Tidal energy - Hydrolien

École thématique sur les technologie EMRs

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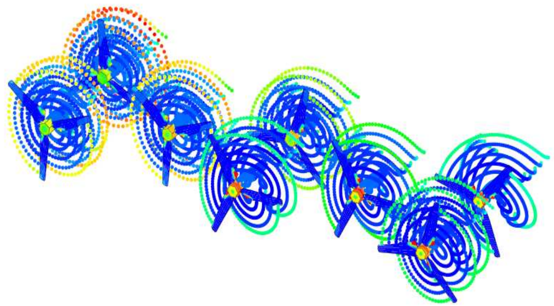
Hydrolien au LOMC

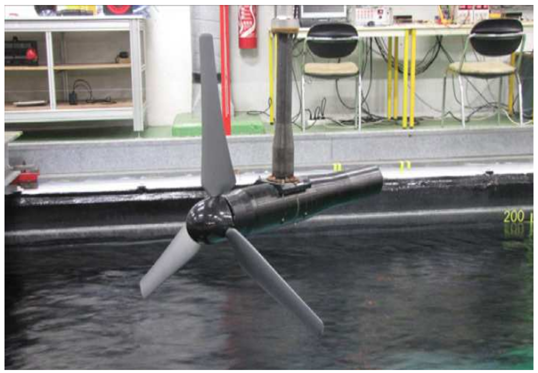
- Code « DOROTHY »
  - Performance et sillage
  - Code parallèle – F90 MPI – CRIANN

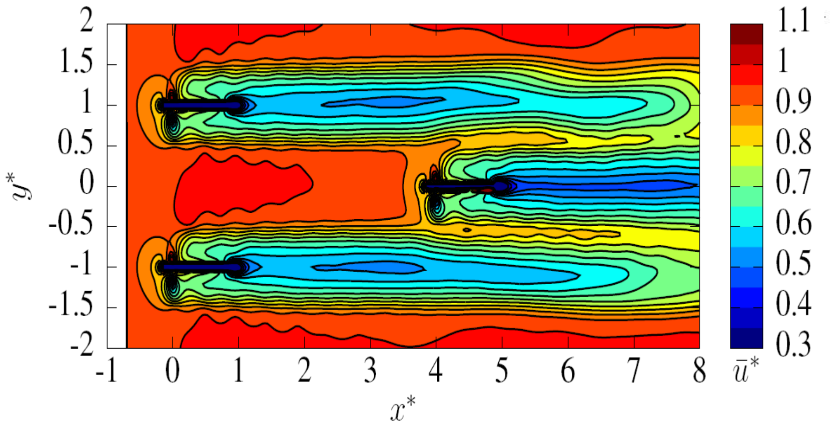
  - Méthode « Vortex »
  - Langrangien

  - Interaction
  - Turbulence

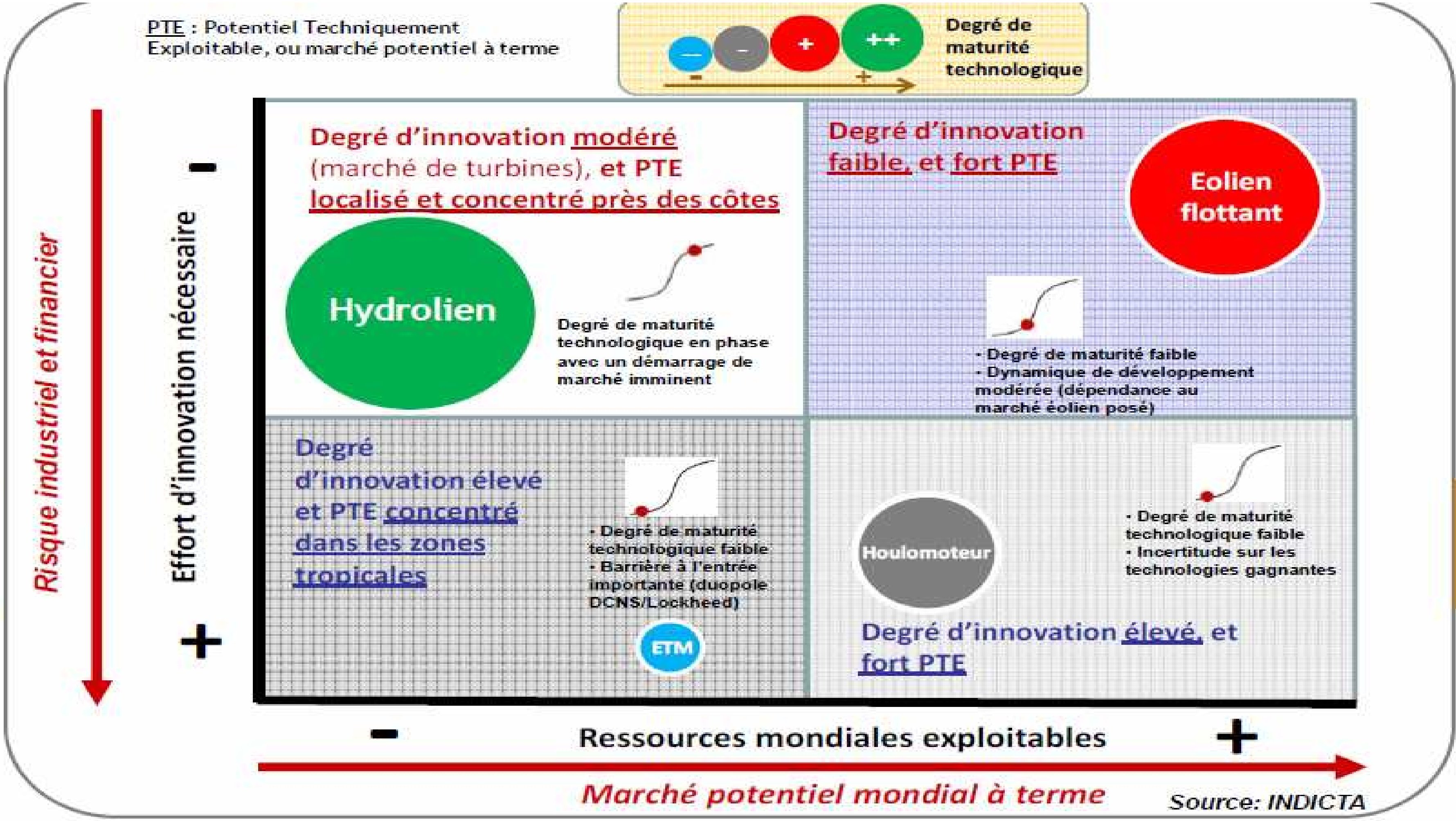


- Expérience à l'IFREMER





Fundamentals of tidal energy



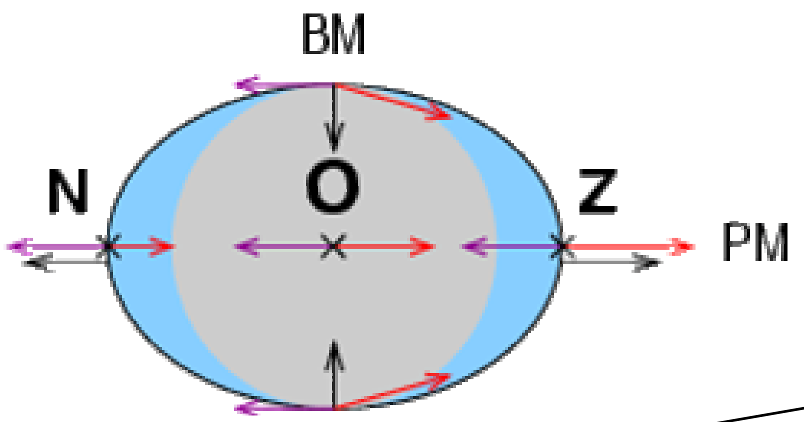
Segmentation des quatre marchés EMR

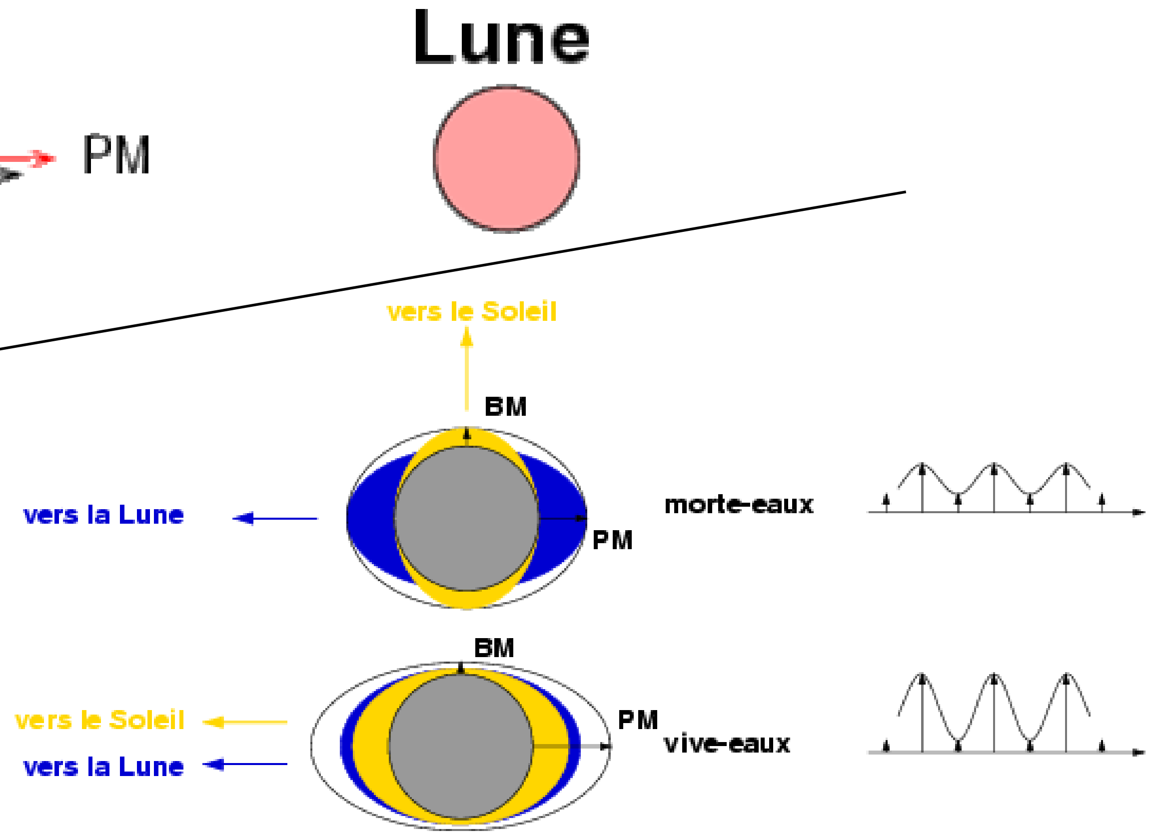
Outline

- Physics of tide and resource
- Physical Basis
- Fundamentals of tidal energy
- Tidal resource
- Resource characterisation
- History of tidal energy
- Technology review
- Conclusion

Physics of tide and resource at the world level

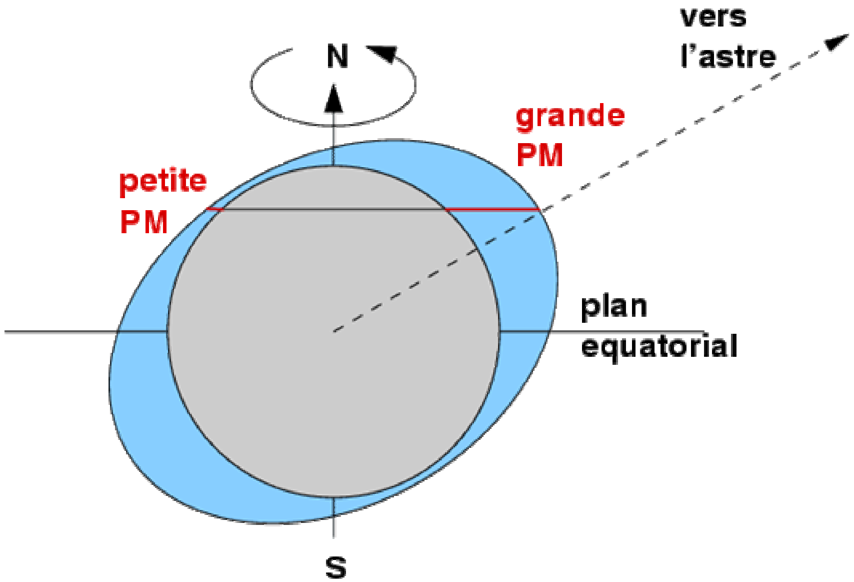
- Physical explanation





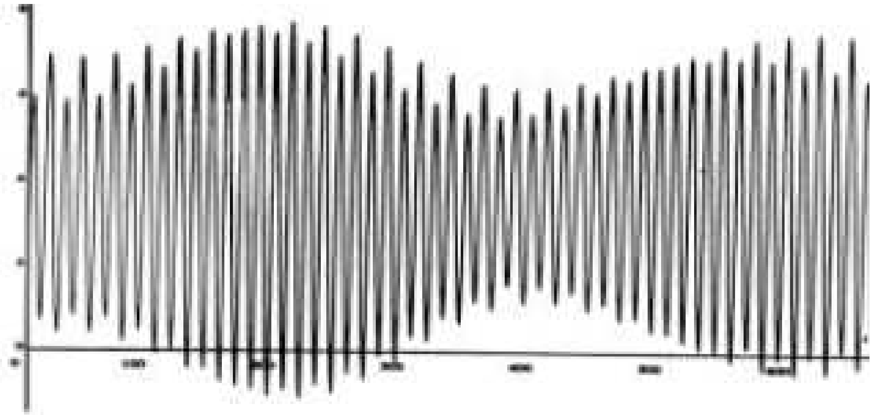
http://www.ifremer.fr/lpo/cours/maree/forces.html

