OFFSHORE WIND TURBINE FOUNDATIONS

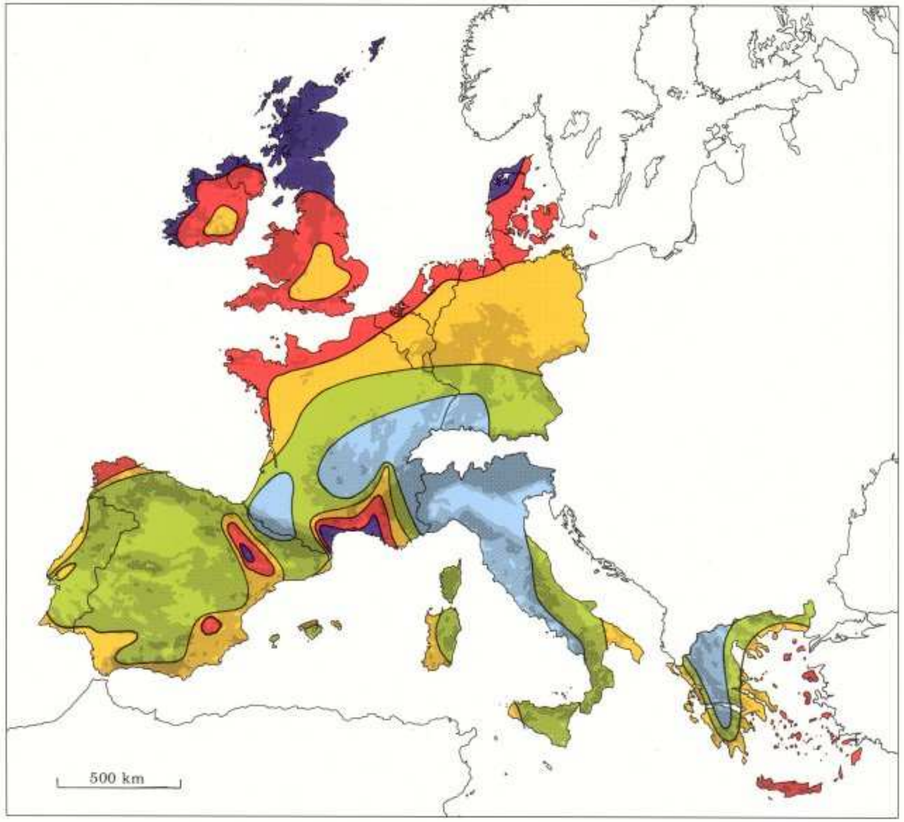
Christophe PEYRARD

EDF R&D - LNHE

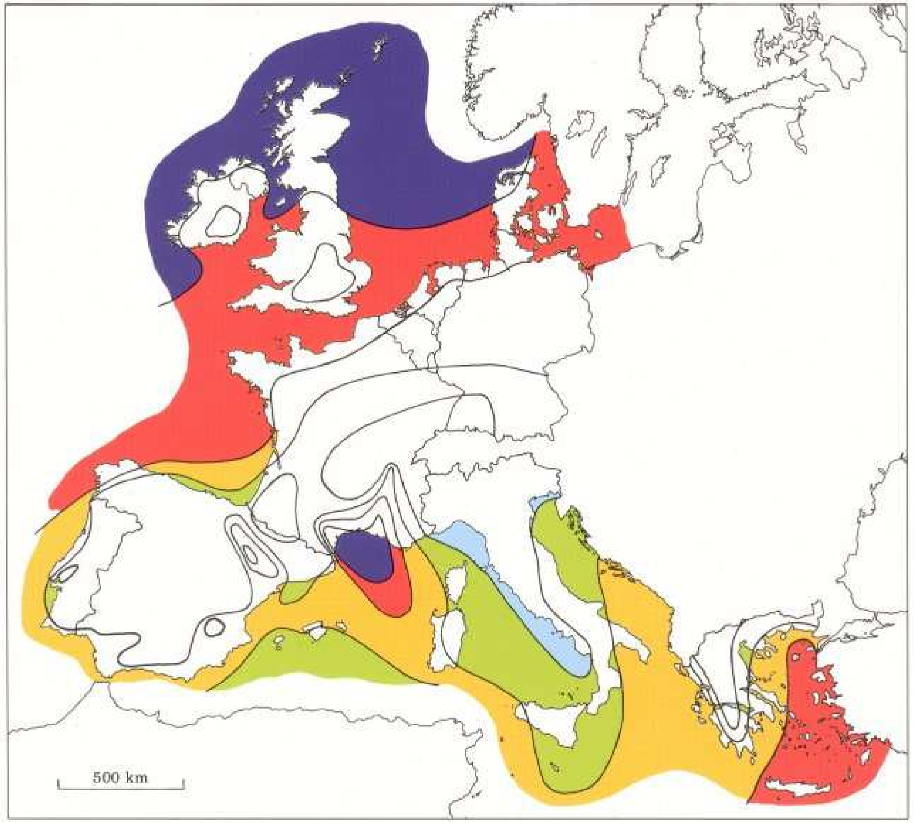
Laboratoire d’Hydraulique St Venant

CHANGER L'ÉNERGIE ENSEMBLE

WIND RESOURCE IN EUROPE



Wind resources[1] at 50 metres above ground level for five different topographic conditions										
	Sheltered terrain[2]		Open plain[3]		At a sea coast[4]		Open sea[5]		Hills and ridges[6]	
	$\mathrm{m\,s^{-1}}$	$\mathrm{Wm^{-2}}$	$\mathrm{m\,s^{-1}}$	$\mathrm{Wm^{-2}}$	$\mathrm{m\,s^{-1}}$	$\mathrm{Wm^{-2}}$	$\mathrm{m\,s^{-1}}$	$\mathrm{Wm^{-2}}$	$\mathrm{m\,s^{-1}}$	$\mathrm{Wm^{-2}}$
🟪	> 6.0	> 250	> 7.5	> 500	> 8.5	> 700	> 9.0	> 800	> 11.5	> 1800
🟥	5.0-6.0	150-250	6.5-7.5	300-500	7.0-8.5	400-700	8.0-9.0	600-800	10.0-11.5	1200-1800
🟨	4.5-5.0	100-150	5.5-6.5	200-300	6.0-7.0	250-400	7.0-8.0	400-600	8.5-10.0	700-1200
🟩	3.5-4.5	50-100	4.5-5.5	100-200	5.0-6.0	150-250	5.5-7.0	200-400	7.0- 8.5	400- 700
🟦	< 3.5	< 50	< 4.5	< 100	< 5.0	< 150	< 5.5	< 200	< 7.0	< 400



Wind resources over open sea (more than 10 km offshore) for five standard heights										
	10 m		25 m		50 m		100 m		200 m	
	$\mathrm{m\,s^{-1}}$	$\mathrm{Wm^{-2}}$	$\mathrm{m\,s^{-1}}$	$\mathrm{Wm^{-2}}$	$\mathrm{m\,s^{-1}}$	$\mathrm{Wm^{-2}}$	$\mathrm{m\,s^{-1}}$	$\mathrm{Wm^{-2}}$	$\mathrm{m\,s^{-1}}$	$\mathrm{Wm^{-2}}$
🟪	> 8.0	> 600	> 8.5	> 700	> 9.0	> 800	> 10.0	> 1100	> 11.0	> 1500
🟥	7.0-8.0	350-600	7.5-8.5	450-700	8.0-9.0	600-800	8.5-10.0	650-1100	9.5-11.0	900-1500
🟨	6.0-7.0	250-300	6.5-7.5	300-450	7.0-8.0	400-600	7.5- 8.5	450- 650	8.0- 9.5	600- 900
🟩	4.5-6.0	100-250	5.0-6.5	150-300	5.5-7.0	200-400	6.0- 7.5	250- 450	6.5- 8.0	300- 600
🟦	< 4.5	< 100	< 5.0	< 150	< 5.5	< 200	< 6.0	< 250	< 6.5	< 300

From the *European Wind Atlas*. Copyright © 1989 by Risø National Laboratory, Denmark

OFFSHORE WIND ENERGY

From DNV

OBJECTIVES OF THE PRESENTATION

- **Offshore Wind Energy**
  - ☐ Development / General context
  - ☐ Bottom fixed context in France
  - ☐ Floating context in France

- **Bottom fixed / Floating foundations**
  - ☐ Engineering
  - ☐ Construction
  - ☐ Installation

- **Technical aspects and challenges**

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OFFSHORE WIND CONTEXT

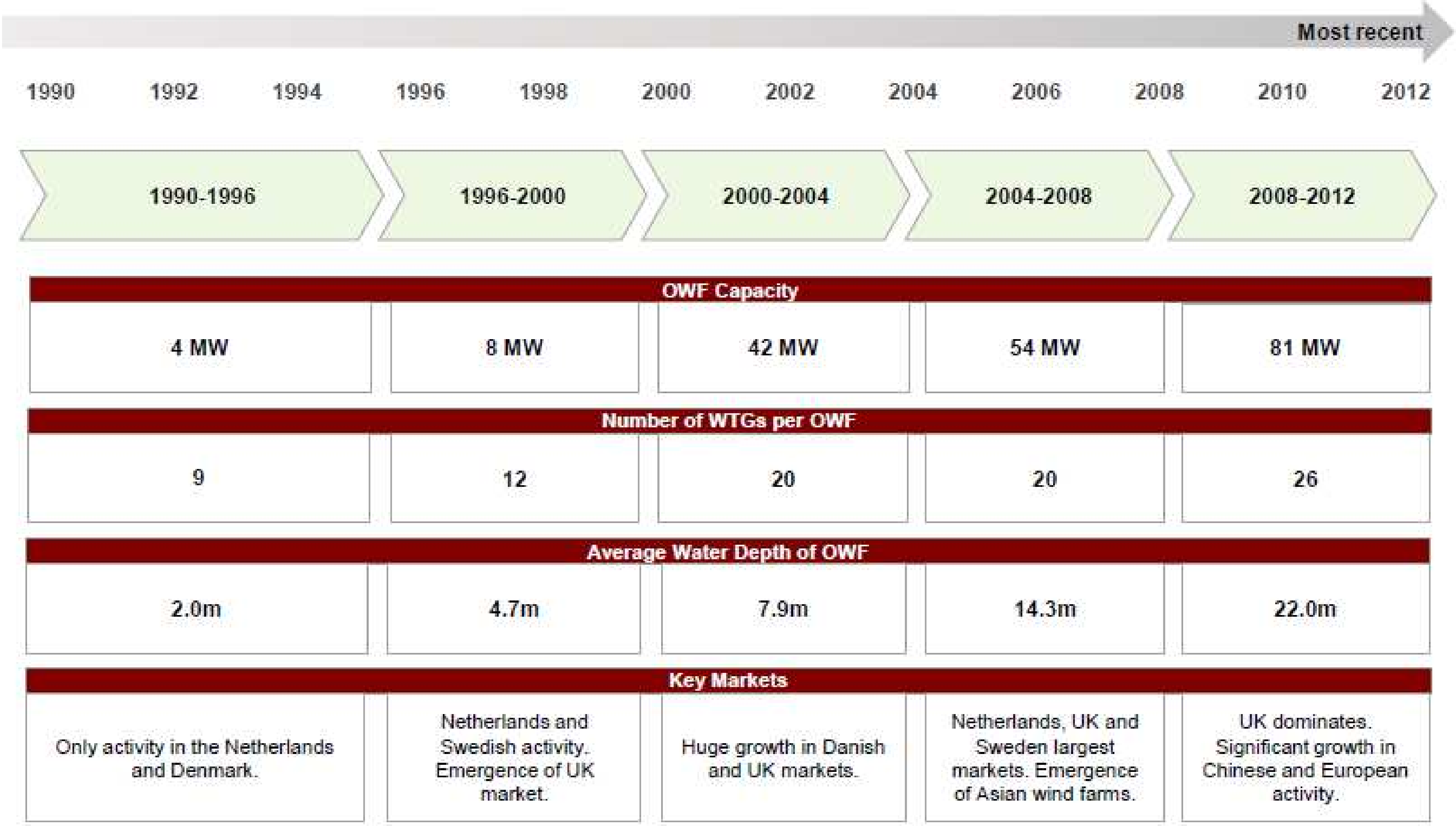
OFFSHORE WIND - HISTORY

- 1st offshore wind turbine installed in Sweden in 1991 (Nogersund; 220kW Wind World W2500; Ø 25 m).
- 1st offshore wind farm in Denmark in 1992 (off Vindeby; 11 x 450 kW Bonus B35/450). Water depth: 2 - 4 m; gravity foundation; 3km from shore.
- Until 2001, various developments off Denmark, Sweden and Netherlands (turbines P< 1MW).
- Denmark started to develop large offshore wind farms:
  - Middelgrunden (2001): 40MW; 20 x Bonus B76 – 2MW turbines.
  - Horns Rev I (2002): 160 MW ; 80 x Vestas V80-2MW
  - Nysted (2003): 166 MW; 72 x Siemens SWT 2.3MW turbines
- Since 2003, the UK then Germany and Belgium have launched large offshore wind projects...

Vindeby farm - Denmark

Horns Rev I farm - Denmark

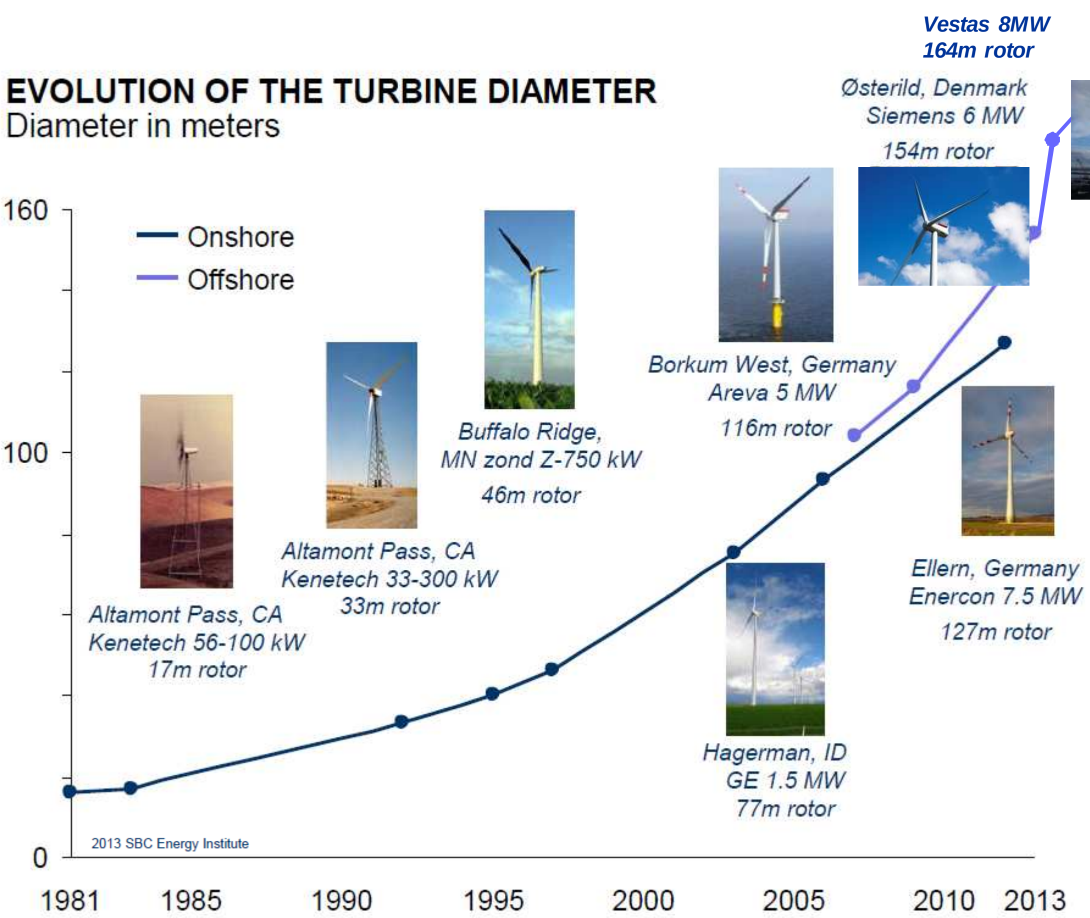
OFFSHORE WIND DEVELOPMENT

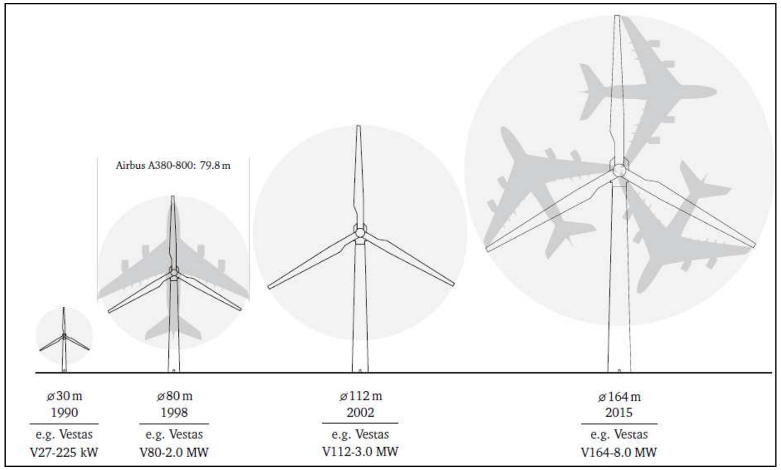


	1990-1996	1996-2000	2000-2004	2004-2008	2008-2012
OWF Capacity	4 MW	8 MW	42 MW	54 MW	81 MW
Number of WTGs per OWF	9	12	20	20	26
Average Water Depth of OWF	2.0m	4.7m	7.9m	14.3m	22.0m
Key Markets	Only activity in the Netherlands and Denmark.	Netherlands and Swedish activity. Emergence of UK market.	Huge growth in Danish and UK markets.	Netherlands, UK and Sweden largest markets. Emergence of Asian wind farms.	UK dominates. Significant growth in Chinese and European activity.

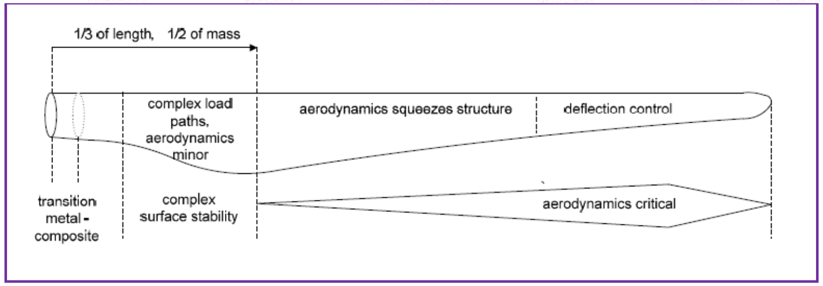
Douglas – Westwood

TURBINES SIZE EVOLUTION





IPCC (2011), "Special report on renewable energy"



83.5 m SSP Blade for Samsung S7.0-171 (Denmark)

EUROPEAN OFFSHORE WIND TARGET 2020

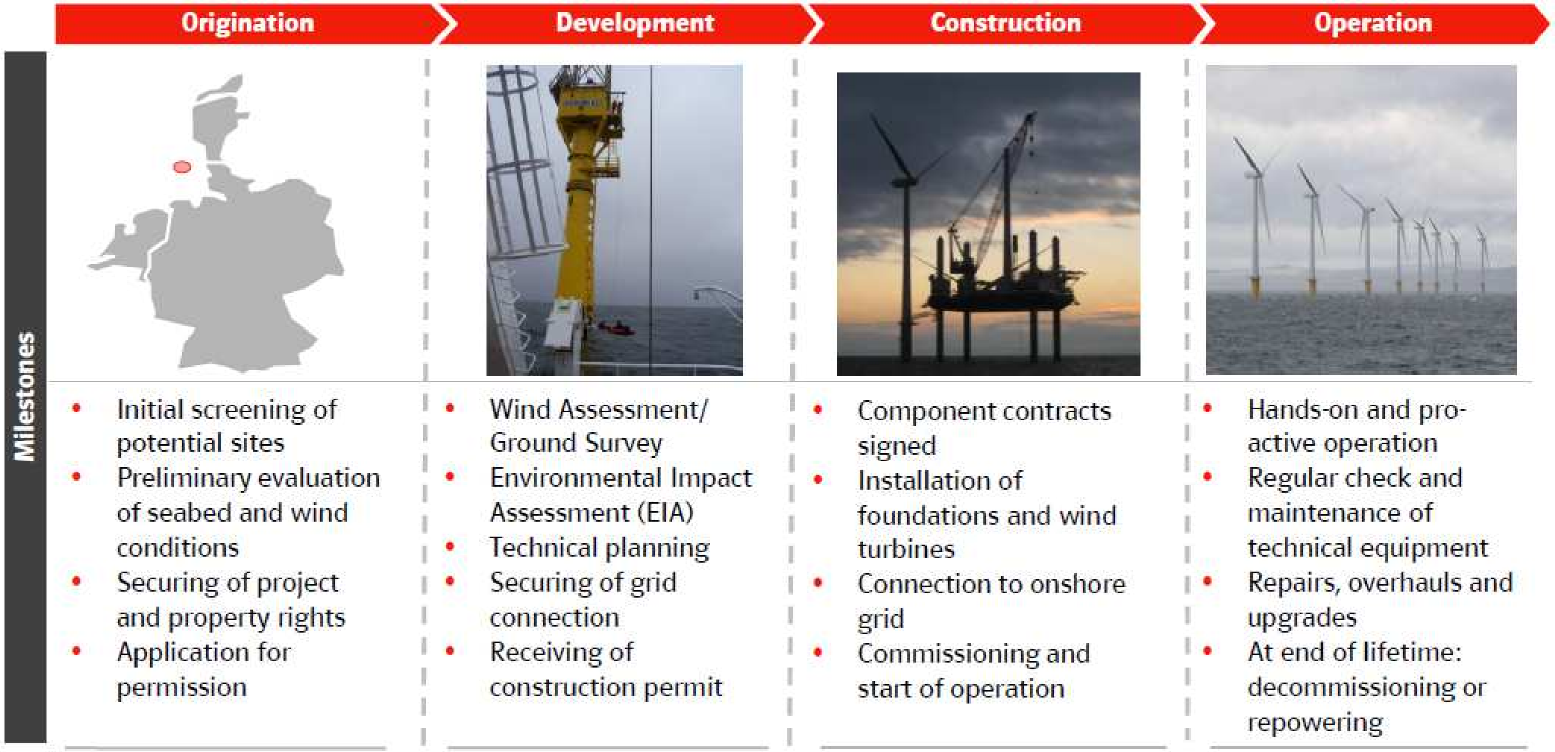
NREAP 2020: 43 GW
EWEA estimate
(mid-2014): 23.5 GW
in 2020

Source: BTM Consult- A Part of Navigant

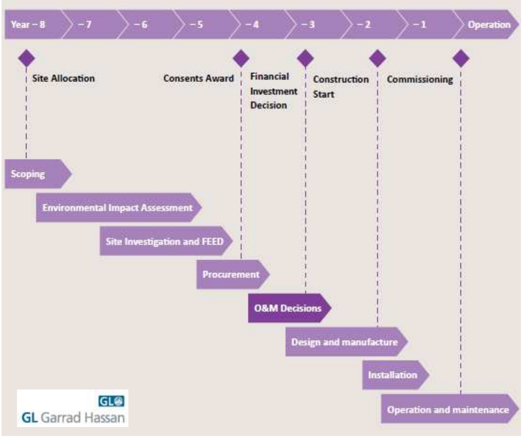
Unit: GW

NREAP: National Renewable Energy Action Plan

OFFSHORE WIND DEVELOPMENT - MAIN STEPS



	Origination	Development	Construction	Operation
Milestones	• Initial screening of potential sites • Preliminary evaluation of seabed and wind conditions • Securing of project and property rights • Application for permission	• Wind Assessment/ Ground Survey • Environmental Impact Assessment (EIA) • Technical planning • Securing of grid connection • Receiving of construction permit	• Component contracts signed • Installation of foundations and wind turbines • Connection to onshore grid • Commissioning and start of operation	• Hands-on and pro-active operation • Regular check and maintenance of technical equipment • Repairs, overhauls and upgrades • At end of lifetime: decommissioning or repowering



