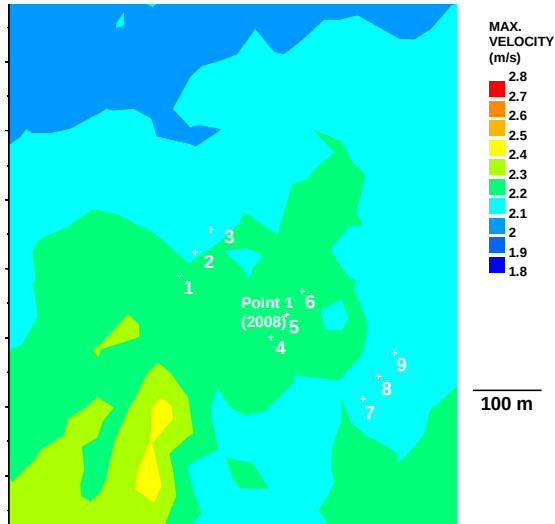


Figure 5: Location of the nine-turbine farm and maximum velocity during one mean spring tide.

5.2 Results: comparison of energy outputs

The objective of this study is to assess the uncertainty of energy outputs obtained from the simplified methods A, B, and C, comparing their results to the energy output given by method D. In effect, the latter method yields the best estimation of the resource at one specific site.

Results of the energy outputs are presented in Table 2. As methods A, and B require at-sea measurements which are available only at position 5, there is no power assessment at the other positions for these methods.

Position	A Farm method (numerical simulation)	A Farm method (at-sea measurements)	B Instantaneous power method	C Schematic tides method	D Real tides method
1				1.80	1.87
2				1.76	1.84
3				1.74	1.82
4				1.77	1.85
5	1.63	1.81	1.61	1.77	1.85
6				1.78	1.85
7				1.66	1.73
8				1.63	1.70
9				1.61	1.68

Table 2: Annual energy yield (GWh) per turbine.

Looking at these figures for the energy output in a year, the first observation is that errors made with simplified methods A, B, and C compared to method D, might not be as important as what could have been expected (15% maximum, obtained in position 5 for the instantaneous power method). The different methods show great differences in their inputs, for example, site bathymetry

is not taken into account in methods A and B. However, even a small error of less than 15% can be significant when selecting sites and/or devices.

The second observation resulting from the underestimation of simplified methods is that results obtained from methods A, B, and C, are always less important than the results obtained from in method D. This demonstrates that energy outputs depend on the method; the less accurate the method, the greater the risk of underestimating energy output.

Looking a little further into details, it appears that measurements in method A give more realistic results than numerical simulations, which could have been anticipated. The Black and Veatch farm method (method A) with current data computed from numerical simulations gives roughly the same output as the instantaneous power method (method B), but this output significantly differs from the real tides method output. On the other hand, the schematic tides method is interesting as it reproduces very well the geographic discrepancies between turbine outputs, even though an error of around 4% is constantly observed. It would be interesting to see if this translation of the power output is observed for different sites, in which case a solution would be to slightly change the coefficients of Remenieras and Smagge's formula [5] in order to match the output in method D.

In conclusion, it is obvious that the method we used as a reference, that of the numerical simulation of a whole representative year of tides at the site, is the best available today. In the near future, we will have precise references, through direct measurements of the power output, which will allow an even better assessment of the different methods' robustness. Furthermore, these measurement references will integrate all the real hydrodynamics effects, such as turbine wake. This provides the perspective of developing and validating models which will account for wake effects in a turbine farm.

6 Conclusion

Within the framework of the Paimpol-Brehat demonstration farm, a certain number of studies have been carried out. One of them is presented here, which, for confidentiality reasons, corresponds neither to the selected site nor to the selected device.

The site is presented, as well as its tidal current characterisation. Several measurement campaigns (ADCP, bathymetry...) have been carried out since EDF studied the feasibility of installing the first tidal current farm in the Bréhat zone. As a result, a numerical model of the Paimpol-Bréhat zone has been built with Telemac-2D to simulate tidal currents.

These two complementary approaches enabled us to gain greater insight and to characterise real tidal conditions over the whole area. In particular, the tidal rose on the site is rather flat, and maximum velocities, both measured and simulated are given close to the future site. This confirms the interest of installing a tidal current turbine farm on the Paimpol-Bréhat site. However, the flow

is bidirectional, with minor asymmetry in direction and magnitude. The numerical model shows that the velocity is not uniform over the zone. All this information will need to be taken into account when choosing the technology and optimising the layout.

Different methods for energy assessment have been presented. They are compared in the latter part of this paper, with regard to a farm of nine turbines in Paimpol-Brehat. The interest of the study lies in the fact that it allows an estimation of the error made while using approximative methods to assess the energy yield. The Telemac system is used, as it allows a simulation of currents for a complete year, over a large geographic area, with sufficient time and spatial resolutions. These results serve as a reference for the assessment of various other methods.

Energy yields show relatively important differences, which confirms that a detailed numerical simulation is necessary to estimate the expected output of a farm over a year. The method providing the closest comparison to the real tides method is the schematic tides method, which interestingly reproduces discrepancies between the different geographic positions of the turbines, and always shows the same error. In perspective, it would be interesting to improve our reference method (the real tides method) in order to take into account the turbine wake effects. This would allow an even more accurate estimation of energy output, and could be compared directly to at-sea measurements which will be available soon.

Acknowledgements

EDF R&D kindly thanks OpenHydro for its partnership and the technical exchanges during this current project, the Local Fisheries Committee of Lannion-Paimpol (Comité Local des Pêches Maritimes et Élevages Marins de Lannion-Paimpol) which shared its knowledge of the zone, and Brittany Regional Council (Conseil Régional de Bretagne) which supports the project (institutionnally and financially).

References

- [1] J.-M. Hervouet. *Hydrodynamics of Free Surface Flows. Modelling with the finite element method*. Wiley, 2007.
- [2] UK, Europe and global tidal stream energy resource assessment. Technical Report 107799/D/2100/05/1 Rev 1, Black & Veatch Consulting Ltd, 2004.
- [3] K. W. Thompson. Time dependent boundary conditions for hyperbolic systems. *Journal of Computational Physics*, 68:1–24, 1987.
- [4] A. Strickler. Beiträge zur Frage der Geschwindigkeitsformel und der Rauheitszahlen für Ströme, Kanäle und geschlossene Leitungen (Some contributions to the problem of the velocity formula and roughness factors for rivers, canals, and closed conduits). In *Mitteilungen des Eidgenössischen Amtes für Wasserwirtschaft*, number 16, Bern, 1923.
- [5] G. Remenieras and P. Smagghe. Sur la possibilité d'utiliser l'énergie des courants marins au moyen de machines analogues aux aérogénérateurs. In *Actes des 4e Journées de l'Hydraulique*, Paris, 1956.
- [6] R. Bedard, M. Previsic, O. Siddiqui, G. Hagerman, and M. Robinson. Epri survey and characterization. tidal in stream energy conversion (tisec) devices. Technical Report EPRI - TP - 004 NA, EPRI, 2005.