Physics of tide and resource at the world level



- Reliable
- Predictable
- Inexhaustible

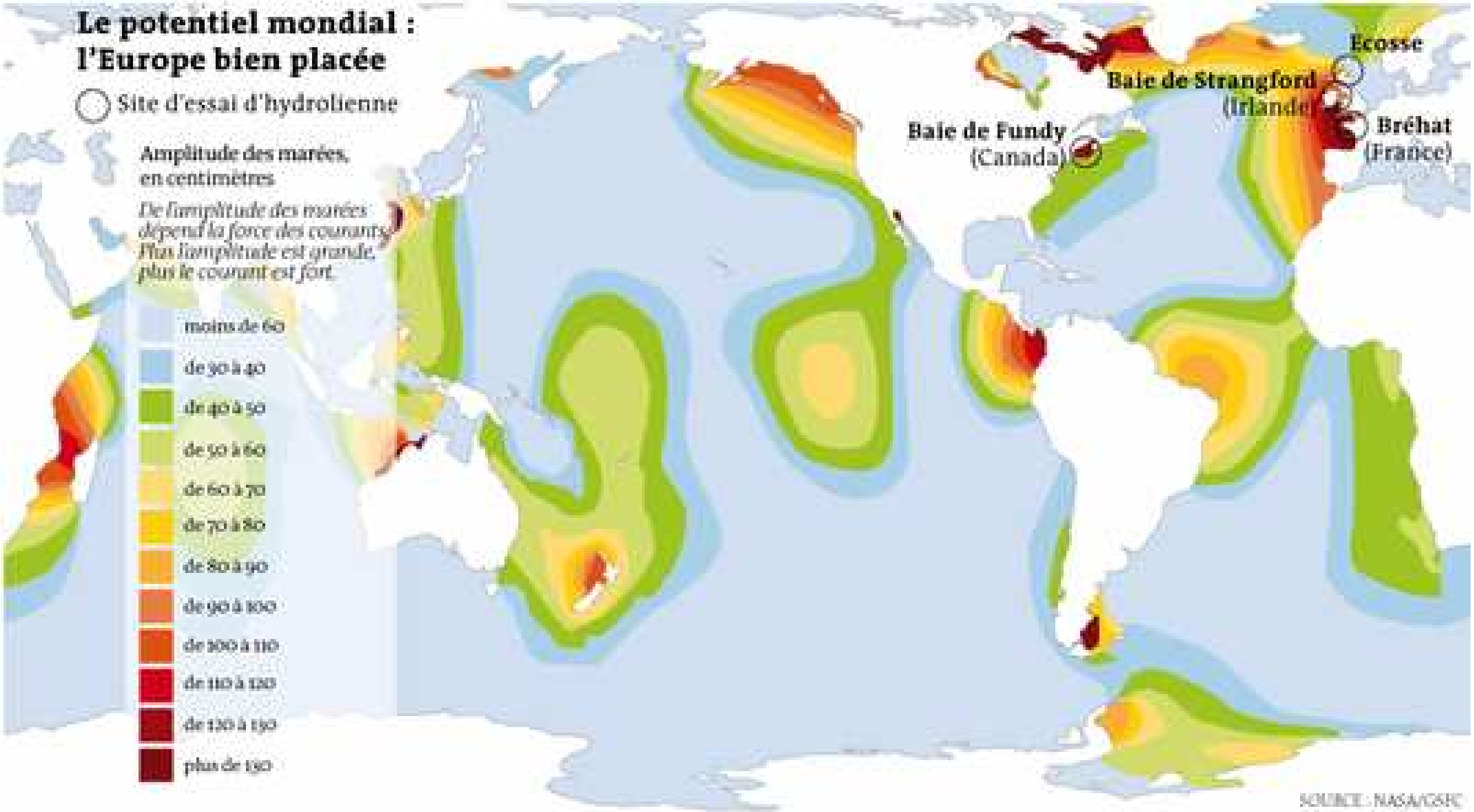
- Spring tide, Neap tide



• Complete cycle takes 29.5 days

http://www.ifremer.fr/lpo/cours/maree/forces.html

Physics of tide and resource at the world level



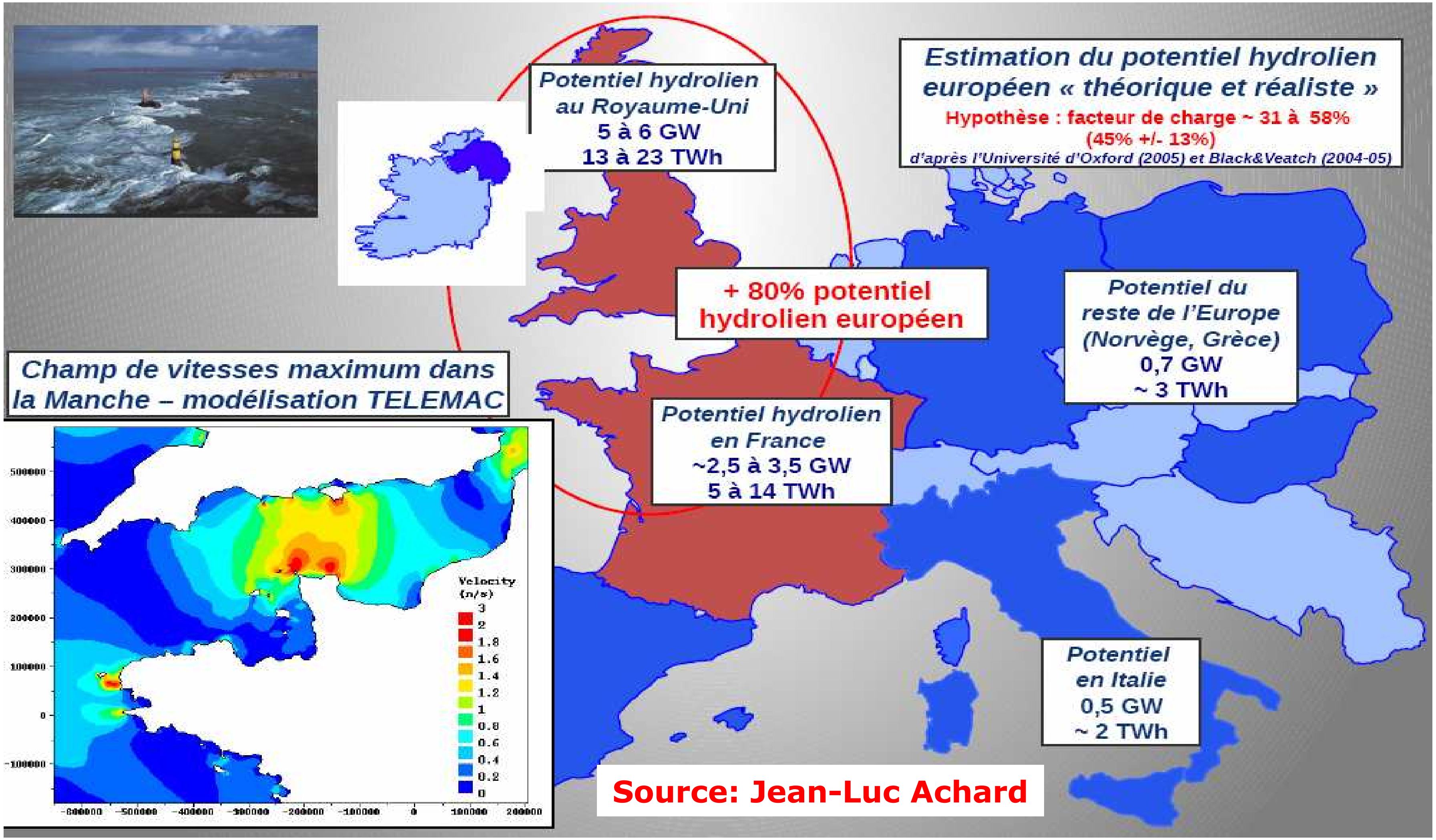
Physics of tide and resource at the world level

Source: Alstom, Ocean Energy Overview

Estimated total world resource: 50 GW – 100GW – more than 10% in FR and UK

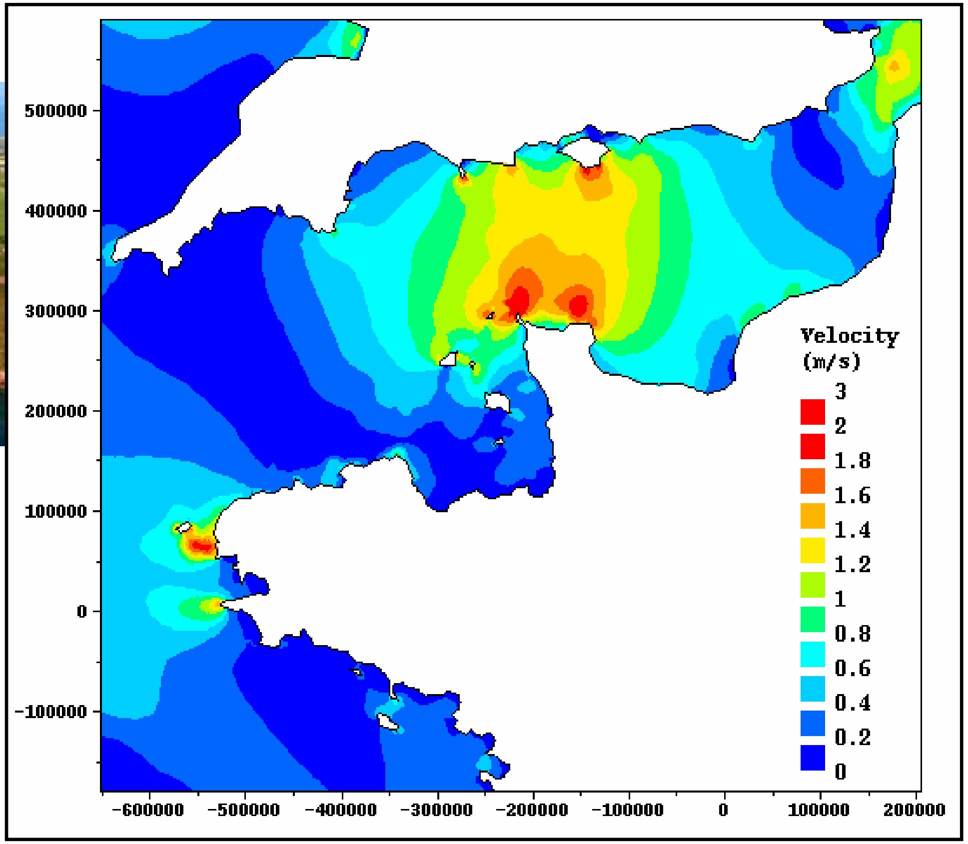
Physics of tide and resource at the European level

Info: 476,1 TWh electricity consumption in France for 2015



Physics of tide and resource at the French level

- Raz Blanchard – 3 or 4 GW (Alderney Race)

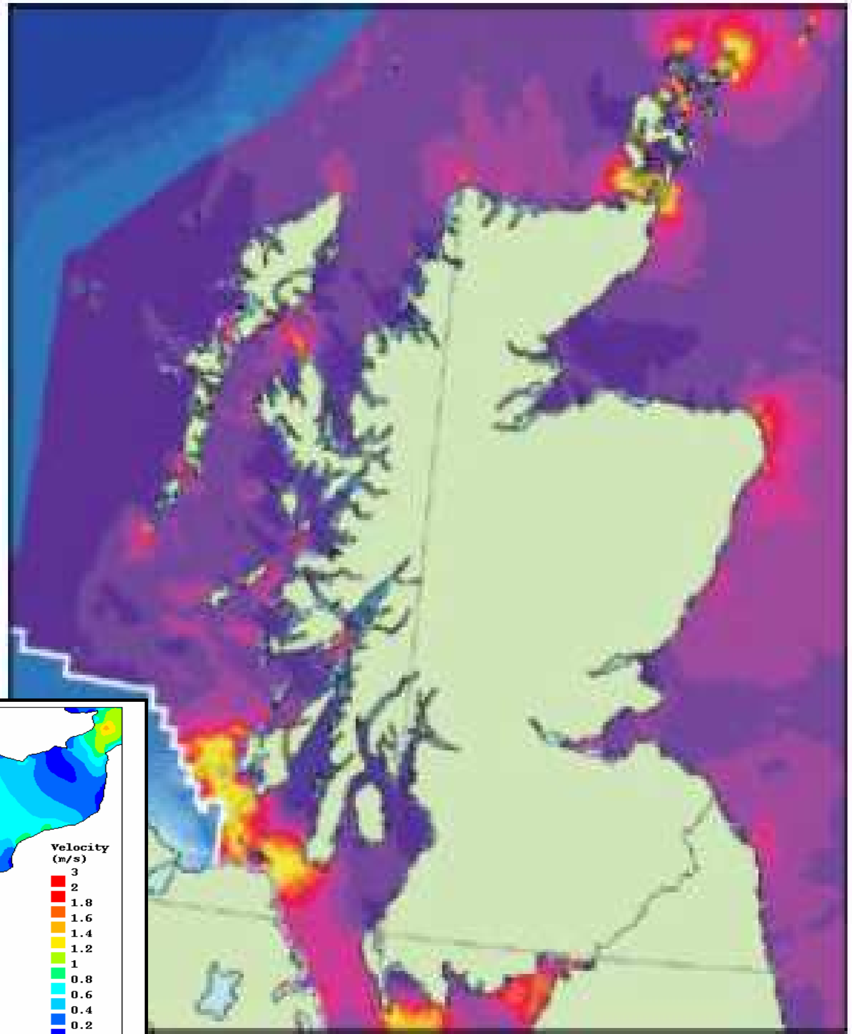


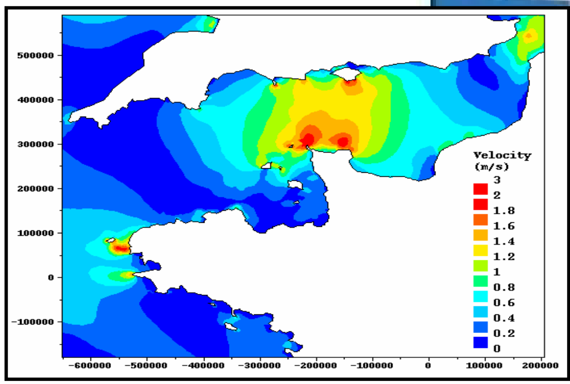
- Passage du Fromveur – < 1GW (Fromveur Straight)

Islands: Ouessant…

Physics of tide and resource at the UK level

- Pentland Firth, Orkney waters and west of Scotland
  - Small islands, far from the main lands…
- Strangford Narrow (Northern Ireland)
- Isle of Wight and Alderney
- Severn Estuary (Tidal Lagoon…)





Outline

- Physics of tide and resource
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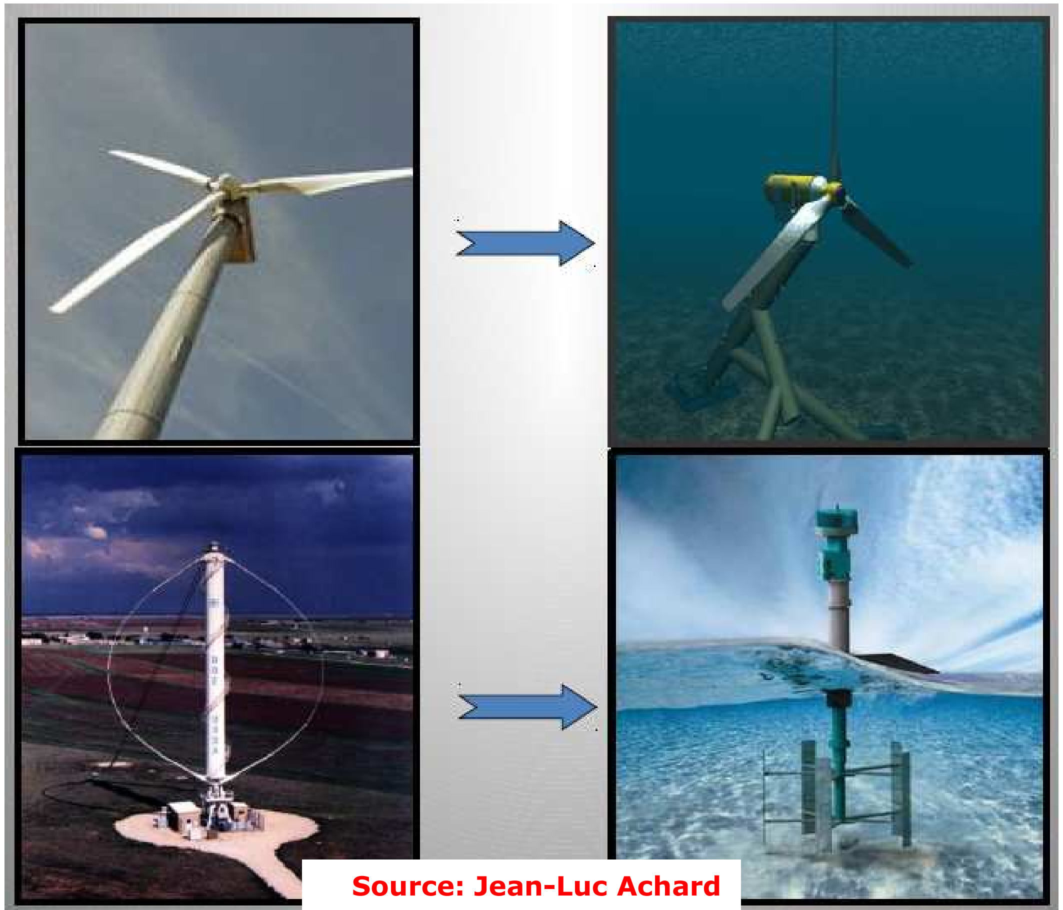
Physical basis

- Two major concepts of turbines:
  - Wind turbine　　　　　　　Tidal turbine

- Axial flux

- Transverse flux



Source: Jean-Luc Achard

Physical basis

- Power in a flow:

$$P_{flow} = \frac{1}{2} \rho S V^3$$

with:

ρ	fluid density
S	swept area (turbine surface)
V	fluid velocity

- Proof…

Physical basis

- Power of a turbine:

$$P_{turb} = \frac{1}{2}\rho C_P S V^3$$

with: ρ fluid density

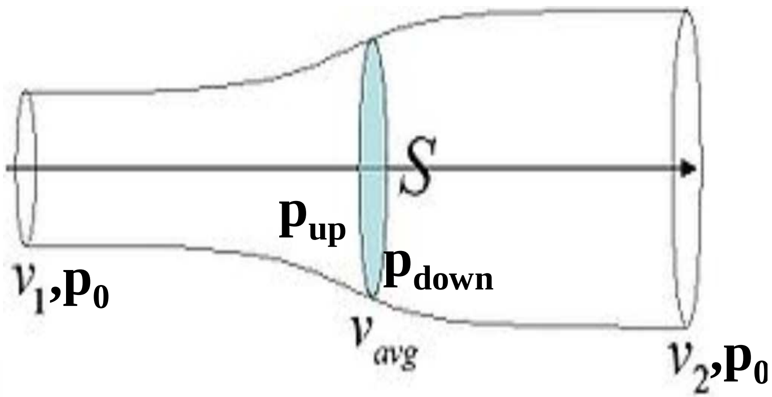
S swept area (turbine surface)

V fluid velocity

- where C_P is the power coefficient.
  not to be confuse with lift (portance) coefficient in French Cp

Physical basis – Betz theory

- Assessment of the C_P value:
  - Similar to wind energy
  - Betz theory applicable
- Power: $P = F.v$



- Bernouilli: $p_{up} - p_{down} = \frac{\rho}{2}(v_1^2 - v_2^2)$
- Force: $F = (p_{up} - p_{down})S = \frac{\rho}{2}(v_1^2 - v_2^2).S$
- Velocity approximation: $v = \frac{(v_1 + v_2)}{2}$

Physical basis – Betz theory

- Power: $P = F.v = \frac{\rho}{2}(v_1^2 - v_2^2).S.v$

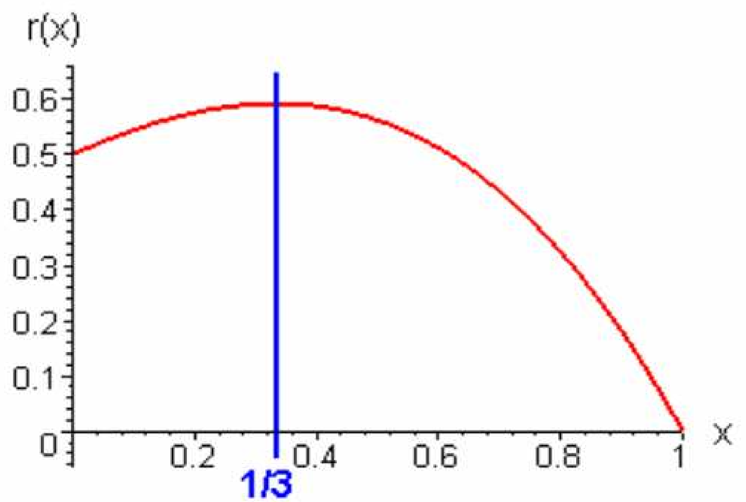
- Ratio: $r = \frac{P}{P_0} = \frac{1}{2}(1 - x^2)(1 + x)$ with $x = \frac{v_2}{v_1}$,

