Floating Offshore Wind Turbines: concepts, technical challenges and modelling

An introduction

Agenda

01 **Motivation**
Why floating?

02 **Technologies**
Main Floater types and stability

03 **Challenes**
Loads on Floating Win Turbines

04 **Modelling**
Coupled physics

Objectives

1. **Why** floating wind?
2. **Technologies**: floater types
3. **How** do we achieve stability?
4. **What** happens to loads?
5. **How** do we model FOWTs?

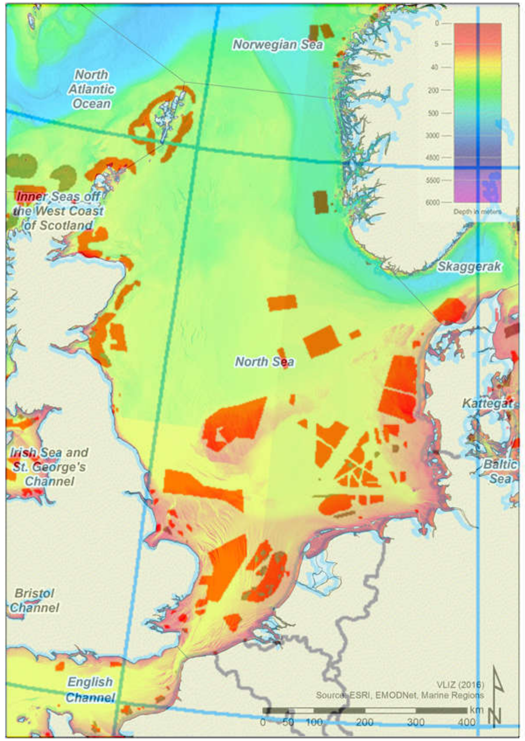
Photo by Øyvind Gravås, Equinor

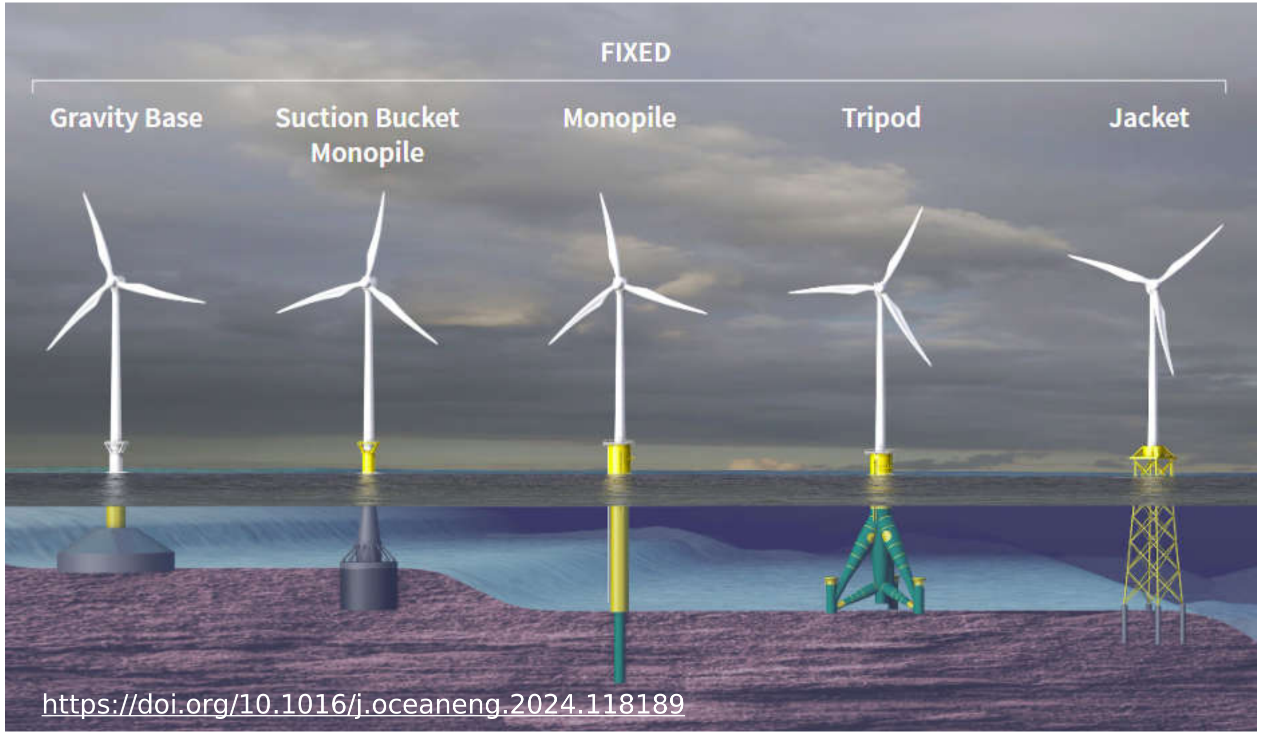
References:
O. Faltinsen, Sea Loads on Ships and Offshore Structures, Cambridge University Press
J. N. Newmann, Marine Hydrodynamics, MIT Press
J. Jonkman, Dynamics of Offshore Floating Wind Turbins – Model Development and Verification
J. Jonkman and D. Math, Dynamics of offshore floating wind turbines – analysis of three concepts

Fixed-bottom offshore turbines

OWTs are established tech. Have proven to be able to operate in harsh sea environment

- ✓ Limited access for maintenance
- ✓ Corrosive conditions
- ✓ High winds
- ✓ Rain (erosion)



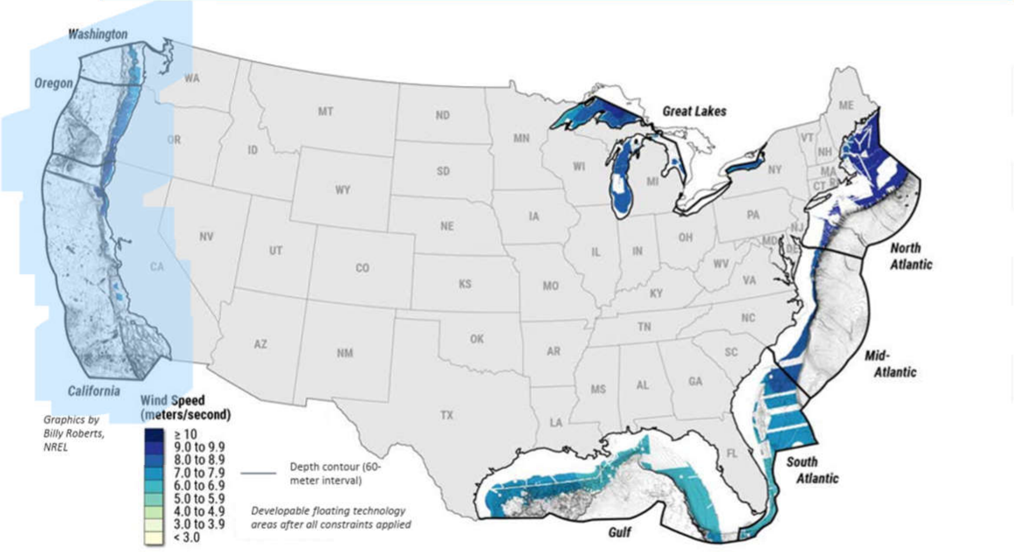


https://doi.org/10.1016/j.oceaneng.2024.118189

Wind resource in deep waters

Significant wind potential can be unlocked if we exploit deep waters

Floating OSW Energy Technology Technical Potential (Open Access)



Fixed-Bottom OSW Energy Technology Technical Potential (Open Access)

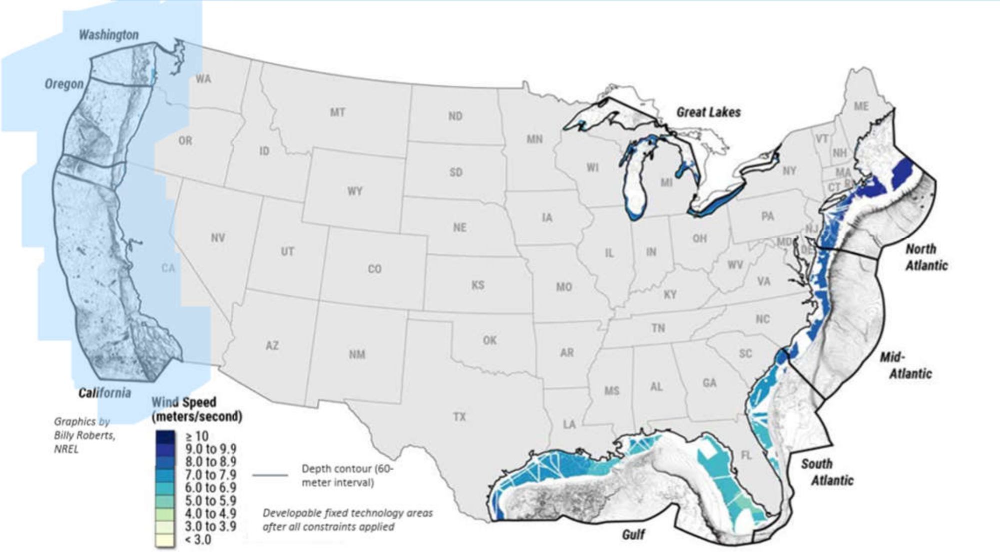


Image courtesy of NREL. A. Lopez et al, Offshore Wind Energy Technical Potential for the Contiguous United States, 15/08/2022, https://www.nrel.gov/wind/offshore-resource.html

