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# Characterising the tidal stream power resource around France using a high-resolution harmonic database

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#### Abstract

Although tidal stream energy is highly predictable, the distribution of the resource varies over small spatial scales and over tidal-to-decadal time scales, requiring detailed models and accurate analysis techniques. The present study investigates the spatial and temporal variability of the tidal stream energy resource around France, using a tidal current harmonic database. The 250 m resolution tidal database covers western Brittany and the western English Channel, two regions that have strong potential for tidal array development. As well as generating a refined resource assessment for the region, a series of simplified parameters are considered to assess resource variability, both spatially and temporally. Particular attention is dedicated to variability over spring-neap time scales (resulting from  $M_2$  and  $S_2$  compound tides) and current asymmetry (governed by  $M_2$  and  $M_4$  velocities). A clear contrast in the nature of the resource is found between sites located off the Cotentin Peninsula, which exhibit low spring-neap variability and

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tidal asymmetry, leading to a more continuous and therefore attractive energy conversion, and sites in western Brittany, with greater variabilities over semi-diurnal and fortnightly time scales.

*Keywords:* spring-neap tidal variability, tidal current asymmetry, horizontal-axis turbines, Fromveur Strait, Paimpol-Bréhat, Alderney Race

### 1 1. Introduction

Technologies for tidal stream energy conversion are still in the early stages 2 of development, although for many countries this sector has the potential to 3 form a significant part of their future energy mix, contributing to a reduc-4 tion in carbon dioxide emissions [1]. However, prior to commercial-scale 5 deployment of tidal stream energy converters, a detailed characterisation of the ambient hydrodynamics is required to improve device design and de-7 termine optimum turbines' locations within a wider region of strong flows. 8 Model-generated regional resource assessments are generally restricted to a 9 reduced number of parameters, focusing primarily on the amplitudes of mean 10 and peak tide-generated velocity and associated stream power [2, 3, 4, 5]. 11 Whereas such resource assessments provide an initial characterisation for 12 site selection based on the spatial distribution of resource hotspots, it is 13 then necessary to characterise the temporal variability of the resource over 14 semi-diurnal-to-decadal timescales. 15

Following this objective, advanced resource assessments have been conducted to characterise spatial and temporal variability of the resource, using tidal analysis to derive the major tidal current harmonic components from model simulations [6, 7, 8]. These large-scale investigations, mainly focusing on the northwest European shelf seas, have provided detailed insights into tidal hydrodynamics that are particularly useful for potential device developers; for example, by exhibiting the spring-neap tidal variabilities of the resource, the expected tidal asymmetry of flow and rectilinear misalignment [7], or the phase diversity between discrete potential tidal stream energy sites [8].

These studies [6, 7, 8] derived a tidal current harmonic database in order 26 to evaluate the variability of the tidal stream energy resource beyond mean 27 tidal conditions. The phase relationship between the principal semi-diurnal 28  $M_2$  tidal current and its quarter-diurnal harmonic  $M_4$  may thus be calculated 29 to characterise asymmetries in energy extraction over tidal time scales [9]. 30 Sites identified with lower spring-neap tidal variability, which is desirable 31 for a more consistent tidal energy yield throughout the lunar cycle, can be 32 identified by computing the ratio between current amplitudes of principal 33 lunar  $M_2$  and solar  $S_2$  semi-diurnal harmonic constituents [7]. Tidal analysis 34 can also expose regions of diurnal inequalities where consecutive tidal cycles 35 are of unequal magnitude, and regions of lunar inequalities where consecutive 36 spring-neap cycles vary significantly. Over longer time scales, this approach 37 could evaluate inter-annual (or longer) variabilities in the resource, although 38 this has not yet been investigated in the literature. 39

Tidal ellipses can furthermore be generated in order to determine the orientation of the flow as either rectilinear or more rotary in character [10, 11, 12]. This approach can quantify the expected reduction in power due to rectilinear misalignment, helping developers optimise device design (e.g. fixed orientation, yawing, or floating-platform turbines). Making use of established tidal current harmonic databases, rather than developing new models, has
the additional advantage of increased spatial definition liable to incorporate
local solutions between 1/30 and 1/60° in coastal areas [13].

Considering these aspects of resource variability, the present study inves-48 tigates the benefits associated with generating a high-resolution tidal current 49 harmonic database for tidal stream resource assessments. Our study focuses 50 on the waters around France, where the strongest tidal currents are located 51 off western Brittany and in the English Channel (Fig. 1). This region hosts 52 two full-scale test sites for horizontal-axis, bottom-mounted, turbines: (1) 53 the OpenHydro demonstration farm off Paimpol-Brehat, and (2) the Sabella 54 device in the Fromveur Strait between the isle of Ushant and the Molène 55 archipelago (Figs. 1 and 2). In the western English Channel, this region cov-56 ers also the Alderney Race ("Raz Blanchard"), where a tidal farm of  $7 \times 2$ 57 MW horizontal-axis turbines is planned as part of the "Normandie Hydro" 58 project (Fig. 2). This regional analysis will finally benefit from an exten-50 sive comparison with several local resource assessments in these tidal stream 60 energy sites [14, 15, 16, 17, 18]. 61

This investigation uses a tidal harmonic database of elevation and depth-62 averaged current components, covering western Brittany and the English 63 Channel, at a consistent spatial resolution of 250 m (Section 2.1). When 64 compared with regional investigations conducted at kilometric spatial reso-65 lutions, the 250 m resolution database used here has the potential to resolve 66 the tidal hydrodynamics in narrow channels and in the vicinity of head-67 lands, both locations accounting for a high proportion of the potential tidal 68 stream energy resource [8]. For each harmonic constituent, tidal current el-69



Figure 1: Maximum depth-averaged tidal current speeds during a year, recomposed from 10 primary harmonic constituents ( $M_2$ ,  $S_2$ ,  $N_2$ ,  $K_2$ ,  $K_1$ ,  $O_1$ ,  $P_1$ ,  $Q_1$ ,  $M_4$  and  $MS_4$ ), in northwest European shelf seas around France. Red lines delineate (1) computational domains over the English Channel and the Bay of Biscay and (2) high-resolution embedded domains off western Brittany and in the western English Channel. The positions of tide gauges used for the evaluation of elevation harmonic components are shown as red filled circles.