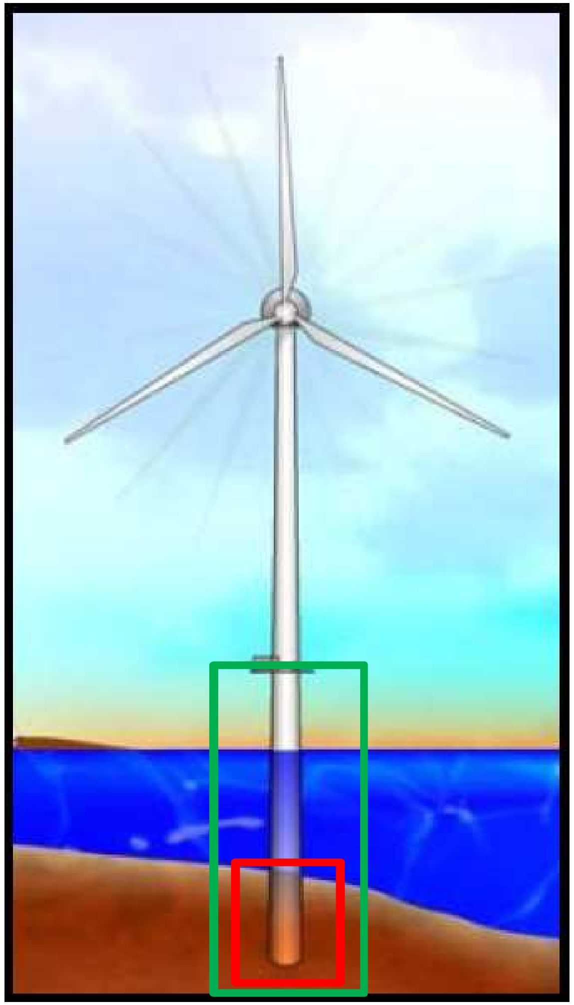
OFFSHORE WIND FOUNDATIONS

BOTTOM FIXED FOUNDATIONS

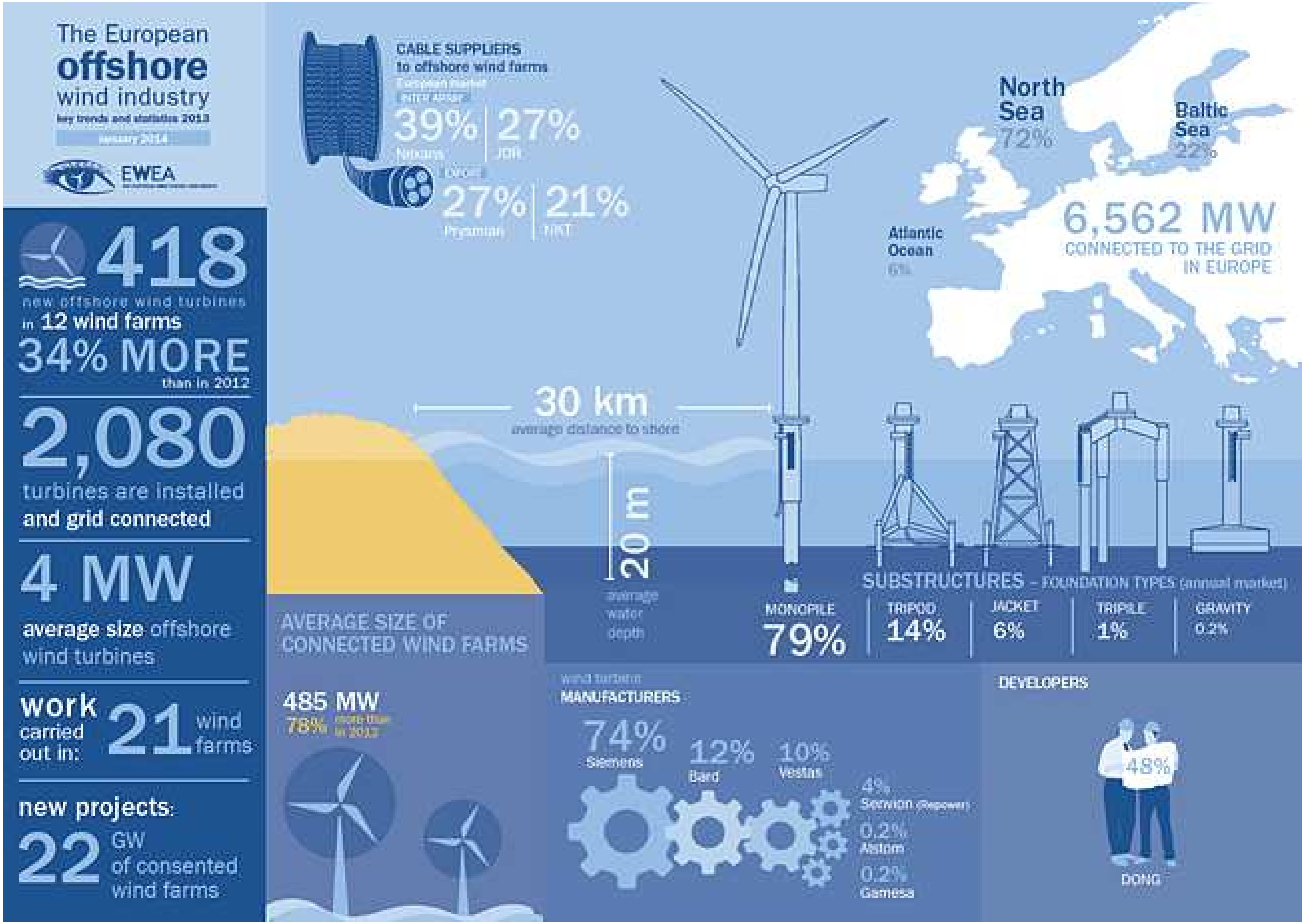
DEFINITION

- **Civil Engineering definition**
  - Under ground part of the structure
  - Soil-structure boundary
  - Soil mechanics / Geotechnical field
  - Definition used by some french utilities

- **Offshore wind field definition**
  - « Under tower » part of the structure
  - Soil-structure and water-structure boundaries
  - Soil mechanics and Fluid Mechanics
  - Definition generally adopted in UK, Germany and many foreign utilities



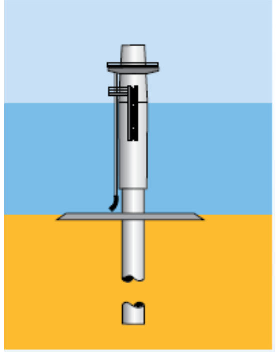
OFFSHORE WIND – KEY DATA 2013

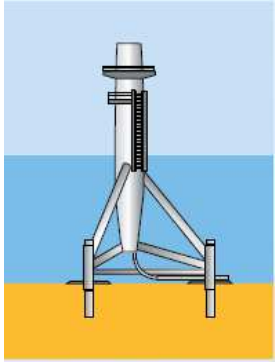


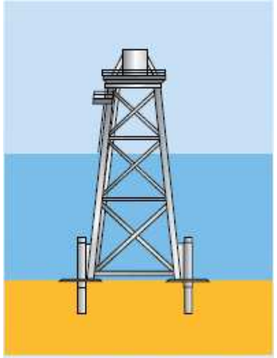
BOTTOM FIXED FOUNDATION

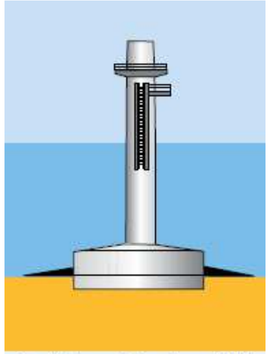
TYPE OF FOUNDATIONS

- **OWT foundations main types :**
  - Monopile
  - Tripod
  - Jacket
  - Gravity Based Foundation (GBF or GBS)

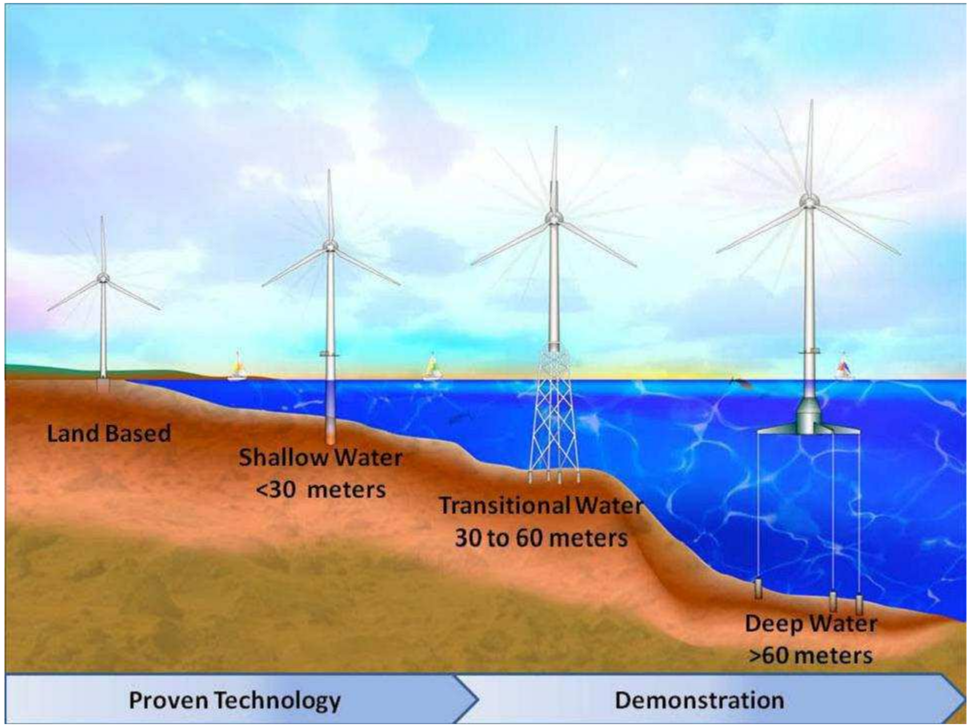

Monopile


Space Frame (Tripod)

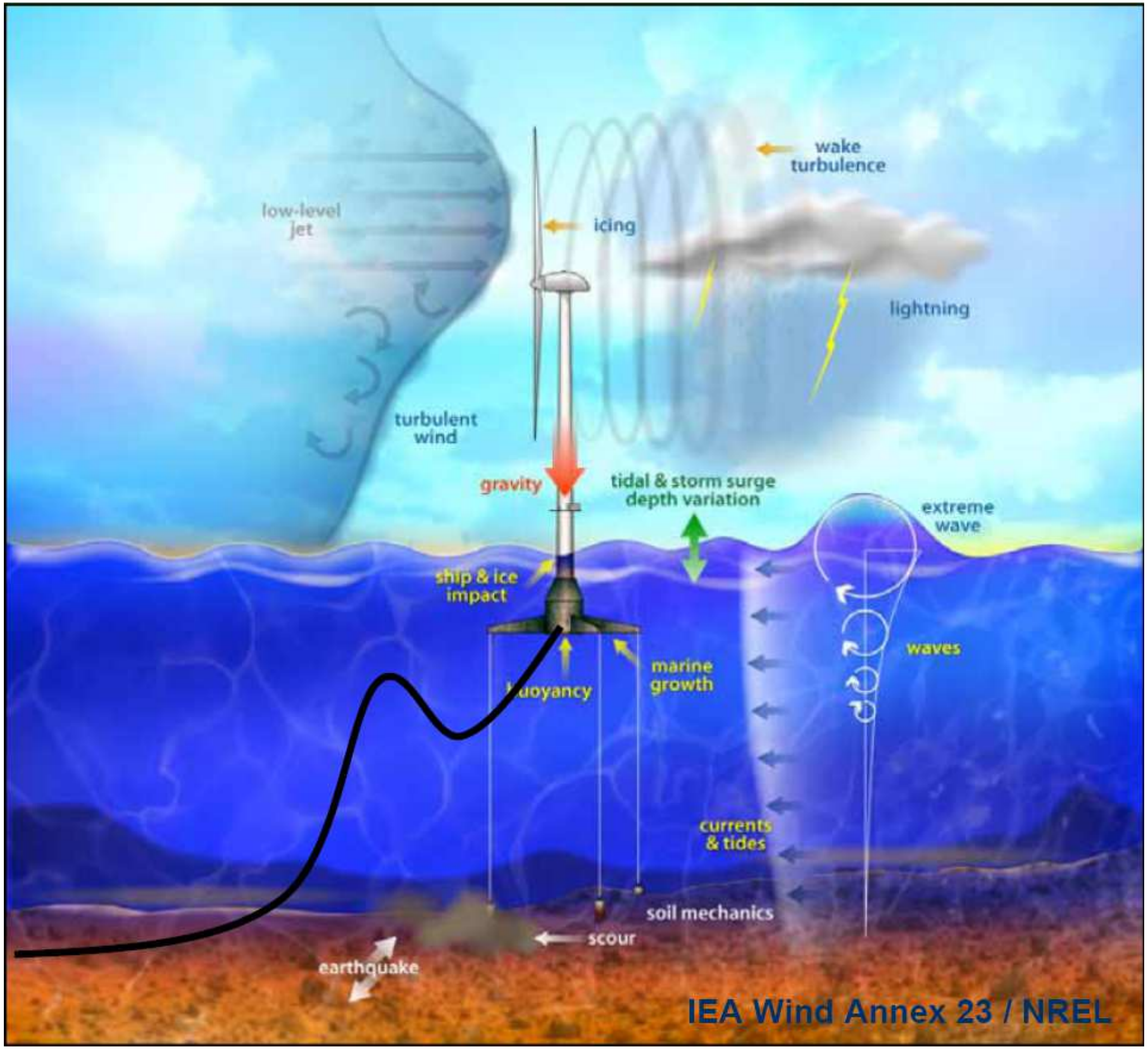

Space Frame (Jacket)


Gravity-based Structure (GBS)

- **Usually, the choice of the structure depends on the water depth and the sea bed (rock, sand…)**
  - Monopile typically until 20/30m
  - Tripod typically until 30/40m
  - Jacket typically until 50/60m
  - GBS typically until 30/50m

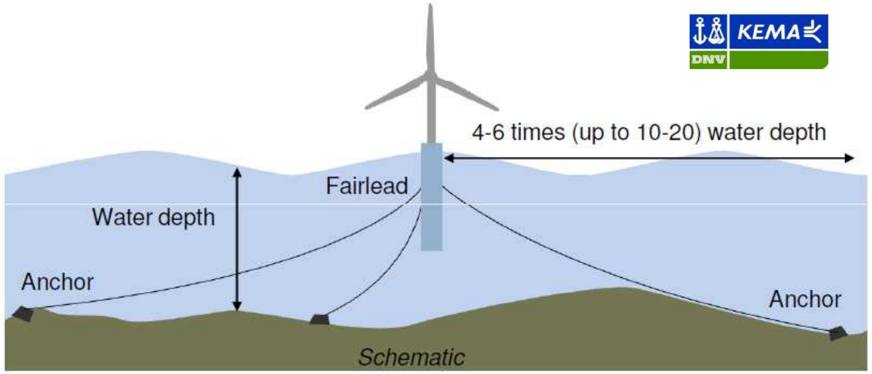


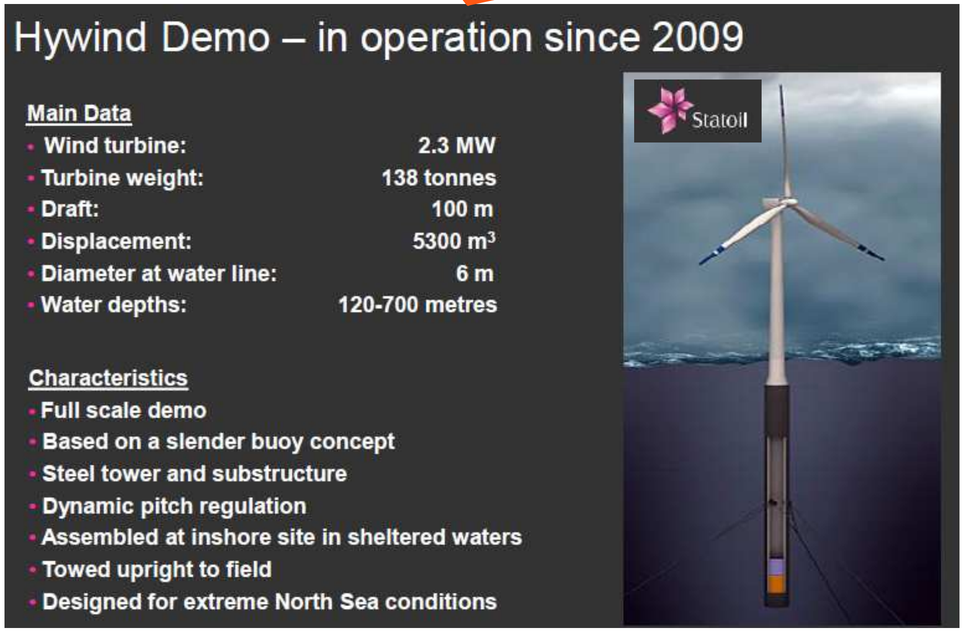
FLOATING FOUNDATIONS



SPAR: HYWIND (2009)

. 800 ml mooring lines
. Turbine Siemens SWT 2.3MW
- Water depth: 220 m





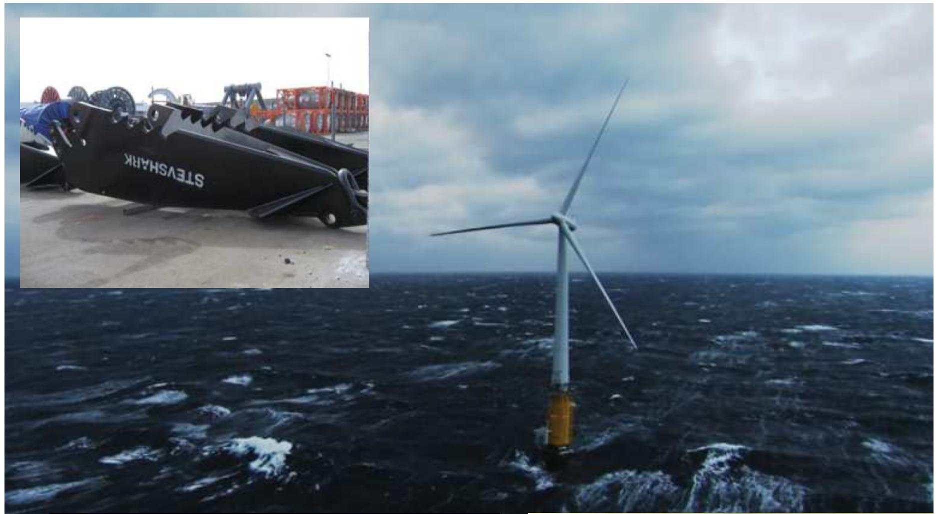
Hywind Demo – in operation since 2009

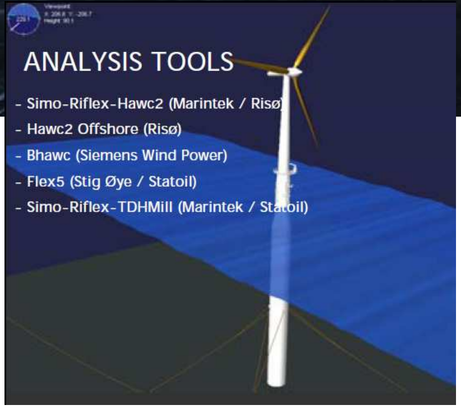
Main Data

Wind turbine:	2.3 MW
Turbine weight:	138 tonnes
Draft:	100 m
Displacement:	5300 m^3
Diameter at water line:	6 m
Water depths:	120-700 metres

Characteristics

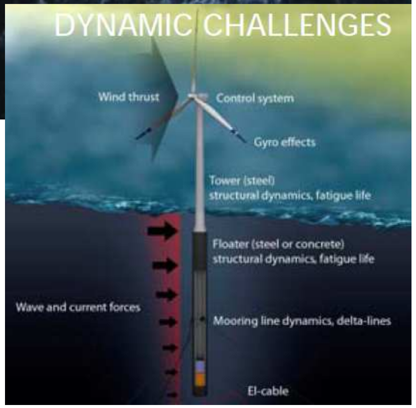
- Full scale demo
- Based on a slender buoy concept
- Steel tower and substructure
- Dynamic pitch regulation
- Assembled at inshore site in sheltered waters
- Towed upright to field
- Designed for extreme North Sea conditions



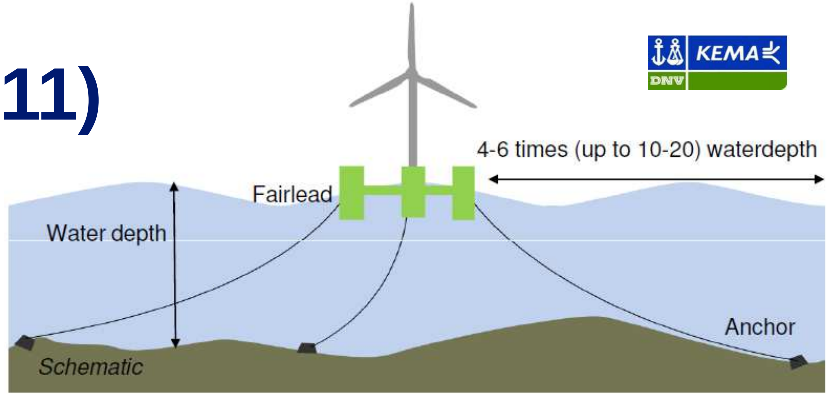


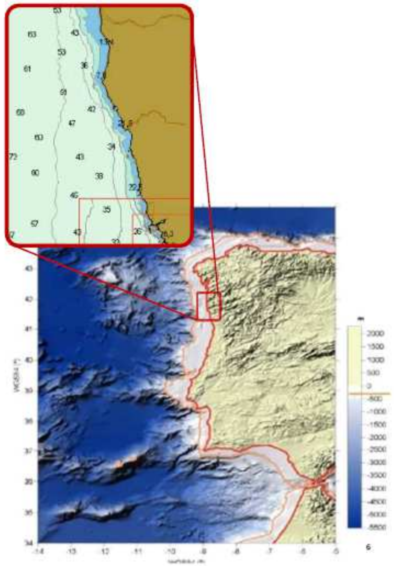
ANALYSIS TOOLS

- Simo-Riflex-Hawc2 (Marintek / Risø)
- Hawc2 Offshore (Risø)
- Bhawc (Siemens Wind Power)
- Flex5 (Stig Øye / Statoil)
- Simo-Riflex-TDHMill (Marintek / Statoil)



SEMI-SUB : WINDFLOAT (2011)





Phase 1 – Demonstration

Capacity: 2MW WindFloat prototype

Location: Aguçadoura, grid connected

~6 km of coast, 40 - 50 m water depth

Turbine: 2MW offshore wind turbine

Test period: 24+ months

Core focus of DemoWfloat

Phase 2 - Pre-commercial

Capacity: ~27MW (~5 WindFloat units)

Location: Portuguese Pilot Zone

Turbine: Likely Vestas and other, Multi MW

Core focus of NER300

JAPANESE PROJECTS : SEMI-SUB AND SPAR (2013)

Fukushima (Mitsui/Hitachi)

- Design for use with a 2MW turbine
- Width 58 m
- Total column length 32 m of which 16 mwill be submerged
- Hub height 60 m

GOTO OWT (Toda/Hitachi)

Full Scale:

- 2MW downwind turbine with 80m rotor diameter
- Total spar length 172m
- Total weight incl. Turbine 3,400 t
- Steel with pre-stressed concrete
- Steel chain mooring, 3 points, catenary, attached to drag anchors

Image Source: Kyoto University

JAPANESE PROJECTS : SEA ANGEL (2015)

Fukushima
7 MW (MHI)
=
Bigest Offshore Wind turbine installed

Items	Scopes	
Turbine	• Verification of 7MW hydraulic turbine.	
Floating	• Development of V-shape semi-sub floating. • Development of the reduction of floating motion by turbine control and O&M program.	
Mooring	• 8 pieces catenary.	• Rotor diameter 164m • Hub height 105m (ASL) • Height of the floater 32m

Installed summer 2015

FUKUSHIMA-FORWARD Project

ADVANCED SPAR 5 MW (2016)

- **Last part of Fukushima forward project**
  - 5MW Turbine
    - Hitachi
    - Downwind type
  - Advanced-spar concept
    - Japan Marine United
    - Low draft solution (30m)
    - Large sections (50m)

→ Japan is still working on prototypes

Full shape

Built in the dockyard of Hitz

Carried to Sumoto port on 2 May

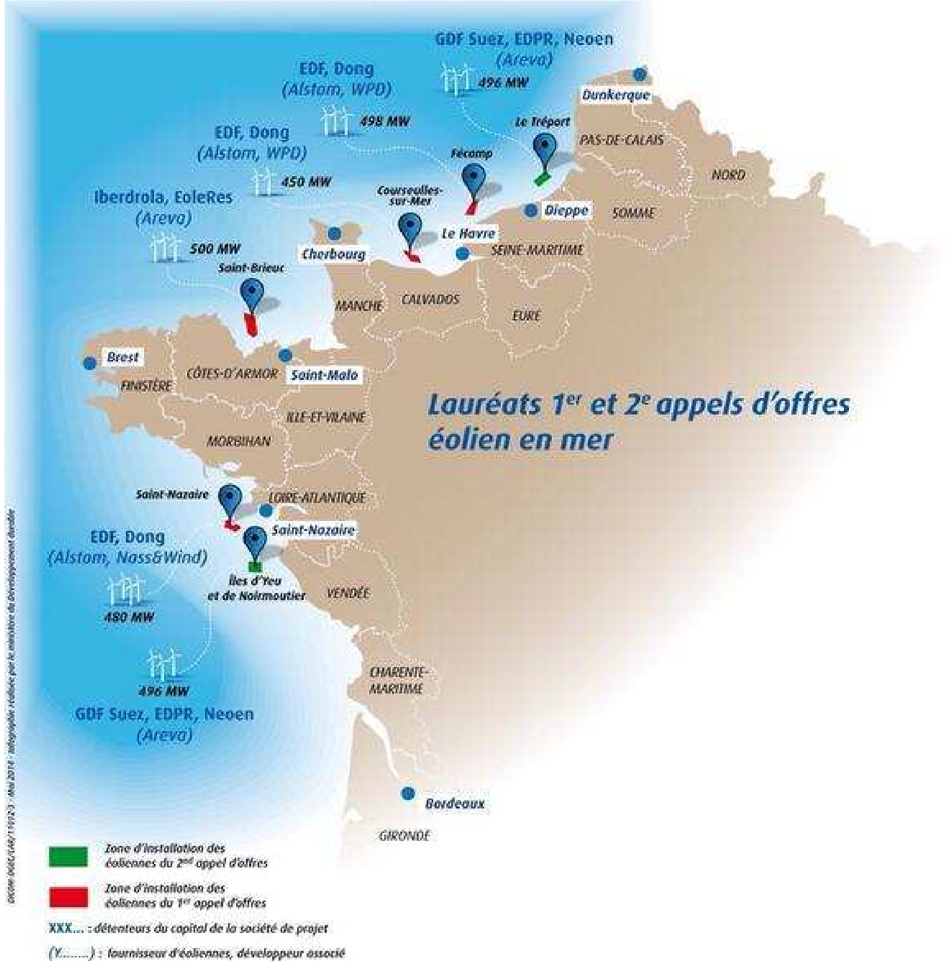
The floater lost control and leaned on 9 May