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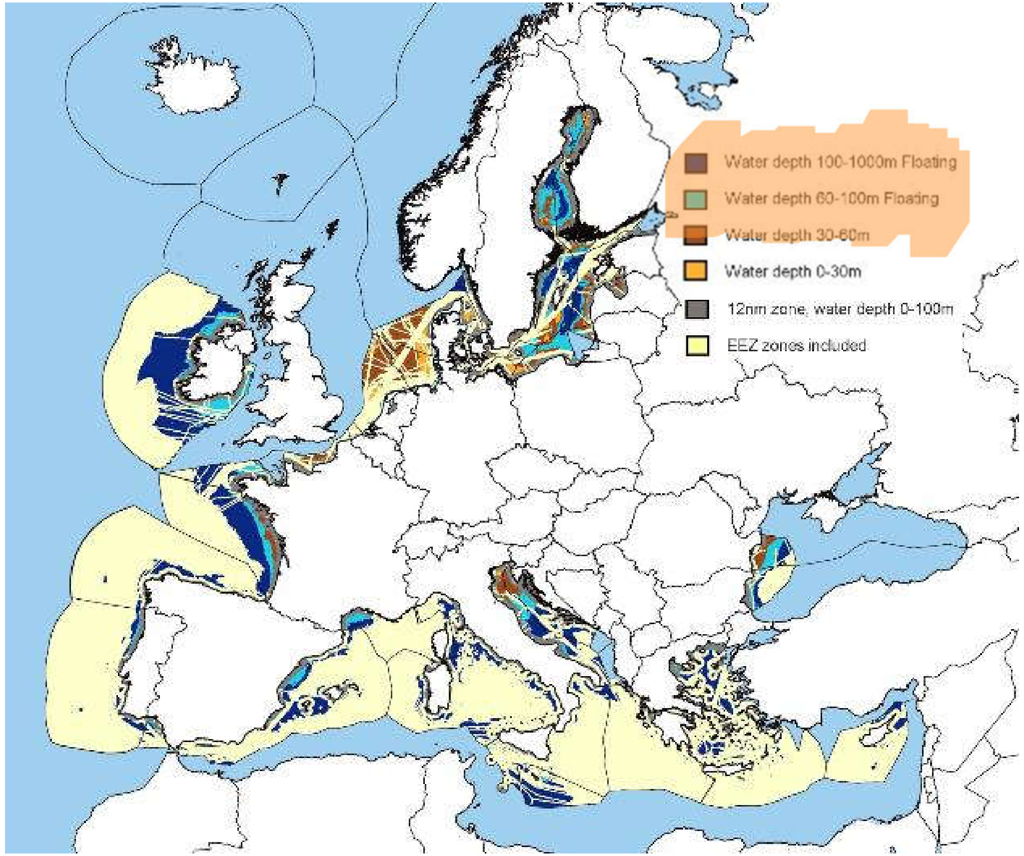


Image from: COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS
An EU Strategy to harness the potential of offshore renewable energy for a climate neutral future, Brussels, 19/11/2022

Floating offshore wind turbines

For installation in medium to deep waters (150-1000m) floating wind is the only solution

- ✓ between 50 and 150 m of depth floating wind promises to be the most cost effective solution

At this early stage several concepts of platforms have been proposed

The size of these machines is unprecedented

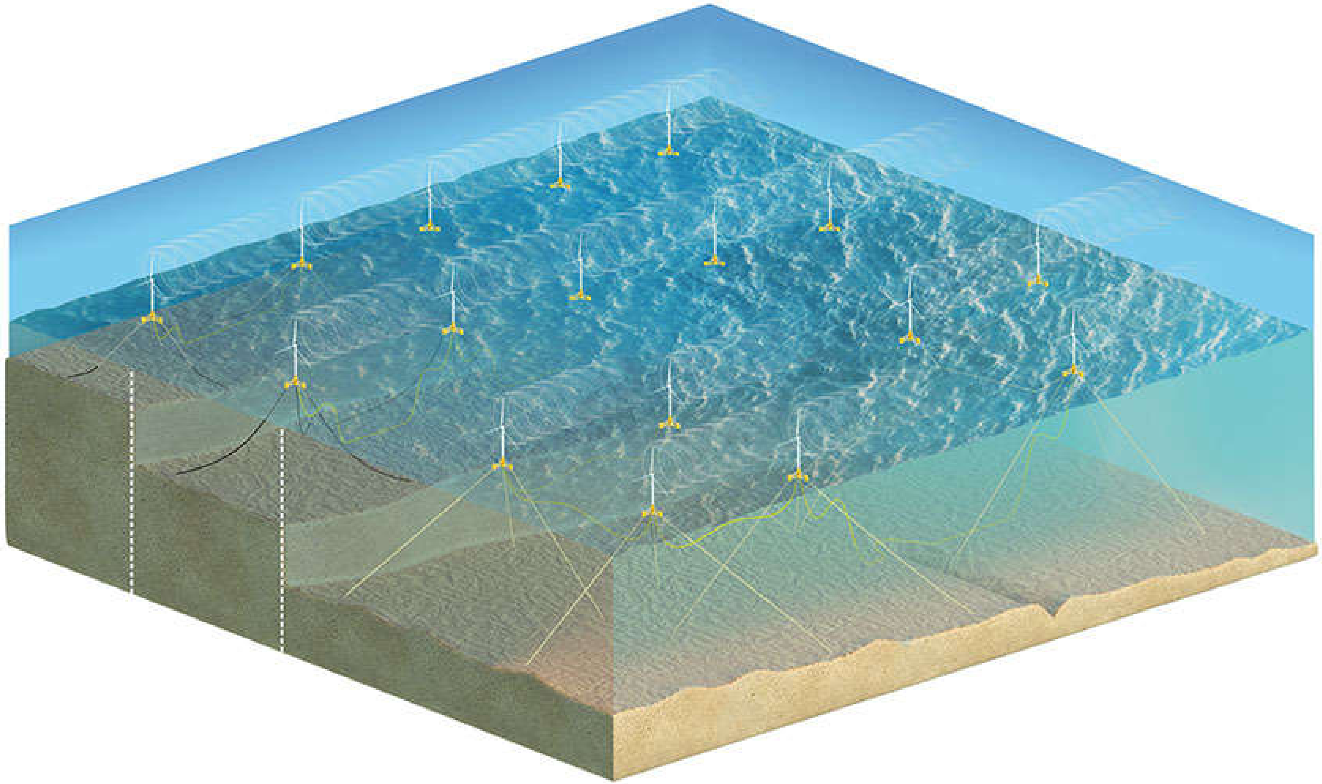
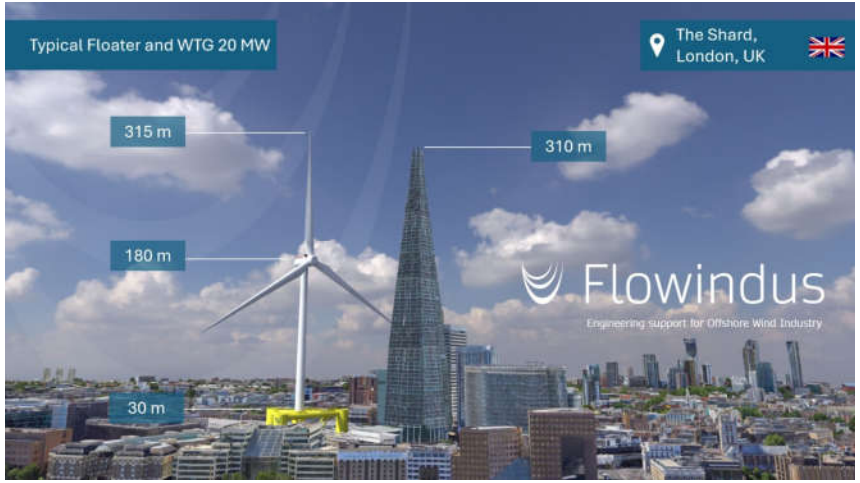
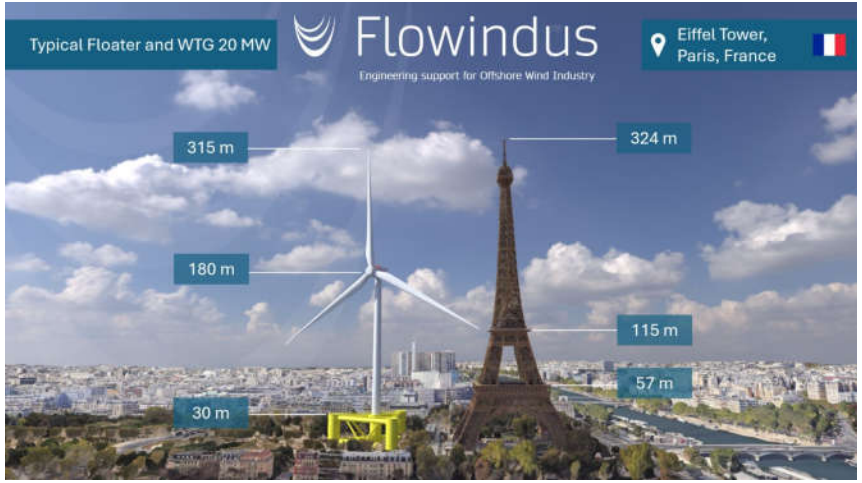
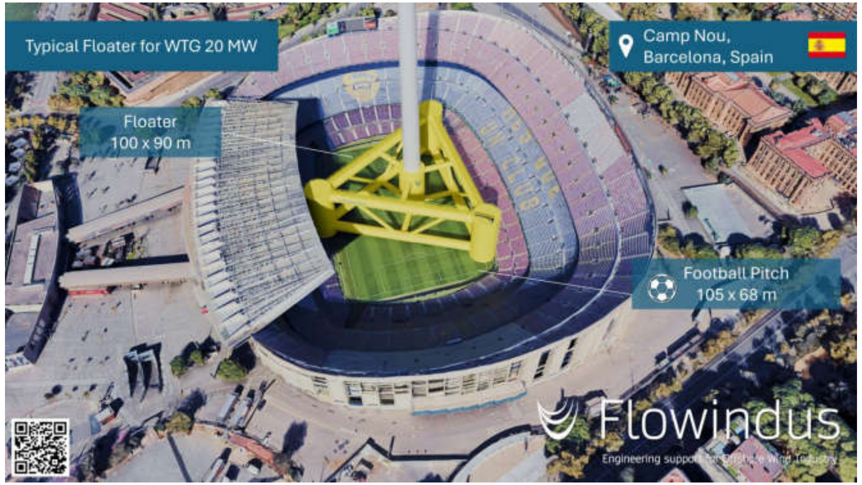


Illustration by Besiki Kazaishvili, NREL, https://www.nrel.gov/wind/floating-offshore-array-design.html

How large ate todays FOWTs?