- Betz theory

x=1/3, et alors r=16/27

D'où la limite de Betz :

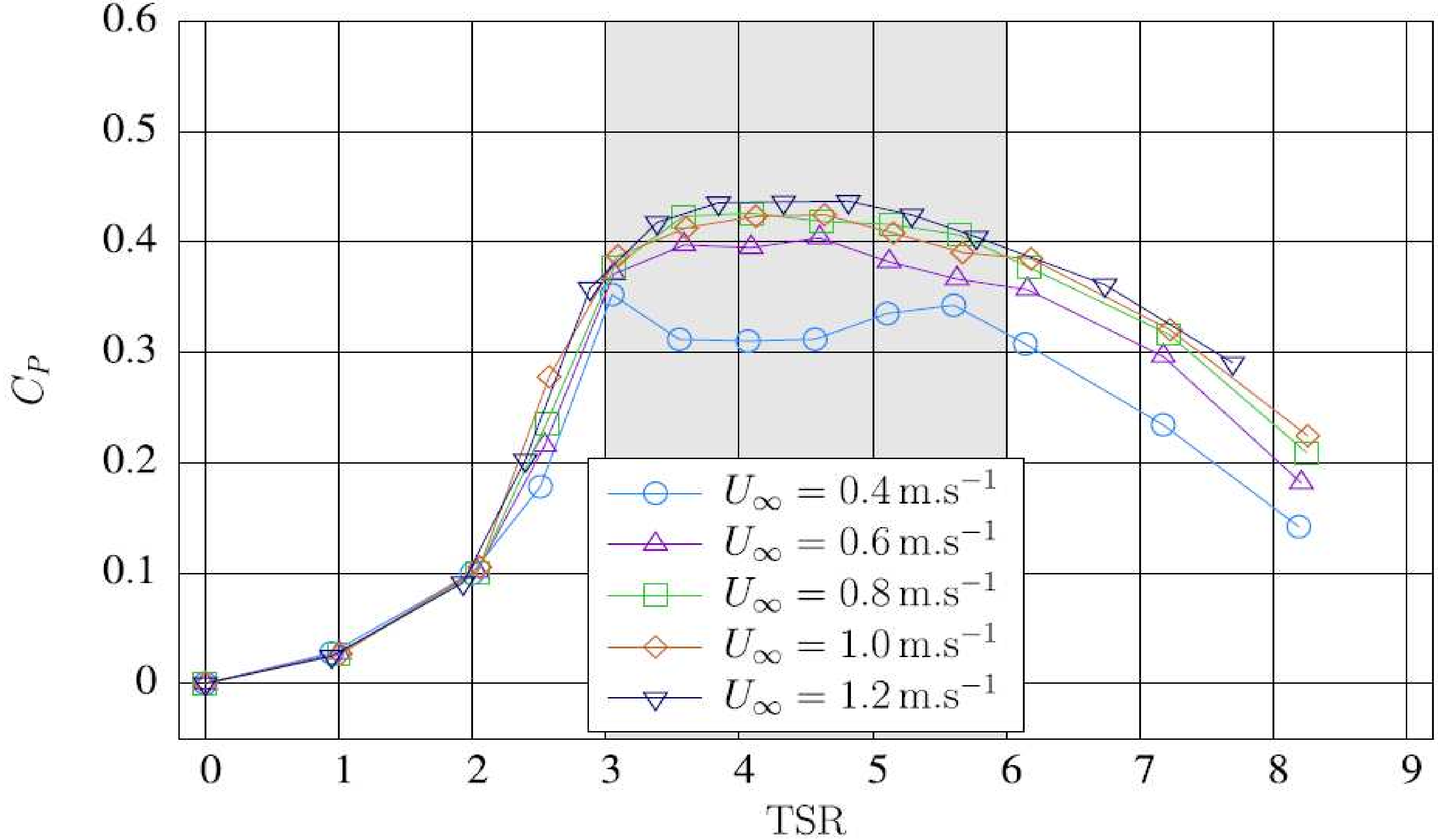
$$P_{extraite}^{max} = \frac{16}{27} P_{incidente}$$



Physical interpretation…

Physical basis – Betz theory

- Real Cp curve, TSR= ΩR/U



Physical basis – Betz theory

- Real Cp curve

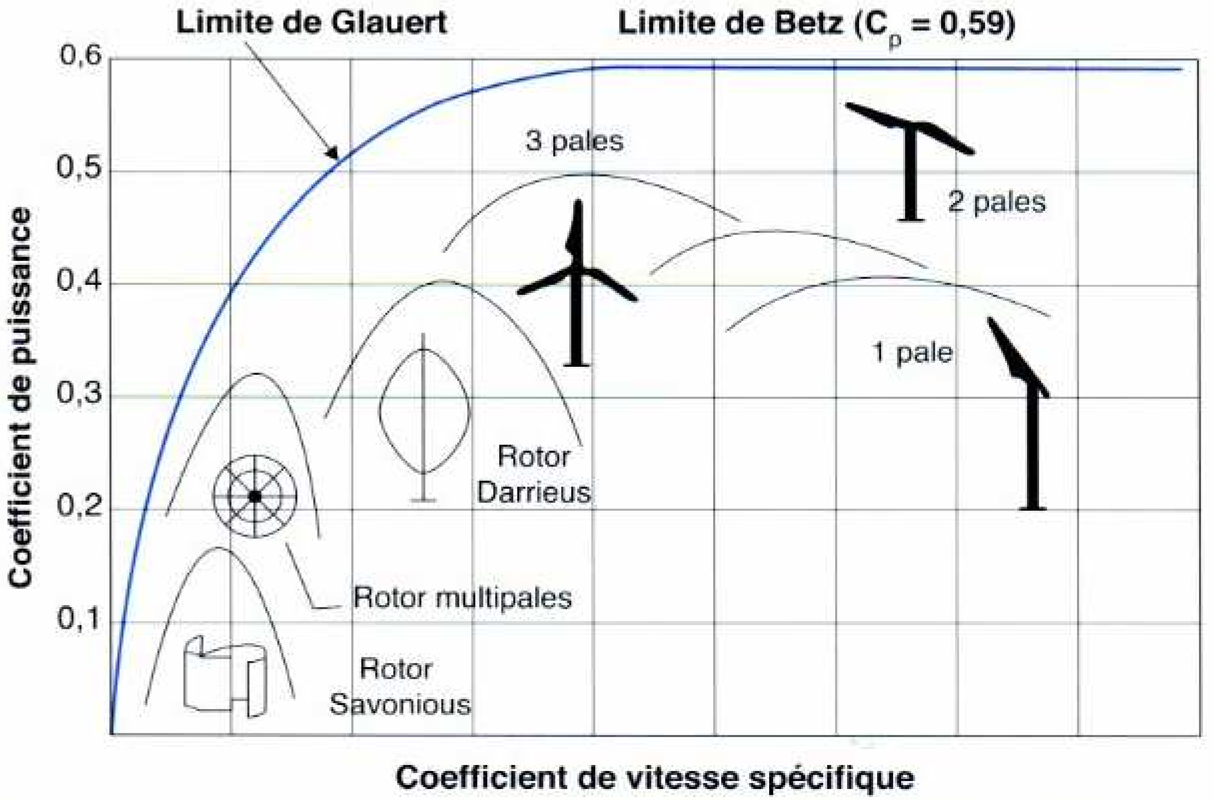


Fig. 3.19 – Les courbes des coefficients de puissance obtenues selon le type de machine et selon leur coefficient de vitesse spécifique λ.

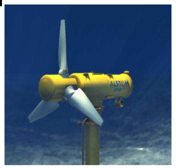
Physical basis

- Some basics of physics…

Rappel sur les équivalences translation-rotation

Translation	Rotation
Force : F (en N)	Couple : T (en N.m)
Masse : m (en kg)	Moment d'inertie : I (en $kg.m^2$)
Vitesse : V (en m/s)	Vitesse angulaire : Ω (en rad/s)
Énergie : $E = ½\, mV^2$ (en J)	Énergie : $E = ½\, I\, \Omega^2$ (en J)
Puissance : $P = FV$(en W)	Puissance : $P = T\Omega$ (en W)
Accélération : $a = F/m$ (en m/s^2)	Accélération angulaire : T/I (rad/s^2)

Different concepts: low speed Ω, high torque T



and vice versa…

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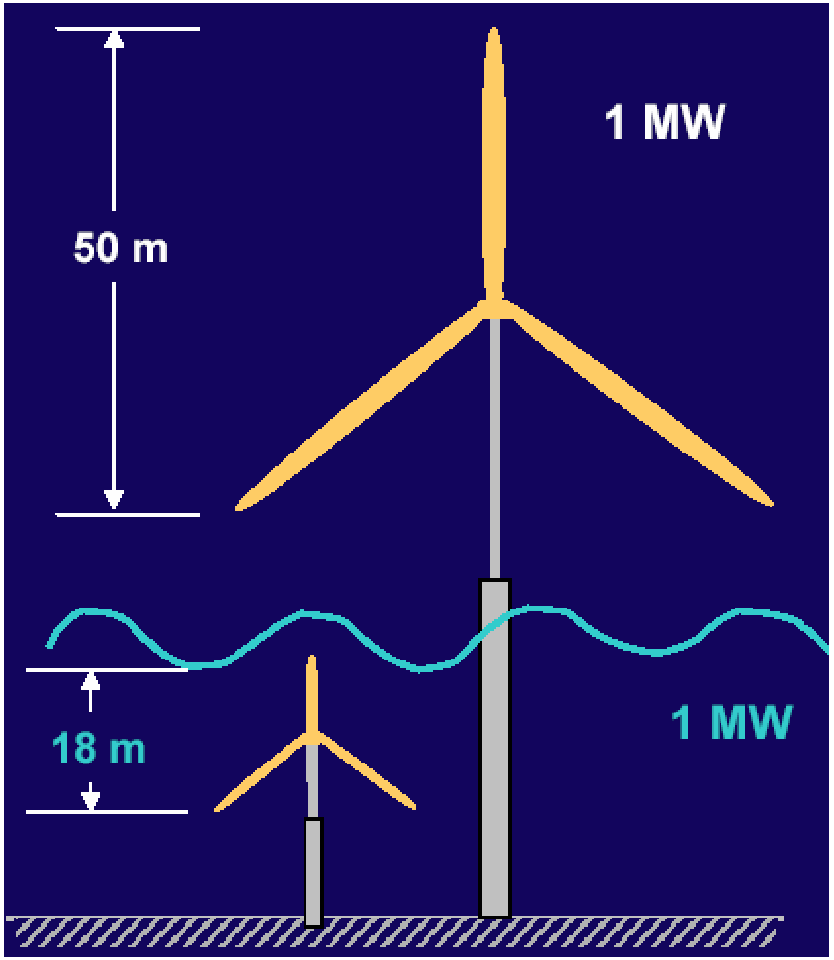
Fundamentals of tidal energy

- Power ≈ 0.5 ρ Cp S V^3
  Cp=0.4

- 1MW wind turbine:
  - Air density **ρ ≈ 1,23** kg/m^3
  - Wind velocity V ≈ 13m/s
  - Turbine diameter: **50 m**

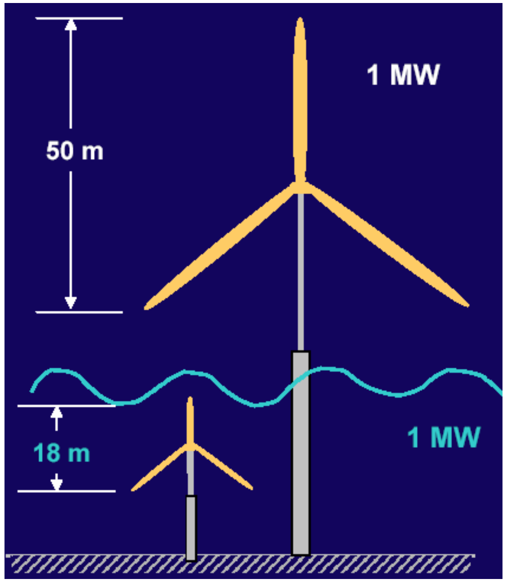
  - Water density **ρ ≈ 1000** kg/m^3
  - Current velocity V ≈ 13m/s (?)
  - Turbine diameter: **1.7m**

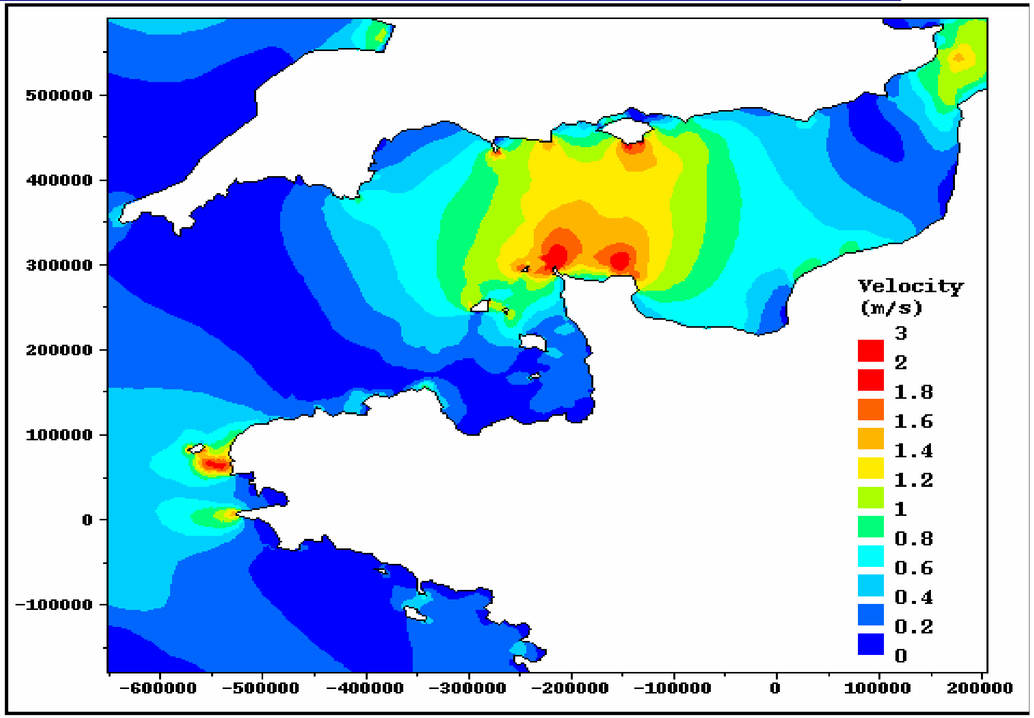
  - Unfortunately,
    more likely V ≈ 2,7m/s
  - Turbine diameter: **18m**



Fundamentals of tidal energy

- Power ≈ 0.5 ρ Cp S V^3
- 1MW wind turbine:
  - Unfortunately more likely V ≈ 2,7m/s
  - Turbine diameter: **18m**



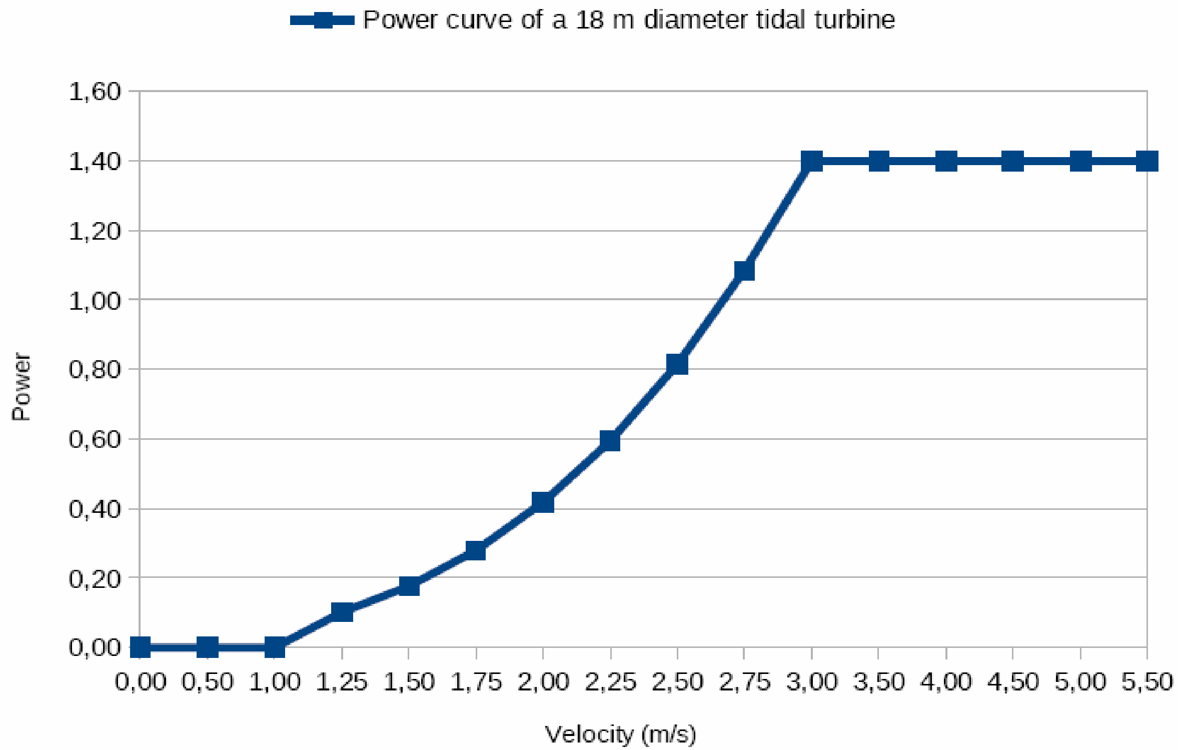


- Maybe we could think about turbine **rated** at lower velocity?