The floater recovered stability again on 14 May

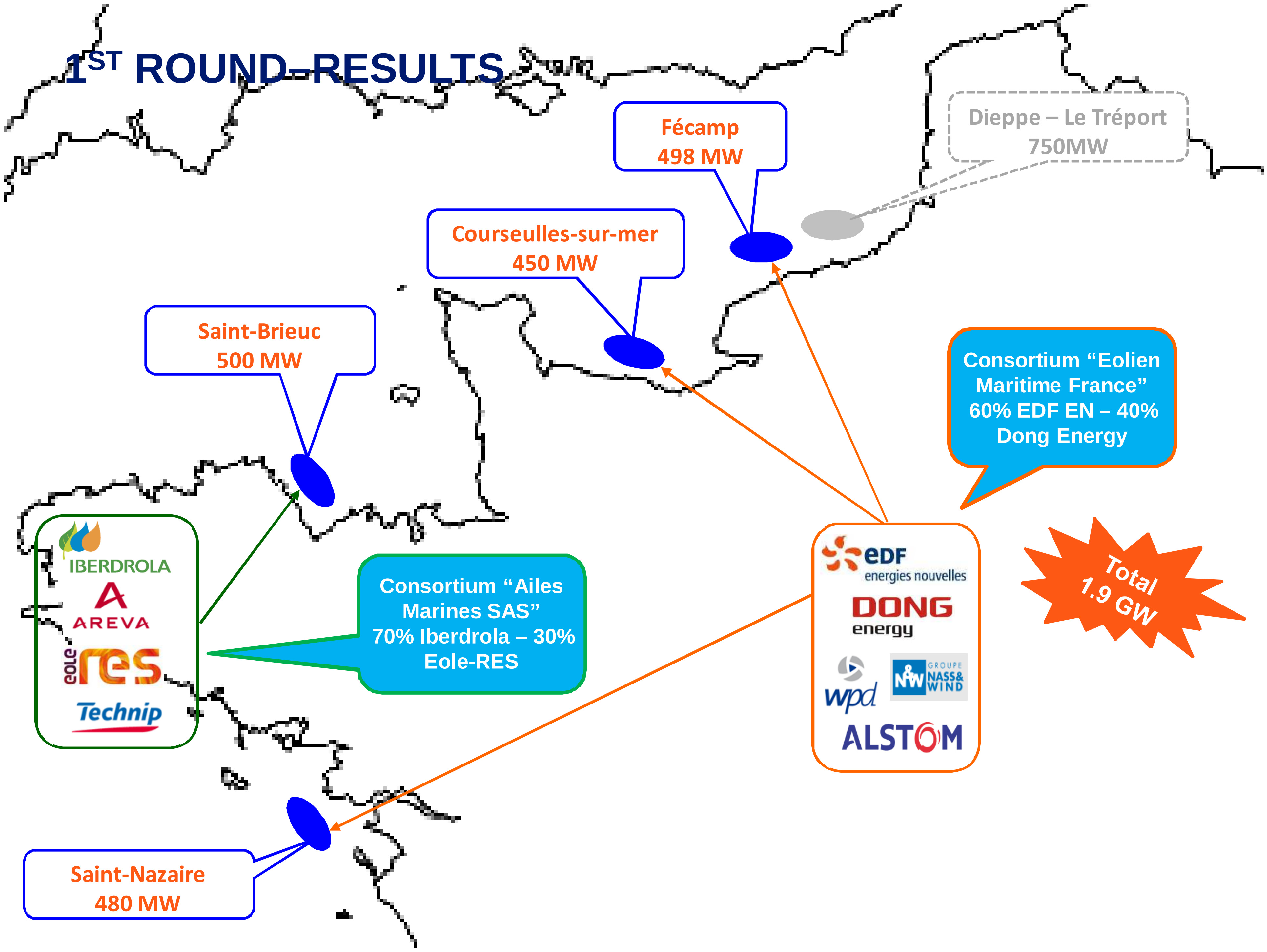
OFFSHORE WIND IN FRANCE

FRANCE

- **2004 : 1st Call for Tender “Centrales Eoliennes en mer”. 1 site awarded: Côte d’Albâtre (Velettes – Enertrag 105 MW with Areva). NIMBY issues... Cancelled.**
- **2011 : 1st Round (Call for Tender) - 3 GW - 5 sites (Le Tréport - Fécamp - Courseulles - St Brieuc et St Nazaire). 4 sites awarded 1.9 GW. Construction: 2019-2020.**
- **2013 : 2nd Round - 1 GW - 2 sites (Le Tréport et Iles d’Yeu & de Noirmoutier). Construction : 2021-2023.**



1ST ROUND–RESULTS



Fécamp
498 MW

Dieppe – Le Tréport
750MW

Courseulles-sur-mer
450 MW

Saint-Brieuc
500 MW

Saint-Nazaire
480 MW

IBERDROLA
AREVA
eole res
Technip

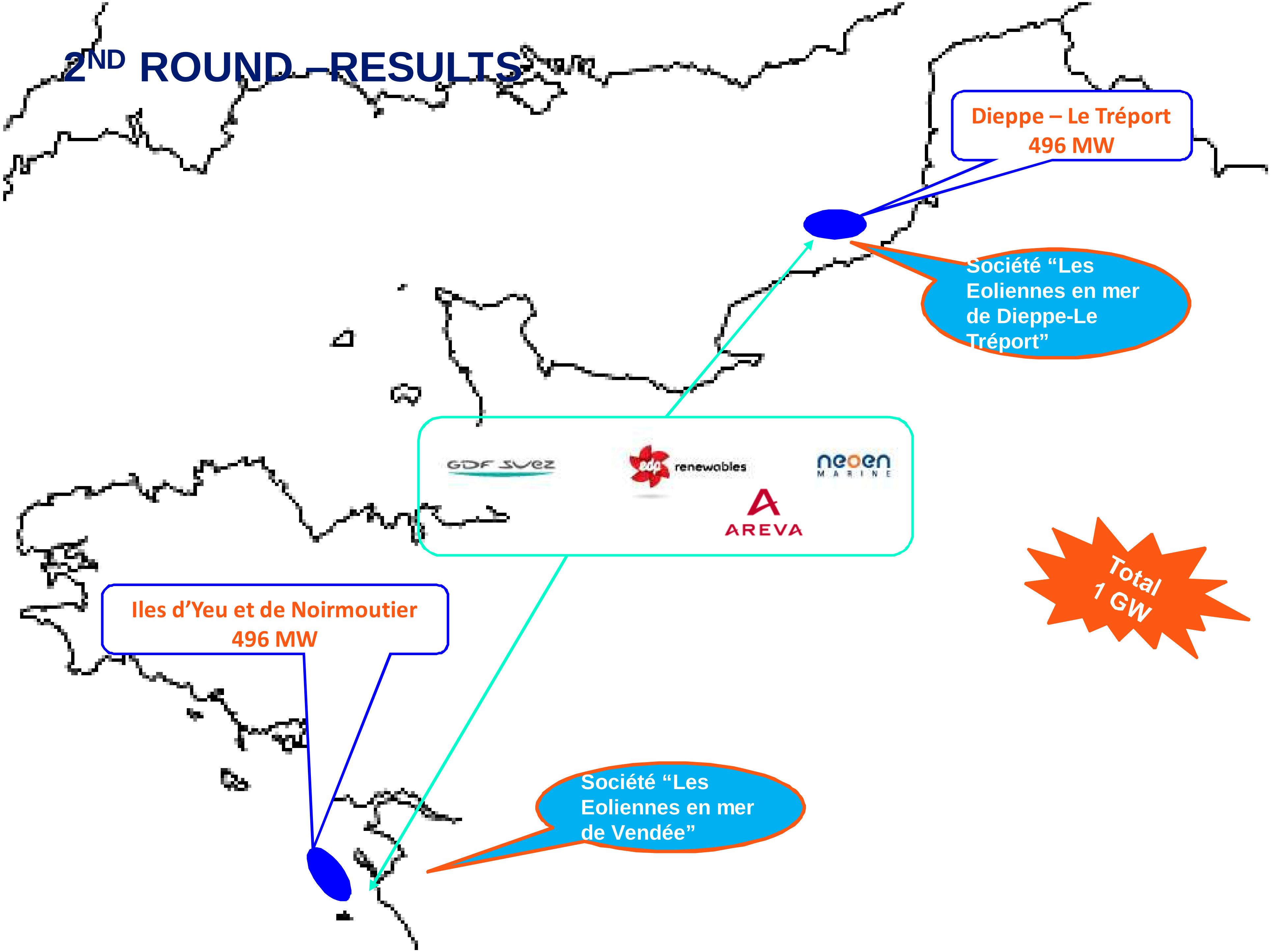
Consortium “Ailes Marines SAS”
70% Iberdrola – 30% Eole-RES

EDF energies nouvelles
DONG energy
wpd
GROUPE NASS&WIND
ALSTOM

Consortium “Eolien Maritime France”
60% EDF EN – 40% Dong Energy

Total 1.9 GW

2$^{\text{ND}}$ ROUND –RESULTS



Dieppe – Le Tréport
496 MW

Société “Les Eoliennes en mer de Dieppe-Le Tréport”

GDF SUEZ

edp renewables

neoen MARINE

AREVA

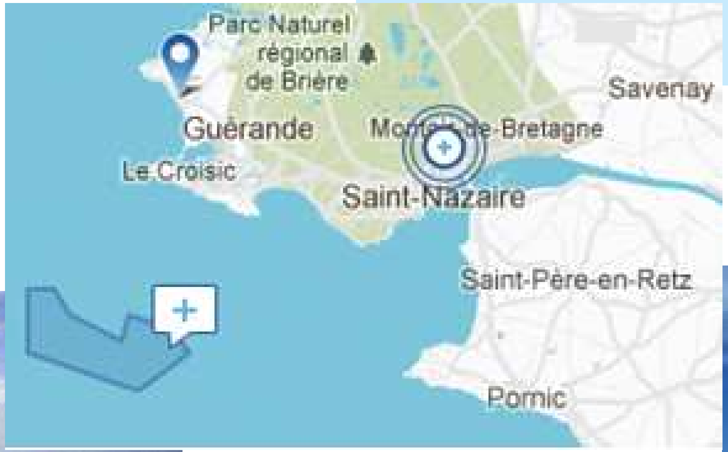
Iles d’Yeu et de Noirmoutier
496 MW

Société “Les Eoliennes en mer de Vendée”

Total
1 GW

INDUSTRIAL SIZE PROJECTS

- **Ambition : 3 GW of Offshore Wind by 2020**
  - ◻ 6 sites on the Atlantic coast
  - ◻ Water depth : 20m-40m
  - ◻ Distance to shore : 10/20 km
- **Large wind farms**
  - ◻ Typical installed power : 500 MW
  - ◻ Turbine : 5MW to 8 MW
    - Diameter ~ 150 m
  - ◻ 70 to 100 turbines / farm



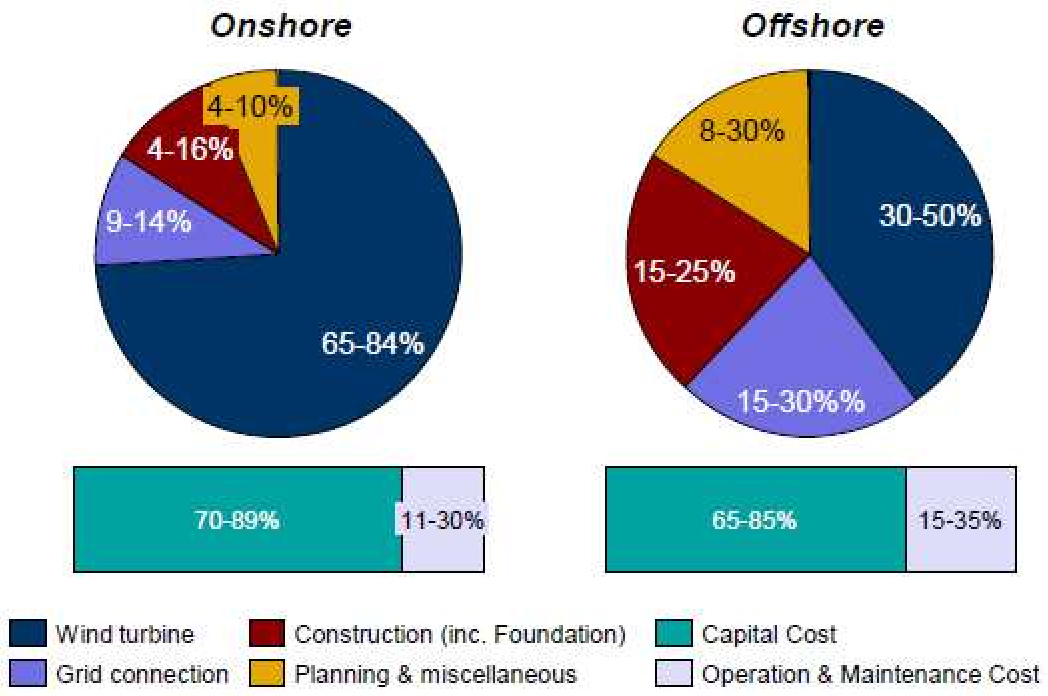
LABORATOIRE D'HYDRAULIQUE SAINT-VENANT

COUT DE L'ELECTRICITE

Réduire le
coût de
l'électricité

TYPICAL ONSHORE & OFFSHORE WIND COST BREAKDOWN

Capital cost breakdown (top) & share of capital in levelized cost of electricity (bottom)



CAPEX = Capital Expenditure

OPEX = Operational Expenditure

CoE = Cost of Electricity

$$CoE = \frac{CAPEX + OPEX}{PRODUCTION}$$

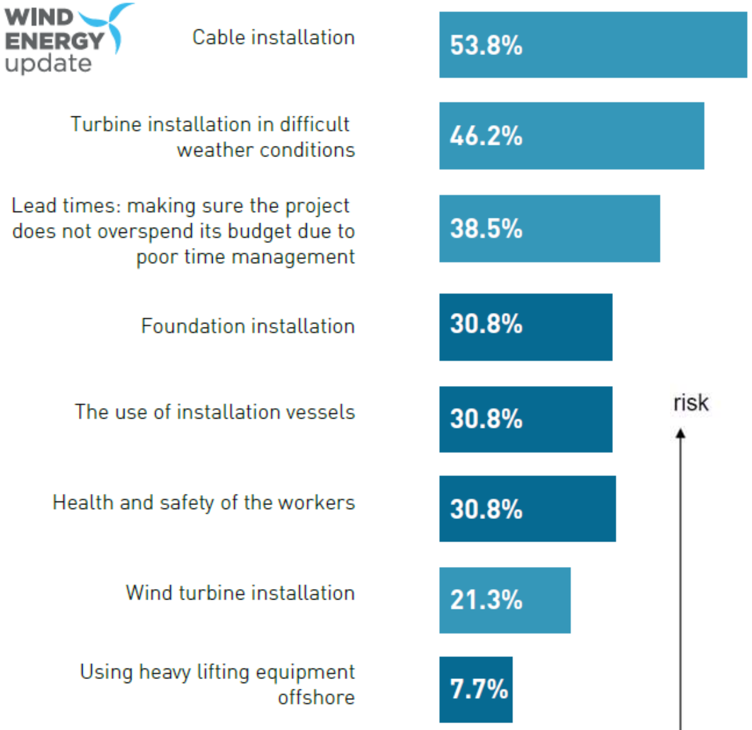
Réduire le coût de l'électricité pour être compétitif lorsque les subventions étatiques s'arrêteront

Un enjeu majeur!

PRINCIPAUX RISQUES LIES A LA CONSTRUCTION

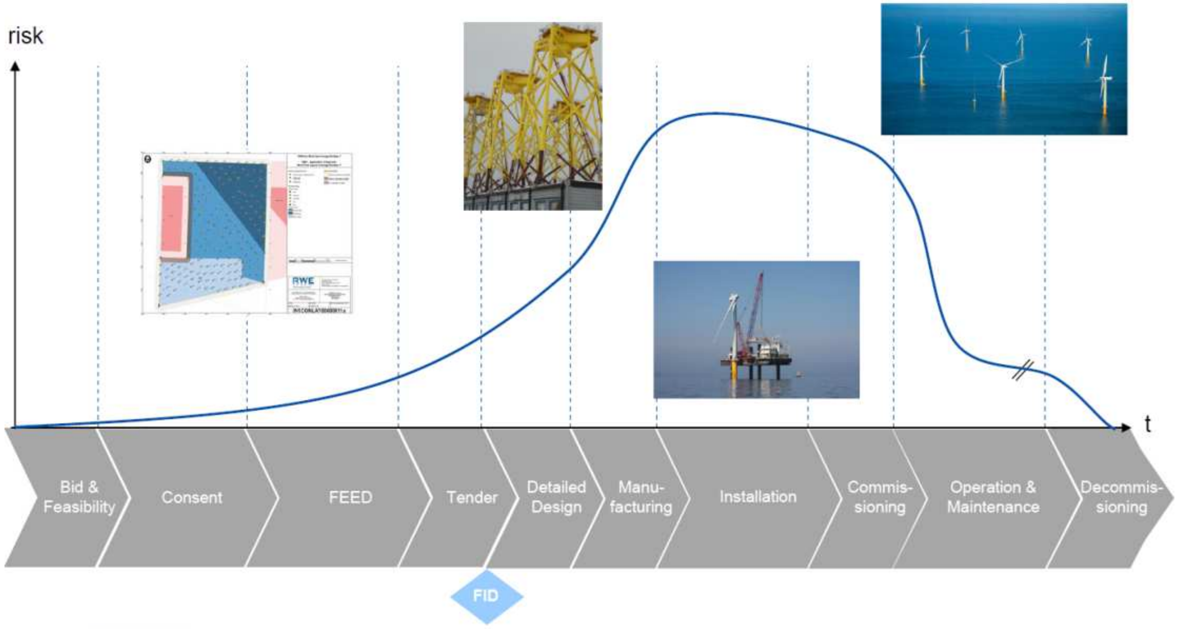
Lever les risques

Résultat du sondage (2012-2013) sur les principaux risques en phase construction, vus par les développeurs de projets en Europe (*Utilities*) :



Cable installation remains the top challenge for the majority of Europe's largest utilities. The cost of cable repair and the complexity of the cable installation procedure (especially in deeper water, further from the shore) could be the reason for this fact.

- **Vision RWE :**



FRENCH FLOATING PROJECTS

ADEME “AAP” : APRIL 2016

4 sites selected on the Fench coasts for precommercial farms
- 20/30 MW by project (3-6 turbines)
- Consortiums (Turbine/Floater/Utility)

1 Atlantic site

Source : Ifremer.

O.-F. - Photo : Winflo 2011.

DCNS

3 Mediteraneum sites

2 PROJECTS ALREADY AWARDED

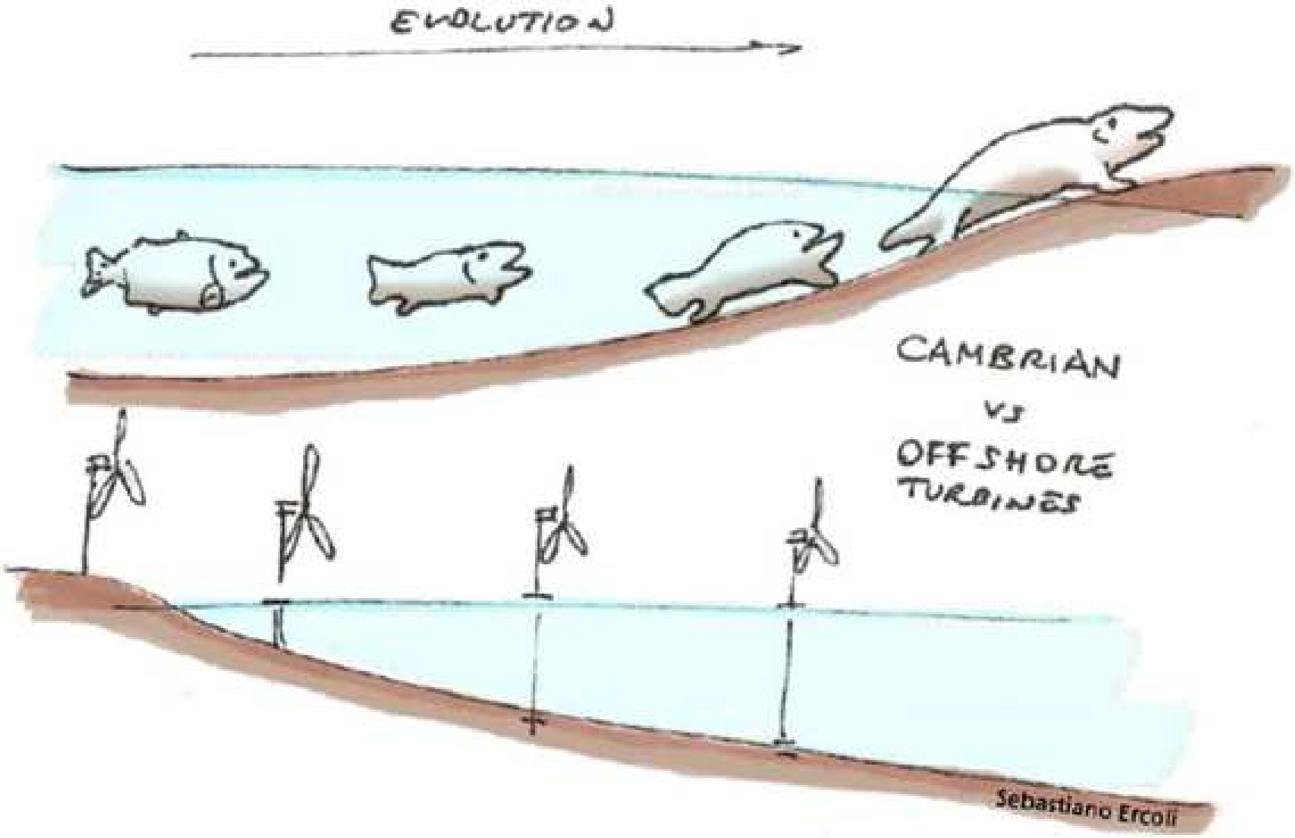
- **Ile de Groix (Atlantic) – 24 MW**
  - ☐ EOLFI
  - ☐ General Electric (ex-Alstom) / 6MW turbine
  - ☐ DCNS
- **Gruissan (Languedoc) – 24 MW**
  - ☐ Quadran
  - ☐ Senvion / 6 MW turbine
  - ☐ IDEOL

- **Demonstrator project**
  - ☐ IDEOL 2MW
  - ☐ Under construction by Bouygues TP
  - ☐ SEMREV 2017

➡ Will be the first Offshore Wind turbine in France !

LABORATOIRE D'HYDRAULIQUE SAINT-VENANT

BOTTOM FIXED
/
FLOATING FOUNDATIONS



LABORATOIRE D'HYDRAULIQUE SAINT-VENANT

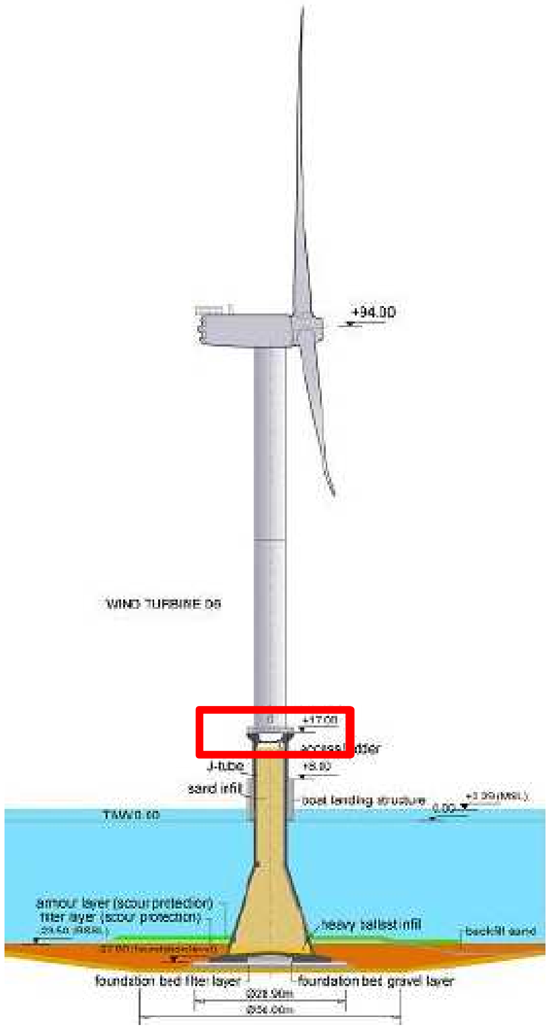
CHANGER L'ÉNERGIE ENSEMBLE

BOTTOM FIXED FOUNDATIONS

BOTTOM FIXED FOUNDATION

DESIGN METHODOLOGY

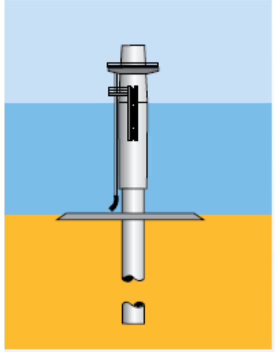
- **Aerodynamic forces**
  - ☐ Coming from the turbine
  - ☐ Provided by the turbine manufacturer
- **Hydrodynamic forces**
  - ☐ Current
  - ☐ Waves
- **Soil response**
  - ☐ Depending on the sea bed type
  - ☐ Depending on the foundation type
- **Transition piece**
  - ☐ Link between sub-structure and Turbine/Mast system
  - ☐ Boundary between hydrodynamic design and aerodynamic design



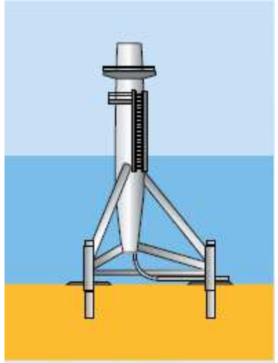
BOTTOM FIXED FOUNDATION

TYPE OF FOUNDATIONS 1/3

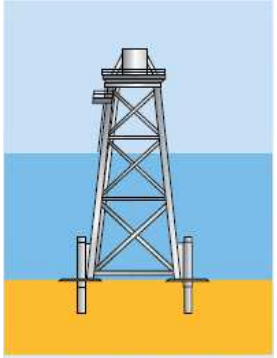
- **OWT foundations main types :**
  - Monopile
  - Tripod
  - Jacket
  - Gravity Based Foundation (GBF or GBS)



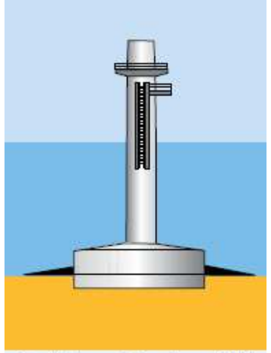
Monopile



Space Frame (Tripod)

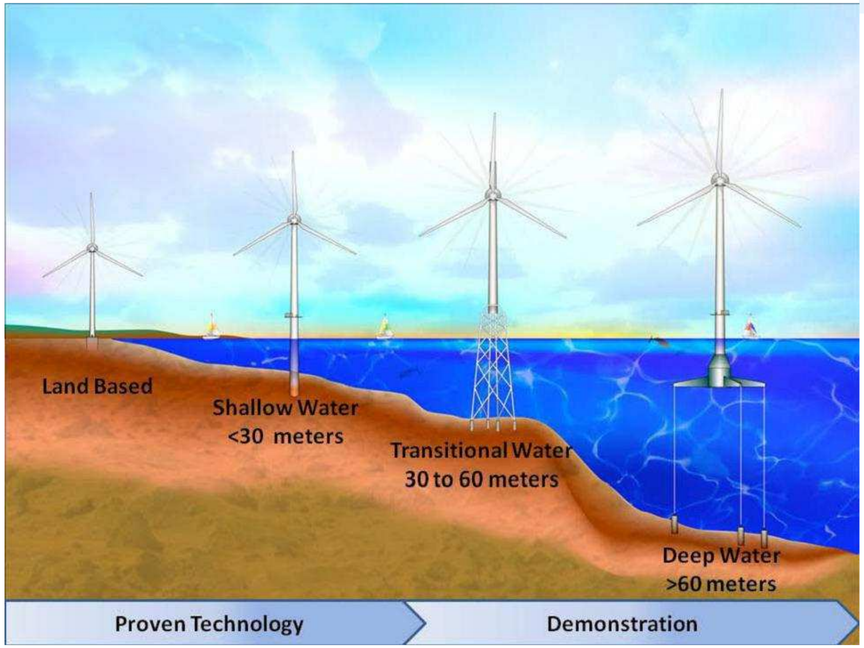


Space Frame (Jacket)



Gravity-based Structure (GBS)