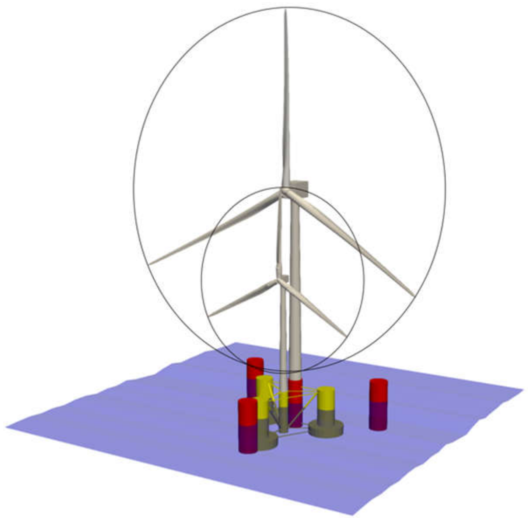




Economies of scale

Platform weight (including ballast) dwarfs the turbine mass, some examples:

	NREL 5MW	IEA 15MW
rated power	5 MW	15 MW
rotor diameter	126 m	240 m
hub height	90 m	150 m
swept area	12469 m^2	45239 m^2
turbine mass	600 t	2250 t
RNA mass	349.4 t	991.4 t
platform	semi-submersible	semi-submersible
Hull steel mass	-	3914 t
ballasted platform mass	13500 t	17850 t
draft	20 m	20 m
Distance between columns	-	77.6 m
mooring system	3-line slack catenary	3-line slack catenary



Installation and O&M

Floating wind has potential advantages in O&M….

- ✓ assembly directly in port
- ✓ turbine can be towed to shore for maintenance

… but also introduce logistical challenges

- ✓ assembly must happen near installation location
- ✓ large port quay areas are necessary

https://commons.wikimedia.org/wiki/File:Hywind.jpg

Technologies

Floater types and stability

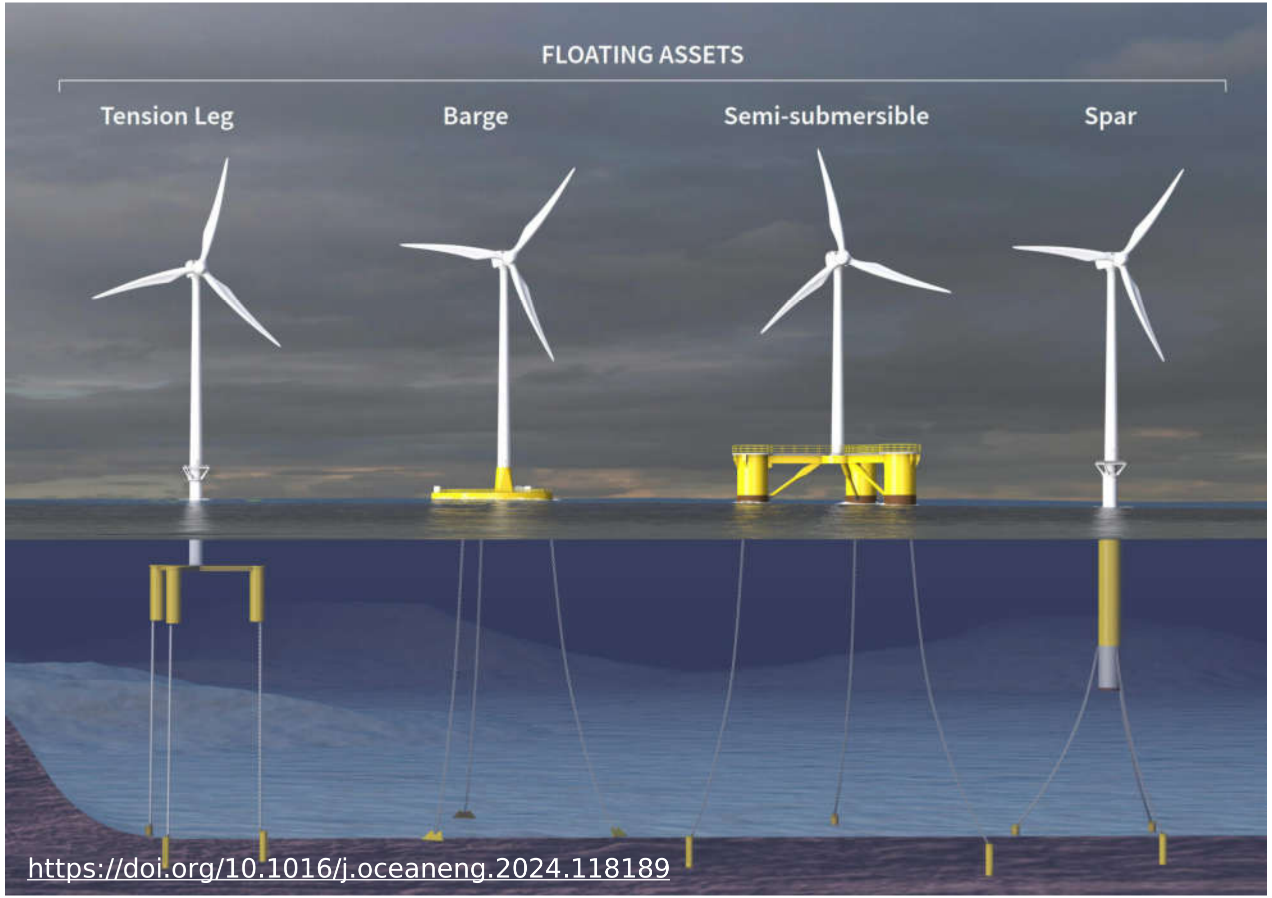
Floater types

More than 50 concepts have been proposed

- ✓ Some feature two-part hulls such as the Stiesdal Tetraspar or the Saipem Hexafloat

Four main concepts have emerged historically

- ✓ The four concepts differ in how stability is achieved
- ✓ All FOWT substructures achive stability by combining these four mechanisms
- ✓ Some of these concepts have been adapted from Oil&Gas industry



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Floater stability

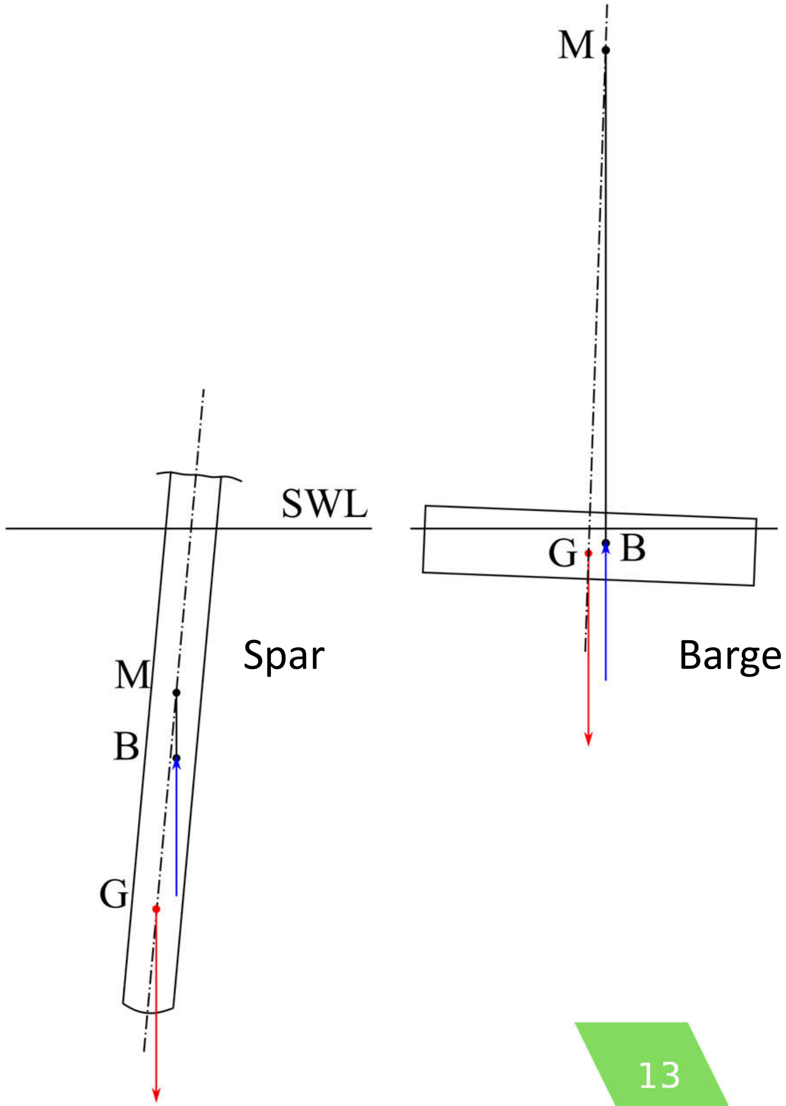
Different floaters achieve stability in different ways

- ✓ Hydrostatic stiffness
- ✓ Ballasting
- ✓ Mooring

Floater is stable if center of Buoyancy (B) is above center of gravity (G) of the entire system. More precisely:

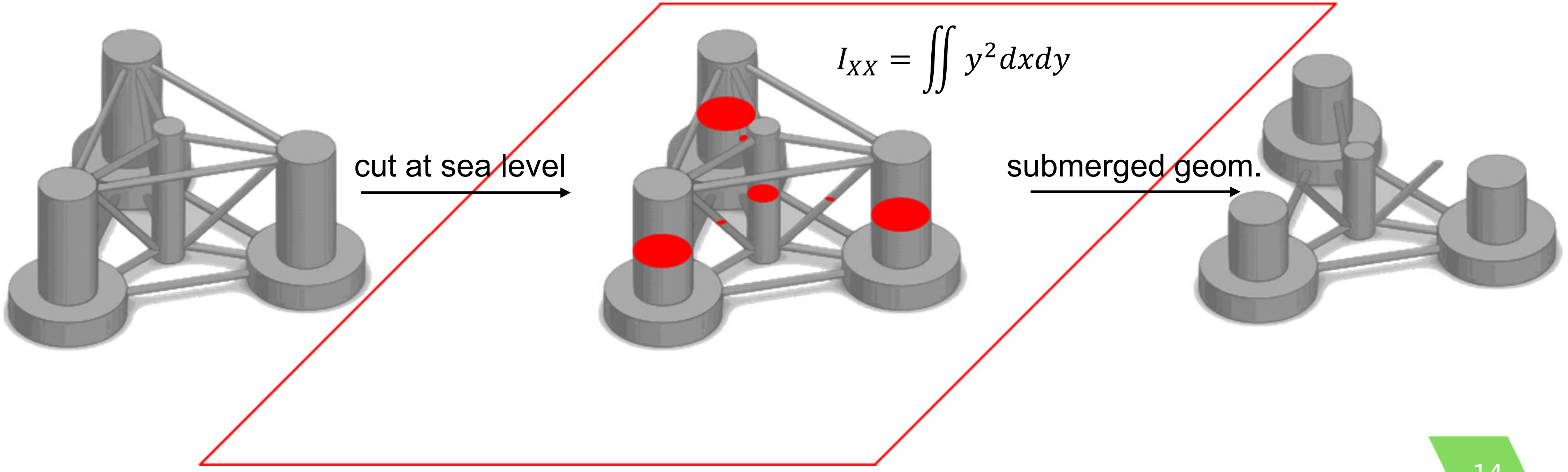
B = Center of buoyancy
G = Center of mass
M = intersection between buoyancy force and symmetry axis
BM = Ixx/V
Ixx = moment of inertia of waterplane area