Fundamentals of tidal energy

- Rated velocity? And a Cut in velocity?
  - An example, a 18 meters diameter turbine

Power (MW)	Velocity (m/s)
0,00	0,00
0,50	0,00
1,00	0,00
1,25	0,10
1,50	0,18
1,75	0,28
2,00	0,42
2,25	0,59
2,50	0,82
2,75	1,08
3,00	1,40
3,50	1,40
4,00	1,40
4,50	1,40
5,00	1,40
5,50	1,40



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Tidal resource

- One of the first publication

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Renewable Energy 29 (2004) 1931–1945

RENEWABLE ENERGY

www.elsevier.com/locate/renene

Analytical estimates of the energy yield potential from the Alderney Race (Channel Islands) using marine current energy converters

A.S. Bahaj *, L. Myers

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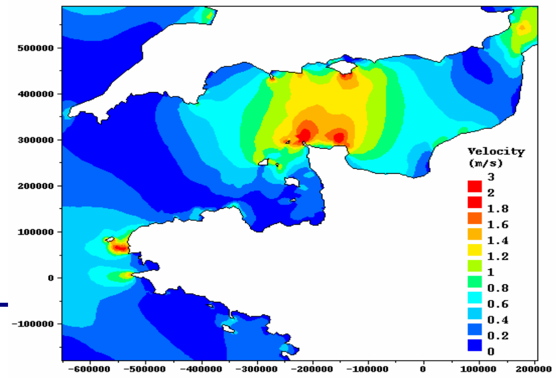
Received 20 January 2004; accepted 23 February 2004

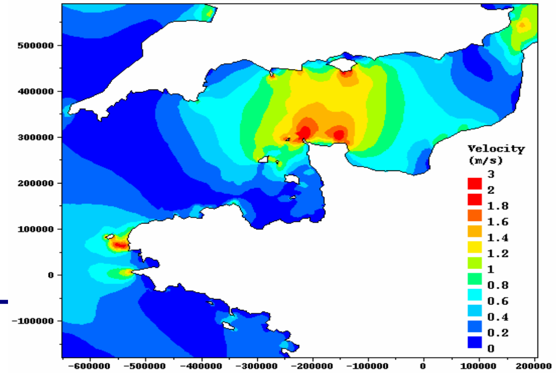
Tidal resource



A.S. Bahaj, L. Myers / Renewable Energy 29 (2004)

Table 1
Typical flow speed distribution between spring and neap tides for the east Race of Alderney

Dover high water (h)	Current speed at intervals (m/s)						
	Spring tide	+1 day	+2	+3	+4	+5	Neap tide
−6	1.7	1.6	1.4	1.3	1.2	1.0	0.8
−5	3.0	2.8	2.6	2.3	2.1	1.9	1.5
−4	4.9	4.7	4.4	4.1	3.8	3.5	3.0
−3	3.8	3.6	3.3	3.1	2.9	2.6	2.1
−2	2.7	2.5	2.3	2.1	2.0	1.8	1.4
−1	1.4	1.3	1.3	1.2	1.1	1.0	0.8
0	1.1	1.1	1.0	0.9	0.9	0.8	0.7
1	2.8	2.6	2.5	2.3	2.2	2.0	1.7
2	3.5	3.2	3.0	2.8	2.6	2.4	1.9
3	3.7	3.5	3.3	3.0	2.8	2.6	2.1
4	3.1	2.9	2.7	2.5	2.3	2.1	1.7
5	1.9	1.8	1.7	1.5	1.4	1.3	1.1
6	1.9	1.8	1.6	1.5	1.4	1.2	1.0



Tidal resource

A.S. Bahaj, L. Myers / Renewable Energy 29 (2004)

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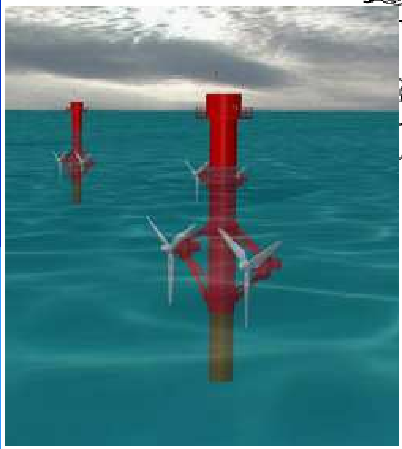
−2	2.7	2.5	2.3	2.1	2.0	1.8	1.4
−1	1.4	1.3	1.3	1.2	1.1	1.0	0.8
0	1.1	1.1	1.0	0.9	0.9	0.8	0.7
1	2.8	2.6	2.5	2.3	2.2	2.0	1.7
2	3.5	3.2	3.0	2.8	2.6	2.4	1.9
3	3.7	3.5	3.3	3.0	2.8	2.6	2.1
4	3.1	2.9	2.7	2.5	2.3	2.1	1.7
5	1.9	1.8	1.7	1.5	1.4	1.3	1.1
6	1.9	1.8	1.6	1.5	1.4	1.2	1.0

$$\text{Available energy density (kW h/m}^2) = \sum_{W=1}^{52}\sum_{D=1}^{7}\sum_{h=1}^{12} 2\left[\frac{1}{2}\rho V^3\right]_{h,D,W}$$

Tidal resource



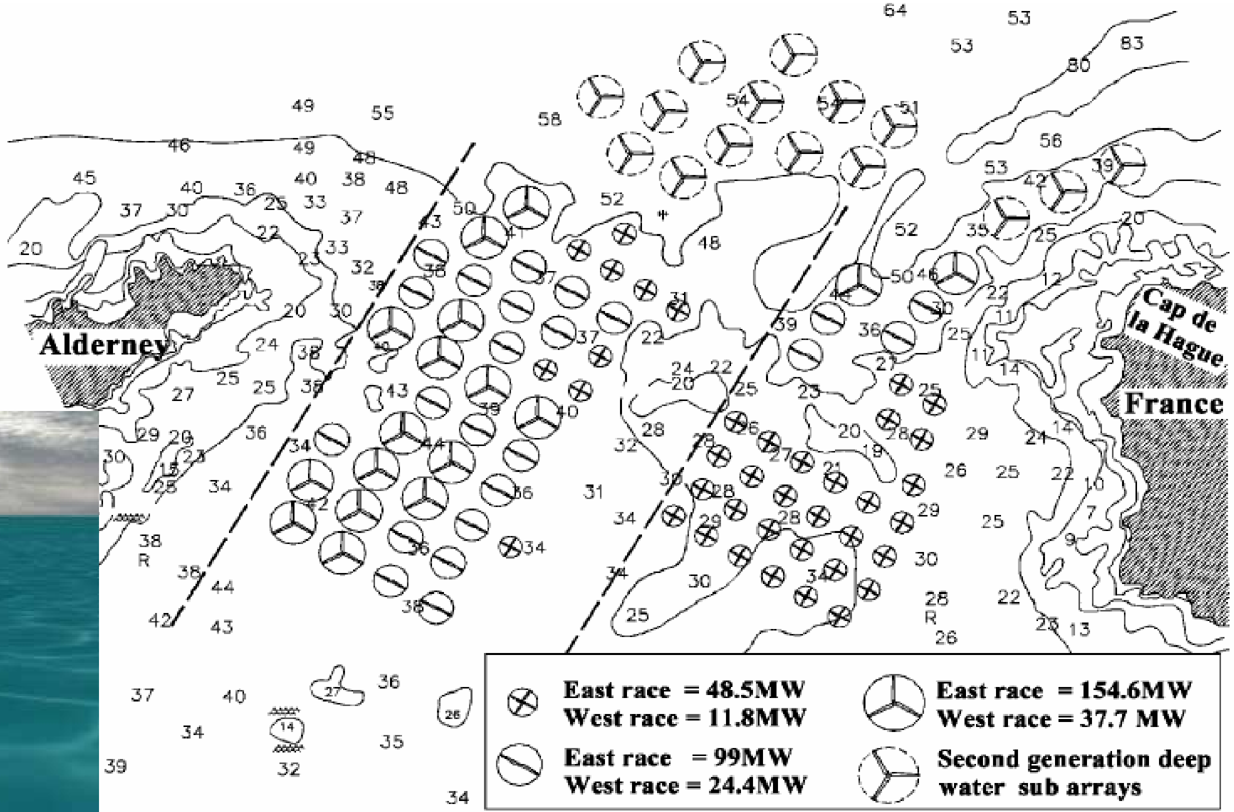


Fig. 8. Layout of the Alderney MCEC array produced from detailed analysis of the Race and simulation of power output from the rotor sizes given in Tables 2 and 3. The values in the figure give spot depths relative to chart datum in meters and their 10 m contours. The key shows the rated power of the sub-arrays and their relative position in the two races is depicted in the figure (see Table 3 for details).

Tidal resource

1940 A.S. Bahaj, L. Myers / Renewable Energy 29 (2004) 1931–1945

Table 3
Parameters used to design an MCEC array that can be installed in the Alderney Race. The annual energy yield was determined using $C_p = 0.3$ with a minimum operating flow speed of 1.1 m/s

Nominal depth (m)	Rotor diameter (m)	Number of dual rotor MCECs in sub array	West Race			East Race		
			Rating of 16 twin rotor sub-array (MW)	Number of sub-arrays	Swept area (m^2)	Rating of 16 twin rotor sub-array (MW)	Number of sub-arrays	Swept area (m^2)
28	14	16	12	9	44334	49	34	167485
36	20	16	24	14	140743	99	4	40212
40	25	16	38	16	251327	155	1	15707
			Total swept area (m^2)		436404	Total swept area (m^2)		223404
			Energy density ($kW\,h/m^2$)		20954	Energy density ($kW\,h/m^2$)		72448
	For $C_p = 0.3$		Annual energy (TW h)		2.67	Annual energy (TW h)		4.73

Total: 1248 turbines

Tidal resource

- Bahaj & Myers 2004 obtained 7,4 TWh for the Alderney Race

  would represents **1,55%** of the total 476,1 TWh electricity consumption in France for 2015

- But more realistically with more recent figures…

Tidal resource – more realistically

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Press Centre > 2014 > 10 ▾ > Alstom improves the performance of its tidal energy solutions with Oceade™ 18 – 1.4MW

< **All from Press Centre**

Alstom improves the performance of its tidal energy solutions with Oceade™ 18 – 1.4MW

01/10/2014

Alstom has taken advantage of its experience with the 1 MW turbine to improve the design of its tidal stream turbine. We are now offering the Oceade™ 18 - 1.4 MW, making the turbine even more efficient, cost-effective and easy to maintain.

With a rotor diameter of 18 metres, the Oceade tidal stream turbine has a nominal power of 1.4MW and three variable pitching blades. It is equipped with plug-and-play modules on rails, easily accessible through an inspection hatch at the rear of the nacelle to enable faster assembly and maintenance. This turbine is buoyant, making it easy to tow to and from the operating site. Installation and maintenance costs are therefore lower because there is no need for specialist vessels and divers. It also reduces the timeframe to install or retrieve the turbine. The unit rotates to face the incoming tide at an optimal angle and thus extract the maximum energy potential.

The Oceade is ready to be deployed at the tidal energy farm that will be selected in the call for expressions of interest launched in September 2013 by the French government.

Tidal resource – more realistically

Area (m2)
254,47

Diameter (m)
18

	Spring Tide Velocity m/s	Power (MW)	Day 1 Velocity (m/s)	Power (MW)	Day 2 Velocity (m/s)	Power (MW)	Day 3 Velocity (m/s)	Power (MW)	Day 4 Velocity (m/s)	Power (MW)	Day 5 Velocity (m/s)	Power (MW)	Neap Tide Velocity (m/s)	Power (MW)
-6	# 1,0	0,06	# 0,9	0,04	# 0,8	0,03	# 0,8	0,02	# 0,7	0,01	# 0,6	0,01	# 0,5	0,01
-5	# 2,7	1,05	# 2,5	0,82	# 2,3	0,62	# 2,1	0,46	# 1,8	0,32	# 1,6	0,22	# 1,4	0,14
-4	# 3,4	1,40	# 3,2	1,40	# 2,9	1,30	# 2,7	1,01	# 2,4	0,76	# 2,2	0,56	# 2,0	0,40
-3	# 2,9	1,31	# 2,7	1,08	# 2,6	0,87	# 2,4	0,70	# 2,2	0,55	# 2,0	0,42	# 1,8	0,31
-2	# 2,2	0,56	# 2,1	0,46	# 1,9	0,37	# 1,8	0,29	# 1,6	0,23	# 1,5	0,17	# 1,3	0,13
-1	# 1,3	0,11	# 1,2	0,09	# 1,2	0,08	# 1,1	0,07	# 1,0	0,05	# 1,0	0,04	# 0,9	0,04
0	# 0,6	0,01	# 0,6	0,01	# 0,5	0,01	# 0,5	0,01	# 0,5	0,00	# 0,4	0,00	# 0,4	0,00
1	# 1,0	0,06	# 0,9	0,04	# 0,8	0,03	# 0,8	0,02	# 0,7	0,01	# 0,6	0,01	# 0,5	0,01
2	# 2,0	0,39	# 1,8	0,30	# 1,6	0,23	# 1,5	0,17	# 1,3	0,12	# 1,2	0,09	# 1,0	0,06
3	# 2,8	1,18	# 2,6	0,95	# 2,4	0,76	# 2,3	0,60	# 2,1	0,46	# 1,9	0,34	# 1,7	0,25
4	# 2,9	1,31	# 2,8	1,09	# 2,6	0,90	# 2,4	0,74	# 2,3	0,59	# 2,1	0,47	# 1,9	0,36
5	# 2,2	0,52	# 2,0	0,43	# 1,9	0,35	# 1,8	0,28	# 1,6	0,22	# 1,5	0,17	# 1,4	0,13
6	# 0,8	0,02	# 0,7	0,02	# 0,7	0,02	# 0,6	0,01	# 0,6	0,01	# 0,5	0,01	# 0,5	0,01

			Spring Tide	Day 1	Day 2	Day 3	Day 4	Day 5	Neap Tide
Energy produc.	12h	MW.h	7,36	6,23	5,14	4,03	3,10	2,33	1,70
Energy produc.	24h	MW.h	14,73	12,45	10,29	8,07	6,20	4,65	3,39

Energy produc.	per week	59,78	MW.h
Energy produc.	per year	3,11	GW.h

Facteur de charge: 25,4%

Tidal resource

- To obtain the 7,4TWh given by Bahaj & Myers for the Alderney Race, one would need

  ≈**2780 turbines**

  like the 1.4 MW
  (with 18 meters diameter rotor)