<sup>70</sup> lipse parameters are derived from amplitudes and phases of eastward and <sup>71</sup> northward components (Section 2.2). We also characterise variabilities in <sup>72</sup> tidal stream power at quarter-diurnal and spring-neap time scales (Section <sup>73</sup> 2.3). After an evaluation of the harmonic database based on a compari-<sup>74</sup> son between predicted and observed tidal currents (Section 3.1), the criteria <sup>75</sup> adopted by Robins et al. [7], which considers peak current speeds in excess of 2.0 m s<sup>-1</sup> in mean spring conditions and water depths over 25 m, is applied
to identify suitable locations for the deployment of turbines in marine areas
around France (Section 3.2). Particular attention is given to spring-neap
tidal variability and asymmetry in power extraction (Sections 3.3 and 3.4).
With respect to previous regional studies, additional investigations are finally
conducted on the orientation and ellipticity of tidal currents at potential tidal
stream energy sites.



Figure 2: Bathymetry of western Brittany and the western English Channel (with respect to the lowest astronomical tide), with the locations of current meters in triangles. Blue triangles show the position of measurement points used for the assessment of MARS predictions. Red triangles (points #1, #2 and #3) correspond to locations selected, in the vicinity of major French tidal stream energy sites, for detailed evaluation of the current harmonic database.

#### <sup>83</sup> 2. Materials and methods

#### 84 2.1. Tidal harmonic database

The tidal harmonic database considered here has been developed from nu-85 merical simulations with the circulation model MARS [19] applied to north-86 western Europe [20]. A depth-averaged version of the numerical model cov-87 ers three nested computational domains with spatial resolutions of: (1) 2 km 88 across the northwest European shelf, (2) 700 m over the English Channel and 89 the Bay of Biscay, and (3) 250 m in western Brittany and the western English 90 Channel (Fig. 1). For the present investigation, we focus on outputs from 91 the 250 m resolution coastal domains since, upon inspection of Fig. 1, these 92 are the regions with the strongest resource. These nested models were driven 93 by sea-surface elevations derived from tidal harmonic components developed 94 by the French Navy SHOM ("Service Hydrographique et Océanographique 95 de la Marine") [21], and surges predicted by the large-scale models at 2 km 96 and 700 m spatial resolutions. Numerical simulations include atmospheric 97 forcings from the meteorological models ARPEGE and AROME of Météo-98 France [22, 23], with spatial and temporal resolutions of 0.5 and 0.025° and 99 6 and 1 hours, respectively. 100

Coastal predictions, at 15 min time intervals, were analysed with the Tidal Toolbox software provided by LEGOS [24], to compute the amplitude and phase of elevation and current harmonic components. These results were available on a staggered Arakawa C-grid. Bi-linear spatial interpolations were implemented to obtain all components at the center of the grid cells. As recommended by Pineau-Guillou [20], results close to offshore sea boundaries (in a band of 10% of the computational domain) were not considered in the <sup>108</sup> present investigation.

#### 109 2.2. Analysis of tidal currents

In the tidal database, the current of a given harmonic constituent is represented as eastward and northward components

$$\begin{cases}
east = U\cos(\omega t - \phi_u) , \\
north = V\cos(\omega t - \phi_v)
\end{cases}$$
(1)

where (U,V) and  $(\phi_u,\phi_v)$  are the associated amplitudes (m) and phases (degrees relative to Greenwich), respectively (Fig. 3), t is time (s) and  $\omega = 2\pi/T$  is the angular frequency of the harmonic component with T (s) the tidal period. However, specific computational methods are required to obtain current ellipse parameters, which characterise the magnitude, orientation



Figure 3: Schematic representation of a tidal current ellipse for a single harmonic current component with associated parameters.

and variation of associated tidal stream currents and, in turn, power. This 117 mathematical problem may be illustrated with the approach of the ellipse 118 semi-major axis (Fig. 3). Indeed, the amplitude of this axis, which accounts 119 for the maximum current speed over the tidal period, cannot be directly 120 computed from U and V, mainly as associated components are characterised 121 by different phases  $\phi_u$  and  $\phi_v$ . Two methods are available to compute tidal 122 current ellipse parameters: the first deals with trigonometric formulations, 123 the second relies on a less intuitive parameterisation in terms of polar vectors 124 [11]. The first method is applied here. As further details about the associated 125 formulations are available in Pugh [11] and elsewhere, this section resumes 126 the mathematical expression used in the present study. The maximum and 127 minimum values of the current speed, also defined as the semi-major and 128 semi-minor axes of the ellipse, are thus obtained from the following two 129 equations: 130

$$u_{max} = \left(\frac{U^2 + V^2 + \alpha^2}{2}\right)^{1/2} , \qquad (2)$$

$$u_{min} = \left(\frac{U^2 + V^2 - \alpha^2}{2}\right)^{1/2} \tag{3}$$

with  $\alpha^2 = [U^4 + V^4 + 2U^2V^2\cos(2(\phi_u - \phi_v))]^{1/2}$ . The rectilinear/circular nature of the tidal current ellipse is determined from the angle:

$$\beta = \arctan\left(\frac{u_{min}}{u_{max}}\right) \,, \tag{4}$$

which accounts for the ellipticity of the current hodograph<sup>1</sup>. Low values of  $\beta$  close to 0° indicate rectilinear currents, while values close to 45° imply