STABILITY FOR GM > 0



Waterplane moment of inertia

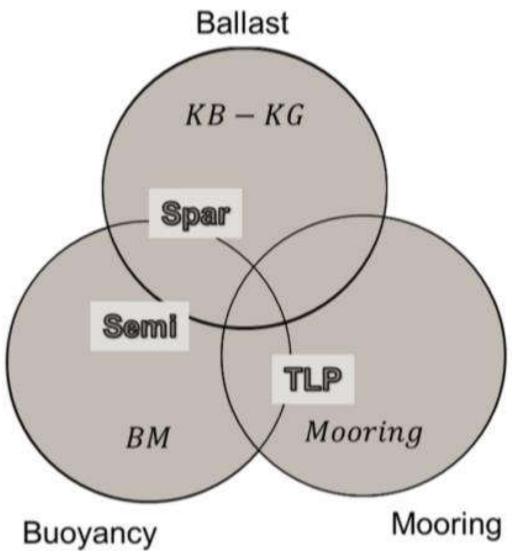
Waterplane moment of inertia can be found by cutting the surface at the water plane and calculating its moment of inertia respect to axis upon which the floater rotates

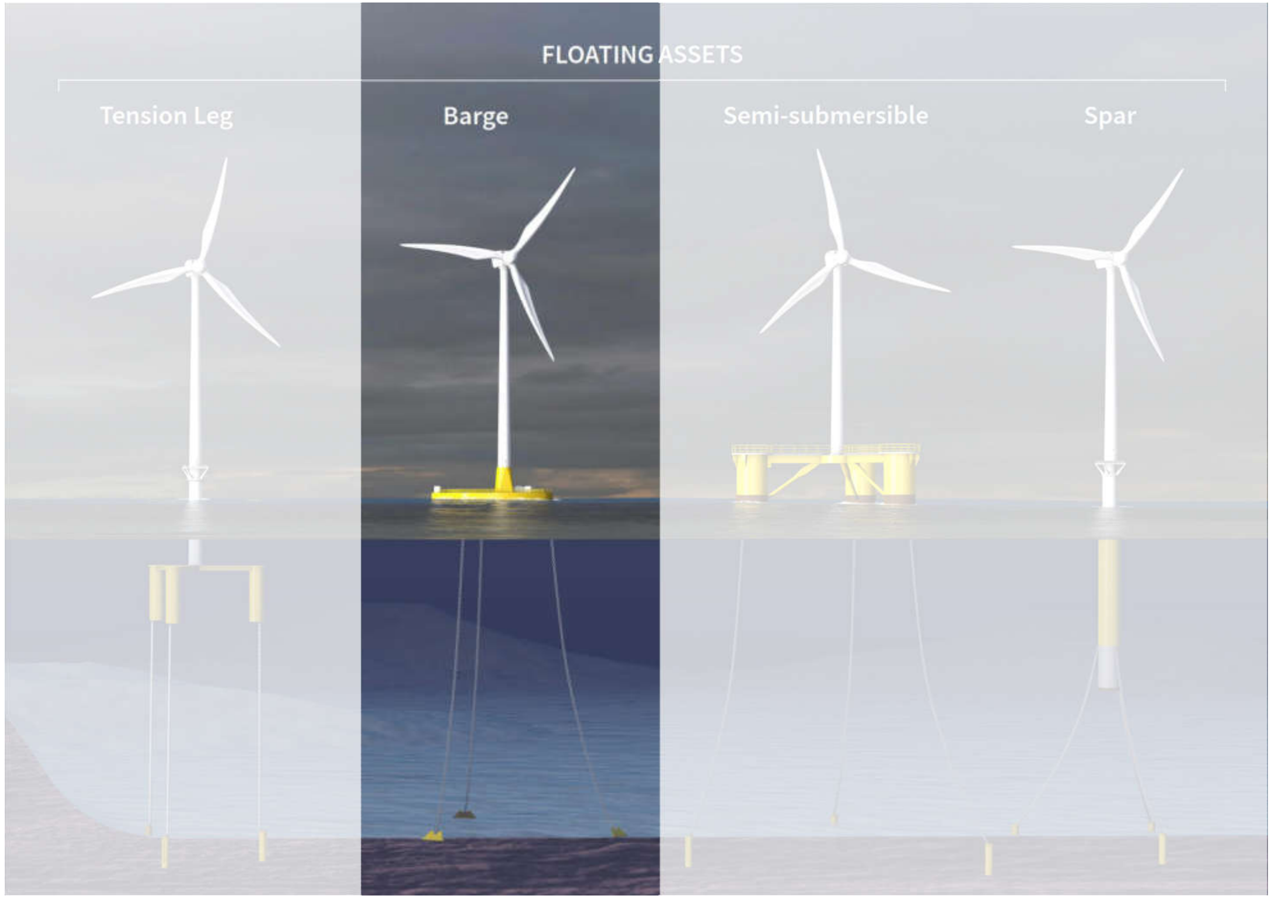


Floater stability: comparison

<u>Barge</u>: Buoyancy, stability trough large waterplane area

- ✓ Very rigid, good stability in response to aerodynamic loads, but waves induce large motions on the structure





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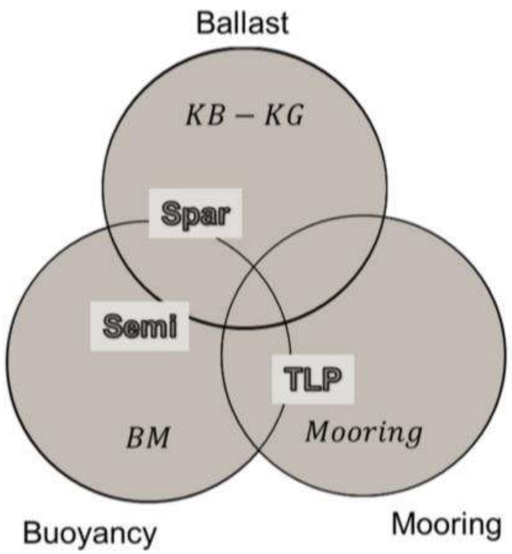
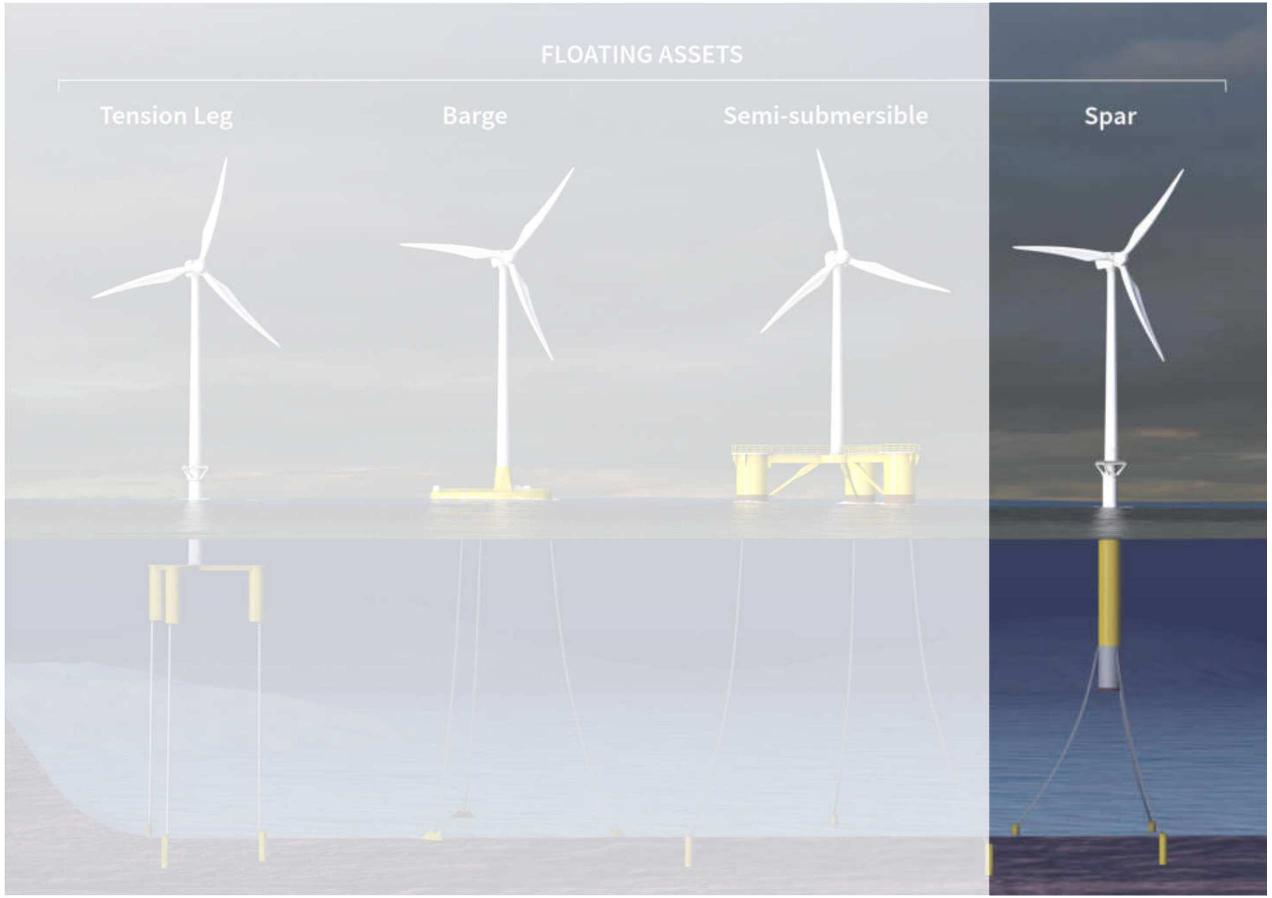
Floater stability: comparison