- Possible but work still need to be done…

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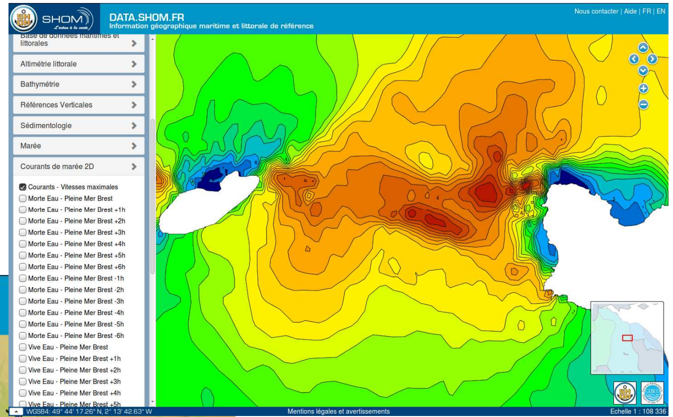
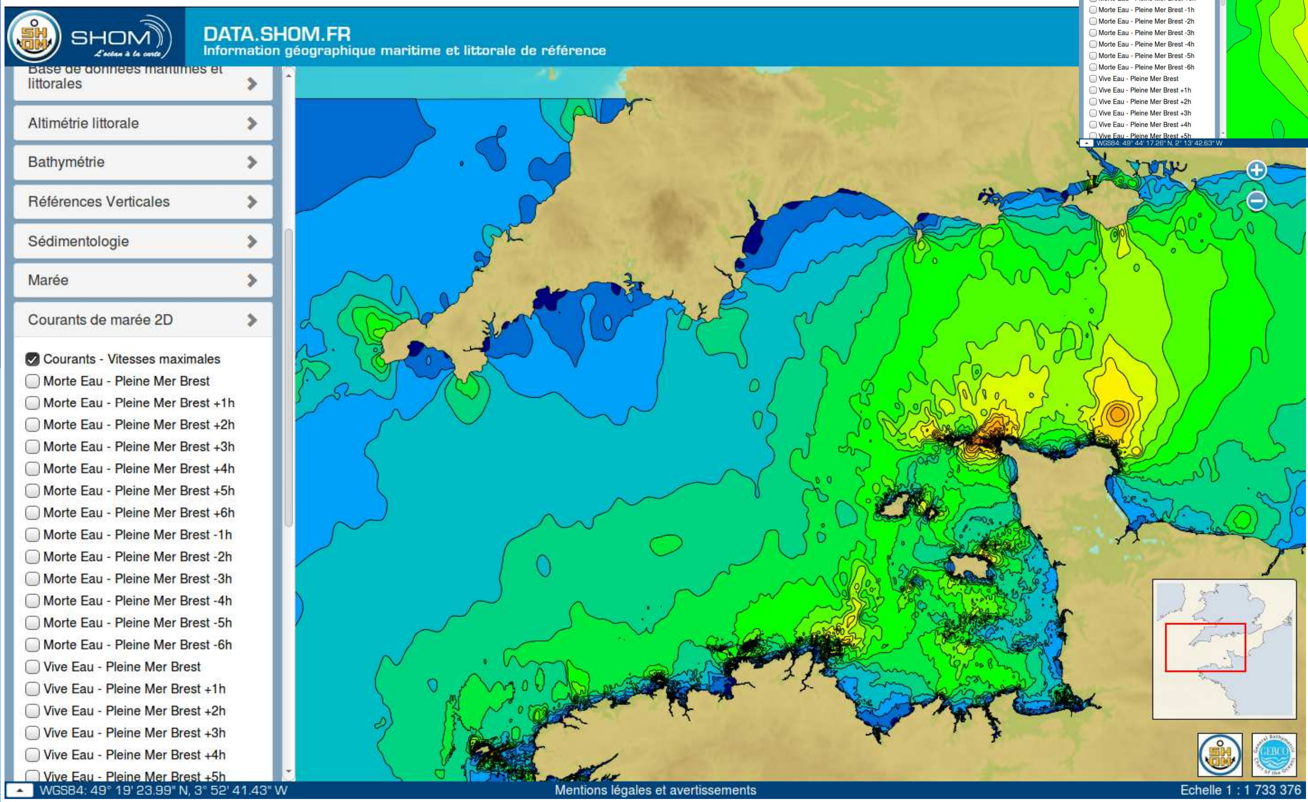
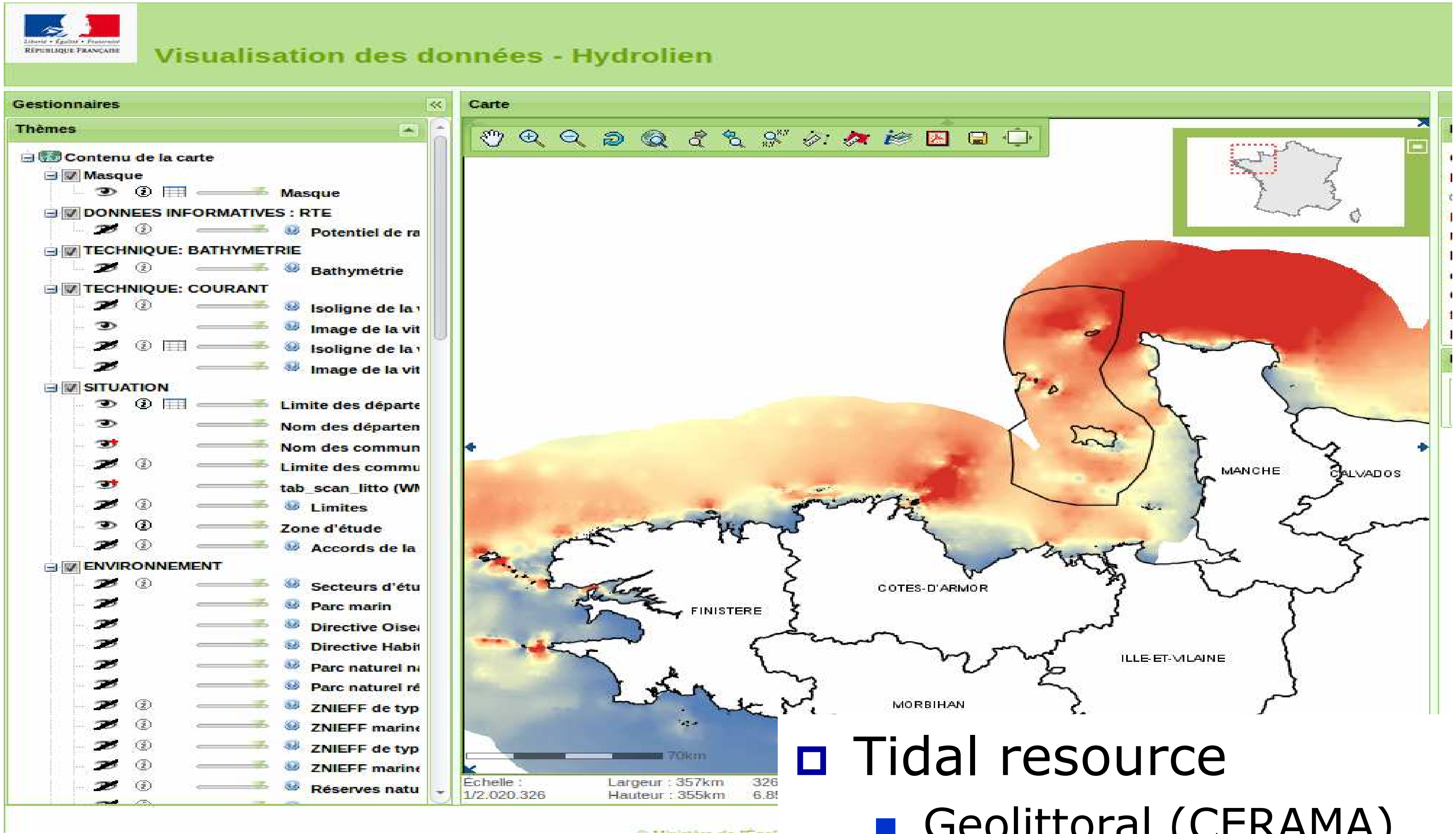
Resource characterisation

- Tidal resource
  - Data SHOM
  - http://data.shom.fr/





Resource characterisation

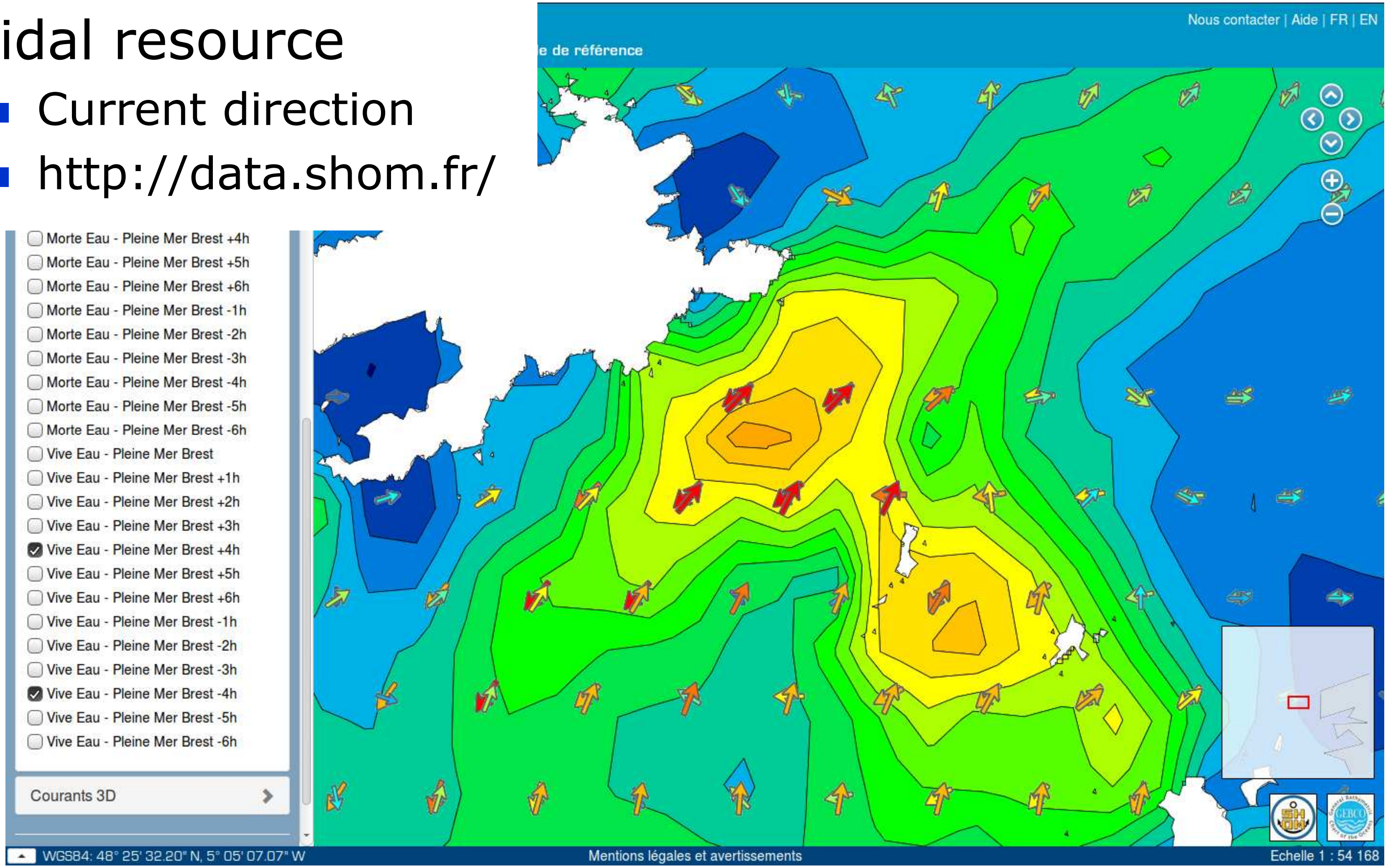


- Tidal resource
  - Geolittoral (CERAMA)

http://www.geolittoral.developpement-durable.gouv.fr/3eme-exercice-deplanification-de-l-eolienen-mer-r398.html

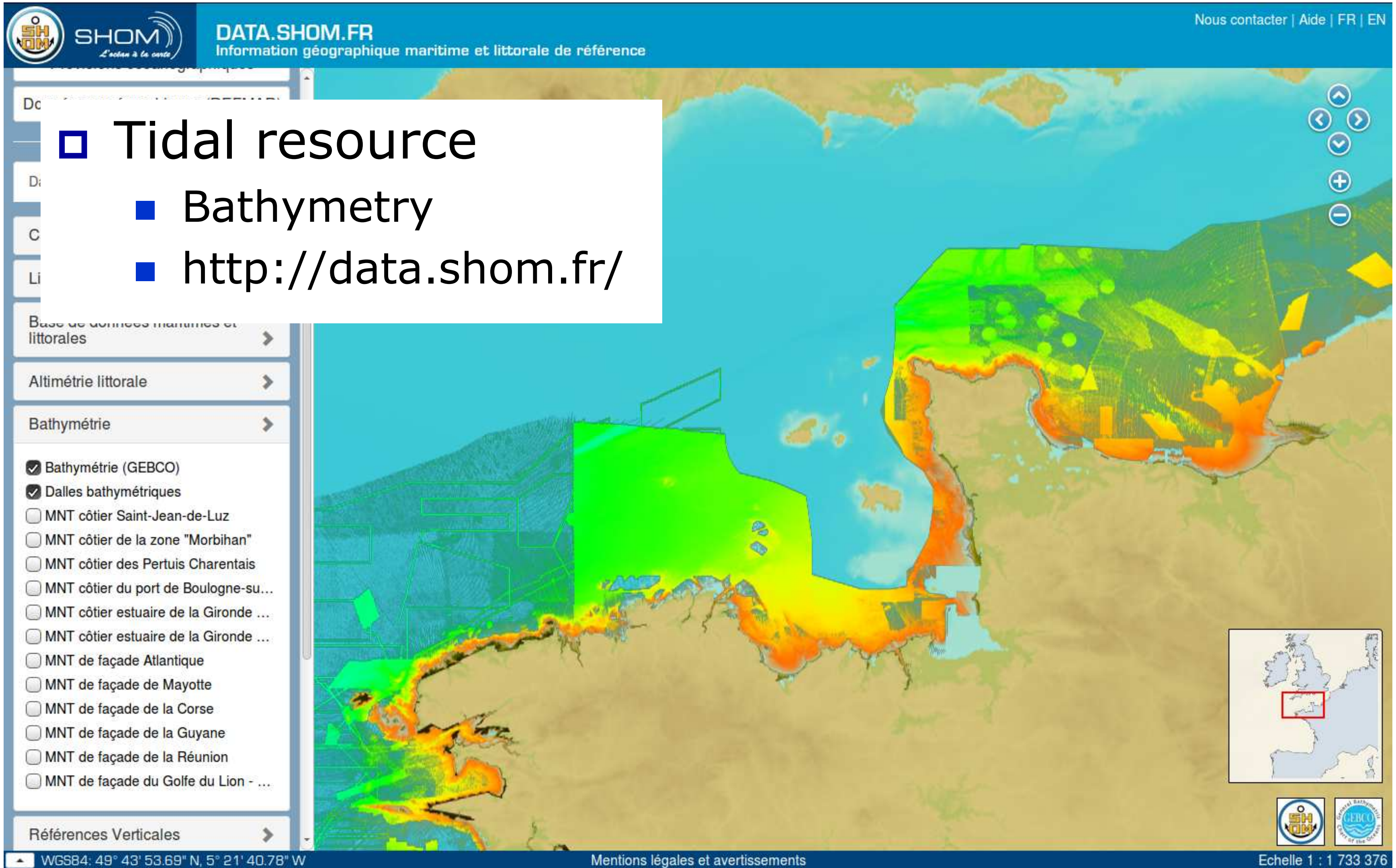
Resource characterisation

- Tidal resource
  - Current direction
  - http://data.shom.fr/

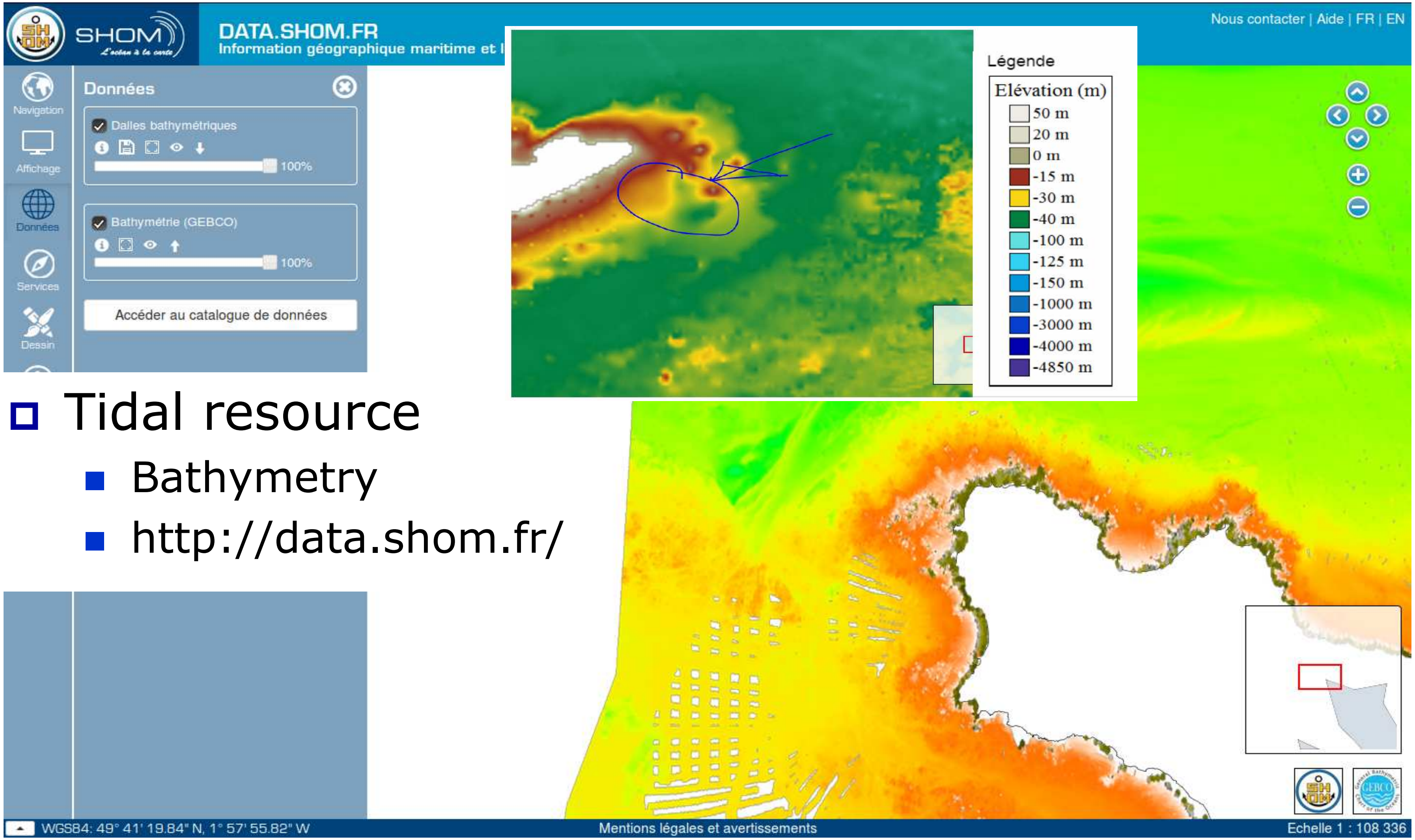


Resource characterisation

- Tidal resource
  - Bathymetry
  - http://data.shom.fr/



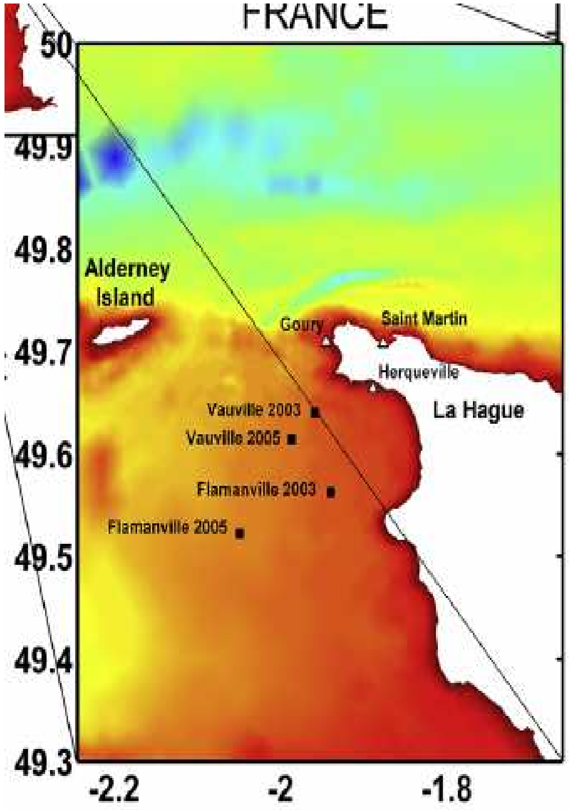
Resource characterisation



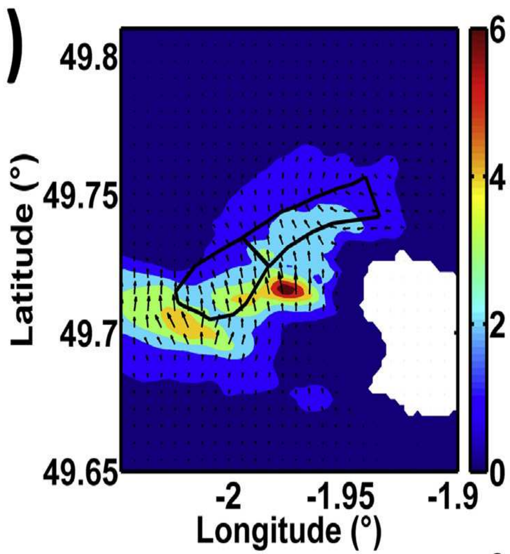
- Tidal resource
  - Bathymetry
  - http://data.shom.fr/