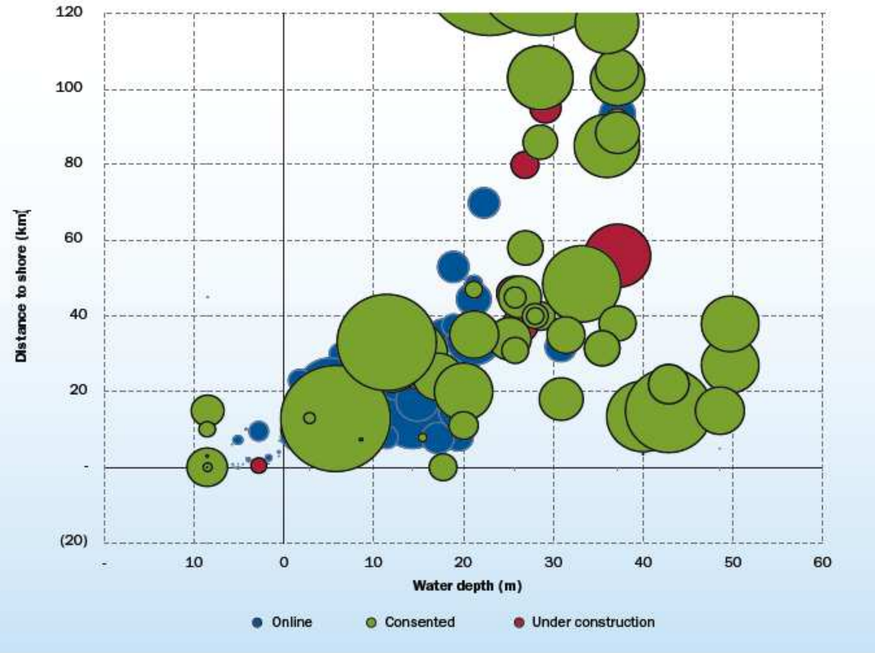
- **Usually, the choice of the structure depends on the water depth and the sea bed (rock, sand…)**
  - Monopile typically until 20/30m
  - Tripod typically until 30/40m
  - Jacket typically until 50/60m
  - GBS typically until 30/50m

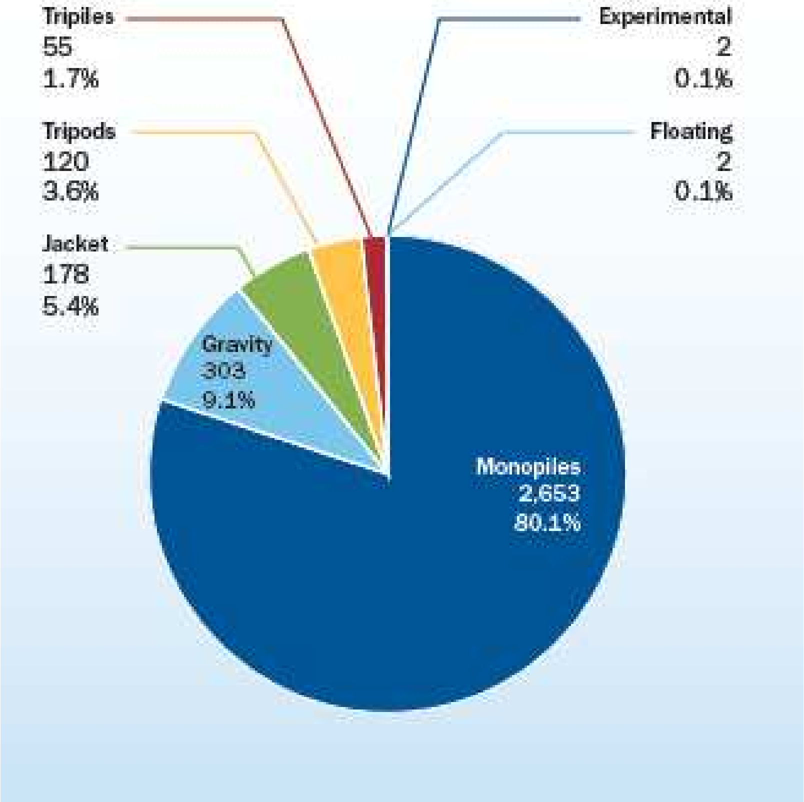


BOTTOM FIXED FOUNDATION

TYPE OF FOUNDATIONS 2/3

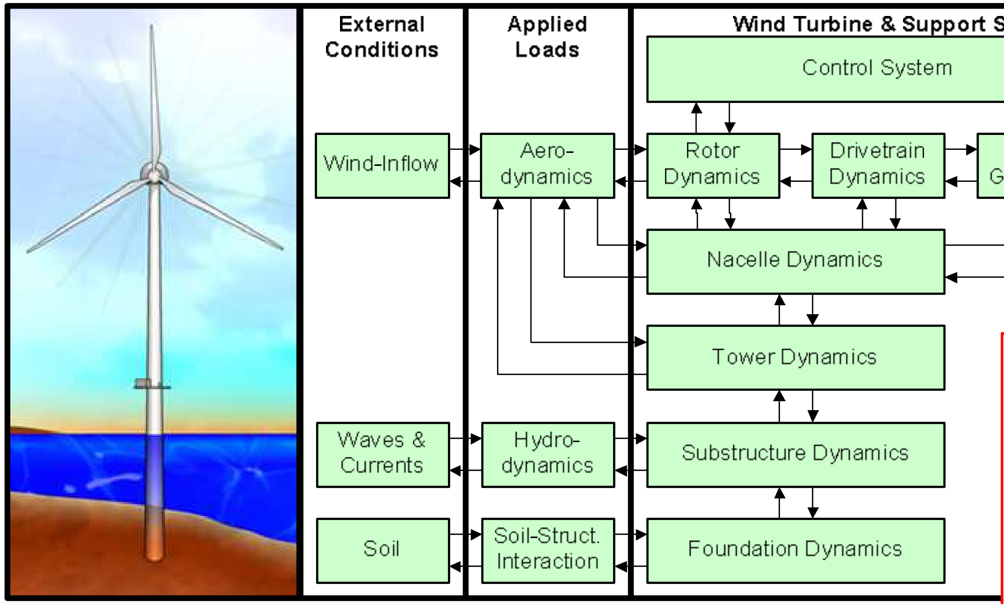
- **Repartition of OWT foundations**
  - End 2012 figures
  - Monopile is the most used foundation type
    - Denmark
    - Germany
    - UK
  - GBF is significant
  - Tripod/Tripile is not common

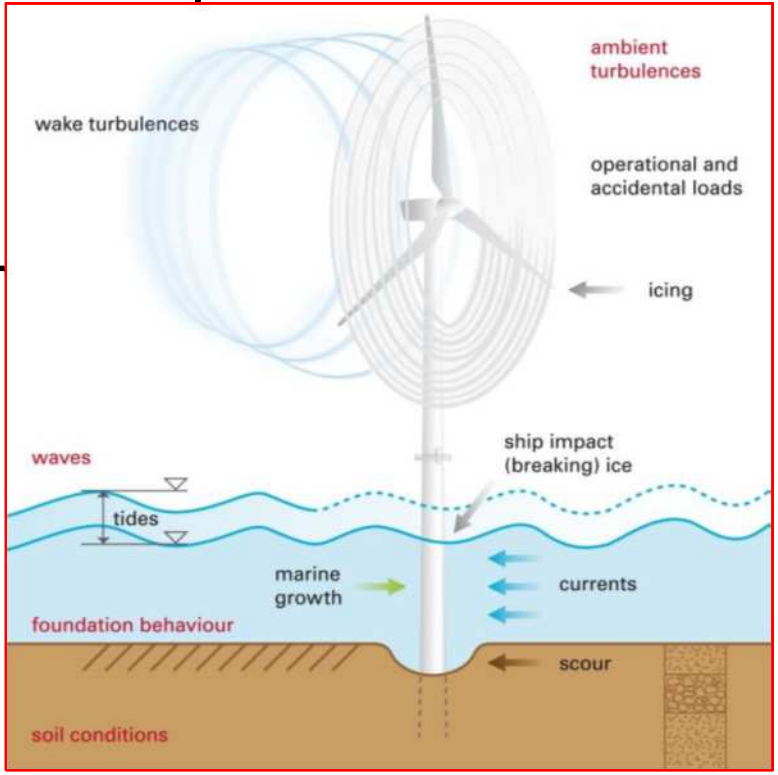


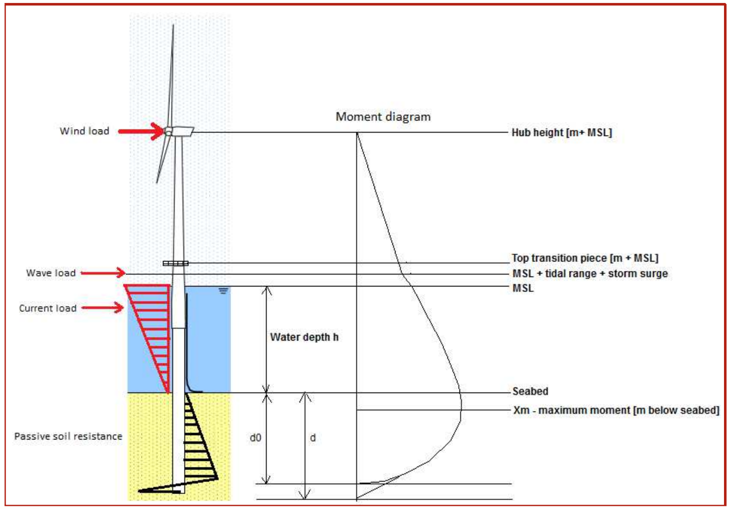


LABORATOIRE D'HYDRAULIQUE SAINT-VENANT

COMPLEX DESIGN…







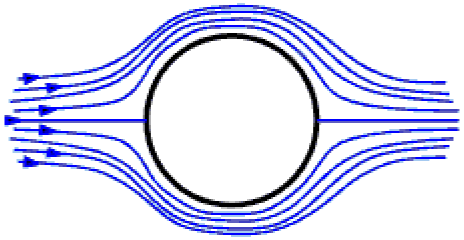
BOTTOM FIXED FOUNDATION

HYDRODYNAMIC MODELS - FORCES

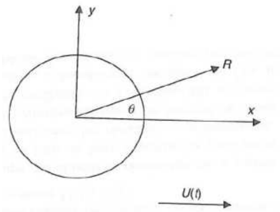
- **Hydrodynamic loads model - Standards**
  - Semi-Empirical approach (Morison formula)
  - Thin bodies approximation

$$F = \boxed{C_M \cdot \rho\pi \frac{D^2}{4}\dot{U}(t)} + \boxed{\frac{1}{2}\rho \cdot C_D \cdot D \cdot U \cdot |U|}$$

Perfect fluid approx.

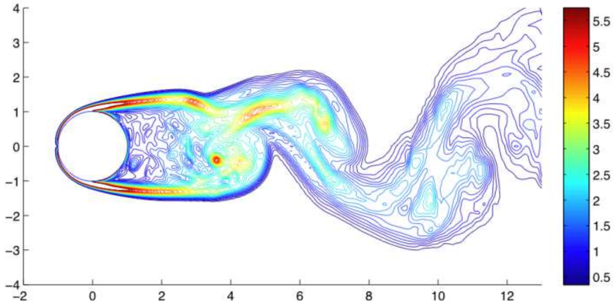


Perfect Fluid



$$\boxed{F(r,\theta,t) = 2\rho\pi\left(\frac{D}{2}\right)^2 \dot{U}(t)}$$

Viscous effect

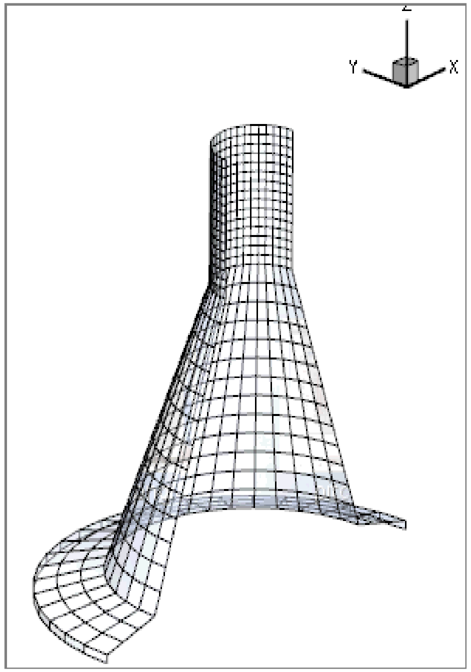


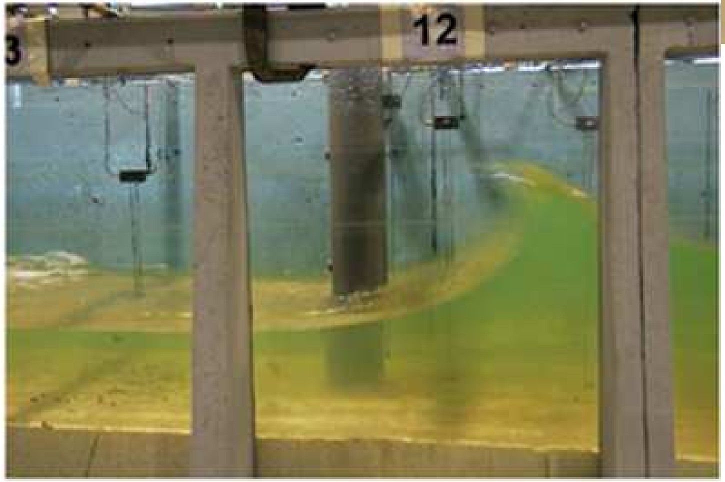
Coefficients
+
Kinematics → **Hydrodynamic Force**

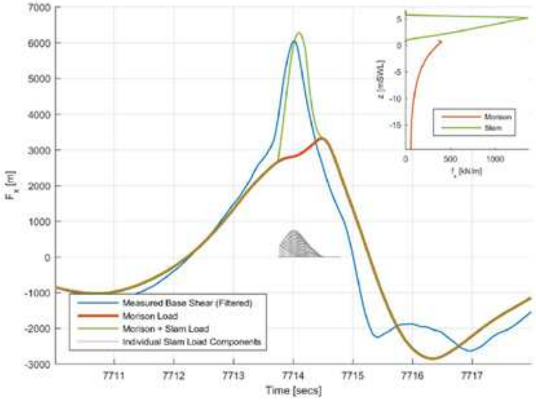
BASIN TESTS

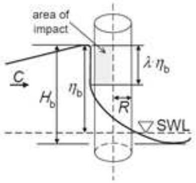
HYDRODYNAMIC FORCES EVALUATION – MODEL CALIBRATION

- **Froude scaling**
  - Inertia forces conserved
  - Reynolds similitude lost
  - State of the art of the O&G industry
- **Typical scale**
  - Between 1/20th and 1/50th
  - Water depth : 40m => 1m to 2m
  - Structure diamter : 7m => 15 to 40 cm
  - ECN, Oceanide, IFREMER…





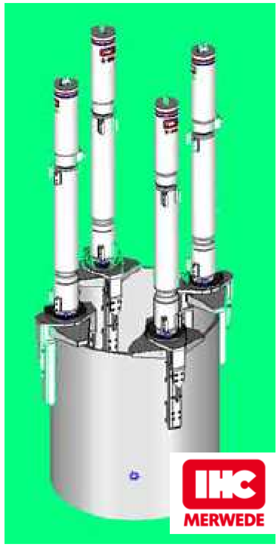


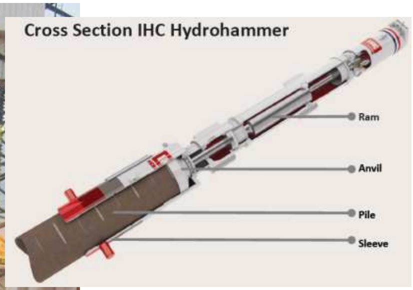


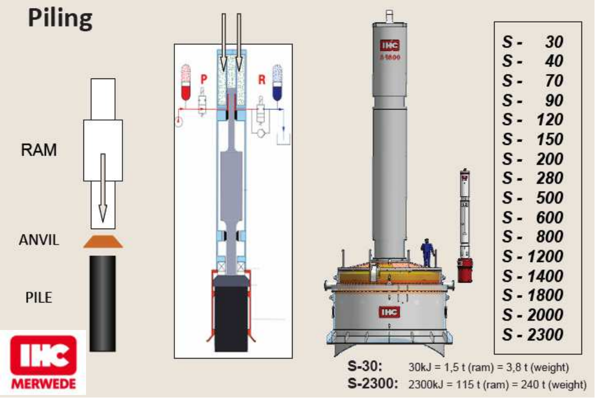
MONOPILE INSTALLATION L

MONOPILE PILING

- Hydro-hammer or vibro-driving devices are used.
- Noise impact on sea mammals: key issue!
- Multi-Hammer are used when diameter > 7.5 m



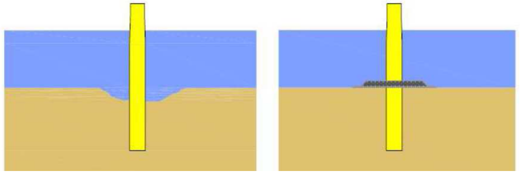

Cross Section IHC Hydrohammer

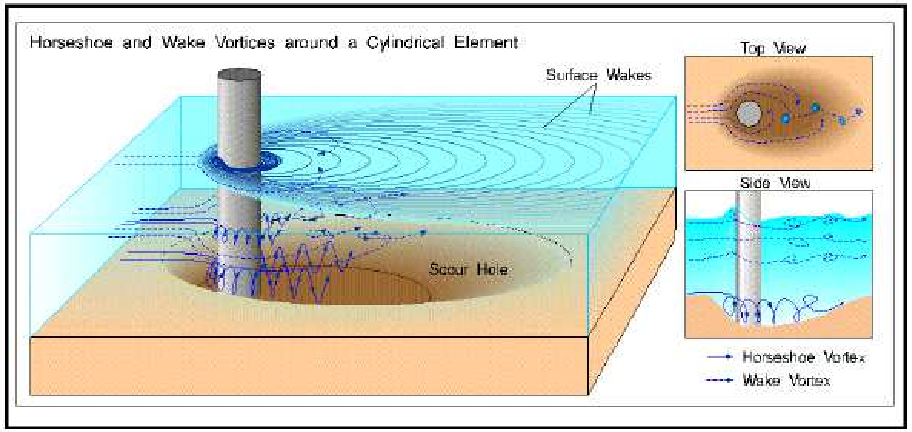

Piling

S - 30
S - 40
S - 70
S - 90
S - 120
S - 150
S - 200
S - 280
S - 500
S - 600
S - 800
S - 1200
S - 1400
S - 1800
S - 2000
S - 2300

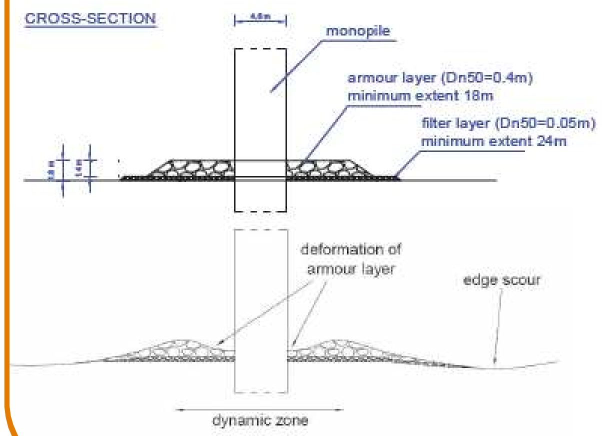
S-30: 30kJ = 1,5 t (ram) = 3,8 t (weight)
S-2300: 2300kJ = 115 t (ram) = 240 t (weight)

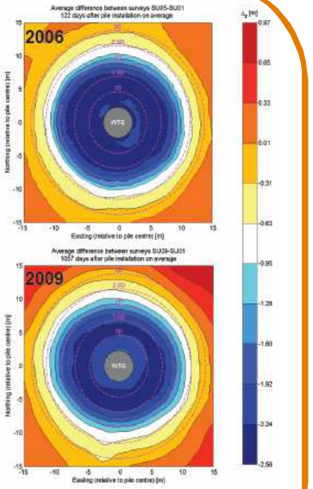
SCOUR PROTECTION





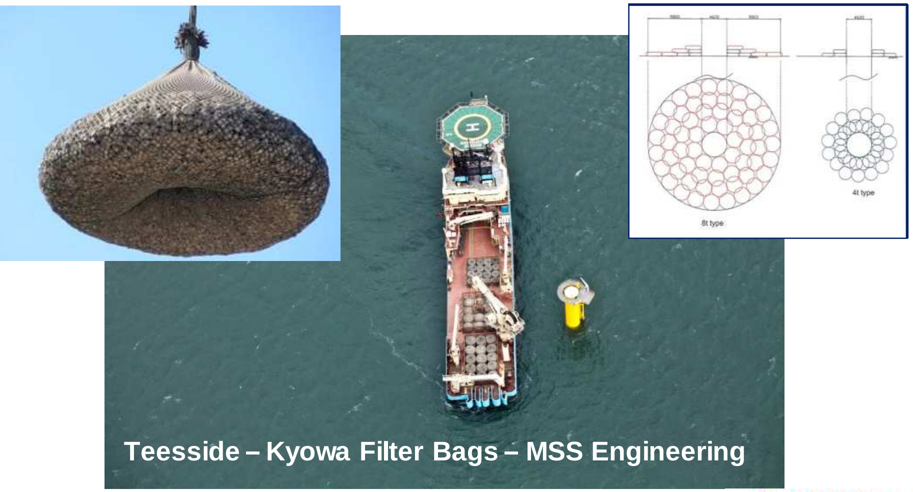
Scour Protection: a rock pad is laid beneath the monopile structure which is driven into the sea-bed. Further stone is placed around the base.





Deltares

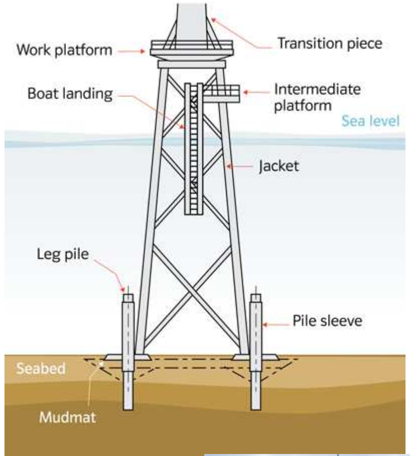
Offshore Windpark Egmond aan Zee – scour protection

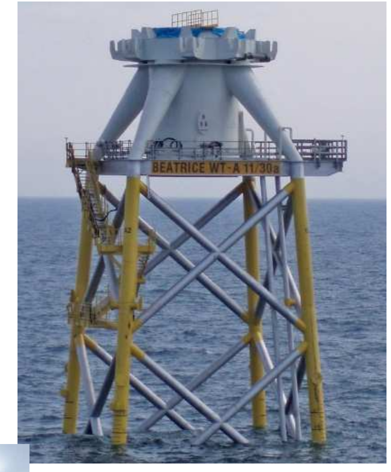


Teesside – Kyowa Filter Bags – MSS Engineering

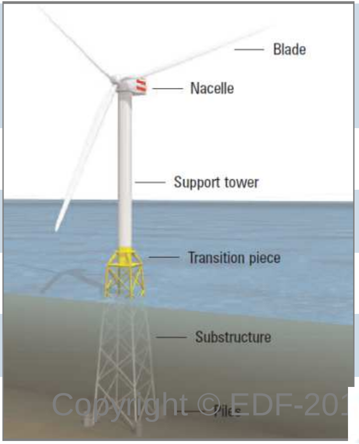
JACKET

- Jacket : steel lattice structure (welded pipes Ø 0.5 – 1.5m) from Oil & Gas industry. ~ 1000tons (> 1km welding!).
- Structure suitable for deep water (< 50-60 m) with heavy turbines (> 5 MW). Small leg monopiles are driven in the seabed (Ø 1 – 2.5m).
- 1st offshore wind installation: demonstration site Beatrice in Scotland in 2006 (2 x REpower 5 MW – 45 m water depth).





Advantages	Disadvantages
Lightweight and stiff structure	Complexity of fabrication
Better global load transmission compared to monopiles	Large number of joints required compared to other latticed structures
Large variations in water depth can be covered through cantilevering piles or modifying the geometry	Logistical issues due to the templates (pre-piling case)
No scour protection required	Complex connection to transition pieces
Structural redundancy	High manufacturing lead-times
Low soil dependency	No standardized design that leads to long certification processes
Good response to wave loads. Little sensitivity to large waves and limited dynamic amplifications of loads due to high stiffness	
Limited storage area compared to GBF	
Faster fabrication compared to GBFs (serial production)	
Better quality control	
Easy decommissioning	



TRIPOD INSTALLATION (ALPHA VENTUS)


Tripods being welded


Tripod up-ended for shipping


Tripods arriving at Wilhelmshaven port


Heavy-lift crane ship on site


Tripod foundation lowered to seabed

Installation complete

VARIOUS GBS CONCEPTS

Type	Features	Example
Self-Buoyant ("*Floating*")	GBS can be floated out and towed to the offshore site using standard tugs. At the site, GBS is filled with ballast.	
Auxiliary Buoyancy ("*Semi-floating*")	Special transport vessel required for buoyancy support. This concept helps reduce concrete volume. Additional ballasting at site.	**Strabag** 
Crane Lowered	GBS cannot float. A heavy lift crane vessel is required. A large transportation barge + heavy crane vessel can also be used. Possible additional ballasting at site.	