<u>Spar</u>: Ballast, stability trough low CoG

- ✓ transparent to waves due to small projected surface in wave direction but typically aerodynamic loading induces larger motions





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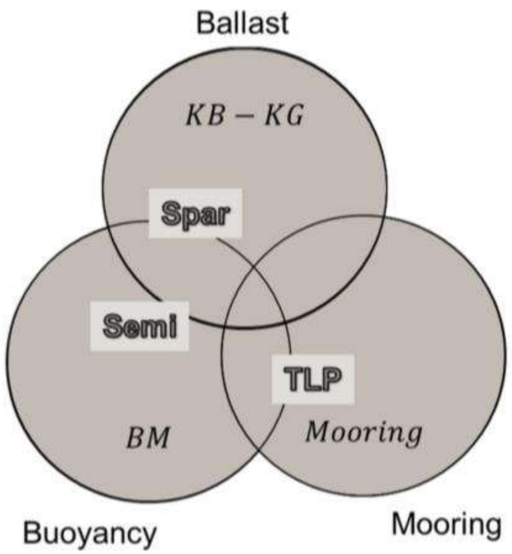
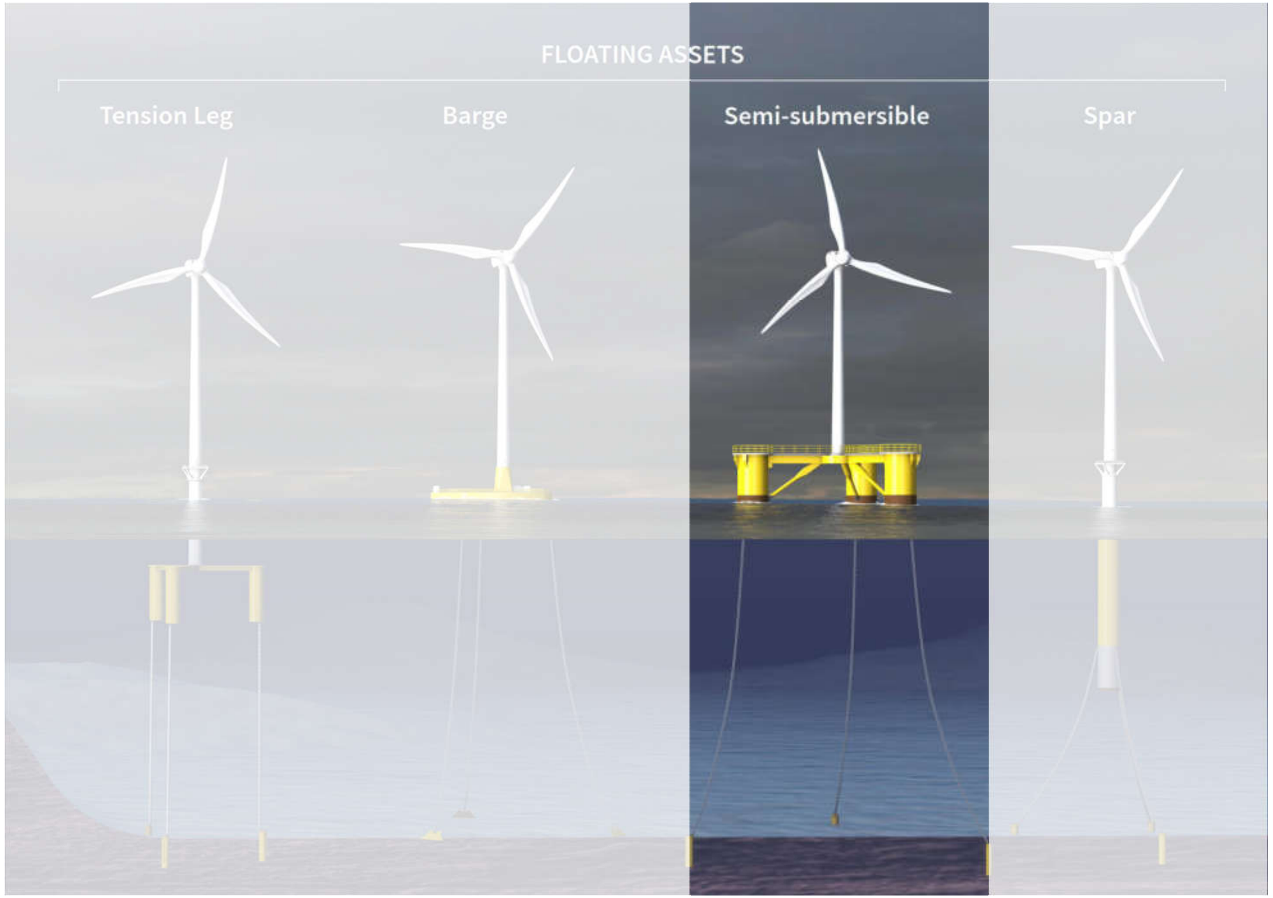
Floater stability: comparison

Semi: Hybrid buoyancy-ballast

- ✓ good compromise between barge and spar. Relatively shallow draft eases installation





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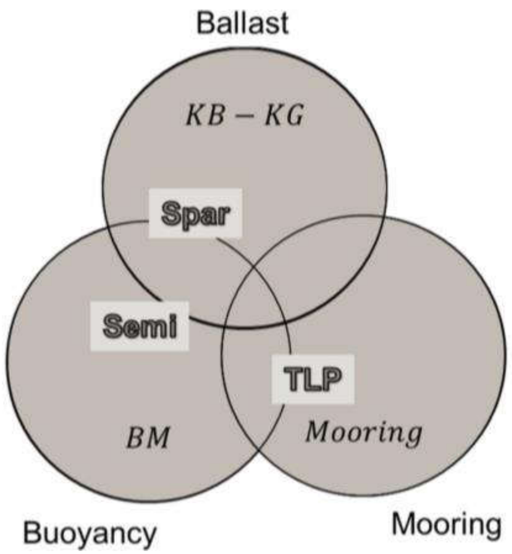
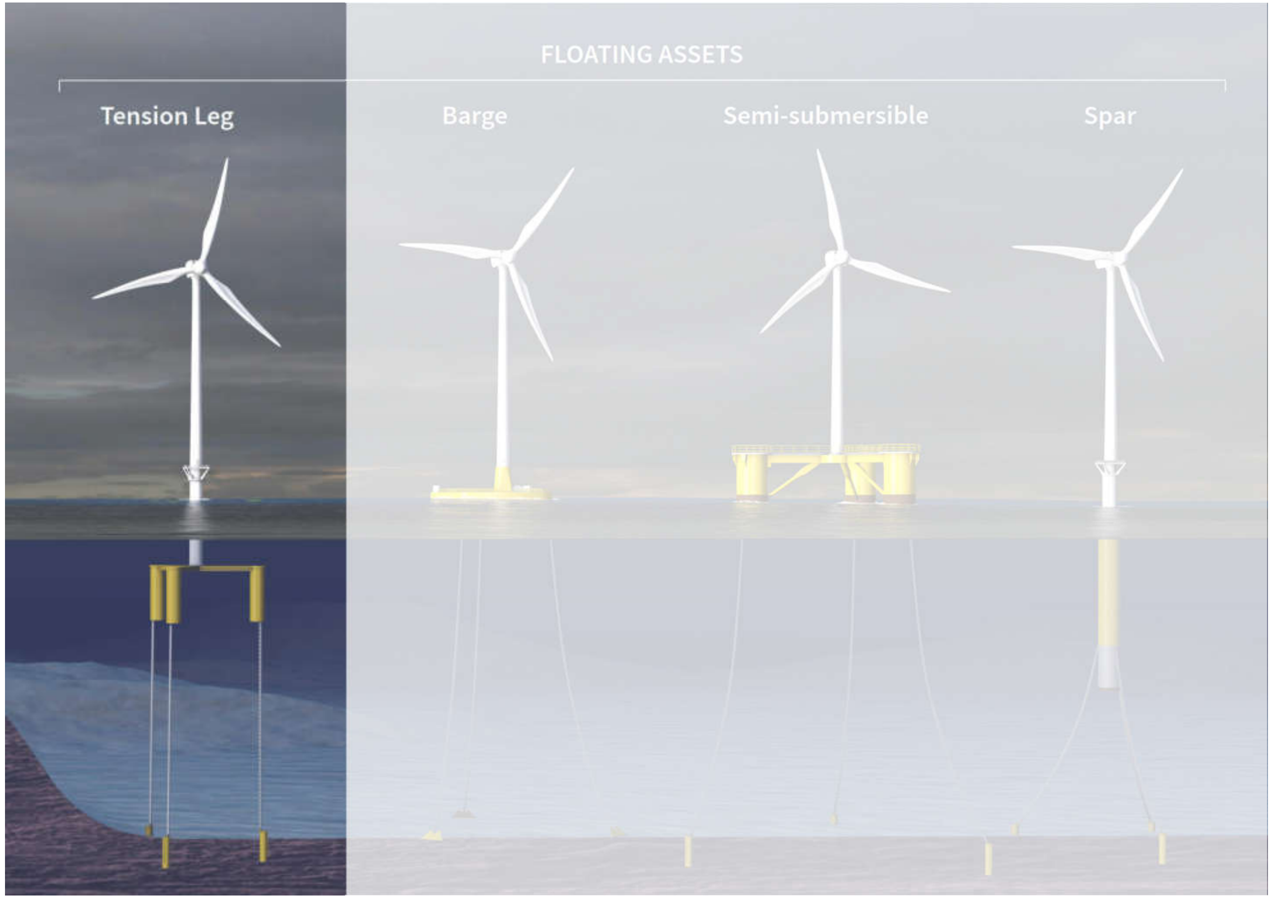
Floater stability: comparison