<sup>&</sup>lt;sup>1</sup>A diagram that provides a vectorial visual representation of the movement of a body or a fluid.

almost circular evolutions. The tidal current vector reaches the maximum amplitude  $u_{max}$  when  $\omega t = \text{phase} = \phi_u - \delta \pm 180^\circ$ , with  $\delta$  an angle obtained from the following relationship:

$$\delta = \frac{1}{2} \arctan\left(\frac{V^2 \sin(2(\phi_u - \phi_v))}{U^2 + V^2 \cos(2(\phi_u - \phi_v))}\right).$$
 (5)

<sup>138</sup> The direction of the maximum current speed is finally given by

$$\theta_{max} = \arctan\left(\frac{V\cos(\phi_u - \phi_v - \delta)}{U\cos(\delta)}\right).$$
(6)

In cases where different harmonic components are considered, this method
cannot be applied, and requires the extraction of the maximum value of the
recomposed time series of the tidal current over a duration compatible with
the tidal periods integrated.

#### 143 2.3. Tidal energy resource metrics

Following the study of Robins et al. [7] at the scale of the northwest 144 European shelf seas, a series of parameters are considered here to characterise 145 spatial and temporal variabilities of tidal currents and associated stream 146 power in coastal areas around France. Attention is primarily given to the 147 variability of tidal currents at fortnightly and semi-diurnal time scales, setting 148 aside analysis on diurnal inequalities, which appear to be of reduced influence 149 in western Brittany and the western English Channel [7] (Section 3.2). The 150 tidal current harmonic components analysed describe the spring-neap tidal 151 variability of the resource and the asymmetry of tidal currents between the 152 flood and ebb phases of the tidal cycle. 153

At potential tidal stream energy sites, minimal differences between spring and neap currents are considered desirable, as this leads to a more consistent energy yield over the fortnightly spring-neap period. Tidal kinetic energy converters, designed to operate over a restricted range of velocities [25], do not appear to be adapted to hydrodynamic environments with high springneap tidal variability. Following Robins et al. [7], this variability is here characterised by the ratio  $R_{var}$  between the maximum amplitudes of the principal lunar M<sub>2</sub> and solar S<sub>2</sub> depth-averaged velocities,  $u_{max}(M_2)$  and  $u_{max}(S_2)$ :

$$R_{var} = 1 - \frac{u_{max}(S_2)}{u_{max}(M_2)} .$$
 (7)

Over the northwest European shelf seas, as the amplitude of  $S_2$  velocities 163 are always weaker than the principal  $M_2$  velocities,  $R_{var}$  varies between 0 164 and 1. Values of  $R_{var}$  close to unity account for reduced spring-neap tidal 165 variability, whilst values close to zero show noticeable differences between the 166 spring and neap tidal cycles. Particular attention is furthermore devoted to 167 the modifications of current directions between simple  $M_2$  components and 168 combined  $M_2$  and  $S_2$  harmonic constituents. Following Lewis et al. [26], this 169 influence is exhibited by characterising misalignment between the flood and 170 ebb current directions during mean spring conditions: 171

$$\theta_{var} = \arccos\left(\frac{-\vec{u}_{flood}.\vec{u}_{ebb}}{|\vec{u}_{flood}|.|\vec{u}_{ebb}|}\right) \tag{8}$$

where  $\vec{u}_{flood}$  and  $\vec{u}_{ebb}$  are the peak velocity vectors during flood and ebb periods at the location considered during mean spring conditions resulting from M<sub>2</sub> and S<sub>2</sub> harmonic components. Low values of  $\theta_{var}$  characterise a reduced asymmetry in current direction, whereas higher values account for a strong tidal current misalignment.

At the semi-diurnal time scale, current asymmetry is another key parameter which characterises the variability in power production between flood

and ebb. As inferred by Pingree and Griffiths [27] and Friedrichs and Aubrey 179 [28], asymmetry in tidal currents may arise from the phase relationship be-180 tween the principal semi-diurnal  $M_2$  and its first quarter-diurnal  $M_4$  har-181 monic. Adopting the parameterisation described in Section 2.2, maximum 182 asymmetry is thus obtained when peak velocities of harmonic current vec-183 tors appear at the same time, which results in the following relationship: 184  $\gamma = 2 \text{phase}(M_2) - \text{phase}(M_4) = 0^\circ \text{ or } 180^\circ \text{ in the range } [0, 360^\circ].$  Symmetry 185 of tidal currents occurs when  $M_2$  and  $M_4$  constituents are out of phase with 186  $\gamma = 90^{\circ}$  or 270°. As the ratio between semi- and quarter-diurnal tidal cur-187 rent amplitude directly exacerbates this asymmetry, a parameter based on 188 Robins et al. [7], is adopted here relying on ellipse characteristics: 189

$$A_1 = \frac{u_{max}(\mathbf{M}_4)}{u_{max}(\mathbf{M}_2)} |\cos(\gamma)| .$$
(9)

<sup>190</sup> High values of  $A_1$  in the range [0,1] account for significant tidal asymmetry, <sup>191</sup> whilst low values indicate more symmetrical currents. In order to ascertain <sup>192</sup> the reliability of this parameter, a comparison is performed with a more <sup>193</sup> classical approach of tidal current asymmetry based on the ratio of peak <sup>194</sup> tidal currents, resulting from M<sub>2</sub> and M<sub>4</sub> components, during flood and ebb:

$$A_2 = 1 - \frac{u_{peak,1}}{u_{peak,2}} \tag{10}$$

where  $u_{peak,2}$  is the maximum of the peak velocity between flood and ebb and  $u_{peak,1}$  is the minimum peak velocity. This parameter, which varies between 0 and 1, should therefore be consistent with  $A_1$ .