Resource characterisation

- Sediment transport and particles
  - Thiebot et al. 2015



mean shear stress exceedance



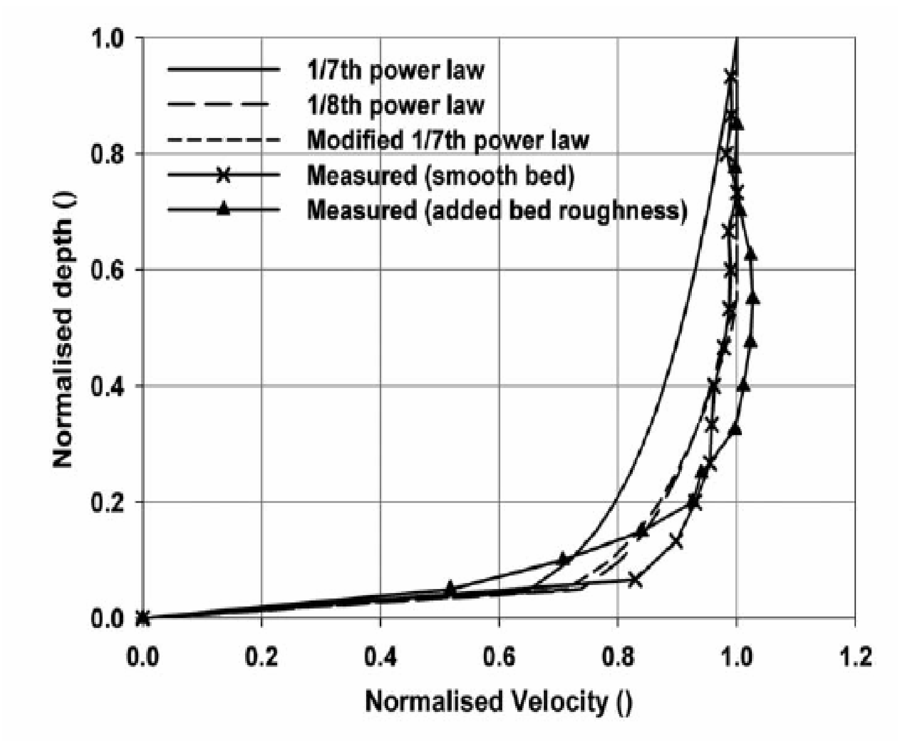
and the macro particles…

Resource characterisation

- Current velocity profile

Lafon et al. 2012

Myers et al. 2010



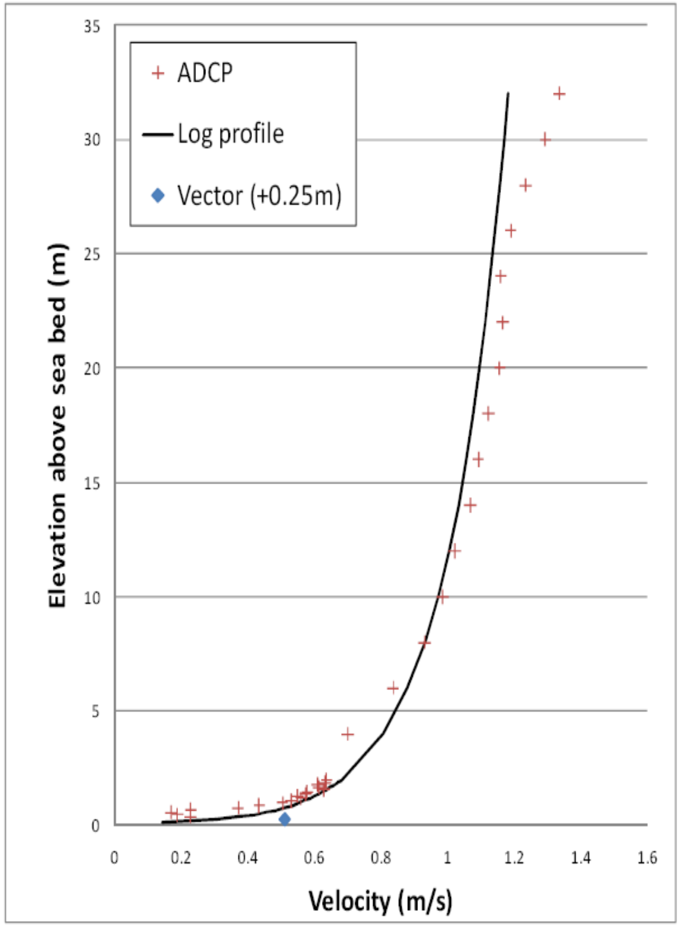


Figure 1: 600s-averaged velocity profile during a mean spring ebb tide at point D.

Resource characterisation

- Current velocity profile
- Bottom tidal turbine
  - V≈1.0m/s
- Floating tidal turbine
  - V≈1.2m/s
- Power difference
  - +72,8%
    as power is in V^3
- But more sensible to wave

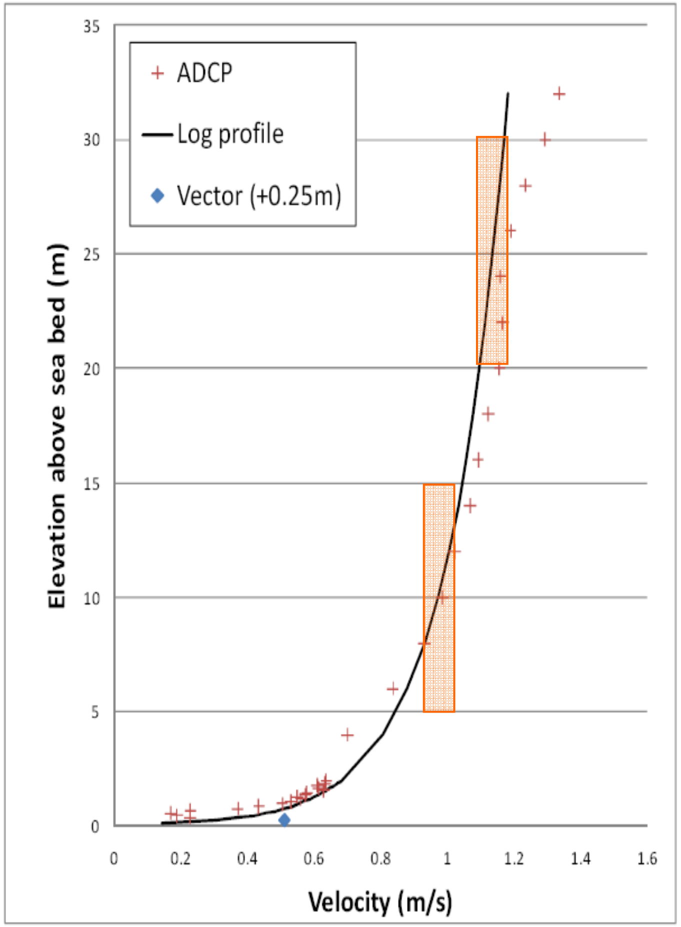
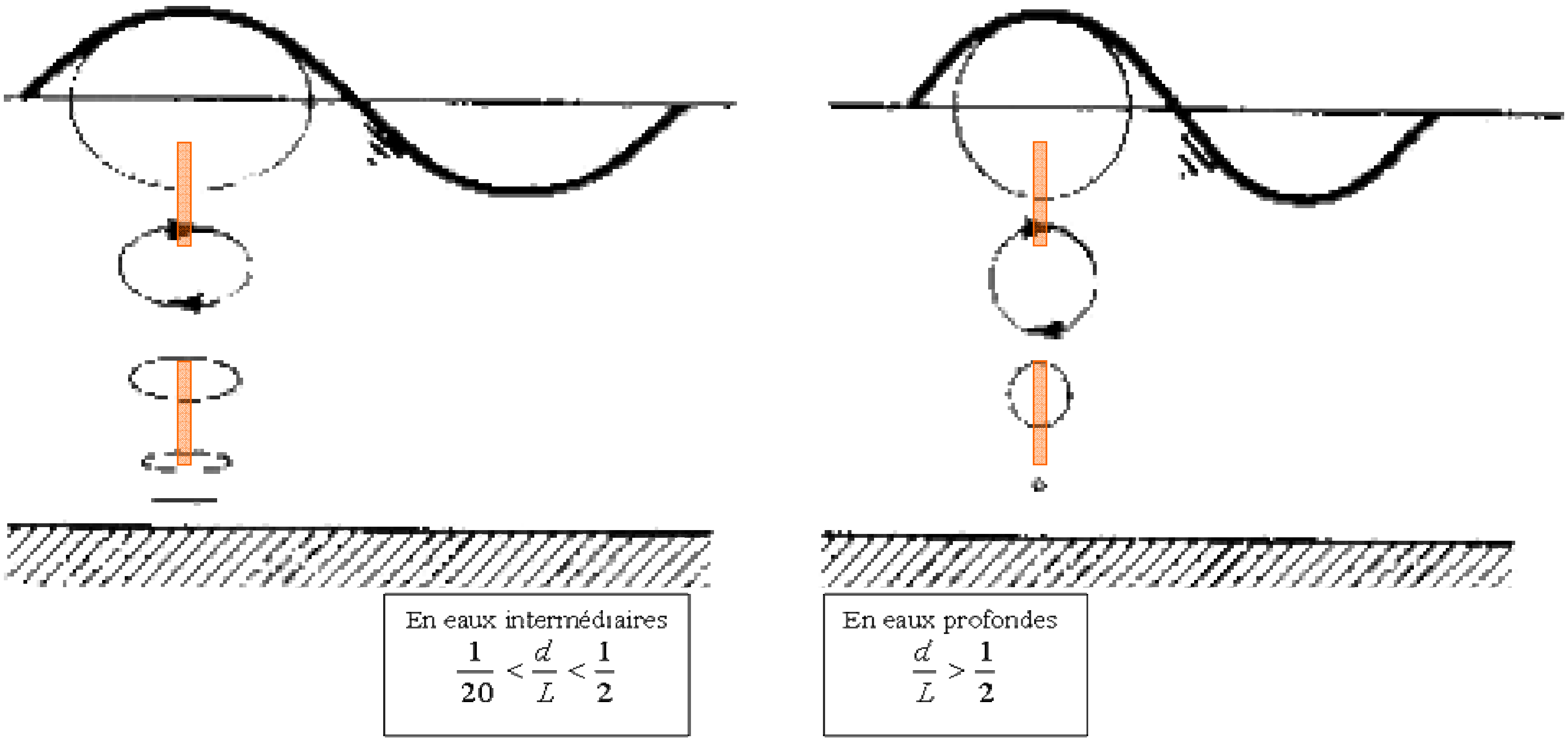


Figure 1: 600s-averaged velocity profile during a mean spring ebb tide at point D.

Resource characterisation

- Wave: L=wave length, d=depth



Resource characterisation

- Turbulence
  - Lafon et al. 2012
  - Turbulence Intensity

$$k = \frac{1}{2}\left[\overline{u'^2} + \overline{v'^2}\right]$$

$$T.I = \frac{\sqrt{2k}}{\sqrt{\overline{u}(z)^2 + \overline{v}(z)^2}}$$

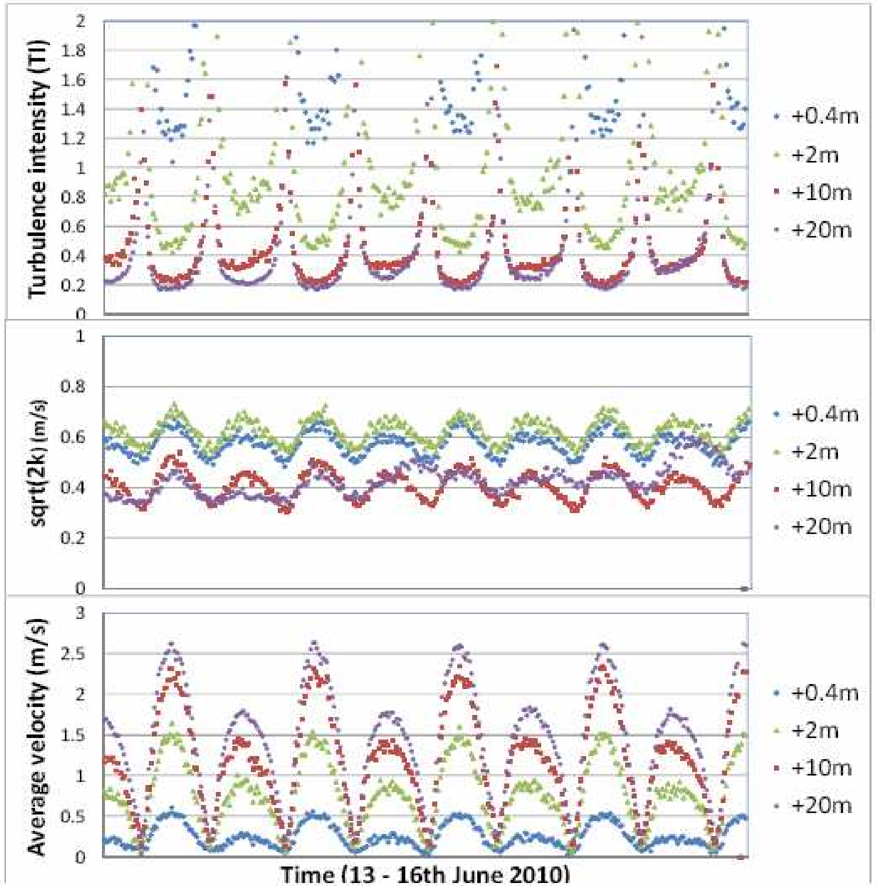
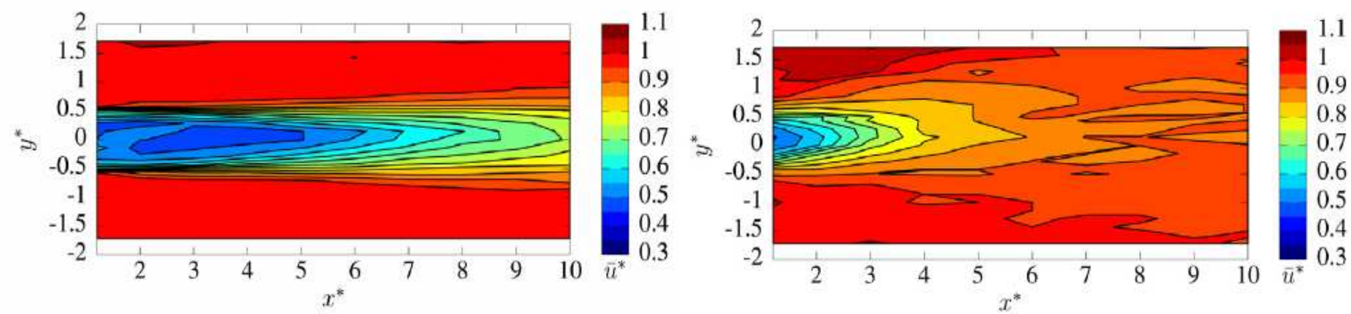


Figure 2: Point E - Turbulence intensity, Turbulence Kinetic Energy, Averaged Velocity (13-16th June 2010).