<u>TLP</u>: Mooring, mooring lines ensure stability

- ✓ very stable, almost bottom-fixed like. Designers must ensure that platform is stable even if one mooring line is lost





https://doi.org/10.1016/j.oceaneng.2024.118189

Degrees of Freedom

From the turbine perspective we can treat the platform as a 6-DOF rigid body

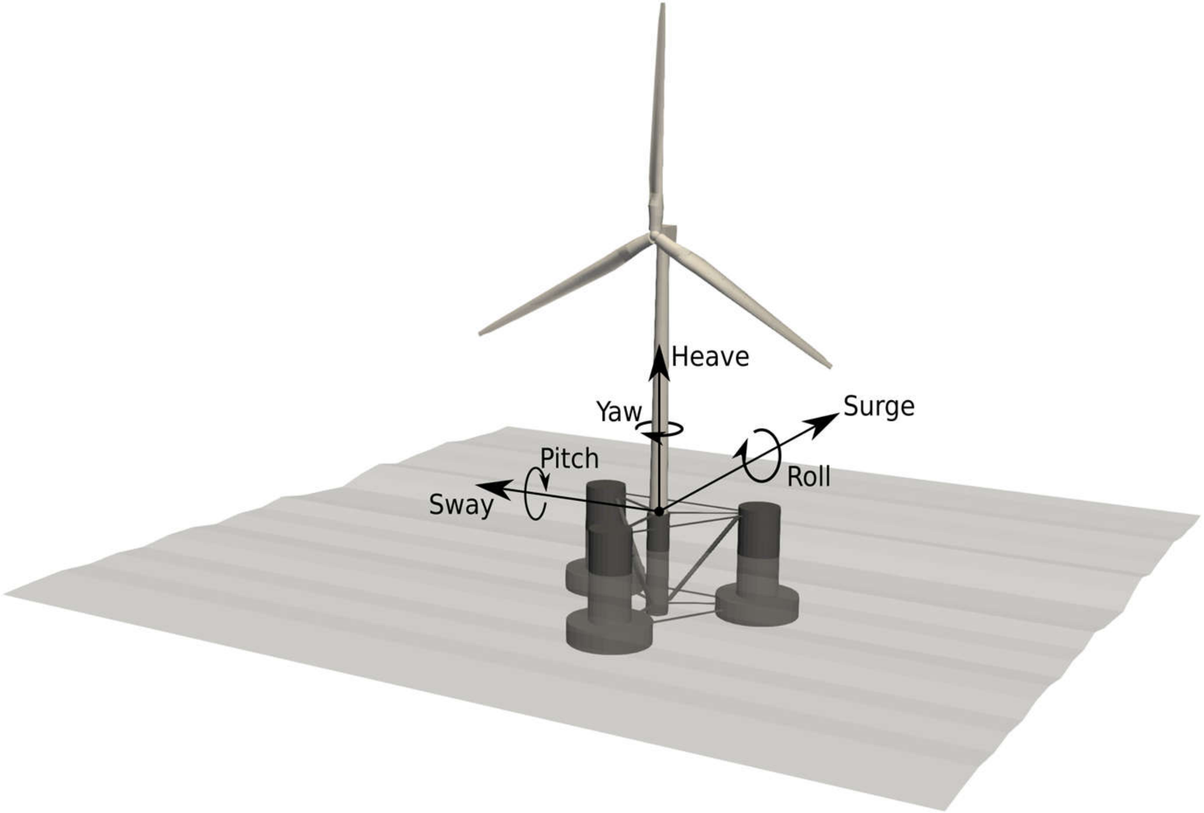
- ✓ 3 translations: Surge, Sway, Heave
- ✓ 3 rotations: Pitch, Roll, Yaw

<u>Platform grants stability in Heave, Pitch and Roll</u>

<u>Moorings stabilize Surge, Sway and Yaw</u>

- ✓ If there is no variation in submerged volume or “shape” of the submerged part of the structure, there is no restoring effect

In a TLP all DOFs are stabilized by moorings



Floater stability: Hydrostatic Forces

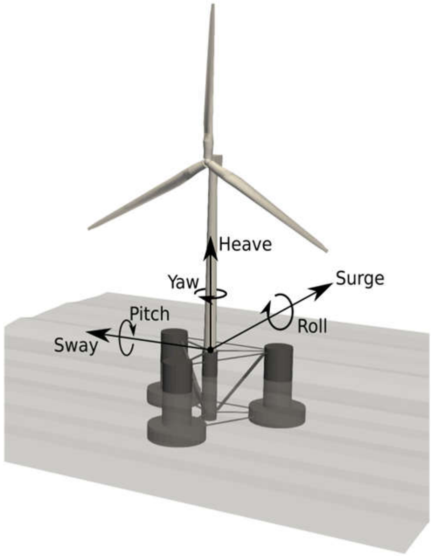
If we linearize our problem with respect to a give floater position, the restoring forces that the floater exerts on the structure can be written as:

$$F^{Hydrostatic} = C^{Hydrostatic} * \mathrm{u}$$

where u is the 6-DOF displacement of the platform and $C^{Hydrostatic}$ is the **hydrostatic stiffness:**

$$C_{ij}^{Hydrostatic} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \rho g A_0 & 0 & -\rho g \iint\limits_{A_0} x dA & 0 \\ 0 & 0 & 0 & \rho g \iint\limits_{A_0} y^2 dA + \rho g V_0 z_{COB} & 0 & 0 \\ 0 & 0 & -\rho g \iint\limits_{A_0} x dA & 0 & \rho g \iint\limits_{A_0} x^2 dA + \rho g V_0 z_{COB} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

Surge
Sway
Yaw

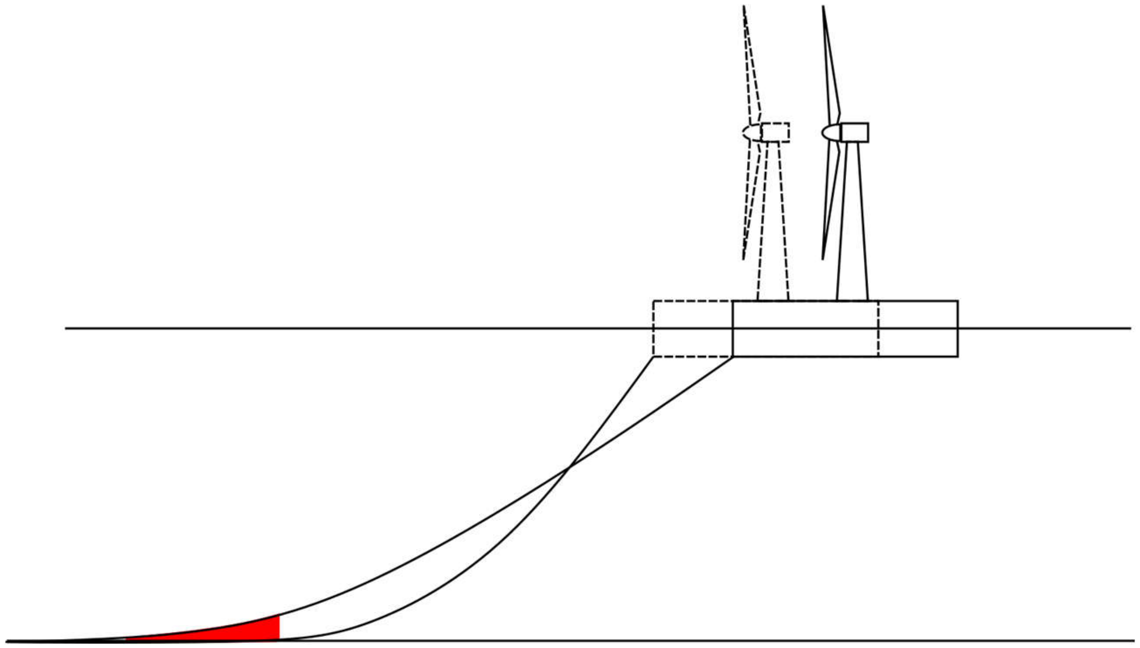


Mooring lines

Catenary moorings rest on the seabed. As the floater moves, it must lift the mooring line

- ✓ catenary (slack) mooring lines stabilize the position of the floater with their own weight

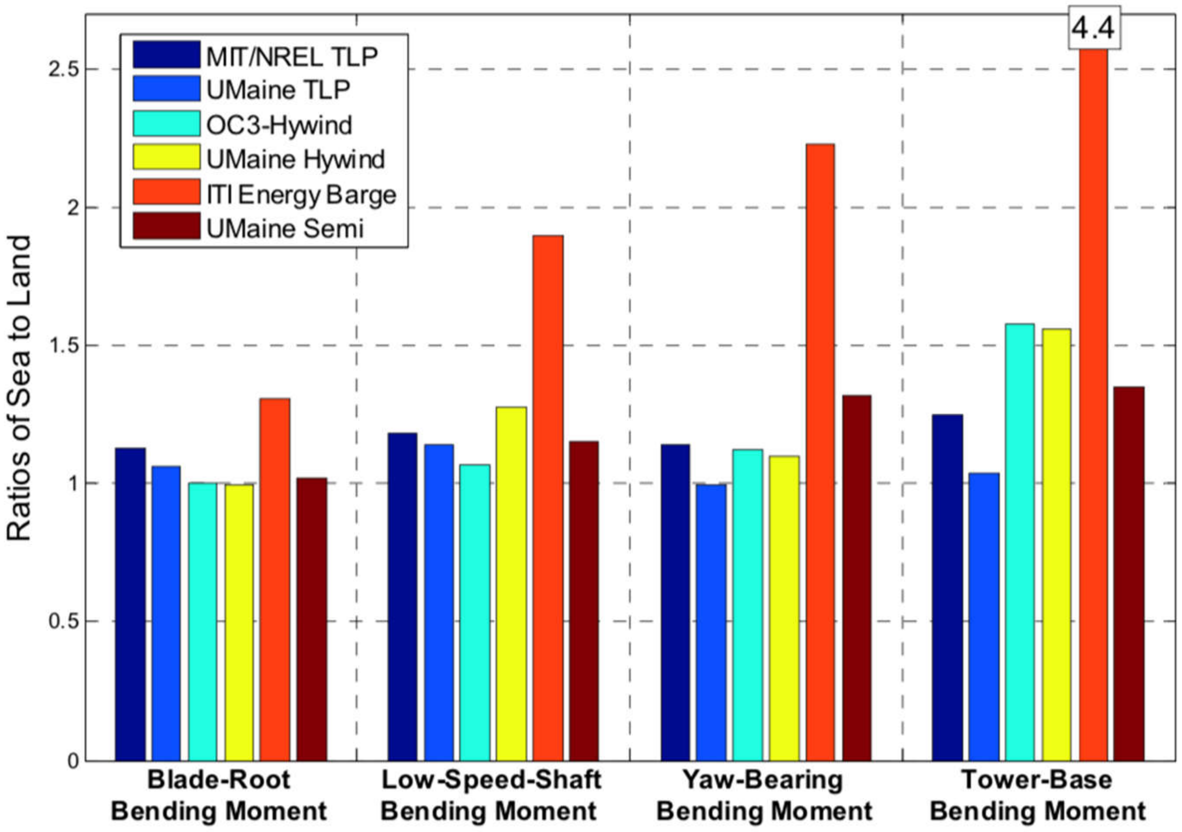
Taught mooring lines (used in TLPs) allow for less floater displacement but apply tension to the anchors, making their installation more difficult and costly.