#### <sup>198</sup> 3. Results and discussion

### <sup>199</sup> 3.1. Validation of the tidal harmonic database

The harmonic database has been assessed by Pineau-Guillou [20] by com-200 paring recomposed tidal water elevations with observations at a series of 18 201 harbours along the coasts of France (Fig. 1). The root mean square error 202 (RMSE) between predictions and observations was calculated, on average, at 203 around 20 cm, matching with the range of mean surges. Maximum RMSE of 204 27 cm is obtained at Boulogne-sur-Mer in the Dover Strait (eastern English 205 Channel). These evaluations have been extended by comparing predicted 206 and observed harmonic components of surface elevations. The spatial dis-207 tribution of major elevation components  $M_2$  and  $S_2$ , at tide gauges, is thus 208 approached with differences less than 5% for amplitude and  $8^{\circ}$  for phase. 209 Further details about the evaluation of the elevation harmonic database are 210 available in Pineau-Guillou [20]. 211

Coastal current predictions of MARS, used to establish the harmonic 212 database (Section 2.1), have been compared with observations compiled by 213 the French Navy SHOM, measured during spring tide conditions, at a series 214 of 37 locations over western Brittany and the western English Channel (Fig. 215 2) [29]. In addition, the validation has been extended to include a series of 216 three available ADCP deployments in two areas with strong potential for the 217 exploitation of the tidal kinetic energy resource: the Fromveur Strait and 218 the Alderney Race. These observations include (see Fig. 2 and Table 1): 219 (1) long-term records conducted by SHOM in western Brittany (point #1), 220 and (2) two short-term campaigns implemented by Bailly du Bois [30] in the 221 western English Channel (points #2 and #3). 222

In relation to the availability of in-situ data, the validation in western 223 Brittany was performed at 10 m above the seabed – this elevation corre-224 sponds to the operating height of proposed horizontal axis turbines in French 225 tidal stream energy sites (Fig. 4). Following Guillou and Thiébot [17], the 226 tidal currents at 10 m above the seabed were obtained from the recomposed 227 depth-averaged currents by assuming a vertical logarithmic velocity profile 228 with a bottom roughness parameter set to  $z_0 = 20$  mm. Whereas a Strickler 229 law is adopted in the depth-averaged MARS model [29], this roughness value 230 of  $z_0 = 20$  mm, adopted over bottom rock outcrops in the Fromveur Strait, 231 provided the best estimates of current amplitude and direction at point #1232 [17]. Depth-averaged currents are recomposed from the 10 primary harmonic 233 components:  $M_2$ ,  $S_2$ ,  $N_2$ ,  $K_2$ ,  $K_1$ ,  $O_1$ ,  $P_1$ ,  $Q_1$ ,  $M_4$  and  $MS_4$ . In spite of a ten-234 dency to overestimate spring current magnitudes, seemingly associated with 235 different parameterisations of bottom friction, and exhibited by the positives 236 values of the mean relative difference  $\text{DIFF}_{\text{rel}}$  (Tab. 2), the numerical results 237 reproduce the variations of tidal velocity, in particular, the abrupt changes 238 between south-west and north-east directions (Fig. 4). 239

The evaluation of depth-averaged current amplitude in the western English Channel (Fig. 5) confirms the ability of the coastal harmonic database to characterise tidal velocities, with RMSE restricted to 0.16 m s<sup>-1</sup>. Further, variation of current direction is estimated with an index of agreement RE [31] over 0.98 at both measurements points #2 and #3. Stronger differences, obtained at point #3, may be associated with tidal recirculations in the vicinity of surrounding headlands that are not fully resolved in the model.

<sup>247</sup> Finally, additional investigations show that the recomposed maximum

depth-averaged velocities based on  $M_2$  and  $S_2$  components, i.e. the mean spring peak currents (Fig. 6), are consistent with current maps established by the SHOM and EDF R&D over western Brittany and the western English Channel [32], identifying areas of strong velocity amplitudes with differences restricted to  $0.2 \text{ m s}^{-1}$ .

Table 1: Details of ADCP deployments.									
Measurement	Coordinates		Water depths	Periods of					
points	Lon.	Lat.	(m)	measurements					
#1	$5.036^{\rm o}$ W	48.449° N	53	$19/03/1993 \rightarrow 02/04/1993$					
#2	$2.055^{\rm o}~{\rm W}$	$49.522^{\rm o}~{\rm N}$	29	$10/08/2003 \to 12/08/2003$					
#3	$1.993^{\rm o}~{\rm W}$	$49.614^{\rm o}~{\rm N}$	25	$09/08/2003 \rightarrow 11/08/2003$					

Table 2: Statistical parameters for the evaluation of observed currents amplitude U and direction Dir at points #1, #2 and #3: the mean relative difference  $DIFF_{rel}$ , the root

mean square error RMSE and the index of agreement RE [31].									
	Measurement	U			Dir				
	points	$\mathrm{DIFF}_{\mathrm{rel}}$	RMSE	RE	$\mathrm{DIFF}_{\mathrm{rel}}$	RMSE	RE		
	#1	$0.18 { m m s^{-1}}$	$0.31 \mathrm{ms^{-1}}$	0.96	$-6.7^{\circ}$	$36.0^{\rm o}$	0.96		
	#2	$0.06~{ m ms^{-1}}$	$0.09~{\rm ms^{-1}}$	0.97	$2.1^{\circ}$	$19.3^{\mathrm{o}}$	0.99		
	#3	$0.10 { m ms^{-1}}$	$0.16 { m  m  s^{-1}}$	0.96	$-5.7^{\circ}$	$24.7^{\rm o}$	0.98		

## <sup>253</sup> 3.2. Identification of potential tidal stream energy sites

In the majority of resource assessments around the United Kingdom [7, 26, 33, 34], the identification of potential tidal stream energy sites is mainly based on current speeds and water depths, neglecting further constrains associated with the practical, political, or environmental issues or



Figure 4: Recomposed (blue line) and observed (red line) time series of current amplitude and direction (anticlockwise convention from the East) 10 m above the seabed at point #1 in March-April 1993.