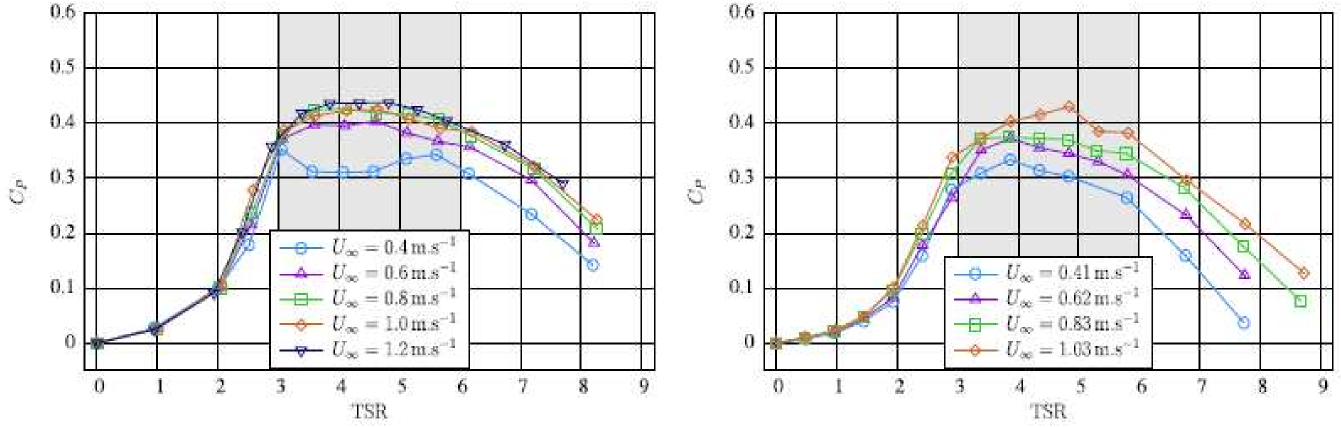
the offshore end of the cable (Fig. 2). At the instant of peak tide velocity, T.I. is in the order of 120% at +0.4m, decreases to 50-70% at +2m, to 30% at +10m and reaches the more typical value of 20% at +20m.

Resource characterisation

- **Turbulence** – Mycek et al. 2014



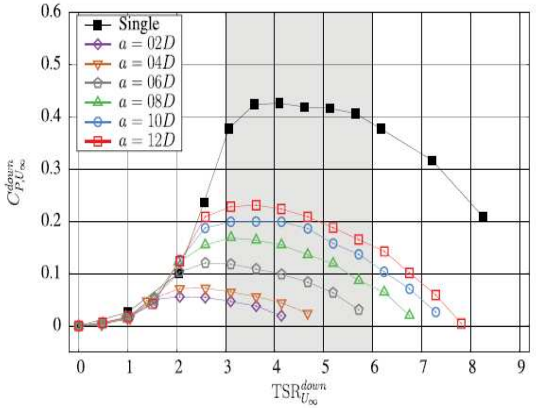
(a) Axial velocity map ($I_\infty = 3\%$) (b) Axial velocity map ($I_\infty = 15\%$)



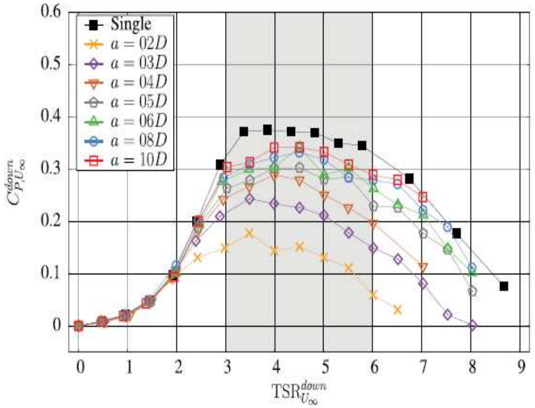
(a) $I_\infty = 3\%$ (b) $I_\infty = 15\%$

Resource characterisation

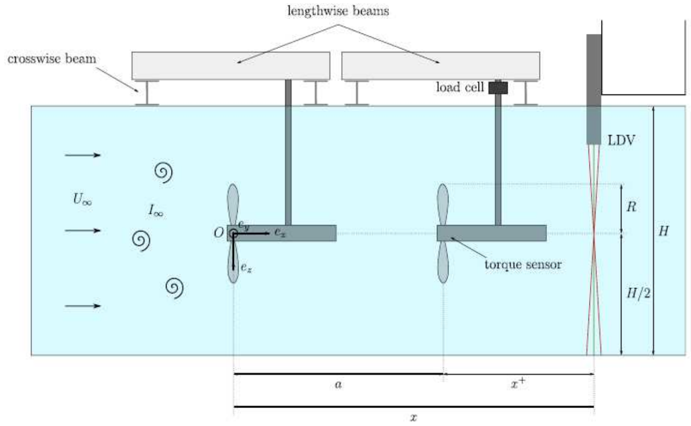
- Interaction
  - Mycek et al. 2014



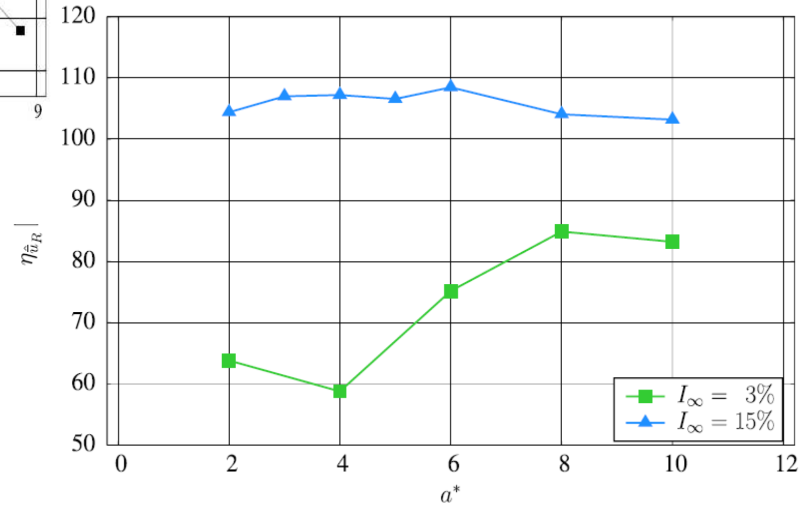
(a) $I_\infty = 3\%$



(b) $I_\infty = 15\%$



$$\eta_u = 100 \frac{\max C_{P,u}^{down}}{\max C_P^{single}}$$



(a) Efficiency $\eta_{\hat{u}_R}$

Outline

- Physics of tide and resource
- Physical Basis
- Fundamentals of tidal energy
- Tidal resource
- Resource characterisation
- History of tidal energy
- Technology review
- Conclusion

History of tidal energy

- « Moulin à marée »
  - Could be back from the roman age?
    To be confirmed…
  - Then in the middle age.
  - Mainly in Brittany, Pays de la Loire, etc.

More than 100 sites in France

Le moulin à marée du Birlot sur l'île de Bréhat, en France.

History of tidal energy

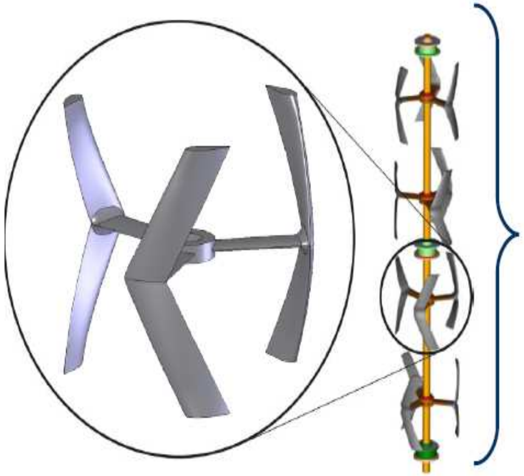
- "Barrage de la Rance"
  - Capacity: 240 MW
  - 24 turbines
  - Yearly prod: 500 GWh
  - Ratio: 23,8%

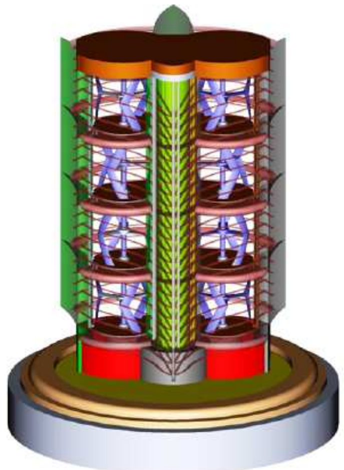
- Inaugurated in 1666

- Drawbacks:
  - Sediment
  - Eutrophysation
  - Fish and marine mammals

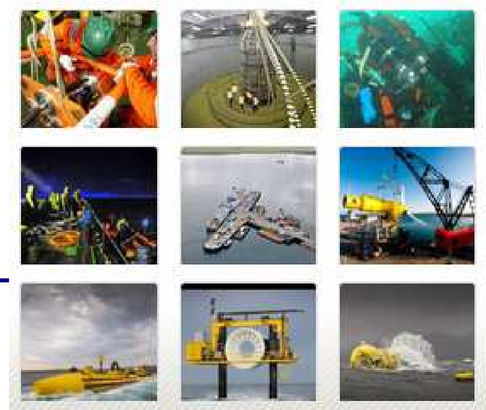
History of tidal energy

- Programme "HARVEST"
  - Research and development programme
- Inaugurated in 2001
- Advantages:
  - Self starting
  - Direction
  - Several in a column

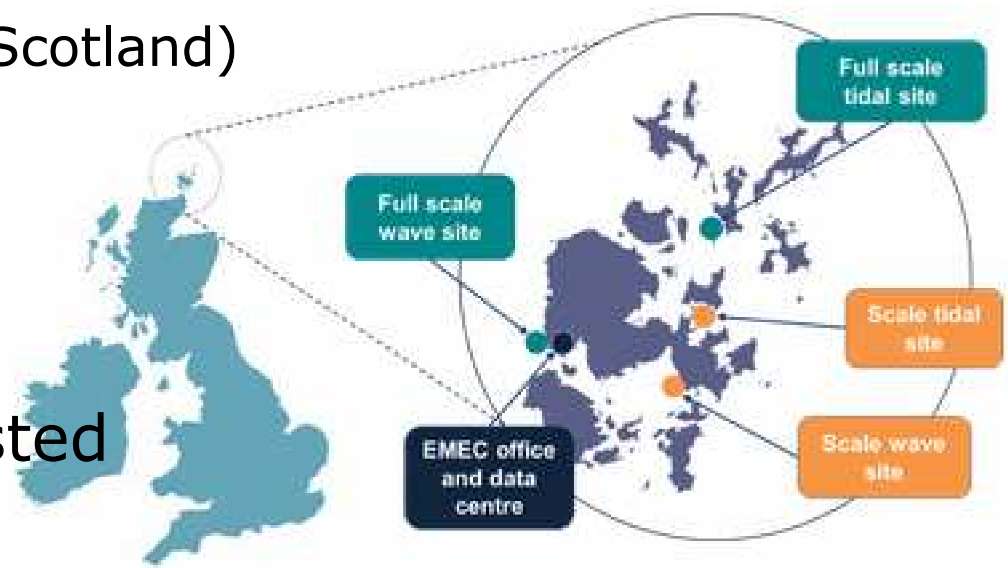




History of tidal energy



- EMEC (European Marine Energy Center)
  - In Orkney (North of Scotland)
- Established in 2003
- Tidal
  - Wave, etc.
- Many companies tested their prototype.



History of tidal energy

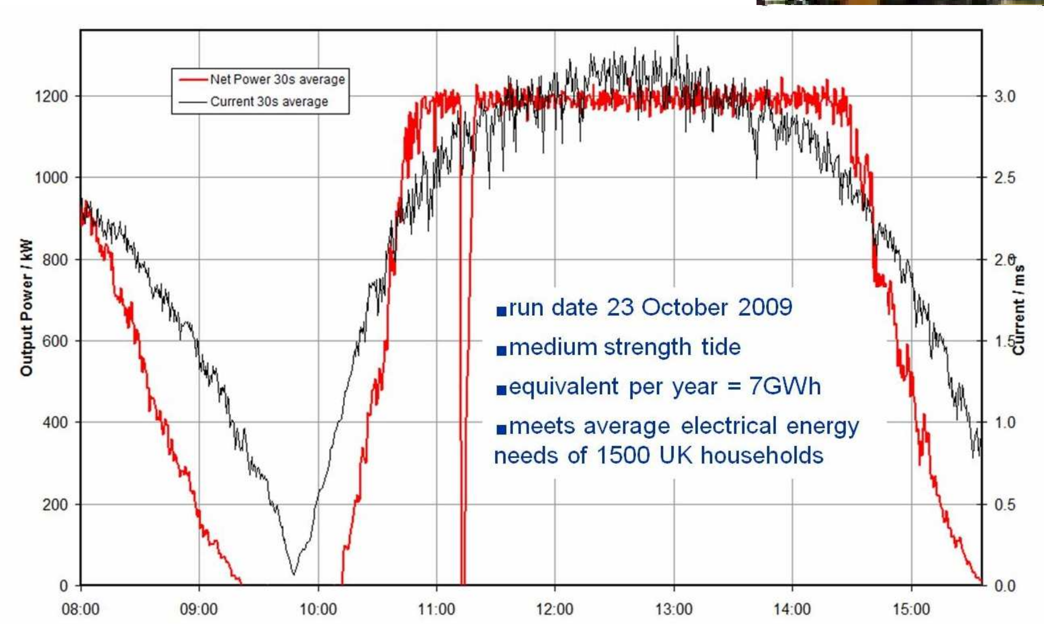
- SEAGEN, Marine Current Turbine
  - Strangford Narrows
  - Northern Ireland
  - 1 twin-turbine

- Inaugurated 18/12/2008

- Drawbacks:
  - Fishing
  - Sailings
  - Fish and marine mammals
  - Noises…

History of tidal energy

- SEAGEN, Marine Current Turbine
  - The "1st tidal" turbine in open water
  - Rated at 2,4m/s

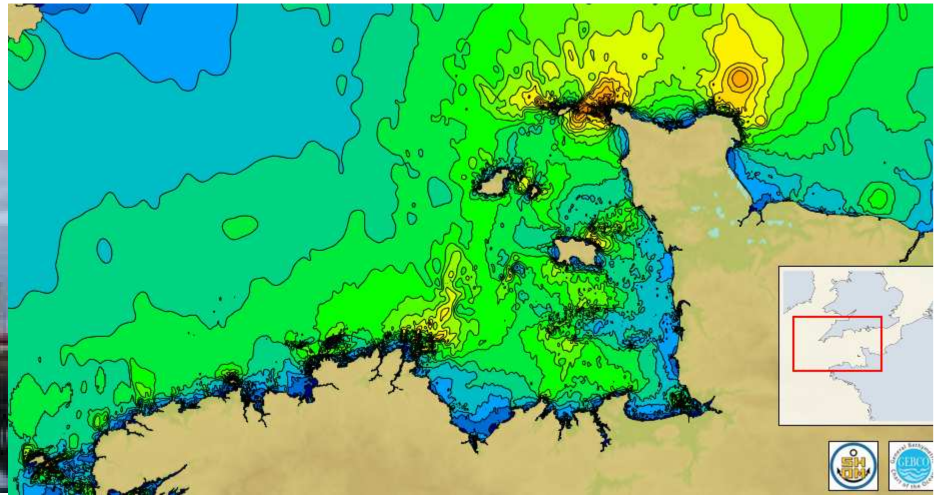


History of tidal energy

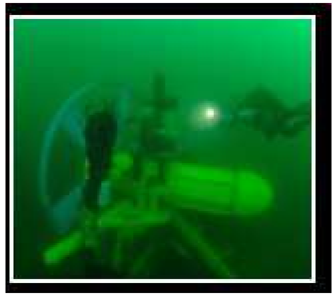
- Since these times:
  - Many, many, many projects…
  - Especially in UK, northern Europe, Canada, US, Italy, and of course France
  - Focus at the French level.