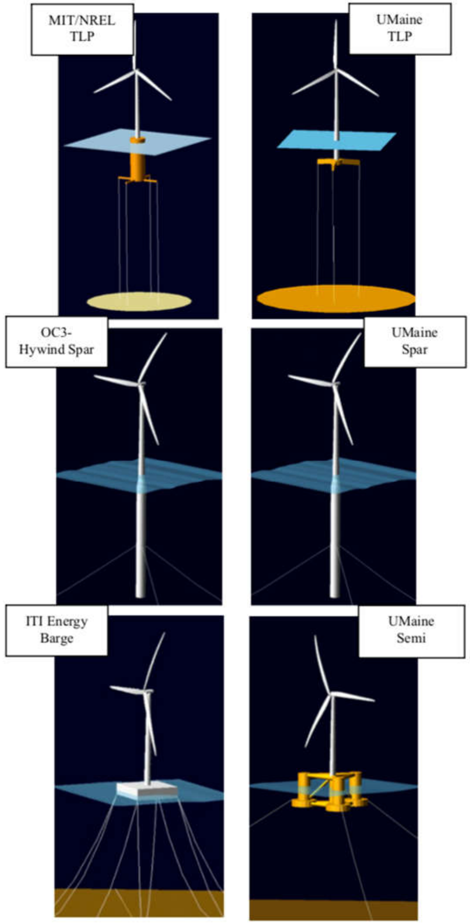


Load Increases

Floating installation increases loads:

- ✓ tower base is affected the most
- ✓ limited effect on blades
- ✓ different concepts behave differently
- ✓ increases are caused by additional gravitational and inertial loading

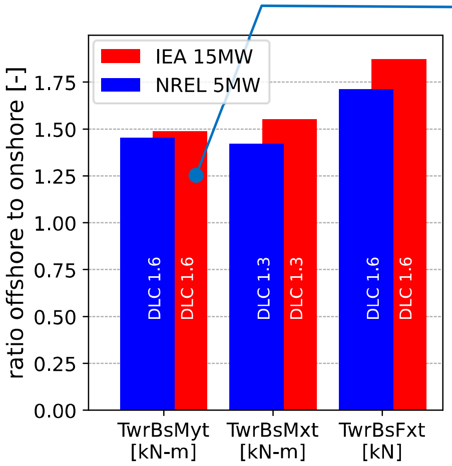


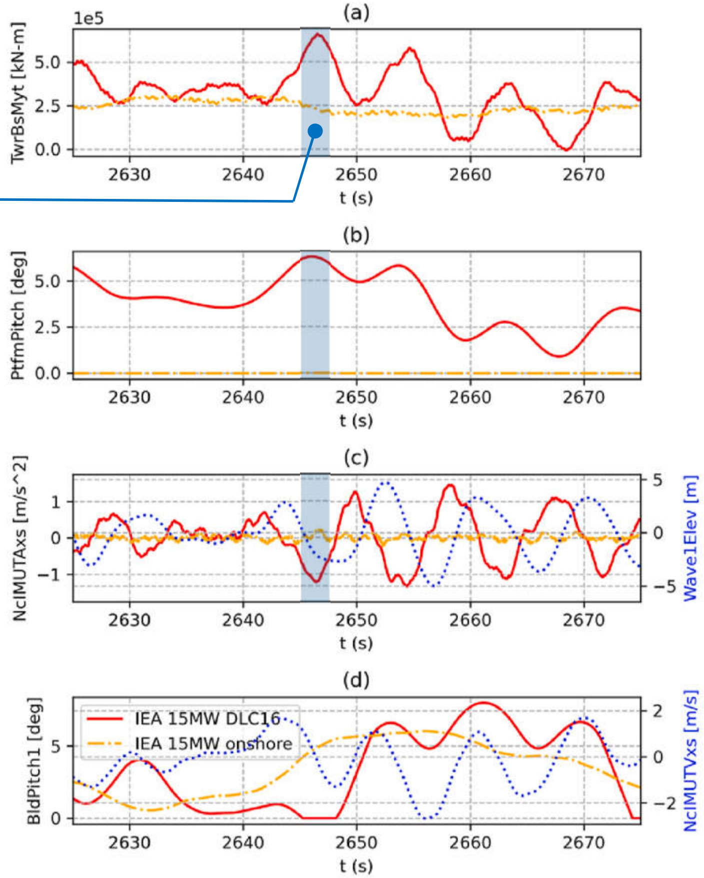


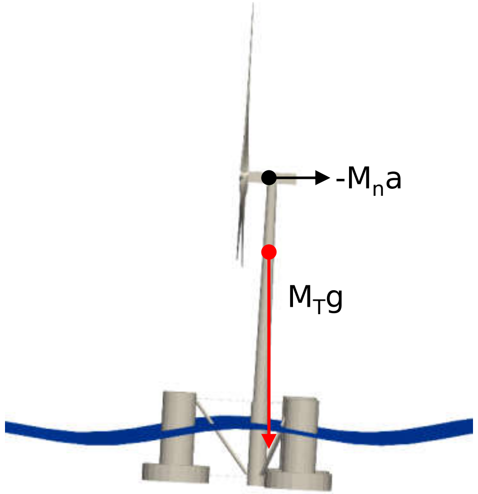
A. Robertson, J. Jonkman, Load Analysis of Several Floating Wind Turbine Concepts, *Presented at the International Society of Offshore and Polar Engineers 2011 Conference, Maui, Hawaii, June 19-24, 2011*

Why do lads increase ?

Platform movement causes additional gravitational and inertial loading







The same effects act on the blades, but…

- ✓ blades are comparatively light (65t in this case)
- ✓ aero loading is much larger than gravitational and inertial

Differences in Tower Stiffness

Fixed-bottom tower natural frequencies (ω_n) typically in soft-stiff region

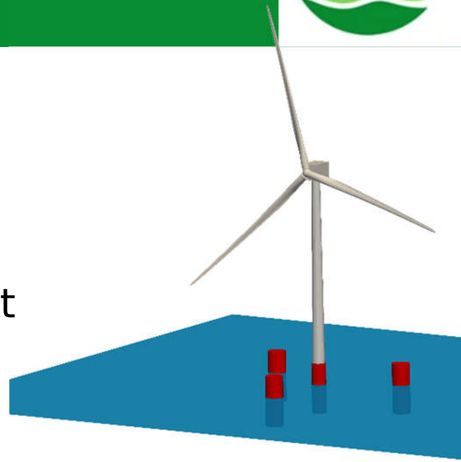
In FOWTS this is hard

- ✓ apparent tower "stiffening" due to floating installation
- ✓ larger 1P and 3P bands due to unsteadiness

FOWT towers are usually stiff-stiff

- ✓ Safer design for 1st generation FOWTs

IEA 15MW RWT:
fixed-bottom: 500t → FOWT: 1300t



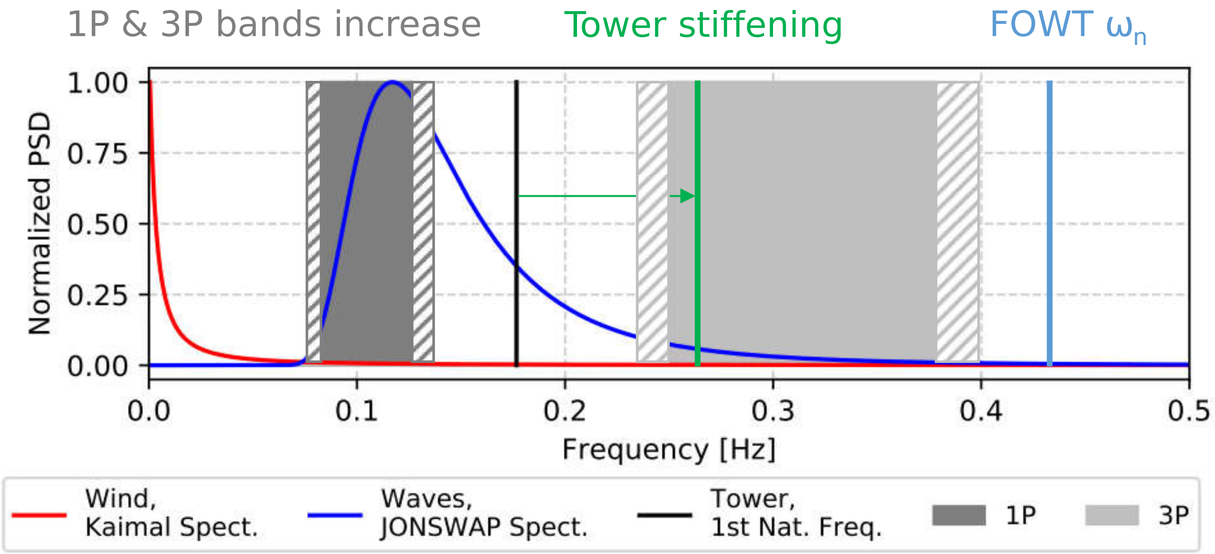
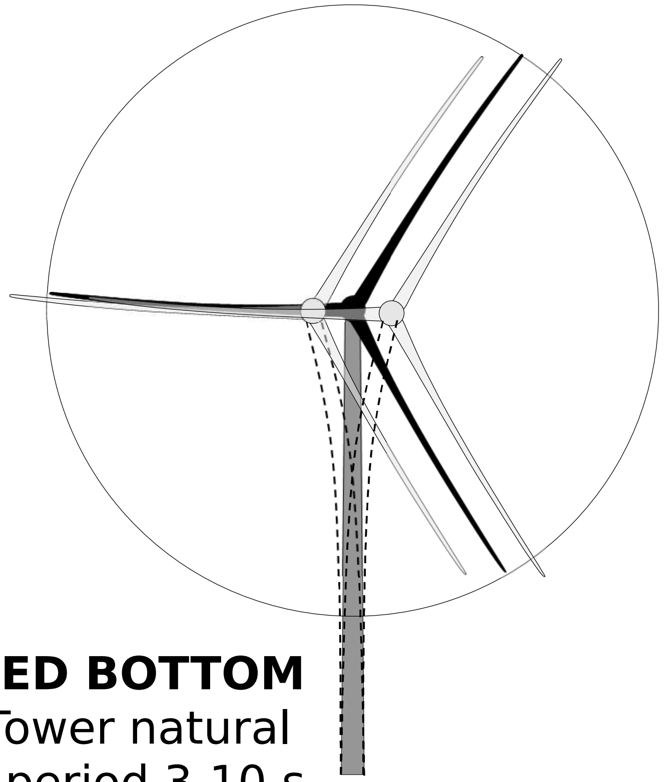