TURBINE INSTALLATION

TURBINE INSTALLATION

TURBINE INSTALLATION

INSTALLATION – HEAVY OFFSHORE VESSELS

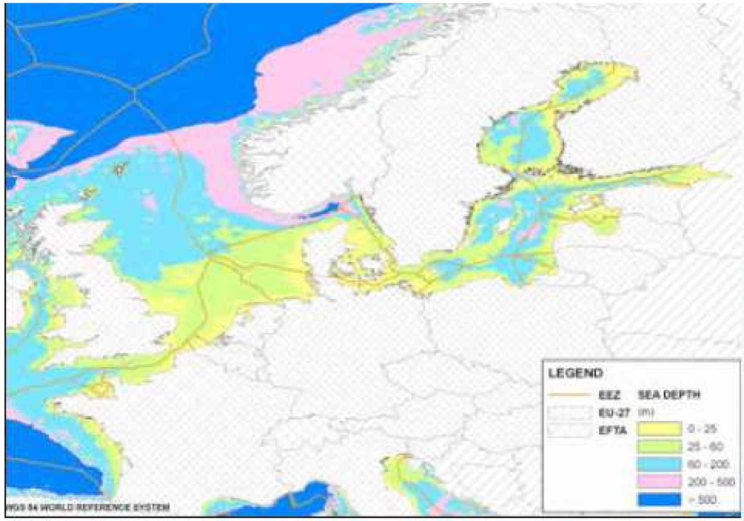
FLOATING FOUNDATIONS TECHNOLOGIES

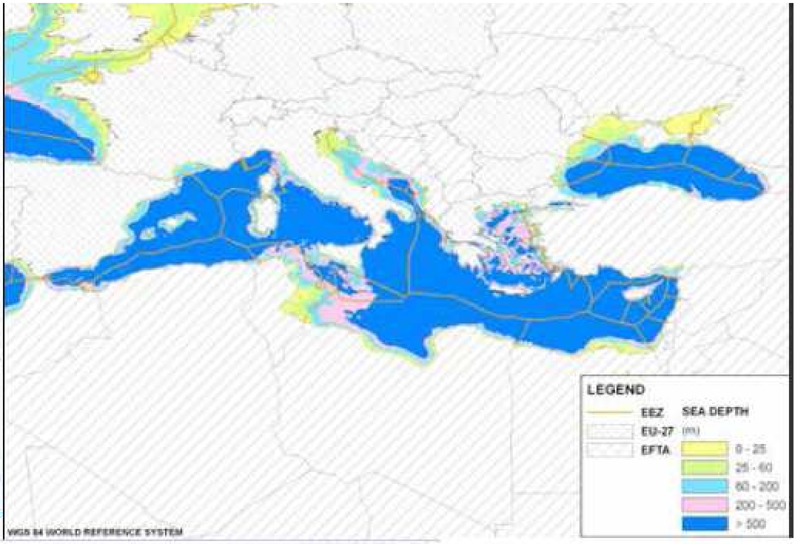
LABORATOIRE D'HYDRAULIQUE SAINT-VENANT

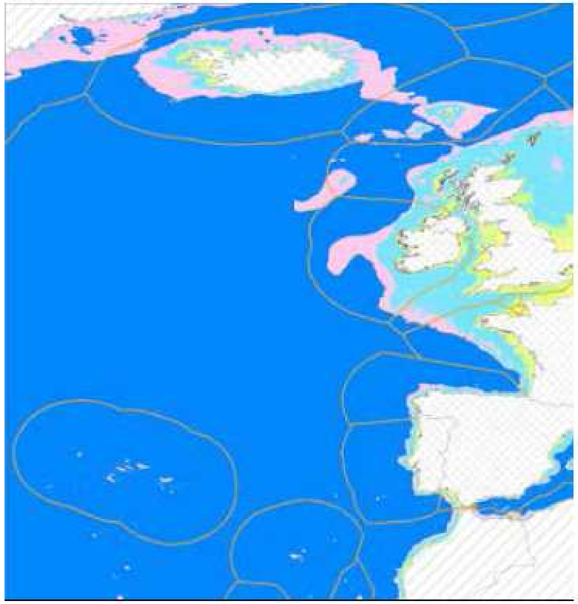
CHANGER L'ÉNERGIE ENSEMBLE

FLOATING FOUNDATION

WHY ?







🟨 🟩 } 0-60m : Bottom Fixed Foundations

🟦 🟪 } 60-500m → Floating (Too deep for Fixed)

🟦 >500m → Floating ?

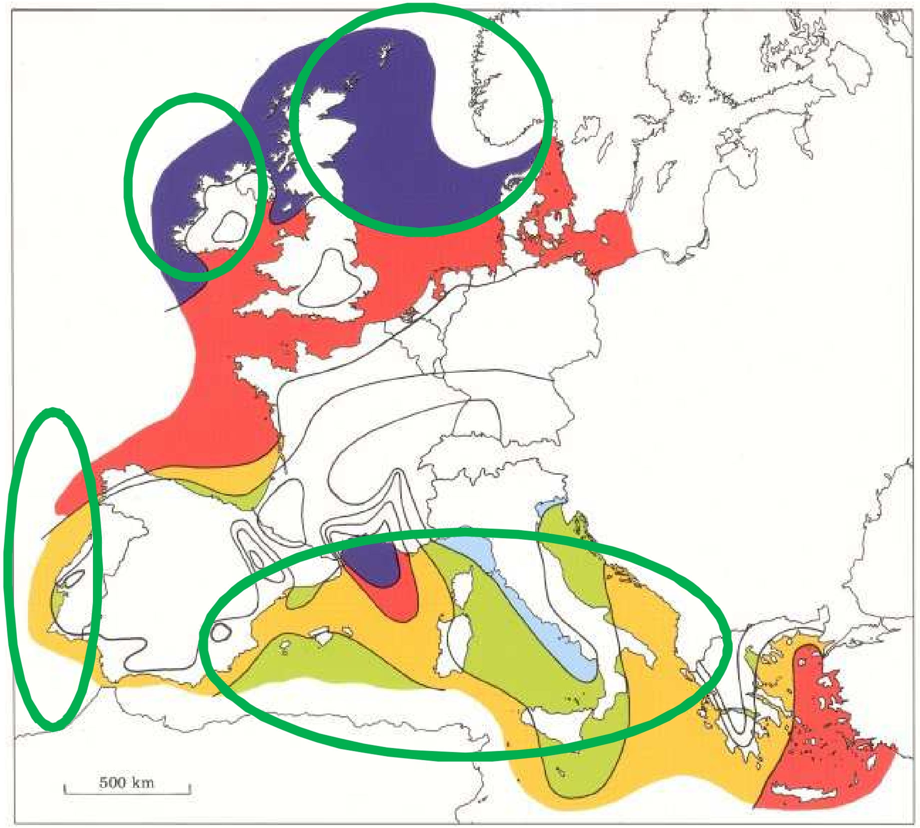
eDF

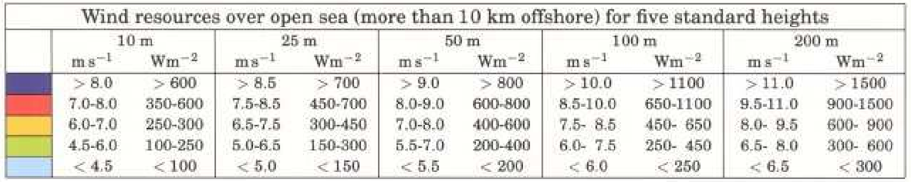
LABORATOIRE D'HYDRAULIQUE SAINT-VENANT

FLOATING FOUNDATION

WHY ?

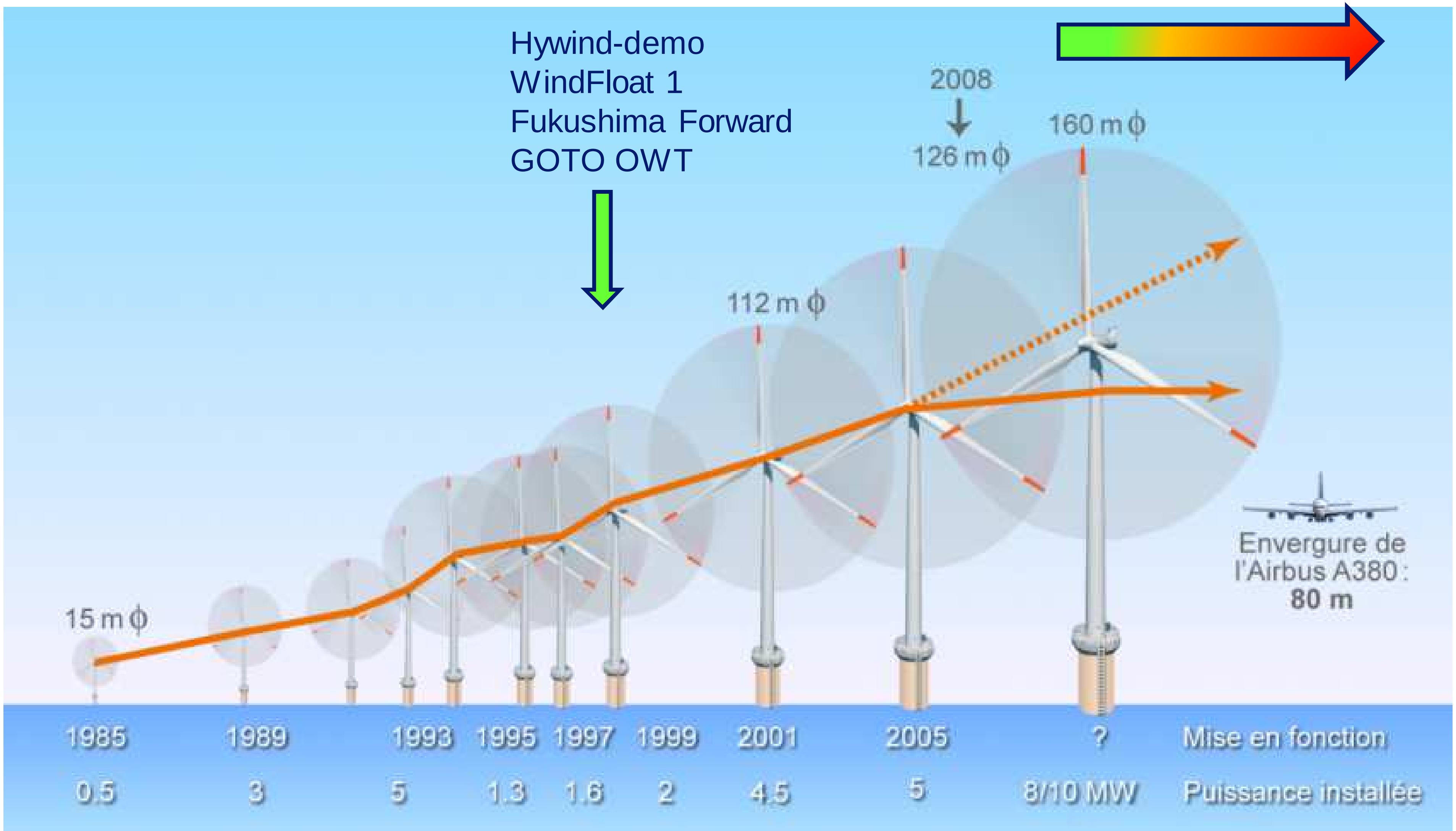
- **Going to deeper waters**
  - Bottom fixed foundation : maximum ~ 50-60 m water depth (structure size, installation vessel: crane, Jack Up...).
- **European Areas**
  - Offshore Norway, Scotland, Ireland
  - Mediteranean Sea
- **Technology from Oil & Gas offshore.**
- **Installation should require less specific vessels**
- **Possibility to assemble both turbine and platform onshore (port) and tow them out on site.**
- **Challenges**
  - Plateform motions
  - Moorings
  - Dynamic electric cable
  - Further from shore means higher winds but also higher sea states





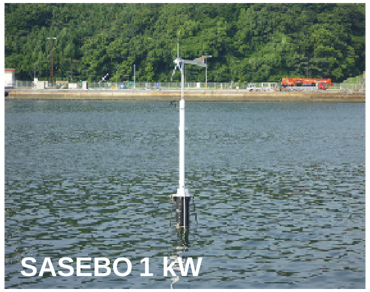
Wind resources over open sea (more than 10 km offshore) for five standard heights										
	10 m		25 m		50 m		100 m		200 m	
	m s^{-1}	Wm^{-2}	m s^{-1}	Wm^{-2}	m s^{-1}	Wm^{-2}	m s^{-1}	Wm^{-2}	m s^{-1}	Wm^{-2}
🟪	> 8.0	> 600	> 8.5	> 700	> 9.0	> 800	> 10.0	> 1100	> 11.0	> 1500
🟥	7.0-8.0	350-600	7.5-8.5	450-700	8.0-9.0	600-800	8.5-10.0	650-1100	9.5-11.0	900-1500
🟨	6.0-7.0	250-300	6.5-7.5	300-450	7.0-8.0	400-600	7.5- 8.5	450- 650	8.0- 9.5	600- 900
🟩	4.5-6.0	100-250	5.0-6.5	150-300	5.5-7.0	200-400	6.0- 7.5	250- 450	6.5- 8.0	300- 600
🟦	< 4.5	< 100	< 5.0	< 150	< 5.5	< 200	< 6.0	< 250	< 6.5	< 300

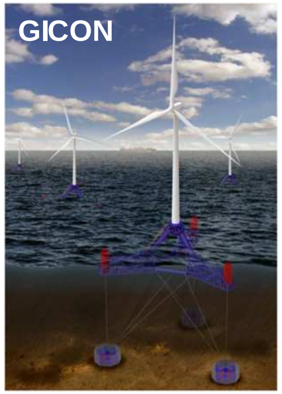
Fukushima Forward
Pre-commercial farms

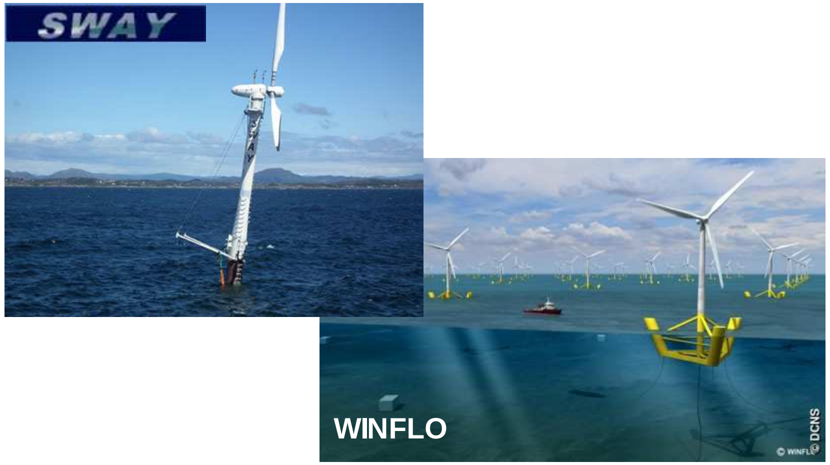


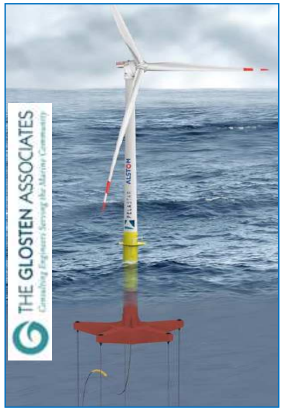
Hywind-demo
WindFloat 1
Fukushima Forward
GOTO OWT

EXAMPLES OF FLOATING PROJECTS...



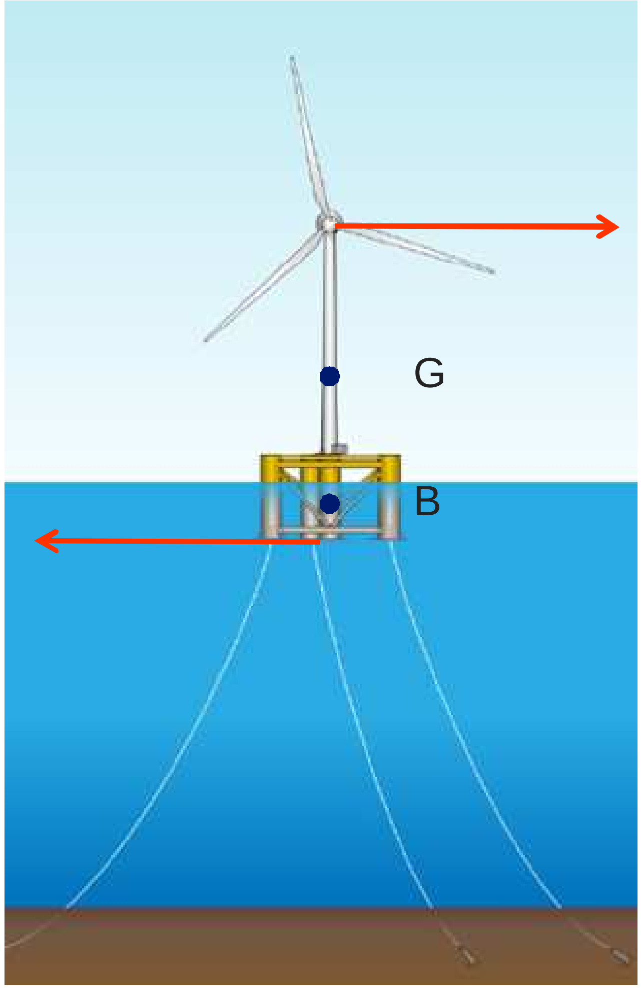






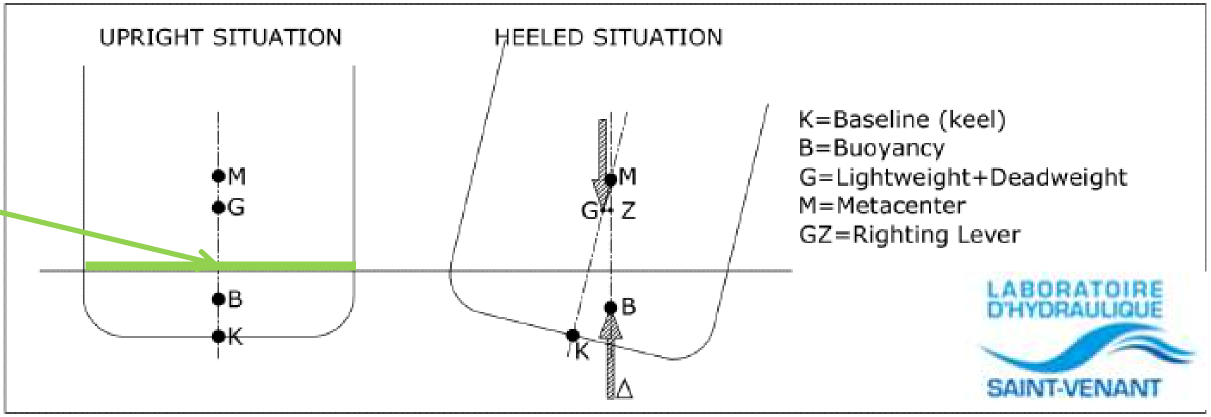
STABILITY
OVERVIEW

- **Stability consists of comparing**
  - Heeling moment due to wind
  - Restoring forces due to buoyancy



- **Wind heeling moment**
  - Rotor thrust
  - Point of application

- **Buoyancy restoring moment**
  - Position of center of buoyancy B
  - Position of center of gravity G
  - Water plane area



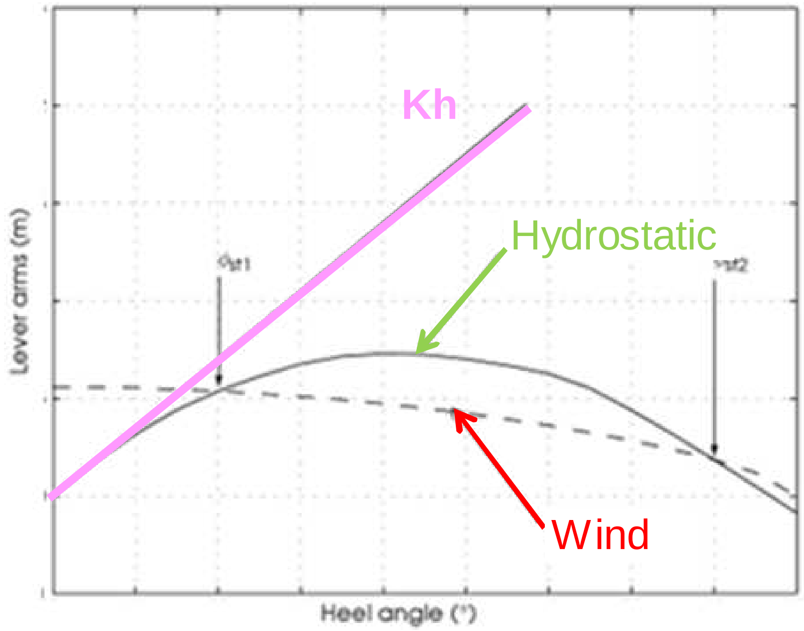
K=Baseline (keel)
B=Buoyancy
G=Lightweight+Deadweight
M=Metacenter
GZ=Righting Lever

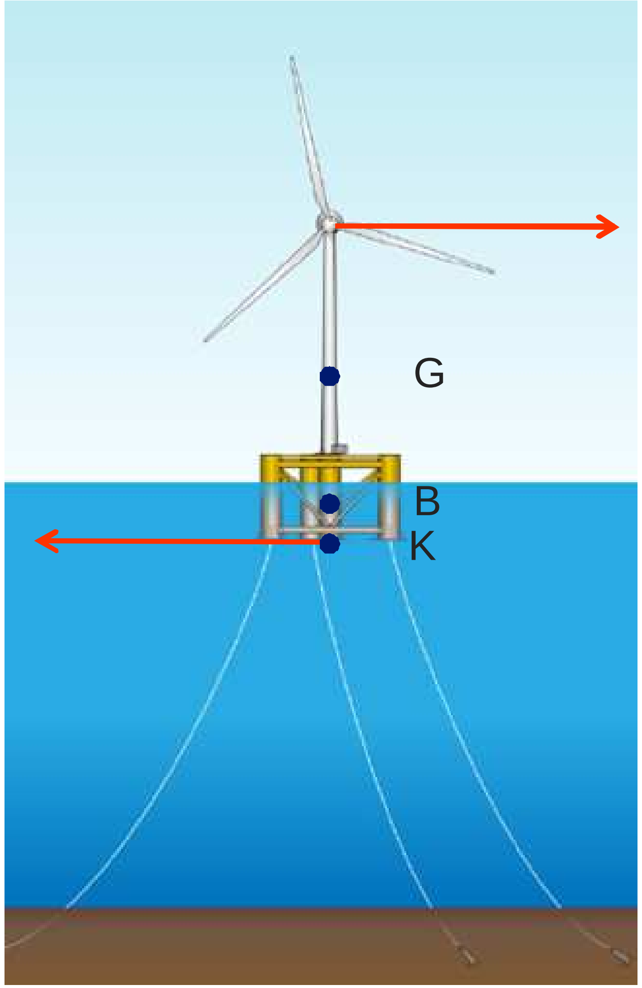
LABORATOIRE D'HYDRAULIQUE SAINT-VENANT

EDF

STABILITY

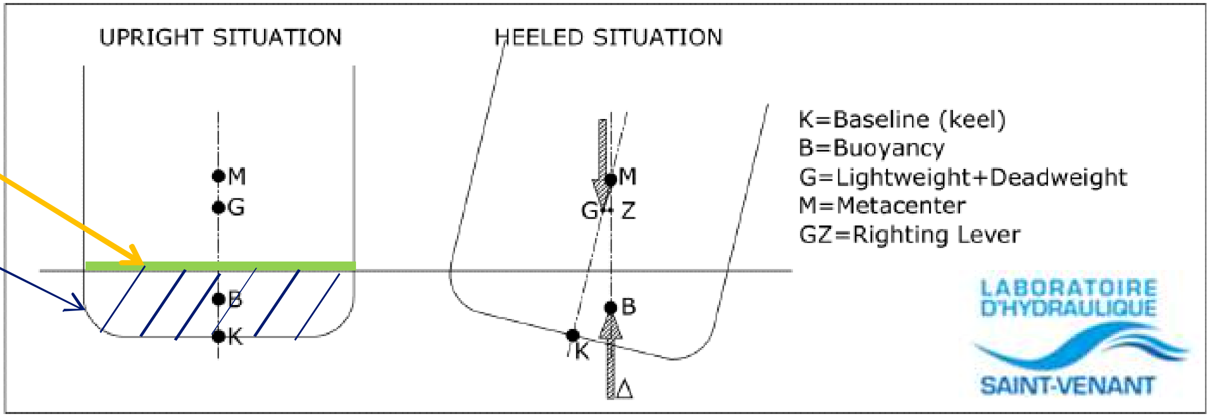
OVERVIEW





- **Hydrostatic stifness**

$$K_H = \rho V g \left(KB - KG + \frac{I}{V} \right)$$



STABILITY

APPLICATION

- **SPAR SOLUTION**

$$K_H = \rho V g \left(\underbrace{KB - KG}_{\text{KB-KG=GB}} + \underbrace{\frac{\overset{\text{small}}{I}}{\underset{\text{~big}}{V}}}_{\text{Low contribution}} \right)$$