Figure 5: Recomposed (blue line) and observed (red line) time series of depth-averaged current amplitude and direction (anticlockwise convention from the East) at points #2 and #3 in August 2003.



Figure 6: Maximum depth-averaged velocities from  $M_2$  and  $S_2$  harmonic components in western Brittany and the western English Channel. The black contours delineate potential tidal stream energy sites characterised by mean spring peak velocities over  $2 \text{ m s}^{-1}$  and water depths over 25 m.

marine activities. The present resource assessment is based on the criteria 258 adopted by Robins et al. [7] to identify potential locations for first- and 259 second-generation technologies of tidal stream energy converters, covering 260 both existing prototype devices in pre-commercial demonstration and at the 261 early stages of technology readiness [34]. This corresponds to areas with: (1) 262 peak current speeds in excess of  $2.0 \text{ m s}^{-1}$  in mean spring conditions, and (2) 263 a minimum water depth of 25 m. Further insights may be provided about 264 these limits from a rationale based on the output power formula of horizontal-265

axis turbines  $P_{out} = (\rho C_p \pi D^2 u^3)/8$  with  $\rho$  the density of sea water (kg m<sup>-3</sup>),  $C_p$  the power coefficient, D the blade diameter (m) and u the tidal current speed (m s<sup>-1</sup>).

Taking into account a range of device power coefficients [25], it is thus 269 necessary to have a peak current speed of at least  $2.0 \text{ m s}^{-1}$  in combination 270 with a minimum turbine diameter of 20 m to attain a power output of 0.5271 MW, the lowest threshold of most horizontal-axis turbines currently tested 272 and implemented at potential tidal stream energy sites (Fig. 7). The min-273 imum current speed is  $2.5 \text{ m s}^{-1}$  to attain a power output of 1 MW with 274 the same device characteristics. In order to ensure a constant immersion 275 of devices and sufficient navigational clearance, a minimum water depth of 276 around 25 m is required for this type of tidal stream power extraction. 277



Figure 7: Minimum turbine diameter required to achieve power outputs of (a) 0.5 and (b) 1 MW, with respect to power coefficient  $C_p$  and tidal current velocity u. Diameters over 25 m are not shown on the figure.

In the present study, the criteria adopted for site selection considers the mean spring peak velocities resulting from M<sub>2</sub> and S<sub>2</sub> harmonic current components in the high-resolution coastal database (Section 2.1), and the water depth extracted from the HOMONIM ("Historique, Observation, MOdélisation des NIveaux Marins", SHOM, Météo-France) database [35, 36] which covers the areas of interest at a spatial resolution of 111 m.

Along the coasts of France, potential tidal stream energy sites are mainly 284 identified in western Brittany and the western English Channel (Fig. 6). 285 Whereas all sites are characterised by a mean kinetic power density that 286 exceeds  $0.8 \text{ kW} \text{m}^{-2}$  during a mean spring tidal cycle, the western area of 287 Alderney (Casquets), the Alderney Race and the Fromveur Strait are the 288 three locations where this power density significantly exceeds  $2.5\;\rm kW\,m^{-2}$ 289 - meeting the resource criteria adopted by the Carbon Trust [37] for the 290 deployment of first-generation turbine devices (Fig. 8, Table 3). The refined 291 calculation of kinetic power density over these regions appears consistent 292 with predictions from high-resolution nested numerical models. These results 293 show: (1) in the Fromveur Strait, zones of high energy formed in between 294 the islands with peak power density in each zone ranging from  $4 \text{ kW m}^{-2}$  to 295 over  $7 \text{ kW m}^{-2}$  [16, 17], and (2) in the Alderney Race, a concentration of 296 tidal stream energy over  $10 \text{ kW m}^{-2}$  around the Cotentin Peninsula [15, 18]. 297 Areas identified off the Cotentin Peninsula and in the Alderney Race are 298 particularly remarkable, accounting for a total surface of around  $1750 \text{ km}^2$  in 299 the embedded coastal domain. The mean power density associated with this 300 potential sea space is estimated at  $1.6 \text{ kW m}^{-2}$ , with minimum and maximum 301 values of 0.9 and  $12.4 \text{ kW m}^{-2}$ , respectively. However, the total surface is 302



Figure 8: Mean kinetic power density distribution during a spring-neap tidal cycle (T=14.765 days)) resulting from  $M_2$  and  $S_2$  components in (a) coastal domains, with magnified views in (b) the Fromveur Strait and (c) the Alderney Race. The black lines delineate potential tidal stream energy sites identified in Fig. 6.

markedly reduced by 80% to  $350 \text{ km}^2$  if a threshold of mean spring peak velocity of  $2.5 \text{ m s}^{-1}$  is imposed. This difference highlights, in particular, the increased sea space associated with the development of tidal stream turbine technologies more suited to harnessing less energetic tidal streams. It should finally be noted that the area located west of Alderney (Casquets) accounts for a total surface of 90 km<sup>2</sup>, with averaged power density during a mean spring tidal cycle liable to exceed 9 kW m<sup>-2</sup> (Table 3).