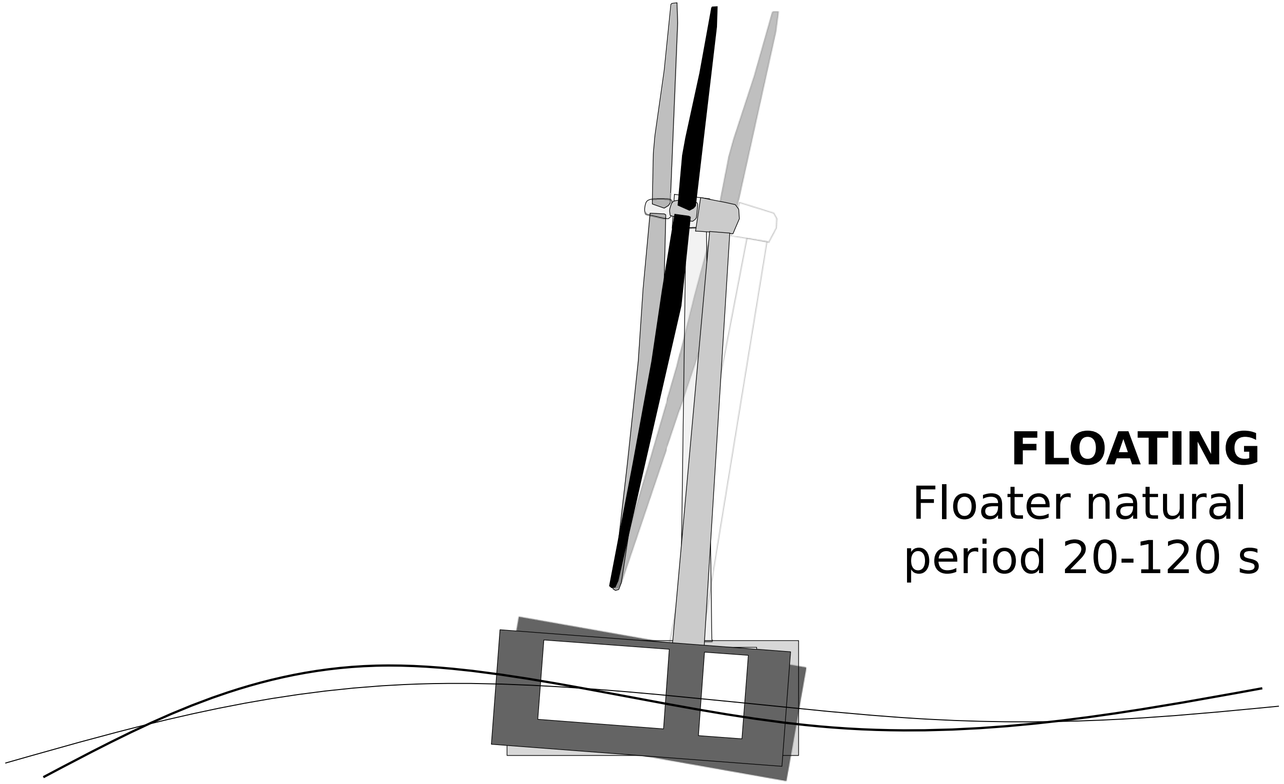
Image from: Gaertner, Evan, Jennifer Rinker, Latha Sethuraman, Frederik Zahle, Benjamin Anderson, Garrett Barter, Nikhar Abbas, Fanzhong Meng, Pietro Bortolotti, Witold Skrzypinski, George Scott, Roland Feil, Henrik Bredmose, Katherine Dykes, Matt Shields, Christopher Allen, and Anthony Viselli. 2020. *Definition of the IEA 15-Megawatt Offshore Reference Wind*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5000-75698.

Tower stiffness – why?

When a turbine is floating the lowest natural frequencies of the structure are not tower oscillations.



FIXED BOTTOM
Tower natural period 3-10 s



FLOATING
Floater natural period 20-120 s

Modeling

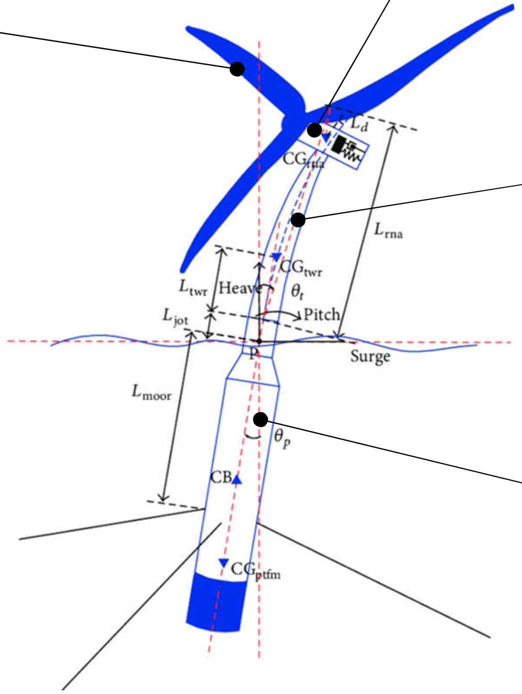
Fully coupled dynamics

AERODYNAMICS

CONTROL

STRUCTURAL DYNAMICS & MOORINGS

TURBULENT WIND



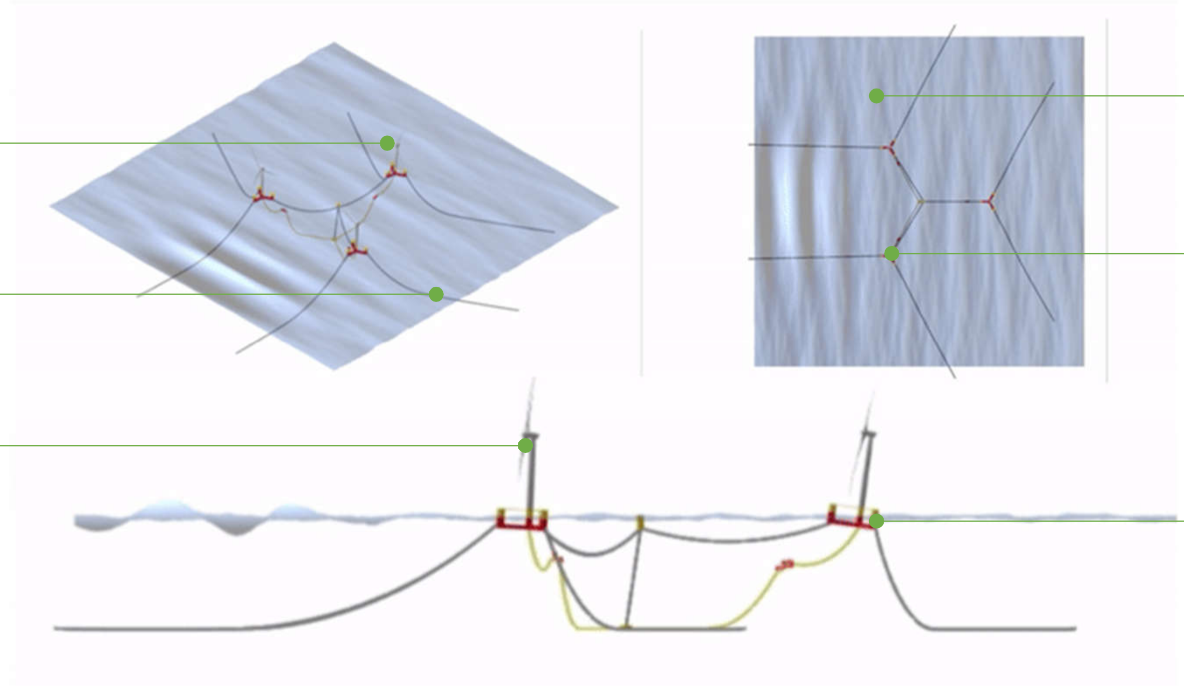
HYDRODYNAMICS
Potential flow
Strip theory

WAVES
1^{st} & 2^{nd} order

Si et al., Modeling and Parameter Analysis of the OC3-Hywind Floating Wind Turbine with a Tuned Mass Damper in Nacelle

Fully coupled dynamics

Coupled physiscs need to be solved simultanously, especially **offshore**



https://www.linkedin.com/posts/qblade_a-simulation-of-a-constrained-45m-wave-impacting

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