History of tidal energy

- Open Hydro in Paimpol Bréhat
  - End 2011: first Open Hydro turbine
  - Sept. 2012: barge and crane problem
    - The tidal turbine stays in the water
    - Other turbines deployment is stopped.
  - Few communication since



History of tidal energy



- Sabella in Ouessant
  - After a test period for its Sabella D3 10kW in Odet river (started in 2008)

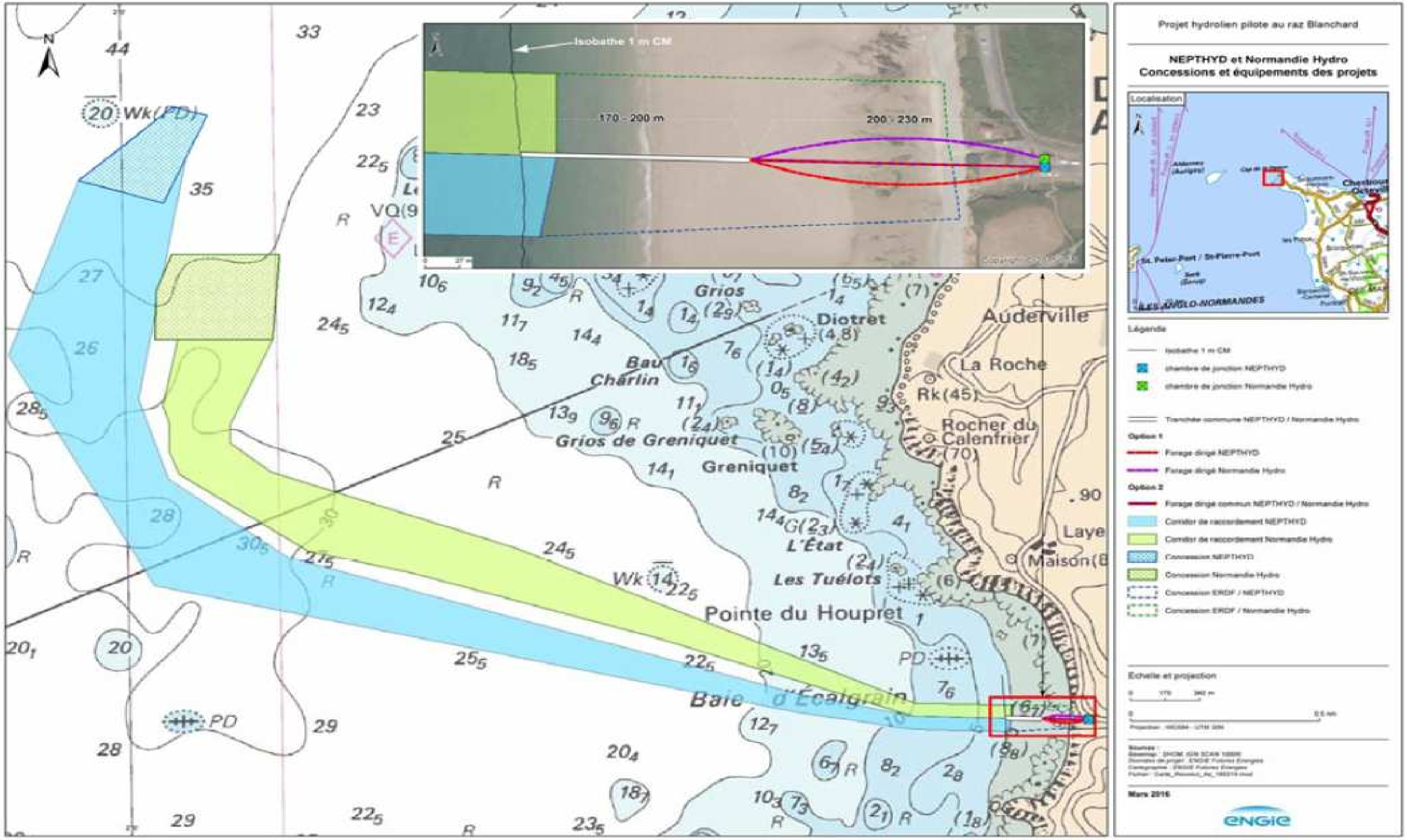
- June 2015
  - Sabella D10
  - 10 meters diameter
  - Depth 55m
  - Connected to the grid in Sept./Oct. 2015
    - Phone recharge during the summer

History of tidal energy

- Follow up of “HARVEST” programme

A Orléans, HYDROQUEST raccorde la première hydrolienne fluviale (ou marine ou estuarienne…) au réseau électrique de distribution géré par ERDF (25 septembre 2015)

History of tidal energy



History of tidal energy

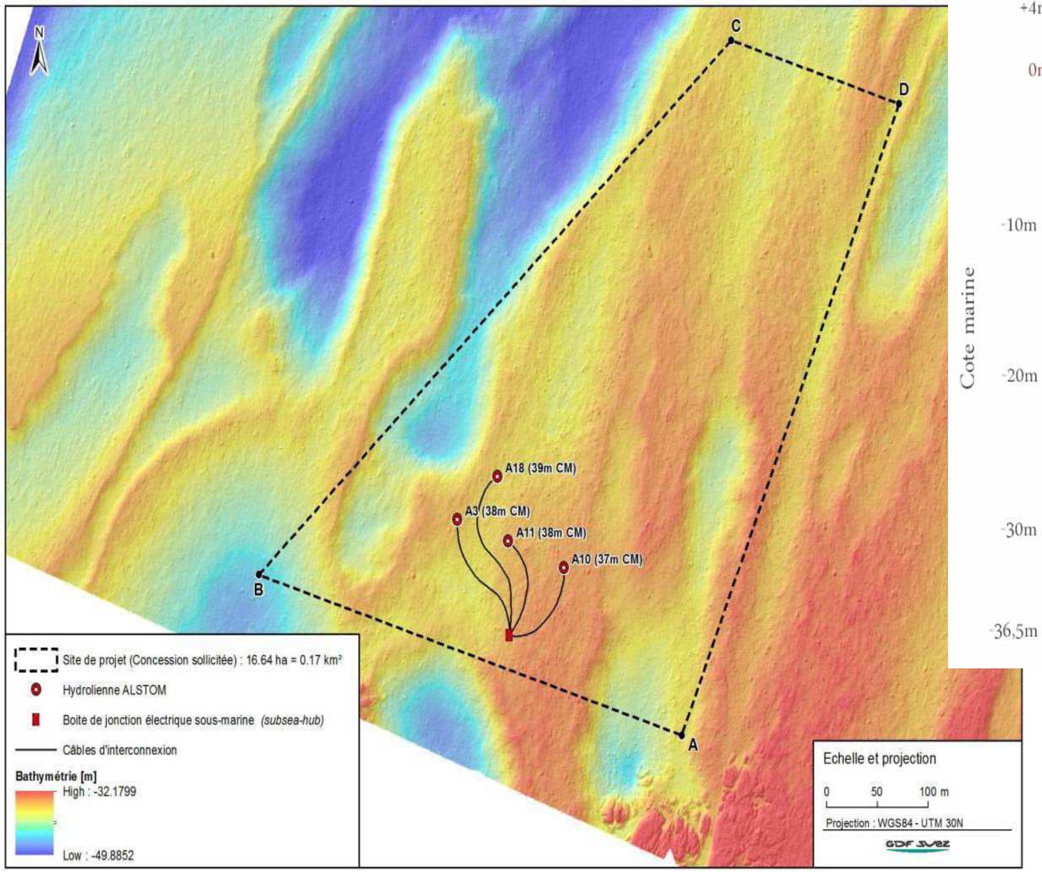
NEPTHYD

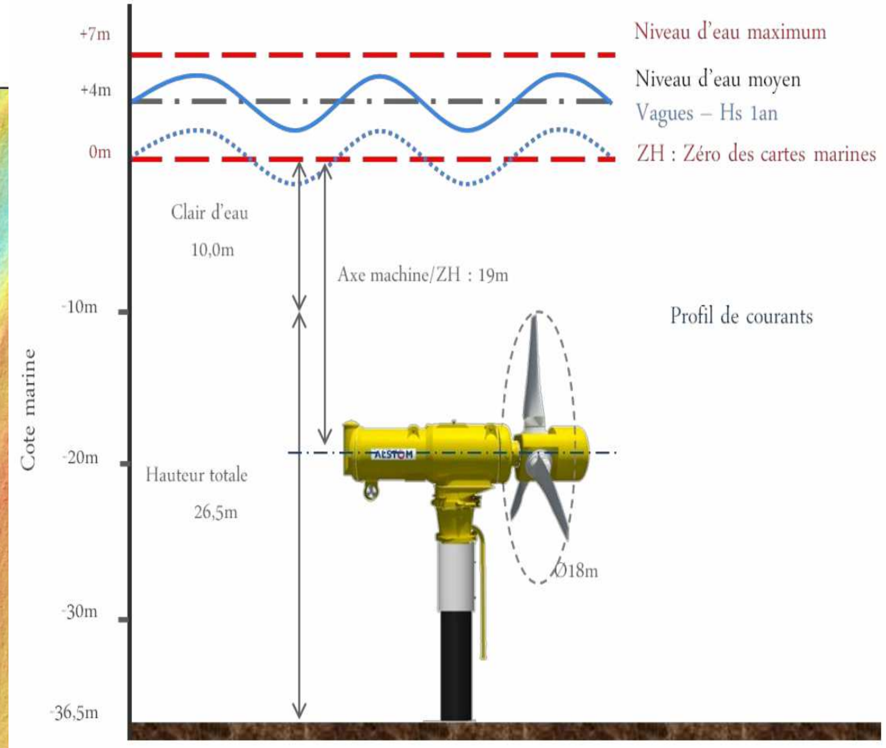
- 4 hydroliennes de type ALSTOM OceadeTM (1,4 MW – Diam 18m)
- Total de 5,6 MW et un productible total de 14,9 GWh/an (fonctionnement de l'ordre de 2 000 heures par an)

Éléments	Spécifications
Position du rotor	Face au courant
Nombres de pales	3
Diamètre du rotor	Environ 18 m
Hauteur minimale entre le haut des pales et la surface marine	10 m
Dimension de la turbine (sans les pales)	L = 20 à 23 m, l = 3,5 à 4 m
Vitesse de rotation des pales *et vitesse instantanée en extrémités de pales*	Entre 3 et 19 tr/mn *(3 à 18 m/s)* Optimale : 14 tr/mn *(13 m/s)* Médiane : 10 tr/mn *(9 m/s)*
Vitesse de courant de démarrage	Environ 0,7 m/s
Vitesse de courant optimale de production	> 3,1 m/s

History of tidal energy

- NEPTHYD





In case of extreme waves…

History of tidal energy

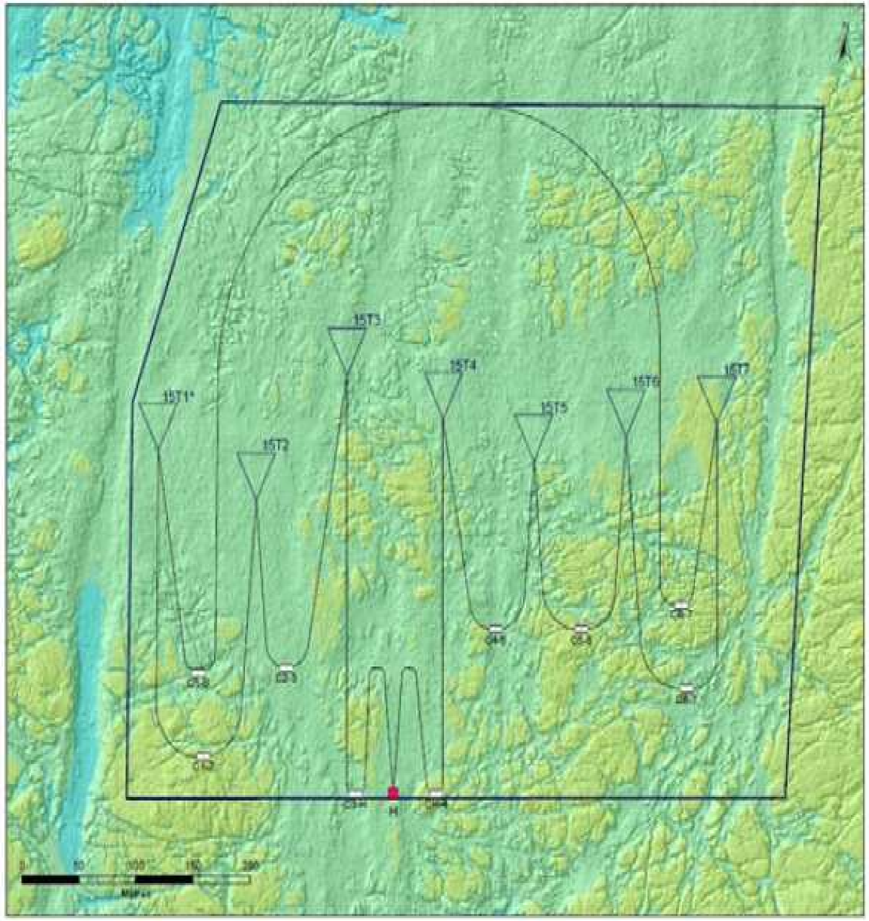
Normandie Hydro

- 7 hydroliennes de type Open Hydro DCNS (2 MW – Diam ≈ 13 m)
- Total de 14 MW et un productible total de 28 GWh/an (fonctionnement de l'ordre de 2 000 heures par an)

Eléments	Spécifications
Position du rotor	Fonctionnement bidirectionnel (au flot et au jusant sans modification d'orientation)
Nombres de pales	*10*
Diamètre du rotor – intérieur – extérieur	 4 m *Environ 13 m*
Hauteur minimale entre le haut du carénage de la turbine et la surface marine	9 à 10 m
Dimension de la turbine (carénage)	L = 9 m, diamètre = 16 m,
Vitesse de rotation des pales et vitesse instantanée en extrémités de pales – intérieures – extérieures	Maximale non connue < 12 tr/mn 90% du temps < 2.5 m/s 90% du temps *< 8.2 m/s 90% du temps*
Vitesse de courant de démarrage	< 1 m/s
Vitesse de courant optimale de production	n.c.

History of tidal energy

- Normandie Hydro



History of tidal energy

- MeyGen in Scotland
  - Sept. 2016
  - First foundations
  - Pentland Firth
  - Developed by Atlantis Resources

  - 4 x 1.5 MW turbines
    - 1 Andritz Hydro
    - 3 AR1500 Atlantis

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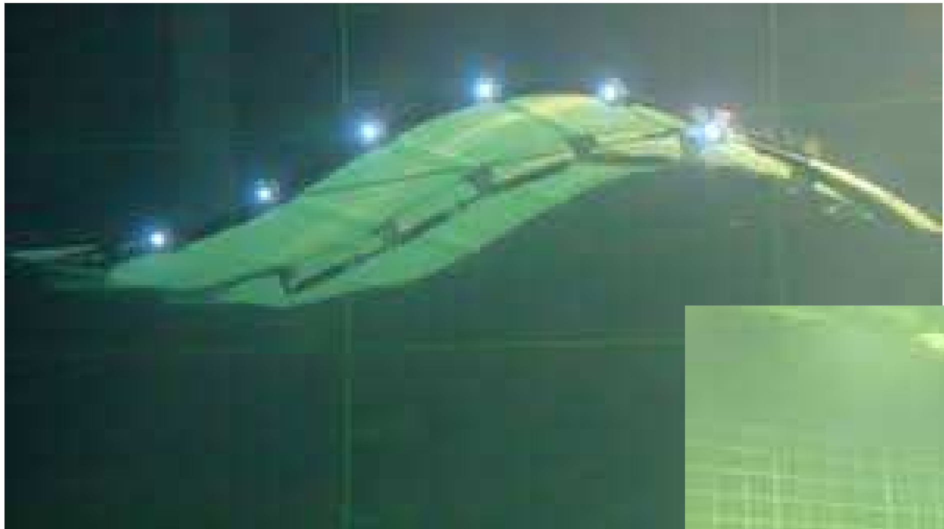
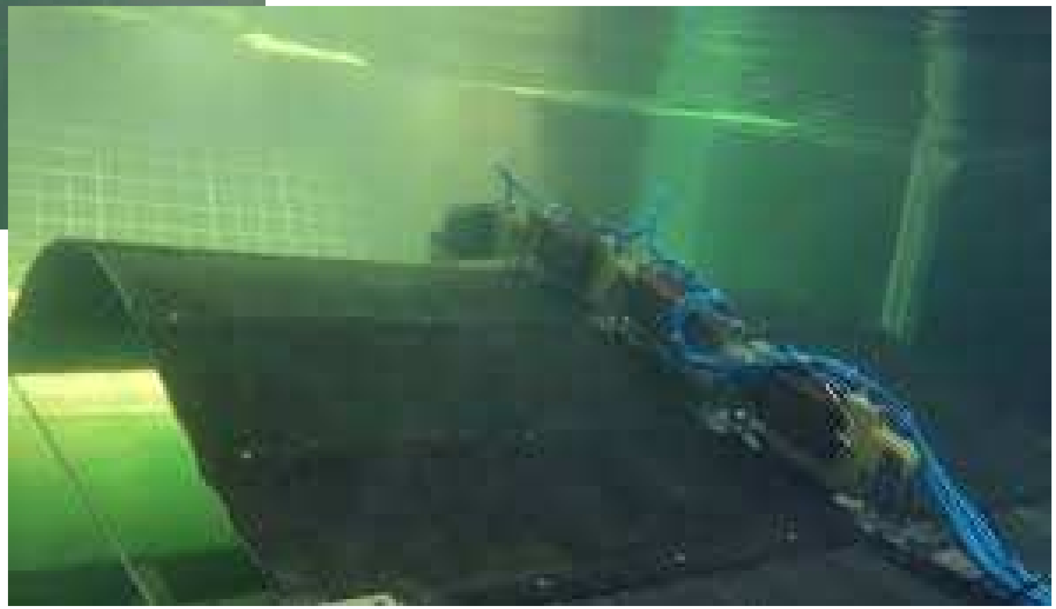
Technology review

- Presentation of Jean-Luc Achard.

Technology review

- EEL Energy





www.eel-energy.fr

Outline

Conclusion

- Objectifs 2020 : Paquet **« climat - énergie »** (Europe et Grenelle de l'environnement)
  - **-20%** d'émission de CO_2 par rapport à 1990
    - voire -30% si accord international après 2012
  - **-20%** de consommation d'énergie
  - **20%** d'énergie renouvelable dans la consommation finale d'énergie
- L'IFREMER estime que pour 2020 :
  - **7,7%** (Energies Renouvelables de la Mer) dont :
    - **5,2%** pour l'éolien off-shore
    - **2,5%** pour les autres (hydrolienne, ETM, vagues, etc.)
- Encore plus en 2025 ou 2030…