Outside of these significant areas, potential tidal stream energy sites occupy surfaces restricted to  $40 \text{ km}^2$  – predominantly in the vicinity of headlands and straits, confirming previous investigations conducted by Neill et

Table 3: Characteristics of major potential tidal stream energy sites associated with the averaged kinetic power distribution during a spring-neap tidal cycle resulting from  $M_2$  and  $S_2$  components (Fig. 8): total surface, mean power density  $P_{mean}$ , minimum and maximum values of the averaged power density  $P_{min}$  and  $P_{max}$  over the sea space of tidal stream energy sites.

Sites	Areal extent	$P_{mean}$	$P_{min}$	$P_{max}$
	$(\rm km^2)$	$(\rm kWm^{-2})$	$(\mathrm{kW}\mathrm{m}^{-2})$	$(\rmkWm^{-2})$
Raz of Sein	15	1.4	0.9	2.8
West of Ushant	40	1.4	0.8	3.2
Fromveur Strait	17	2.9	0.9	7.9
North-western Brittany	7	1.1	0.9	1.7
Paimpol-Bréhat	18	1.1	0.9	1.8
East of Sark	8	1.4	0.9	2.6
East of Guernsey (Big Roussel)	26	1.5	0.9	2.3
West of Alderney (Casquets)	90	1.5	0.9	9.9
Off Cotentin Peninsula	1753	1.6	0.9	12.4

al. [8]. Over these areas, the mean value of the associated power density is 313 estimated between 1.1 and 1.5  $\rm kW\,m^{-2}$  with peak values below 3.2  $\rm kW\,m^{-2}$ 314 (Table 3). These locations include the well-known French tidal stream energy 315 sites in the Raz of Sein and off Paimpol-Bréhat, and also potential locations 316 to the west of Ushant island and to the east of Guernsey (Big Roussel). In 317 the Channel Islands Gulf, our resource assessment confirms conclusions from 318 reports commissioned by the Carbon Trust [33, 38]. However, potential sites 319 off the northwest coast of Guernsey and off the northeast coast of Jersey were 320 not identified here. This is consistent with results obtained by Coles et al. 321 [18] with a depth-averaged tidal circulation model covering these areas with 322 a mesh resolution of 250 m. Other potential tidal stream energy sites with 323

<sup>324</sup> surfaces areas less than 8 km<sup>2</sup> are also identified along the northern coast of <sup>325</sup> western Brittany and to the east of Sark. Over these two regions, the mean <sup>326</sup> power density is estimated at 1.1 and 1.4 kW m<sup>-2</sup>, respectively (Table 3).

We investigated the rectilinear/circular nature of tidal currents by focus-327 ing on the ellipticity associated with the principal lunar semi-diurnal compo-328 nent  $M_2$  (Fig. 9). In the English Channel, the spatial distribution of param-329 eter  $\beta$  (Eq. 4) appears consistent with the numerical investigation conducted 330 by Fornerino and Le Provost [10], indicating strong gyratory currents in the 331 areas surrounding Guernsey and Jersey. However, with the exception of sites 332 identified in the Raz of Sein and to the west of Alderney, the values of  $\beta$  for 333  $M_2$  were less than 5° at potential tidal stream energy sites. This means that 334 these sites contain near rectilinear M<sub>2</sub> tidal currents, a key property required 335 for the installation of horizontal-axis turbines with a fixed orientation. 336

Finally, the capacity factor of a series of horizontal-axis turbines varying 337 in rated power is evaluated in order to provide potential developers further 338 insights into device operating times (Fig. 10). Indeed, the capacity factor 330 accounts for the fraction of the year the turbine generator is operating at 340 rated power. Capacity factor was thus computed, defined as the averaged 341 power produced over a year divided by the rated turbine power. This analysis 342 relies on velocities recomposed from the 10 primary tidal harmonic compo-343 nents used to calculate Fig. 1. The power curves considered are based on the 344 OpenHydro device [39], by assuming a cut-in speed of  $0.7 \text{ m s}^{-1}$  and rated 345 speeds of 1.7, 2.1, 2.5 and 2.7 m s<sup>-1</sup>, matching rated powers of 0.5, 1.0, 1.5 346 and 2.0 MW, respectively. The capacity factor of 0.5 MW devices exceeds 347 40% in most potential tidal stream energy sites, with maximum values over 348



Figure 9: Spatial distribution of angle  $\beta$  (Eq. 4), characterising the ellipticity of M<sub>2</sub> tidal currents in western Brittany and the western English Channel. The black lines delineate potential tidal stream energy sites identified in Fig. 6.

70% in the Fromveur Strait, the Alderney Race and west of Alderney in 349 relation to higher current speeds (Fig. 10-a). The capacity factor is natu-350 rally reduced for higher rated powers with values restricted to 35% for 1.5 351 MW turbines in most potential locations, with exceptions in the three sites 352 previously identified (Fig. 10-c). However, the associated averaged power is 353 found to increase for high rated power. In the Alderney Race, the averaged 354 power produced over a year is thus restricted to 0.3 MW for 0.5 MW devices, 355 whereas it would exceed 1.1 MW for 2 MW turbines. 356



Figure 10: Annual capacity factor based on power curves with rated powers of (a) 0.5, (b) 1.0, (c) 1.5 and (d) 2.0 MW. The black lines delineate the potential tidal stream energy sites identified in Fig. 6.