Stability from the distance between Center of Gravity and Center of buoyancy

STABILITY

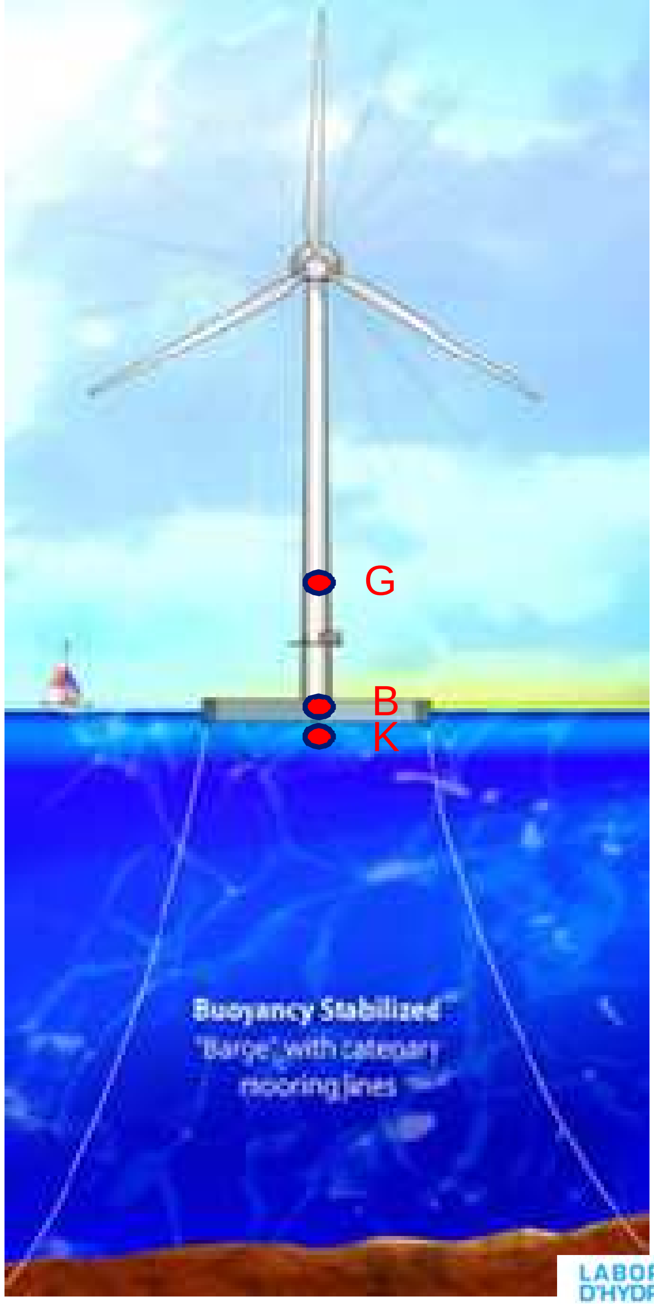
APPLICATION

- **BARGE SOLUTION**

$$K_H = \rho V g \left(\underbrace{KB - KG}_{\text{KB-KG=GB<0}} + \underbrace{\frac{\overset{\text{Big}}{\boxed{I}}}{\underset{\sim\ \text{small}}{\boxed{V}}}}_{\text{High contribution}} \right)$$

$$\Downarrow$$

Stability from the size of the water plane aera

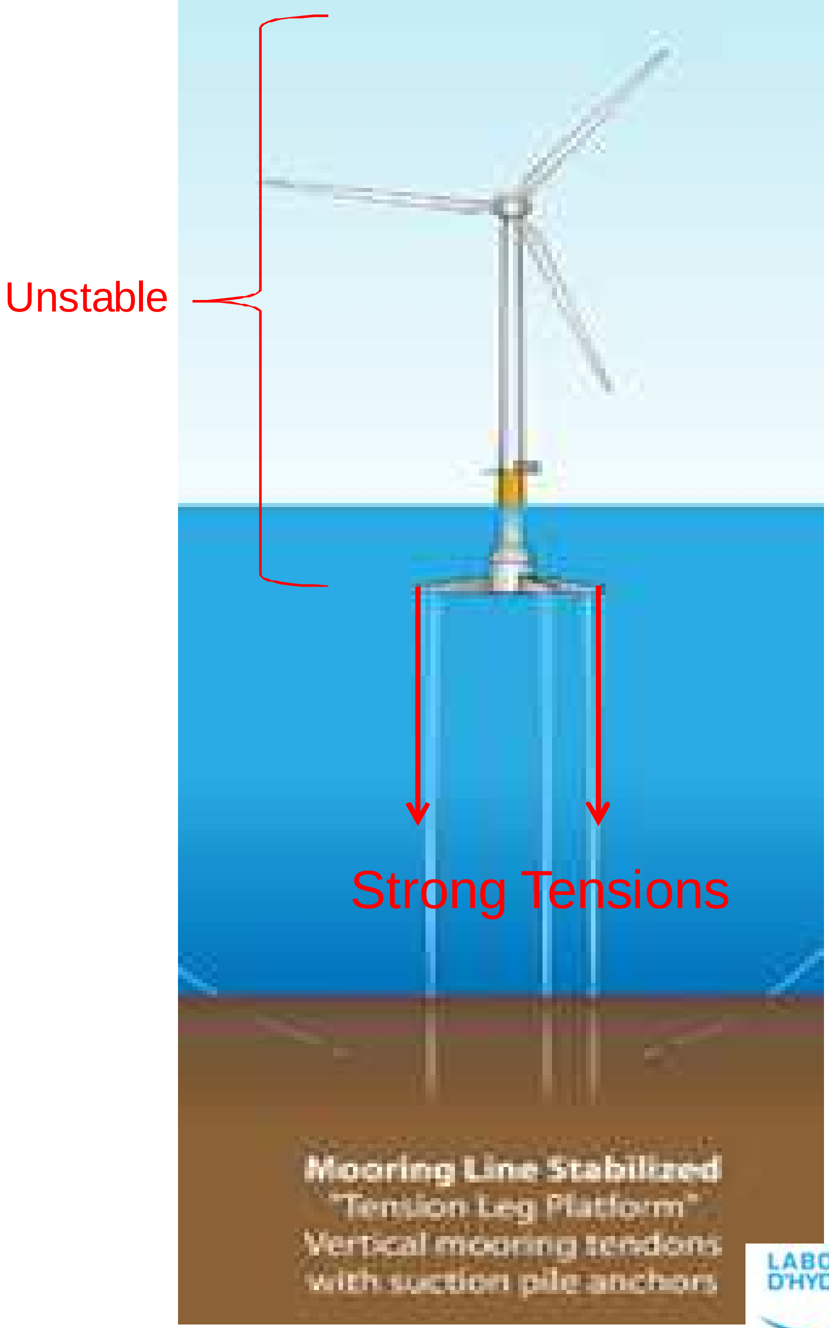


STABILITY
APPLICATION

- **TLP SOLUTION**

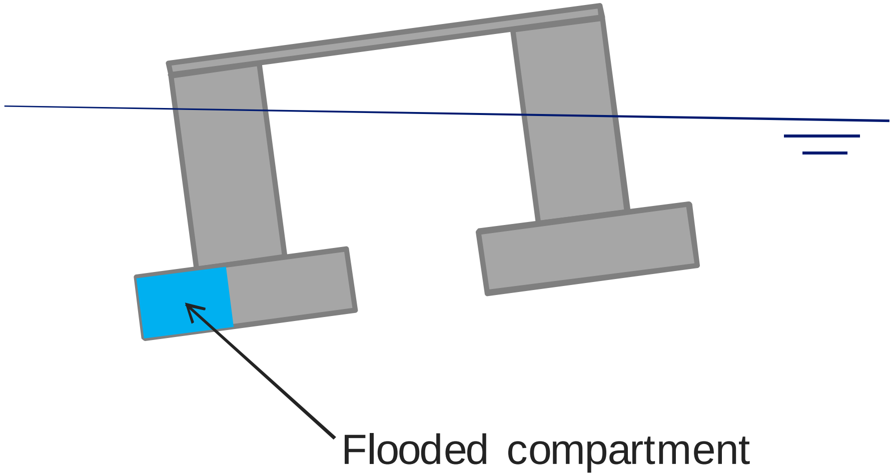
$$\xcancel{K_H = \rho V g \left(\underbrace{KB - KG}_{KB\text{-}KG=GB} + \underbrace{\frac{I}{V}}_{\text{Contribution}} \right)}$$

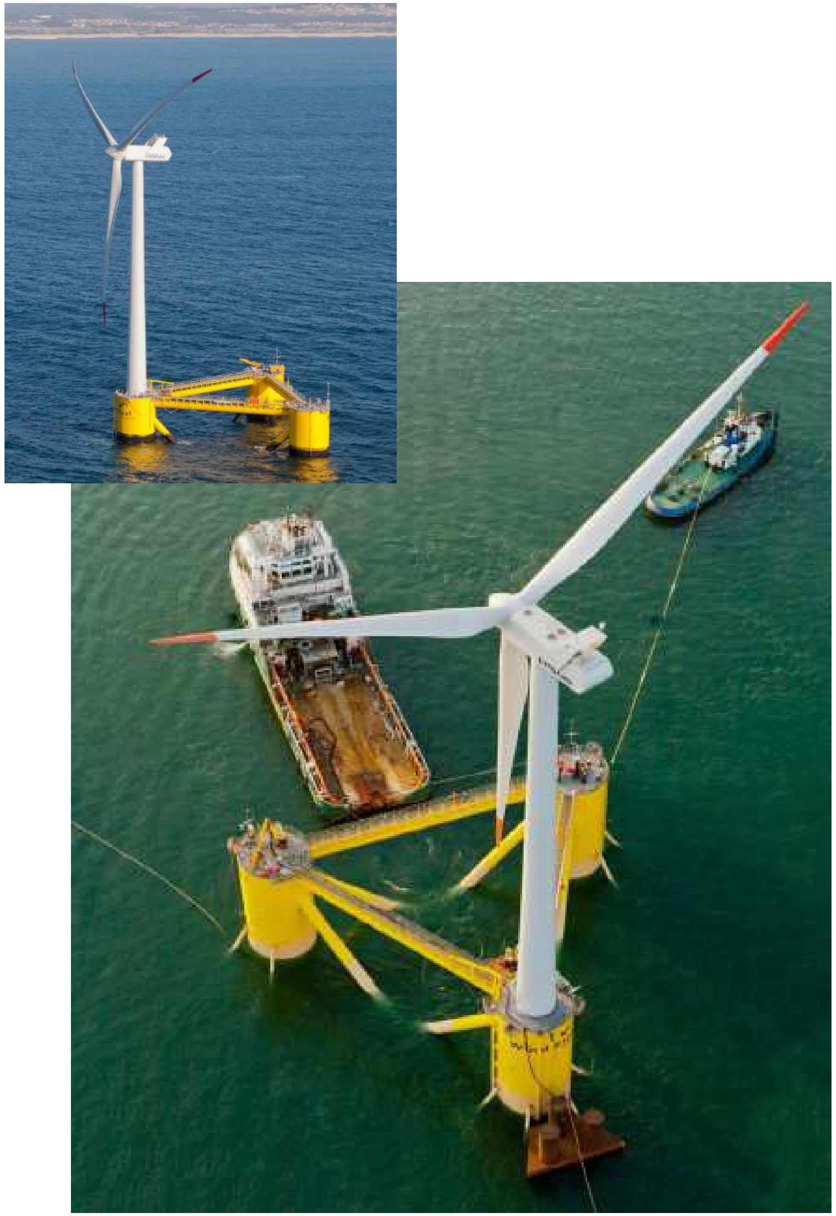
Stability from the tendons



STABILITY
ADDITIONAL CASES

- **In addition, you need to consider**
  - Damaged cases, when the floater is partilly flooded
  - Towing and installation phases

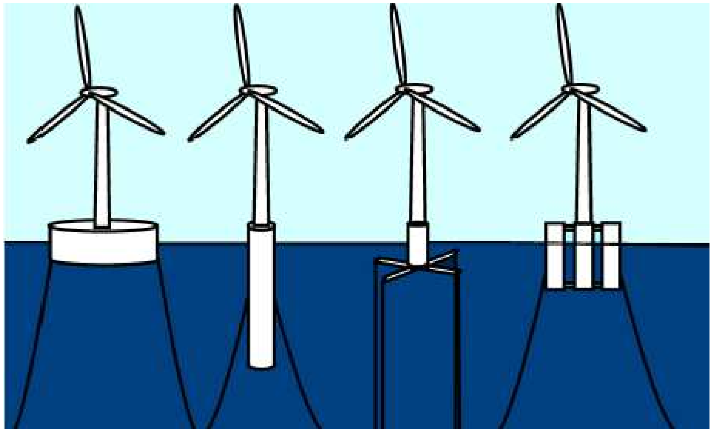


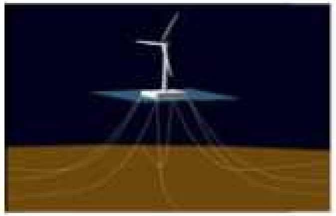


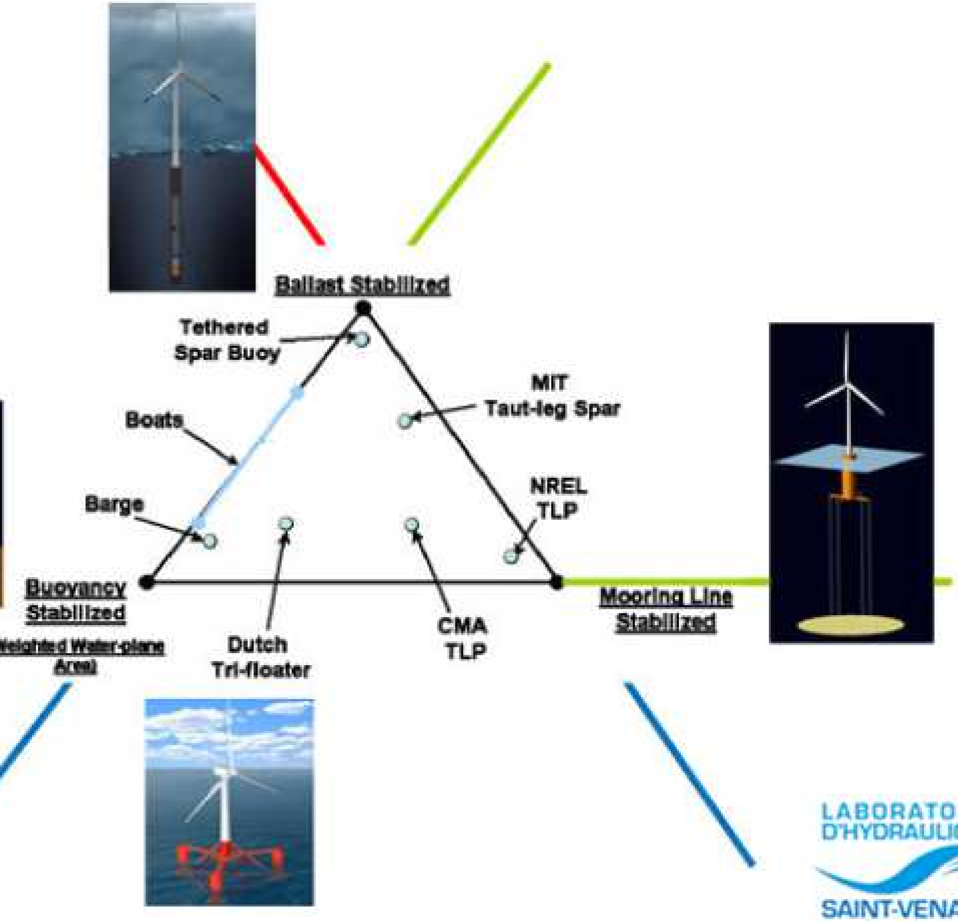
FLOATING PLATEFORMS

TYPES OF FLOATERS

- **Generally, 4 types of floaters are considered**



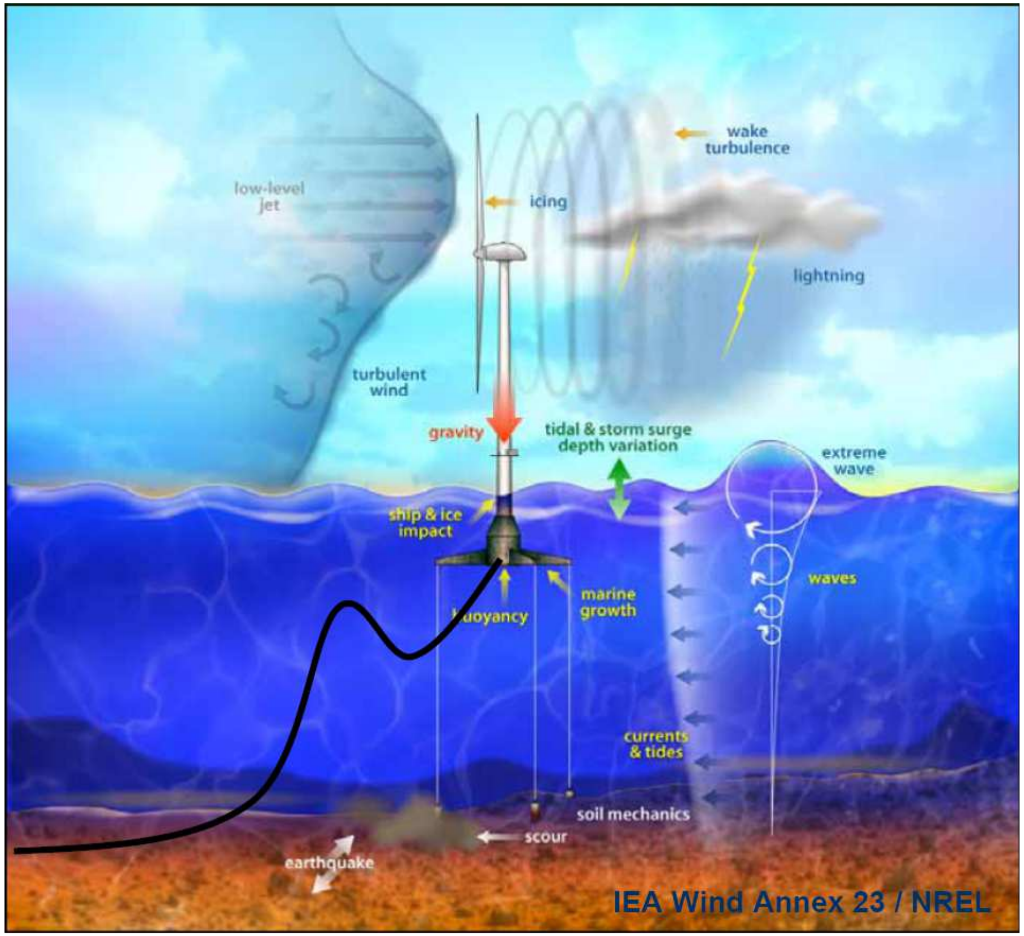




FLOATING PLATEFORMS

DESIGN PROCESS

- **Metocean study**
- **Stability**
  - ☐ Plateform counterbalance wind heeling moment
- **Motions**
  - ☐ Maximum motions&accelerations to insure system resistance
  - ☐ Maximum motions for power performance
- **Station-Keeping**
  - ☐ Insure IAC security
  - ☐ Avoid drift
- **Installation**
  - ☐ Is the plateform easy to build / install / maintain



IEA Wind Annex 23 / NREL

MOTIONS AND ACCELERATIONS ANALYSIS

OVERVIEW

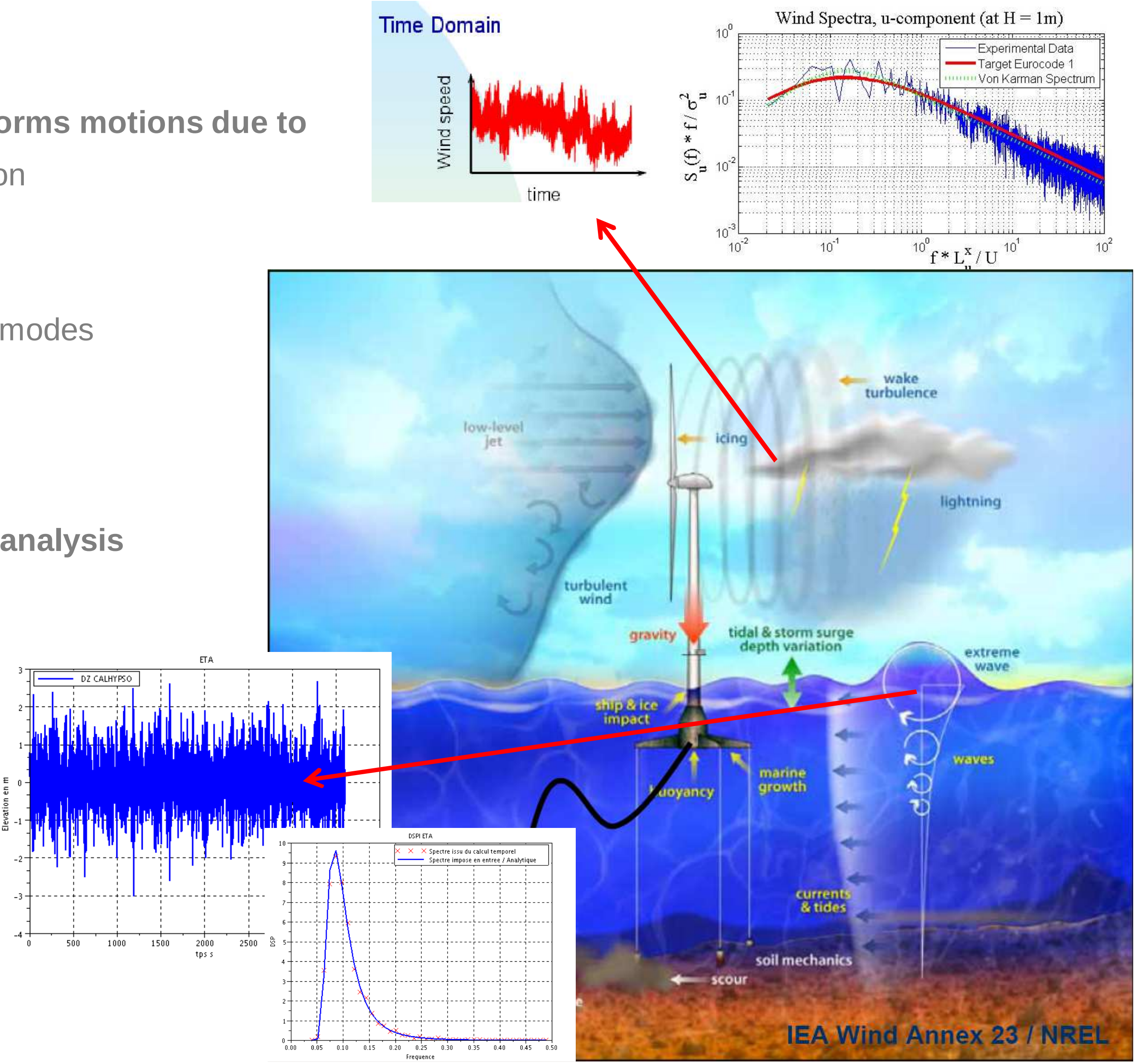
- **Floating offshore wind plateforms motions due to**
  - ☐ Wind : stochastic phenomenon
  - ☐ Waves : irregular sea states
  - ☐ Current
  - ☐ Plateform / Structure natural modes

⇨ Non-linear moorings

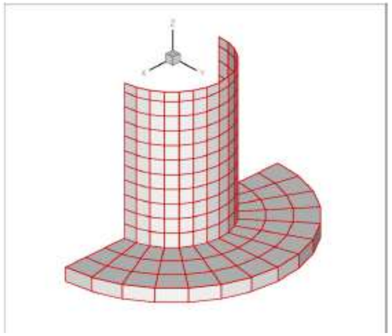
⇨ Non-linear forces

- **Need to perform a numerical analysis**
  - ☐ Aerodynamic models
  - ☐ Hydrodynamic models
  - ☐ Structural models

⇨ Keep in mind :
~10 000 load cases



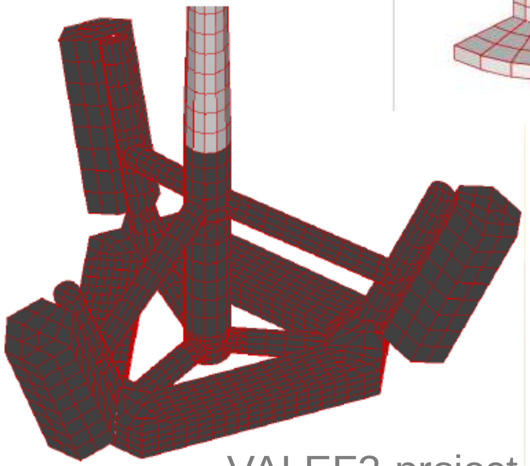
MOTIONS AND ACCELERATIONS ANALYSIS
MODELLING APPROACH - HYDRODYNAMICS – POTENTIAL FLOW

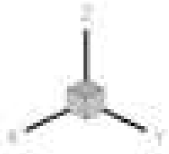


- **Hydrodynamic models used in most of the FOWT projects**
  - ◻ Potential flow + no viscosity
    - Irrotational
    - No drag forces
  - ◻ Linear hypothesis
    - Small waves
    - Small motions

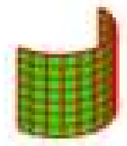
- **Differences between bottom fixed and floating**
  - ◻ Need for buoyancy/stability leads to « Large » structures
    - ⇒ Thin bodies hypothesis not fully respected
  - ◻ Structure experiences significant motions
    - ⇒ Need to model waves – motions interactions
  - ◻ Wave-Structure intercation

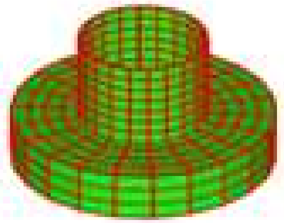
⇒ Diffraction / Radiation approach

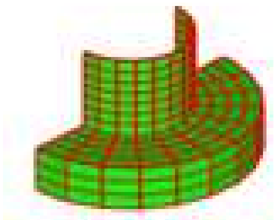




VALEF2 project







MOTIONS AND ACCELERATIONS ANALYSIS

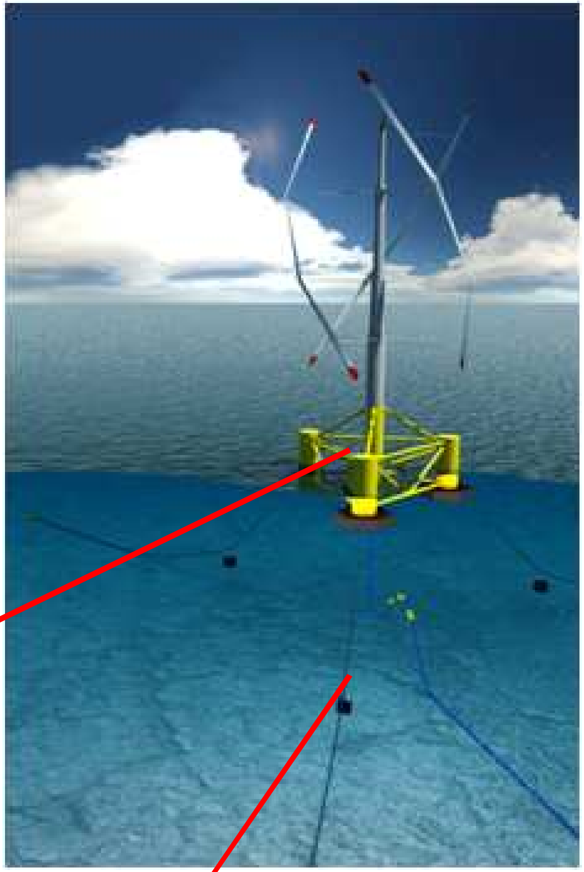
MODELLING APPROACH – HYDRODYNAMICS - POTENTIAL FLOW

- **Numerical tools**
  - Comercial
    - WAMIT
    - DIODORE
    - HYDROSTAR
    - AQWA
  - Non-commercial
    - NEMOH (Free - Open Source – Ecole Centrale Nantes)
- **Outputs**
  - Added mass
  - Radiation Damping
  - Hydrodynamic forces
  - Hydrostatic stiffness

○ Waves induced by motion

○ Forces

○ Buoyancy



Equation Of Motion

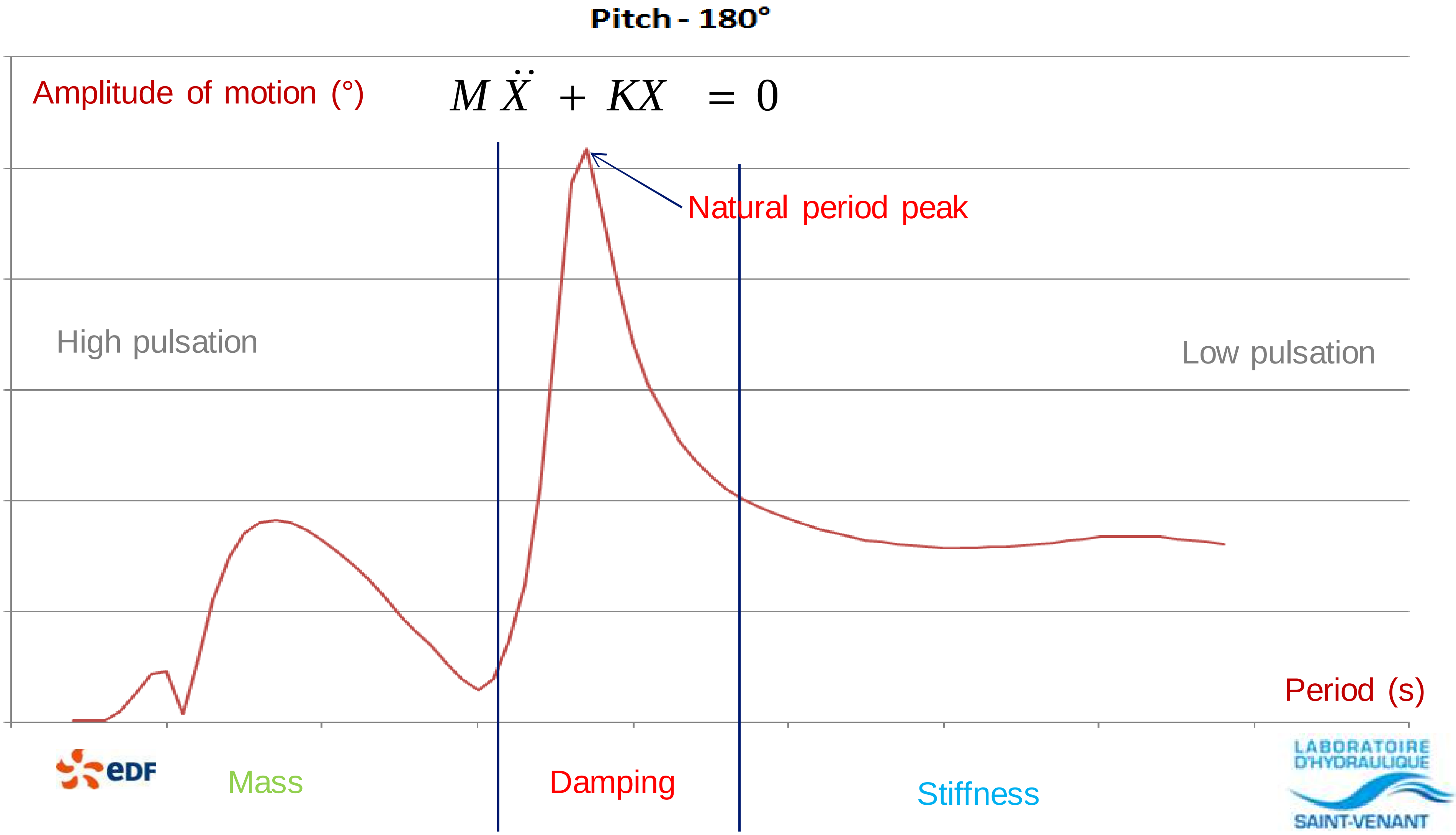
$$(M + M_A(\omega))\ddot{\mathbf{x}} + (D + B(\omega))\dot{\mathbf{x}} + (K + K_H)\mathbf{x} = \mathbf{F_e}$$