#### 357 3.3. Spring-neap variability

Confirming the investigation conducted by Robins et al. [7] over the 358 north-west European shelf seas,  $R_{var}$  (Eq. 7) varies between 0.55 and 0.80 359 in western Brittany and the western English Channel (Fig. 11). A clear 360 gradient of the spring-neap tidal variability of currents is exhibited in the 361 Channel Islands between a south-western area characterised by high vari-362 ability  $(R_{var} < 0.61)$  and a north-eastern region with reduced variability 363  $(R_{var} > 0.67)$ . This difference is exhibited between the Alderney Race and 364 the Fromveur Strait by retaining two locations with contrasting values of 365  $R_{var} = 0.629$  in the Fromveur Strait (point p1) and  $R_{var} = 0.695$  in the 366 Alderney Race (point p2). 367

Fig. 12 displays the extracted depth-averaged velocities resulting from 368  $M_2$  and  $S_2$  harmonic components and the generated "technical" resource by 369 applying the power curve of a 1.5 MW OpenHydro device and by neglecting 370 turbine interactions and feedback between energy extraction and the hydro-371 dynamics. While the tidal velocity reaches slightly stronger magnitudes at 372 the location considered in the Fromveur Strait ( $u_{max} = 3.41 \text{ m s}^{-1}$  at point 373 p1 against  $3.36 \text{ m s}^{-1}$  at point p2), currents generate less power than at the 374 point retained in the Alderney Race. The generated power over a mean 375 spring-neap tidal cycle is thus estimated at 223 MWh at point p1 while it 376 reaches 235 MWh at point p2. Whereas this difference accounts for about 5%377 of the total spring-neap generated power, with capacity factors estimated at 378 42.1 and 44.2%, differences between sites increase significantly during neap 379 tide conditions. Indeed, both locations show maximum spring tidal current 380 velocities over the rated speed of the OpenHydro device, with differences in 381

generated power mainly attributed to neap conditions. During neap tides,
the maximum generated power is thus estimated at 0.63 MW at point p2,
while it is restricted to 0.43 MW at point p1 (Fig. 12).

Further investigations, conducted to calculate tidal current misalignment, depict low values of the parameter  $\theta_{var}$  (Eq. 8); restricted to 2° between the flood and ebb current directions of peak mean spring currents, in the majority of potential tidal stream energy sites. Such misalignment direction lies below the limit under which power reductions may be apparent for horizontal-fixed



Figure 11: Spatial distribution of parameter  $R_{var}$ , characterising the variability of tidal current amplitude over a mean spring-neap cycle in (a) coastal domains, with magnified views in (b) the Fromveur Strait and (c) the Alderney Race. The black circles in (b) and (c) show the positions of points p1 and p2 used for the extraction of recomposed currents amplitude and direction (Fig. 12). The black lines delineate potential tidal stream energy sites identified in Fig. 6.



Figure 12: Predicted depth-averaged tidal current velocities U over a mean spring-neapspring cycle, and associated generated practical power,  $P_{out}$ , based on the 1.5 MW Open-Hydro power curve in (top) the Fromveur Strait (point p1,  $R_{var} = 0.629$ ) and (bottom) the Alderney Race (point p2,  $R_{var} = 0.695$ ). The red line accounts for the effective tidal velocity which generates power.

axis turbines. Indeed, Galloway et al. [40] estimated this limit at 7.5° by 390 relying on experimental data and a Blade Element Momentum (BEM) code. 391 More recently, Frost et al. [41] demonstrated, from Computational Fluid Dy-392 namics modelling, a drop of 7% in the maximum theoretical available power 393 between misalignment angles of 0 and  $10^{\circ}$ . Directional asymmetry exceeds 394 15° in limited locations of potential tidal stream energy sites. Confirming the 395 investigation conducted by Lewis et al. [26] in the Irish Sea, this concerns 396 mainly areas associated with tidal recirculations appearing around Cap de la 397 Hague (the north-western headland off the Cotentin Peninsula), and west of 398 Alderney and Ushant islands. Taking into account the reduced ellipticity of 399

the current harmonic M<sub>2</sub> in the majority of sites of interest (Section 3.2, Fig. 9), the tidal current appears thus nearly rectilinear during mean spring conditions, an additional condition required to optimise the exploitation of the tidal kinetic energy resource. Whereas further investigations are required, relying on refined numerical modelling in potential tidal stream sites and integrating the influence of a greater number of harmonic components, these results support the implementation of fixed-orientation (non-yawing) devices.

# 407 3.4. Asymmetry of tidal currents

Fig. 13 shows the spatial distributions of asymmetry metrics  $A_1$  (Eq. 9) 408 and  $A_2$  (Eq. 10) in western Brittany and the western English Channel. A 409 close correlation is obtained between both parameters, confirming the relia-410 bility of parameter  $A_1$  to characterise the asymmetry of tidal currents from 411 the amplitude and phase of harmonic components  $M_2$  and  $M_4$ . At regional 412 scale, numerical results appear consistent with results reported by Robins 413 et al. [7], exhibiting strong tidal asymmetry in the Channel Island Gulf. 414 However, the refined spatial resolution in the present study resolves tidal 415 current asymmetry at the scale of straits, as well as in the vicinity of islands 416 and headlands. Contrasting asymmetries are thus exhibited between sites. 417 The region off the Cotentin Peninsula shows globally weak tidal asymmetry, 418 whereas high values of parameters  $A_1$  and  $A_2$  are obtained in the vicinity of 419 Alderney and coastal headlands, in relation to the formation of tidal residual 420 eddies [42]. 421

Further, the Fromveur Strait is characterised by pronounced tidal current asymmetry. As described elsewhere in the literature [17, 43, 44], this asymmetry is associated with one area experiencing northeast-directed flood-



Figure 13: Spatial distribution of parameters  $A_1$  (top) and  $A_2$  (bottom) characterising the asymmetry of tidal currents in (a) coastal domains, with magnified views in (b) the Fromveur Strait and (c) the Alderney Race. The blue circles in (b) show the positions of points p3 and p4 used for the extraction of recomposed currents amplitude and direction in Fig. 14. The black lines delineate potential tidal stream energy sites identified in Fig. 6.



Figure 14: Predicted depth-averaged tidal current speeds U during mean spring-neap conditions and associated generated practical power,  $P_{out}$ , based on the 1.5 MW OpenHydro power curve in the central (point p3) and southern (point p4) Fromveur Strait. The red line accounts for the effective tidal velocity which generates power.

dominated flows, and another area experiencing southward ebb-dominated flows. For this region, we confirm the relationship between tidal current asymmetry and the relative phase lag of the M<sub>2</sub> component to M<sub>4</sub>, as previously shown from surface velocity measurements by Thiébaut and Sentchev [43], and from numerical simulations by Guillou and Chapalain [44]. The results also confirm the asymmetry in tidal currents off Paimpol-Bréhat reported by Pham and Martin [45].

We extracted depth-averaged tidal velocities from  $M_2$ ,  $S_2$  and  $M_4$  components, and calculated the associated generated practical power from a hypothetical OpenHydro device at two points in the central (point p3) and southern (point p4) Fromveur Strait (Figs. 13-b and 14). The two locations

considered are characterised by similar spring-neap tidal variabilities, with 436 values of parameter  $R_{var} \simeq 0.64$ . At point p3, the flow is largely symmetrical 437  $(A_1 = 0.01;$  Fig. 14-a), with mean spring-neap power estimated at 242 MWh 438 (Fig. 14-c). However, at point p4, the flow is asymmetrical  $(A_1 = 0.12; \text{ Fig.})$ 439 14-b), with mean spring-neap power estimated as 12% less (213 MWh; Fig. 440 14-d). During the 6-day period from neap to spring conditions, variations 441 of peak practical power were up to 1.0 MW between two consecutive tidal 442 cycles at point p4 (characterised by tidal asymmetry), whereas variations of 443 p3 were restricted to 0.5 MW. This result suggests that fine scale resource 444 assessments are beneficial for device optimisation at array scales. Finally, our 445 results highlight the interest of the Alderney Race, characterised by reduced 446 tidal current asymmetry (Fig. 13), for the exploitation of the tidal kinetic 447 energy resource. 448

#### 449 4. Conclusions

A high-resolution tidal harmonic database has been exploited to pro-450 vide detailed insights into the characteristics of tidal currents and associated 451 power in the coastal waters of France, focusing on western Brittany and the 452 western English Channel – two areas that have strong potential for the ex-453 ploitation of the tidal kinetic energy resource. The harmonic database has 454 been assessed by comparing recomposed tidal water elevations with observa-455 tions at a series of harbours along the coasts of France. This evaluation has 456 been extended by comparing recomposed tidal currents with a series of three 457 in-situ ADCP datasets available in the vicinity of principal areas identified 458 for tidal array development. In addition to a map of potential tidal stream 459

energy sites based on current magnitudes and water depths, a method is proposed to exploit, at reduced computational costs, the amplitudes and phases
of current harmonic components, and to characterise the spatial and temporal variabilities of the resource. The main outcomes of the present study are
as follows:

1. The resource identified in the western English Channel, off the Cotentin 465 Peninsula, has great potential for tidal stream energy – comprising 466 a significant part of the tidal kinetic energy around France. Tidal 467 currents reach  $4 \text{ m s}^{-1}$  in this region during spring conditions, and the 468 total exploitable surface area is estimated to be  $1750 \text{ km}^2$ , based on the 469 criteria of mean spring currents greater than  $2.0 \text{ m s}^{-1}$  and water depths 470 greater than 25 m. The average power density during mean spring tidal 471 conditions varies between 0.9 and  $12.4 \text{ kW m}^{-2}$ , with a mean value 472 estimated at  $1.6 \text{ kW m}^{-2}$ . This accounts for a concentration of tidal 473 stream energy in the Alderney Race, around the Cotentin Peninsula. 474

2. Strong values of the kinetic power density (over 7 kW m<sup>-2</sup> during a mean spring tidal cycle) are also obtained in the western area of Alderney (Casquets) and the Fromveur Strait. Other potential locations include areas restricted to 40 km<sup>2</sup>, in the Raz of Sein, off Paimpol-Bréhat, to the west of Ushant and to the east of Guernsey (Big Roussel).

480 3. However, there is significant temporal and spatial variability in the
481 amplitude and direction of tidal stream power. Such variabilities can
482 both reduce the total energy yield, and reduce the consistency of the
483 energy yield over daily-to-fortnightly time scales.

484 4. The majority of potential tidal stream energy sites investigated here

- are characterised by near-rectilinear flows in spring conditions which
  favours the installation of fixed-orientation devices.
- 487 5. However, some regions show greater spring-neap tidal variability than
  488 others (e.g. less variability to the north-east of the Channel Islands and
  489 more variability in western Brittany). Sites off the Cotentin Peninsula
  490 show, in particular, reduced spring-neap tidal variability, contributing
  491 to reduced variations in energy conversion.
- 6. Tidal currents off the Cotentin Peninsula are largely symmetrical, whereas
  more pronounced tidal asymmetry occurs off Paimpol-Bréhat, in the
  western part of the Isle of Ushant and in the Fromveur Strait.

Our results, established using high-spatial resolutions (250 m), provide po-495 tential developers with key information to optimise the design and location of 496 kinetic energy converters. The series of metrics reported here may help pre-497 liminary assessments of resource variability, both spatially and temporally, 498 particularly useful in areas which have been the subject of a reduced number 499 of investigations of the tidal stream energy resource. However, such resource 500 assessment has naturally to be complemented by refined numerical modelling 501 that integrates, in particular, the complex interactions and modulations of 502 tidal currents with meteorological forcings (wind, waves), and focusing on 503 hydrodynamic characteristics throughout the water column. 504

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