→ 6 degrees of freedom equation

MOTIONS AND ACCELERATIONS ANALYSIS

MODELLING APPROACH – FREQUENCY DOMAIN MODELLING

$$(M + M_A(\omega))\ddot{\mathbf{x}} + (D + B(\omega))\dot{\mathbf{x}} + (K + K_H)\mathbf{x} = \mathbf{F_e}$$



MOTIONS AND ACCELERATIONS ANALYSIS

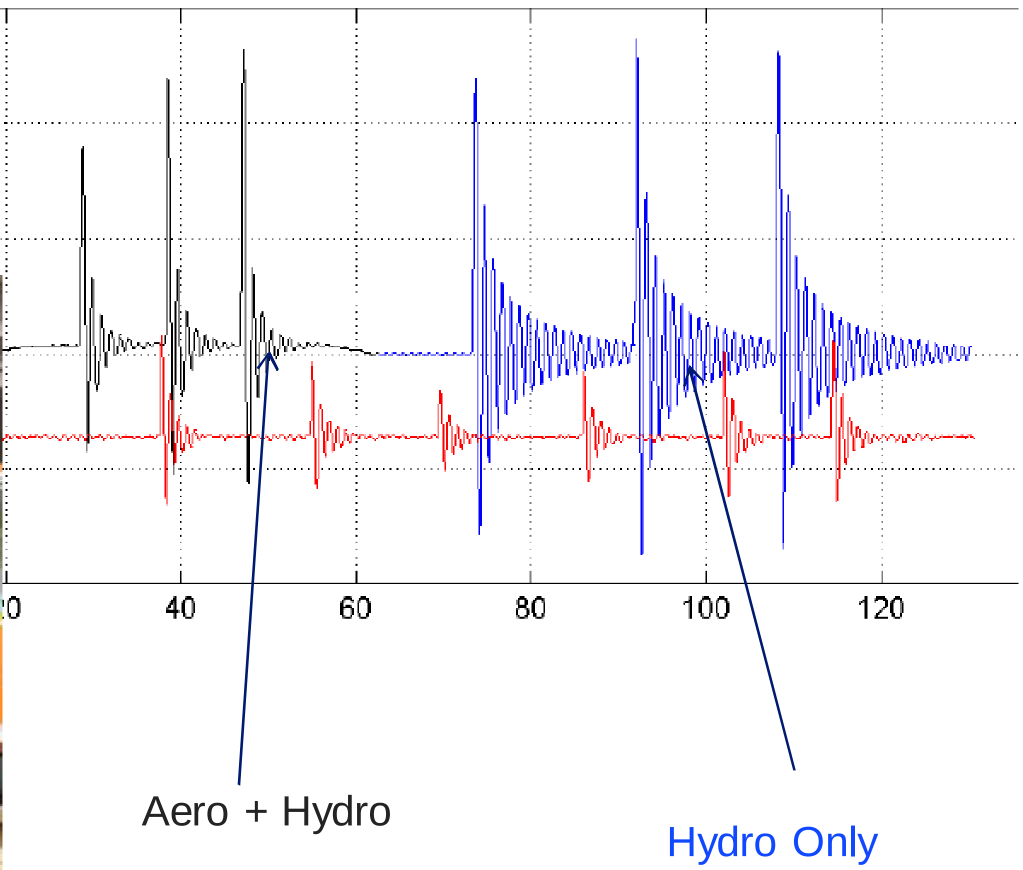
AERO/HYDRO COUPLING – DAMPING

- **Aerodynamic Damping : WINFLO project**

Influence on motions

Control strategy

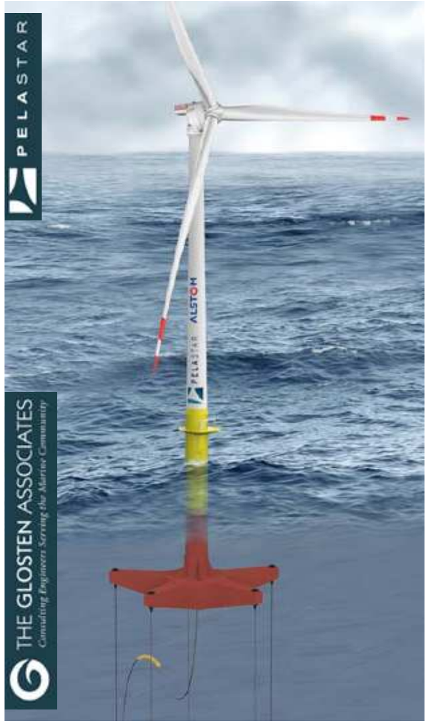
Pitch decay test

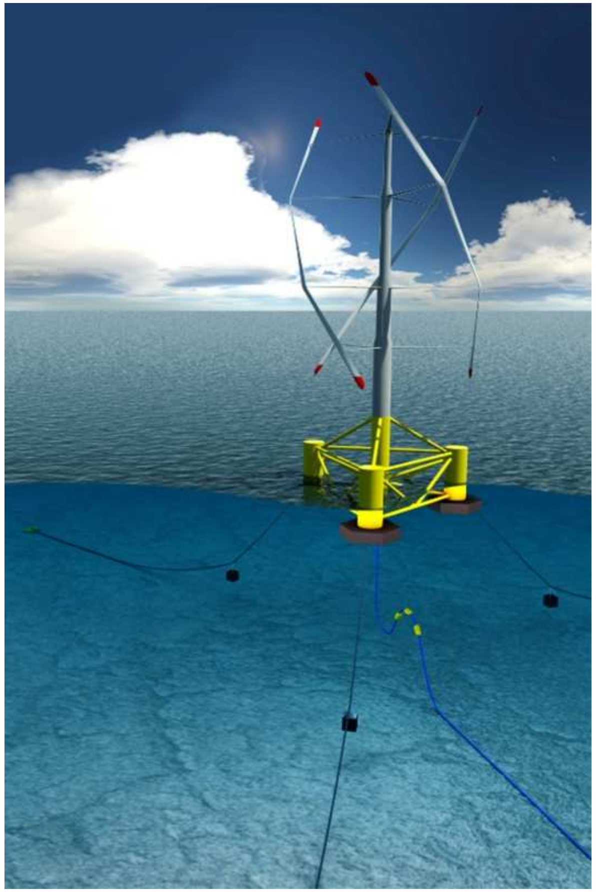


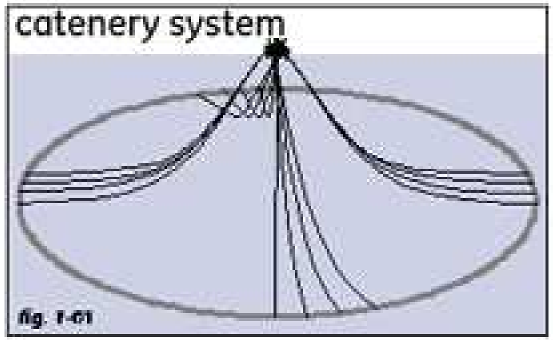
STATION KEEPING ANALYSIS

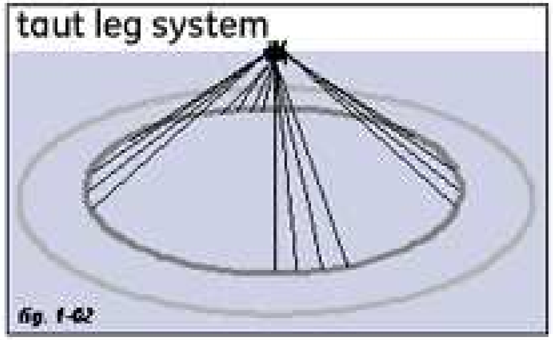
TYPE OF MOORING SYSTEM

- **Catenary lines**
  - ☐ Weight
  - ☐ Large Mooring radius
    - Several times water depth
    - ~ 400 m – 800 m
    - Farm application?
  - ☐ Used for the 5 multi MW FOWT projects
- **TLP**
  - ☐ Tension
  - ☐ Low Mooring radius
    - ~ 50 m
    - Good for farm application
- **Taut or semi-taut lines**
  - ☐ Intermediate solution
  - ☐ Generally with synthetic rope





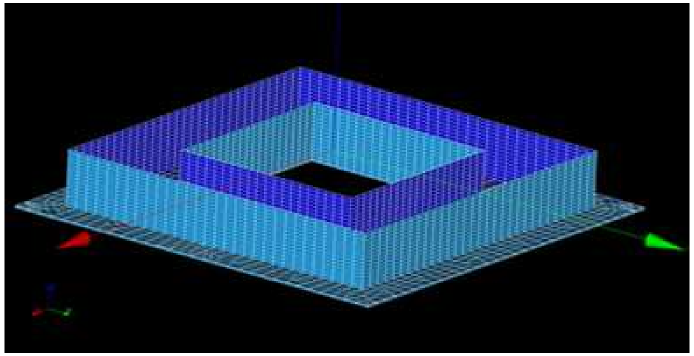




STATION KEEPING SYSTEM

APPLICATION TOOLS

- **All FOWT projects use mainly time domain approach to design their system**
  - ☐ Motion and acceleration analysis
  - ☐ Mooring sizing
- **Some numerical tools from Oil&Gas and Onshore wind have been adapted and coupled**
  - ☐ Orcaflex / No aerodynamic module
  - ☐ Deeplines Wind
  - ☐ Bladed
  - ☐ FAST (free & OpenSource) / No dynamic mooring
- **Keep in mind that another software is often necessary to solve the Diffraction/Radiation problem**



BASIN TESTS
FULL SYSTEM SCALING

- **Froude scaling**
  - Well adapted for wave-structure interaction
  - Aerodynamics very sensitive to Reynolds number
  - Hard (impossible) to scale
    - Geometry
    - Thrust
    - Rotor speed and wind velocity
- **Typical scale**
  - Between 1/20th and 1/50th
  - Water depth : 100m => 2m to 5m
  - Catenary lines ~ 600m => 10m to 30m

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LABORATOIRE
D'HYDRAULIQUE
SAINT-VENANT

BASIN TESTS
OTHER STRATEGIES FOR FULL SYSTEM MODELLING

- **Need for full system behavior assesment**
  - ☐ Froude scaling / Reynolds scaling
  - ☐ Multi-MW prototypes Expensive & time consuming

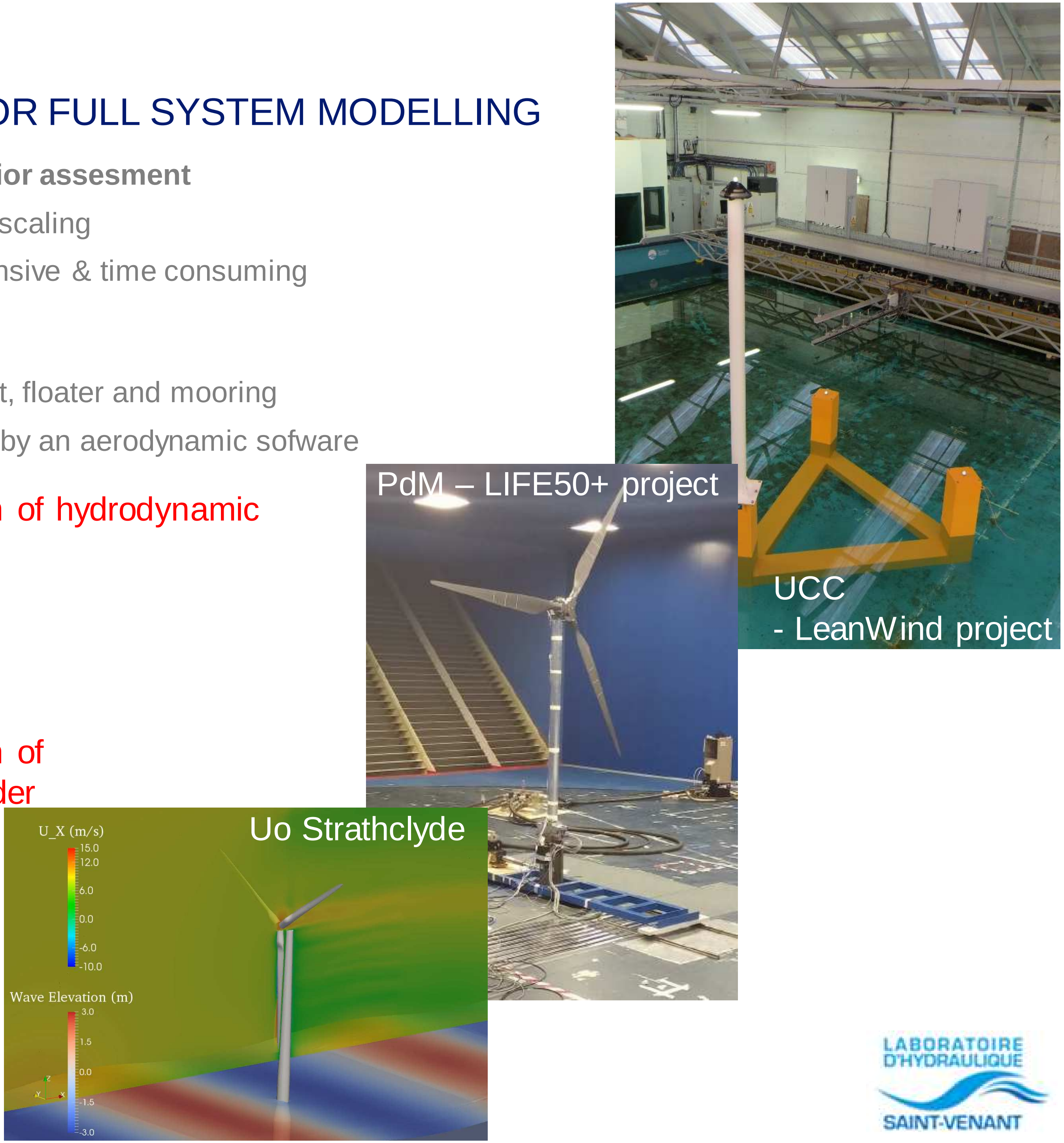
- **Software In the Loop (SIL)**
  - ☐ Froude scaling for the mast, floater and mooring
  - ☐ Fan on top of mast, drived by an aerodynamic sofware

→ Experimental validation of hydrodynamic behavior

- **Wind Tunnel tests**
  - ☐ Reynolds scaling
  - ☐ Hexapod

→ Experimental validation of aerodynamic loads under wave induced motions

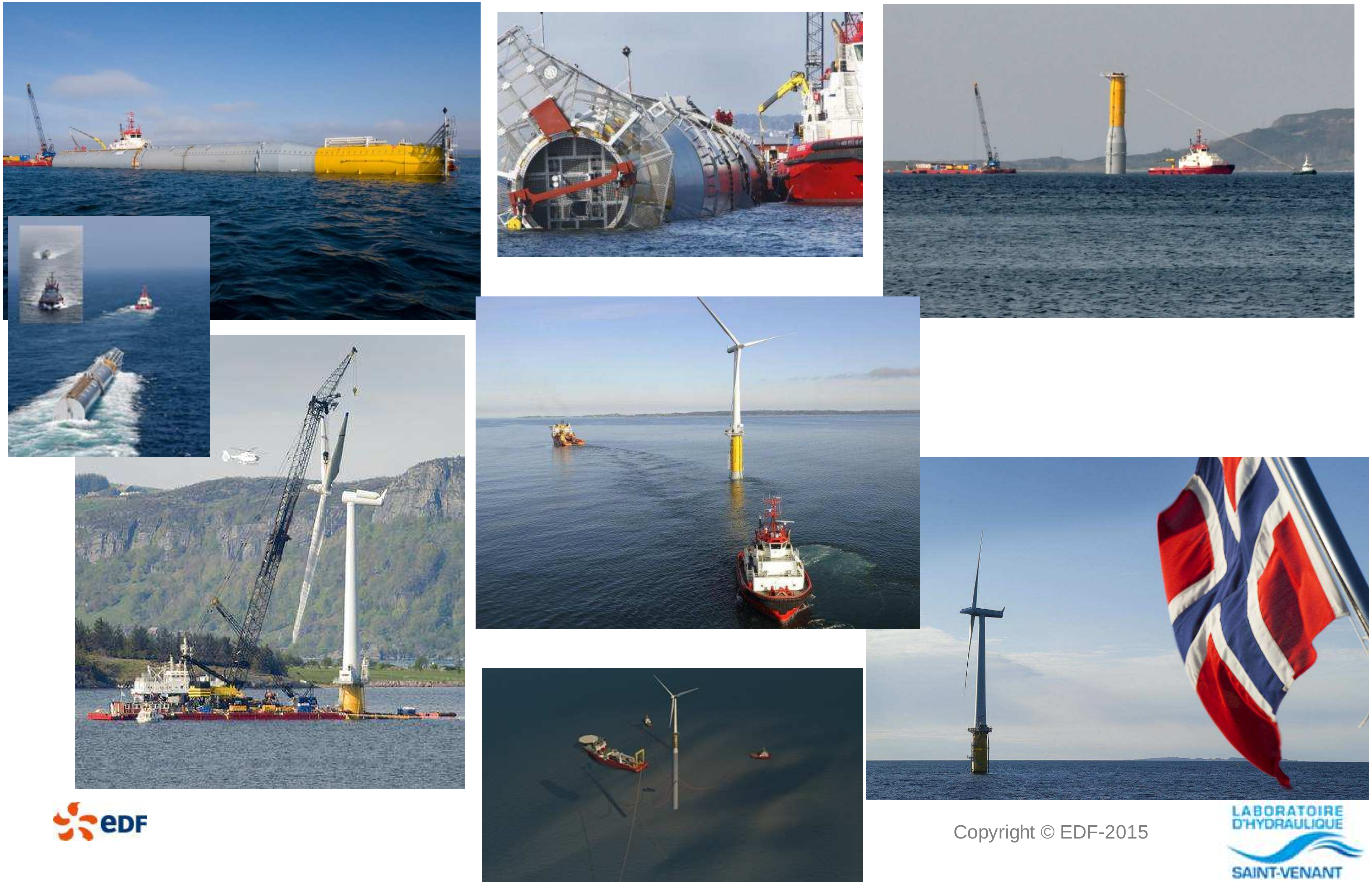
- **CFD**
  - ☐ Global system modelling
  - ☐ High CPU cost



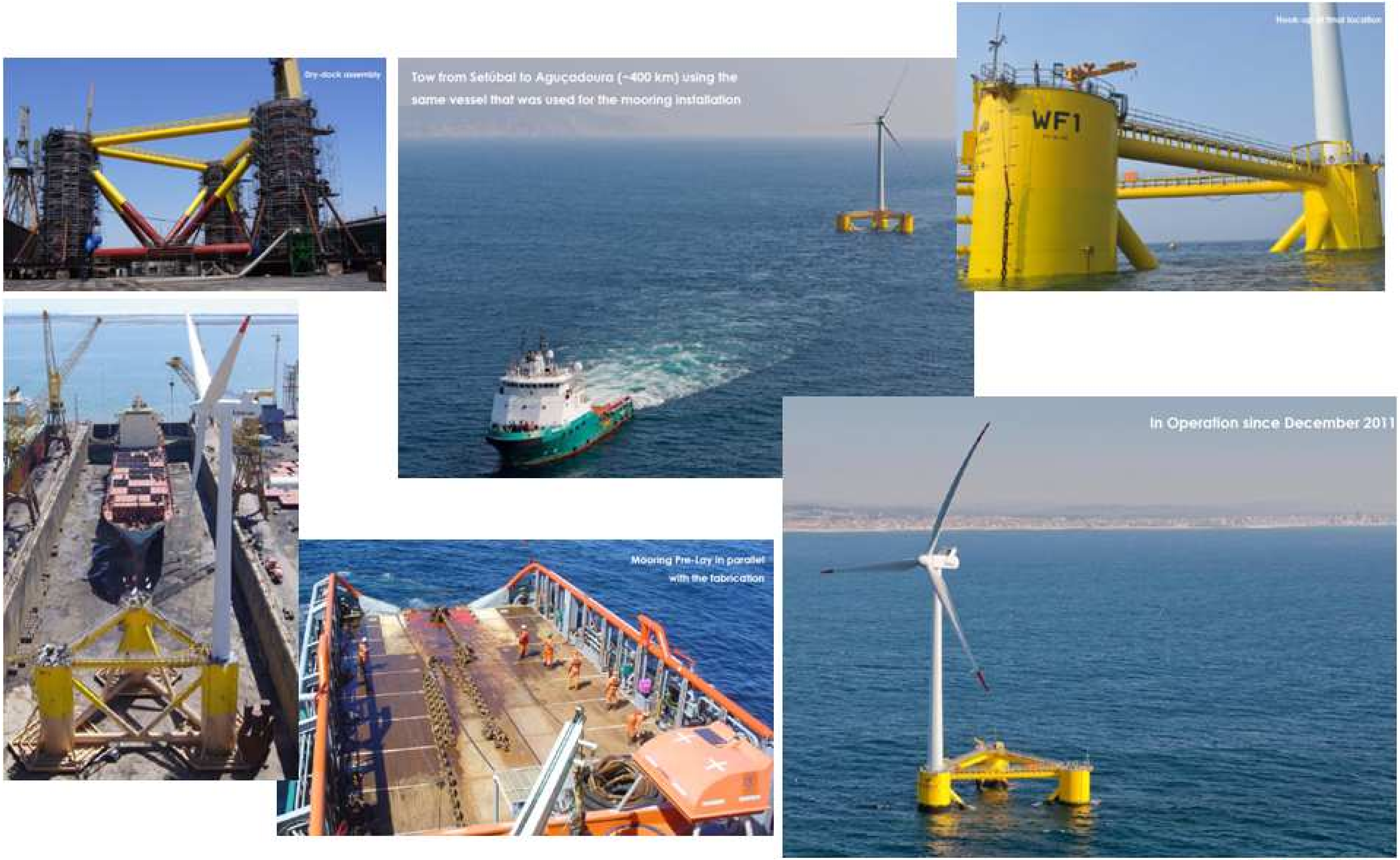
INSTALLATION

GLOSTEN

INSTALLATION - SPAR



INSTALLATION - SEMISUBMERSIBLE



Dry-dock assembly

Tow from Setúbal to Aguçadoura (~400 km) using the same vessel that was used for the mooring installation

Hook up at final location

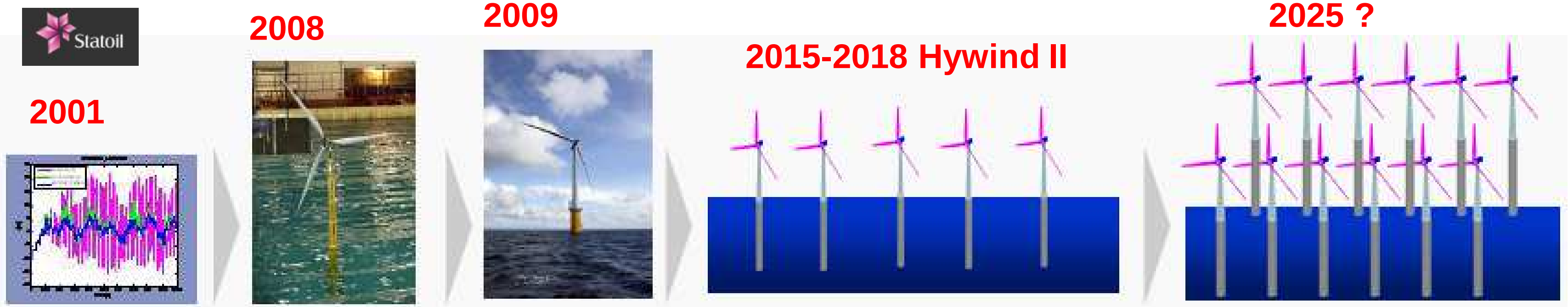
Mooring Pre-Lay in parallel with the fabrication

In Operation since December 2011

NEXT STEP FOR FLOATING - HYWIND SCOTLAND

- “Roadmap” Hywind-Statoil

Statoil



- Hywind Scotland Pilot Park (2013 – 2017)

	Hywind Scotland
Installed capacity (5 WTGs)	30 MW
Area (sea level)	~4 km^2
Water depth	95-120 m
Average wind speed (@100 m)	10.1 m/s
Mean waves, Hs	1.8 m
Offshore export cable length	Ca.30 km
Onshore cable length	Ca.2-3 km
Transmission voltage	33 kV
Mooring	Pre-laid chains
Anchor	Suction

Winner of Scottish Floating Offshore Wind Call for Tender (2013)

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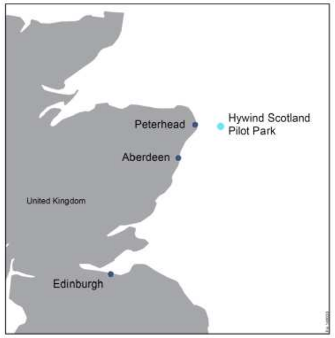
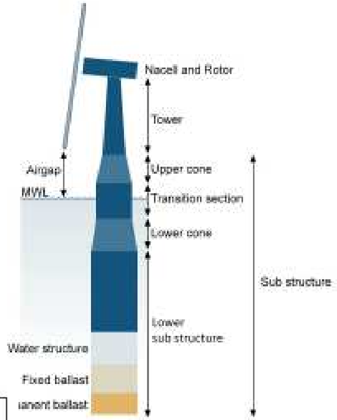
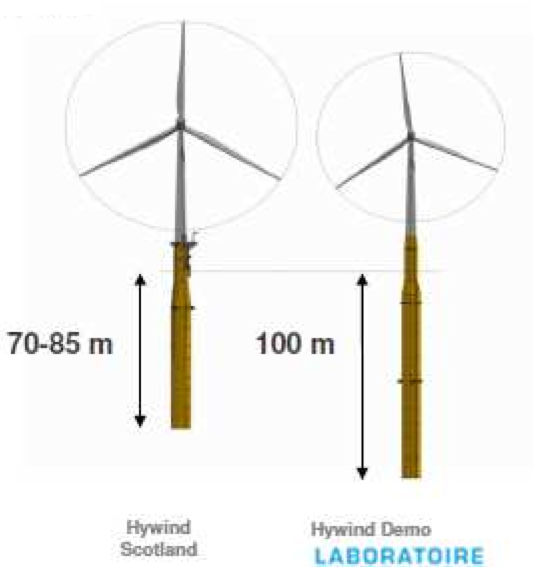
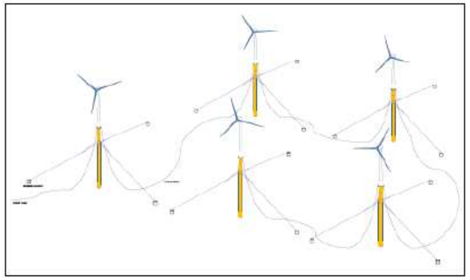




Hywind Demo and Hywind Scotland

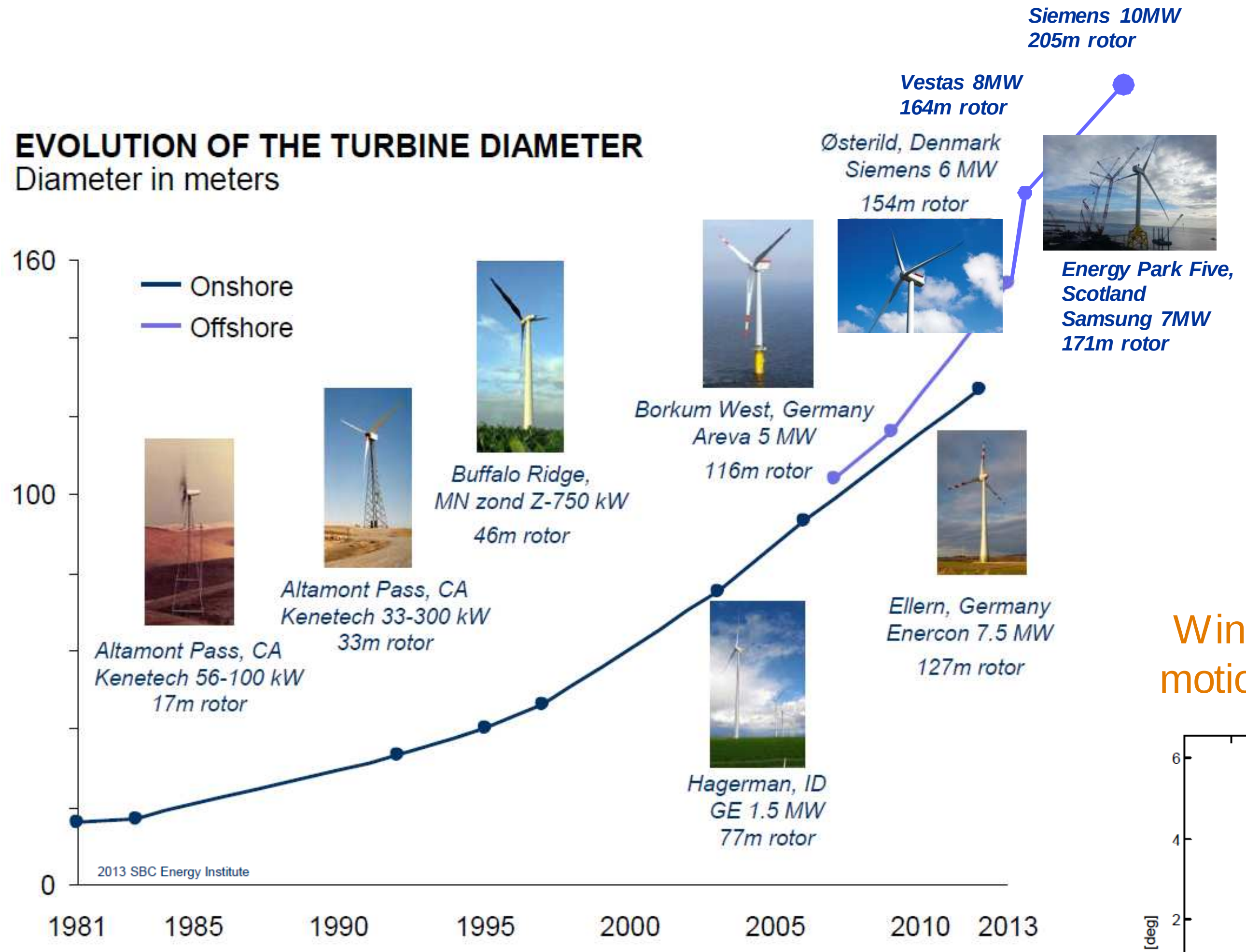




LABORATOIRE D'HYDRAULIQUE SAINT-VENANT

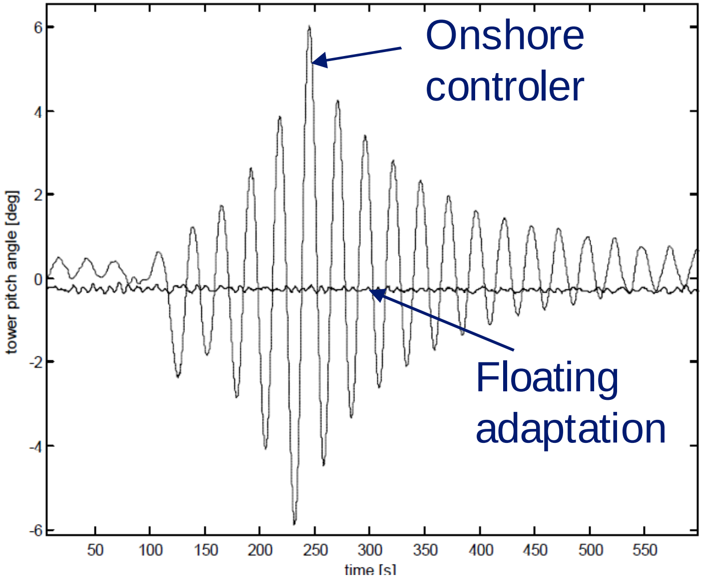
SOME CHALLENGES
FOR
OFFSHORE WIND

TURBINE SIZE AND CONTROLER

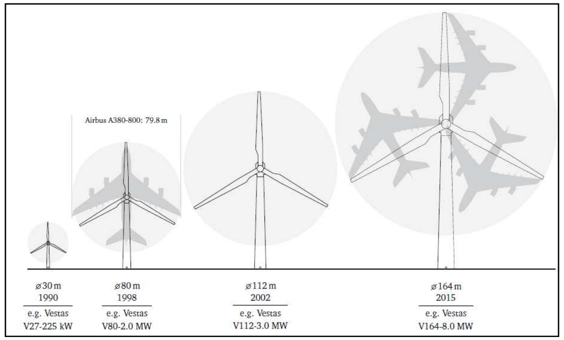


Wind induced motion damping

Fatigue reduction



83.5 m SSP Blade for Samsung S7.0-171 (Denmark)



FLOATING WIND

STILL AT A R&D STAGE

- **Need for stability**
  - Reduce turbine thrust
  - Increase turbine tolerance to tilt
  - Innovative floater solution

- **Flexible system design**
  - Mooring lines length
  - Mooring lines materials
  - Export cable / Offset of the FOWT

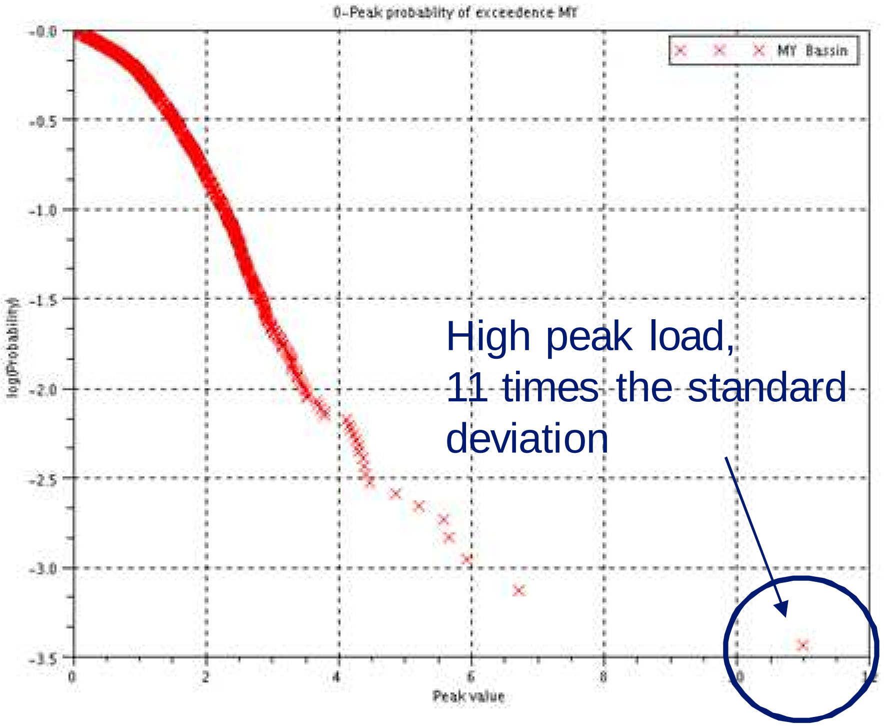
- **Projects technical de-risking**
  - Global behavior of a complex system
    - Basin test strategy ?
    - CFD ?

IMAGE

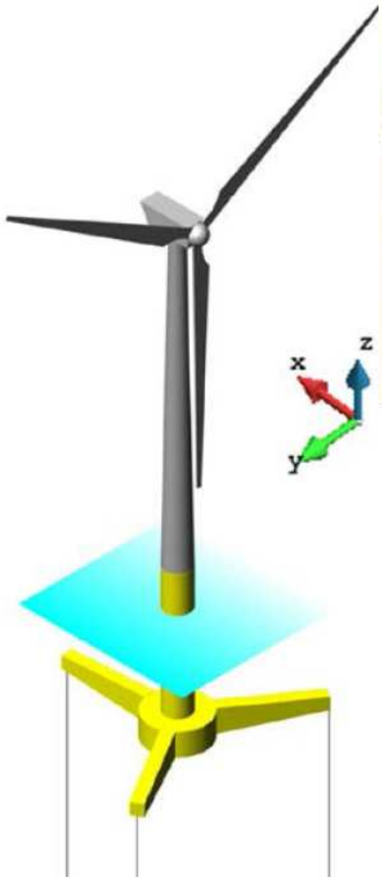
HYDRODYNAMIC LOADS

BETTER ESTIMATION FOR BETTER DESIGN

- **Ringing loads observed on Gravity Based Foundations**
  - ☐ Ringing is a high order hydrodynamic phenomenon
  - ☐ Induces very high loads ⇔ Design for Extrem storms



High peak load, 11 times the standard deviation



- **TLP structures can also experience ringing loads**
  - ☐ Example : Heidrun Tension Leg Plateform
  - ☐ Impact on tendons design

⇨ Develoment of fully nonlinear hydrodynamic models (Potential flow / Navier-Stokes)

⇨ High CPU cost/High research cost

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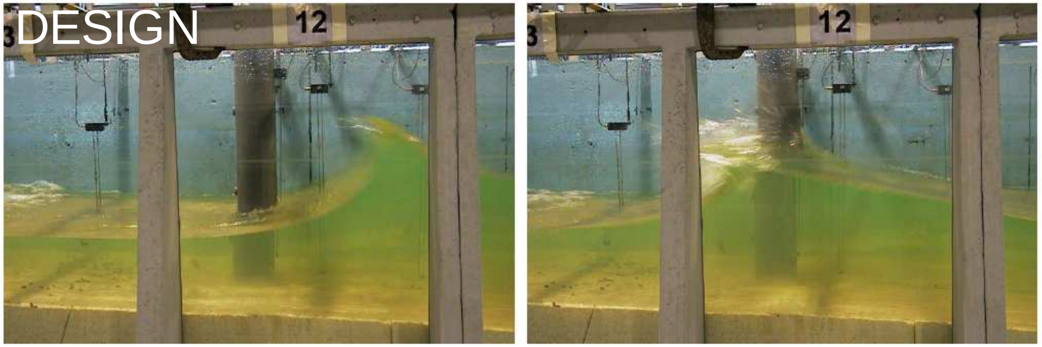
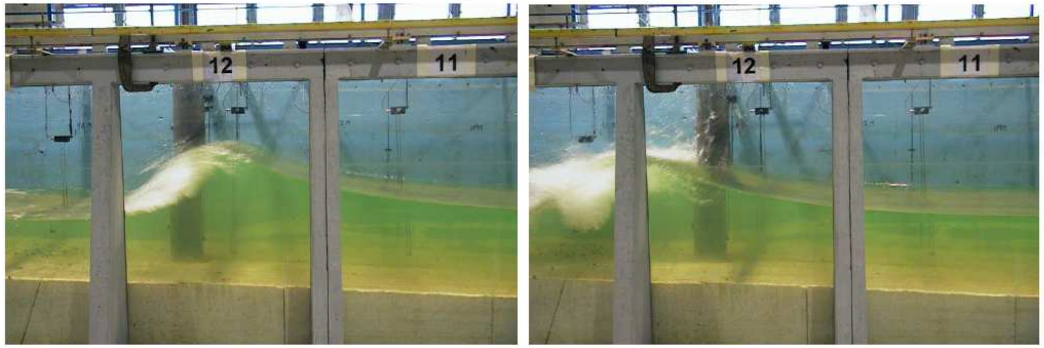
HYDRODYNAMIC LOADS
BETTER ESTIMATION FOR BETTER DESIGN

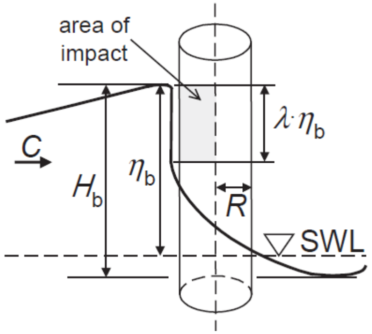
- **Breaking waves**
  - When steepness increase until a level of about 14%
  - Impact loads
  - Complex fluid mechanics problem

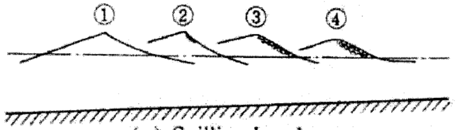


Test EOL59 : bottom slope 5% – $d_{offshore}$ = 0.8 m – T = 2.4 s – $H_{offshore}$ = 0.288 m

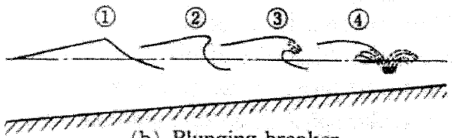


Test EOL107 : bottom slope 2.5% – $d_{offshore}$ = 1.0 m – T = 1.6 s – $H_{offshore}$ = 0.280 m

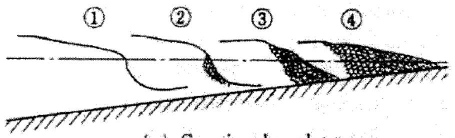




(a) Spilling breaker

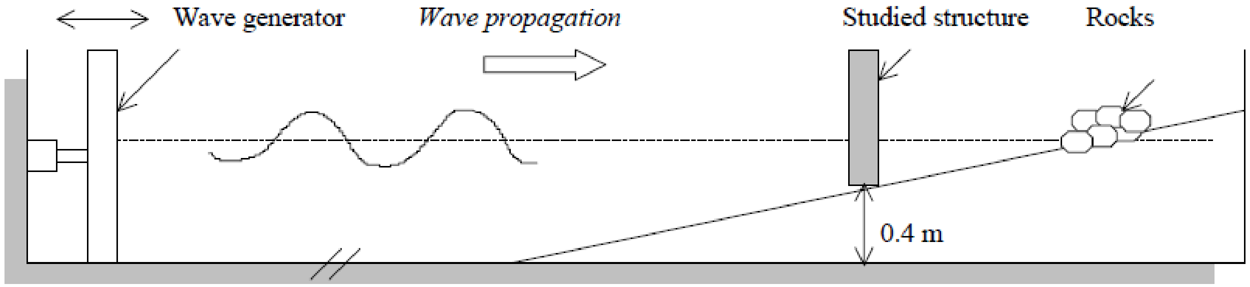


(b) Plunging breaker



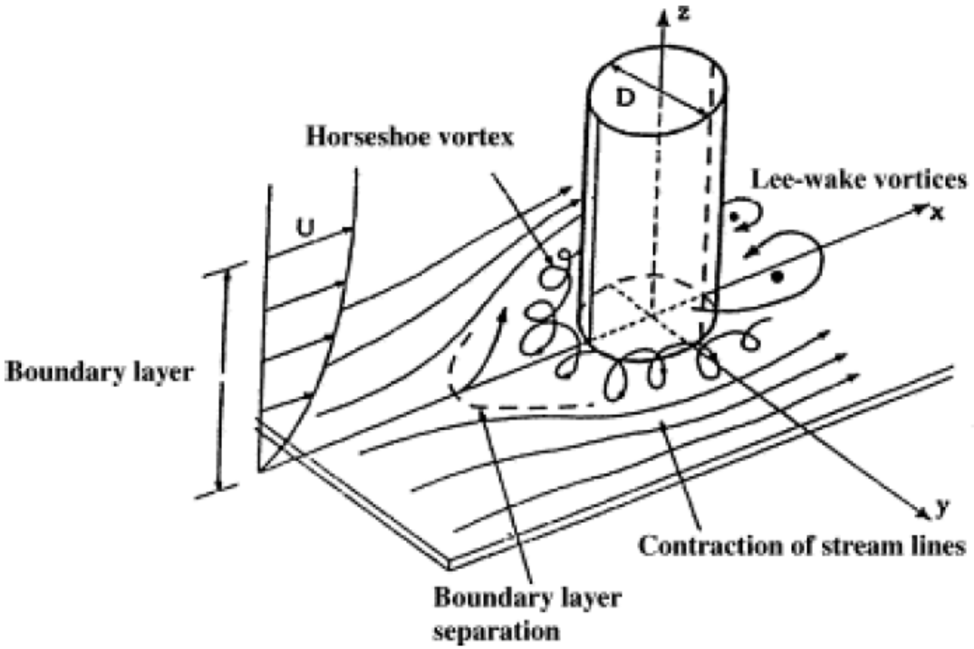
(c) Surging breaker

➡ Needs for experimental work



➡ Or CFD (VoF, SPH methods…)

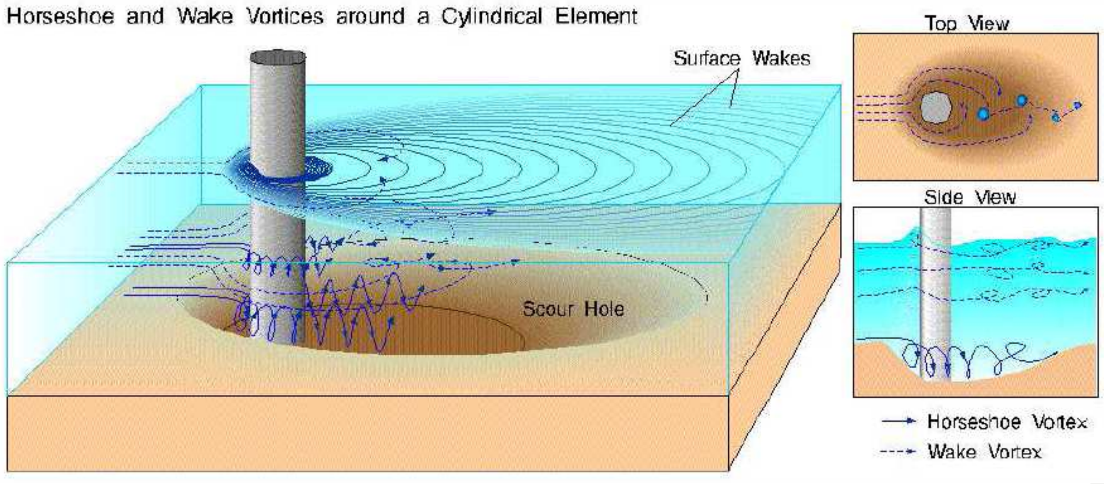
SCOURING

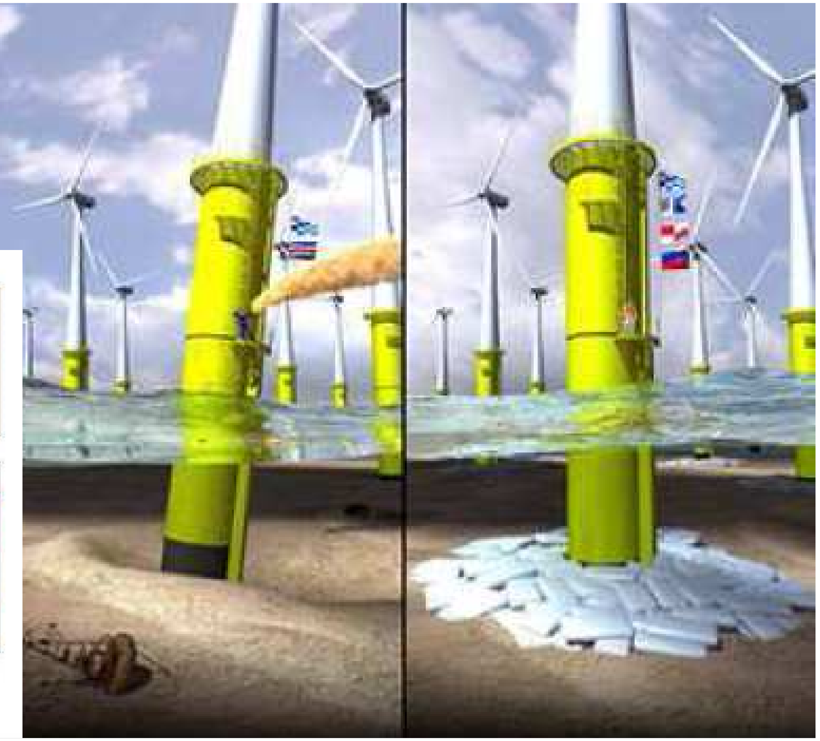


- **Sediment convection by fluid**
  - ☐ Waves
  - ☐ Currents
- **Scouring issues**
  - ☐ Can be very critical
  - ☐ Modelling
  - ☐ Protection

Loss of stability for the foundation

Stifness – Natural frequencies

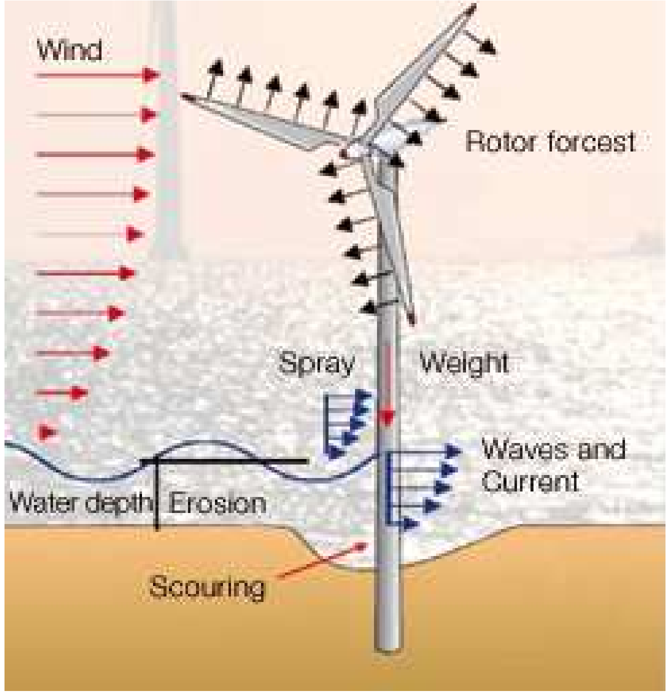




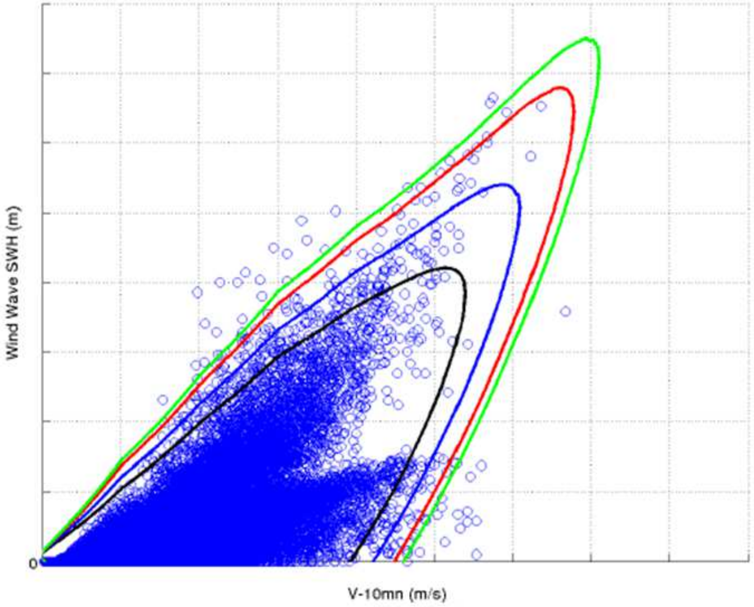
DESIGN METHODOLOGY

DESIGN LOAD CASES (DLC)

- **Very high number of load cases to design an OWT**
  - ~ 20000 DLCs
  - Fatigue + Extreme events
  - Standards and Guidelines : IEC, DVN, GL, ABS…
- **Due to the number of parameters**
  - Wind
    - Direction / Intensity / Turbulence
  - Wave
    - Direction / Height / Period / Spectrum
  - Turbine
    - Start up / Shut down / Grid loss
  - ….
- **Design strategy**
  - Response based design ?
  - Fatigue assesment



Wind and Waves induced Force&Moment in the same order of magnitude



PROJECT ACCEPTABILITY

CRITICAL ISSUE IN THE DEVELOPEMENT

- **YYY**
  - XXX

IMAGE

THANK YOU

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