



Cyprus, 03/09/2025

Offshore Wind Energy

Prof. Alessandro Bianchini

Università degli Studi di Firenze, Italy



A few info on this lecture



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[alessandro-bianchini-607b167](https://www.linkedin.com/in/alessandro-bianchini-607b167)



Alessandro Bianchini, PhD

*Associate Professor, University of Florence
Vice President, EAWE*

Applied Research for Energy Systems (ARES) Research Group
Department of Industrial Engineering, University of Florence
Via di Santa Marta 3, 50139 Florence, Italy
E-mail alessandro.bianchini@unifi.it

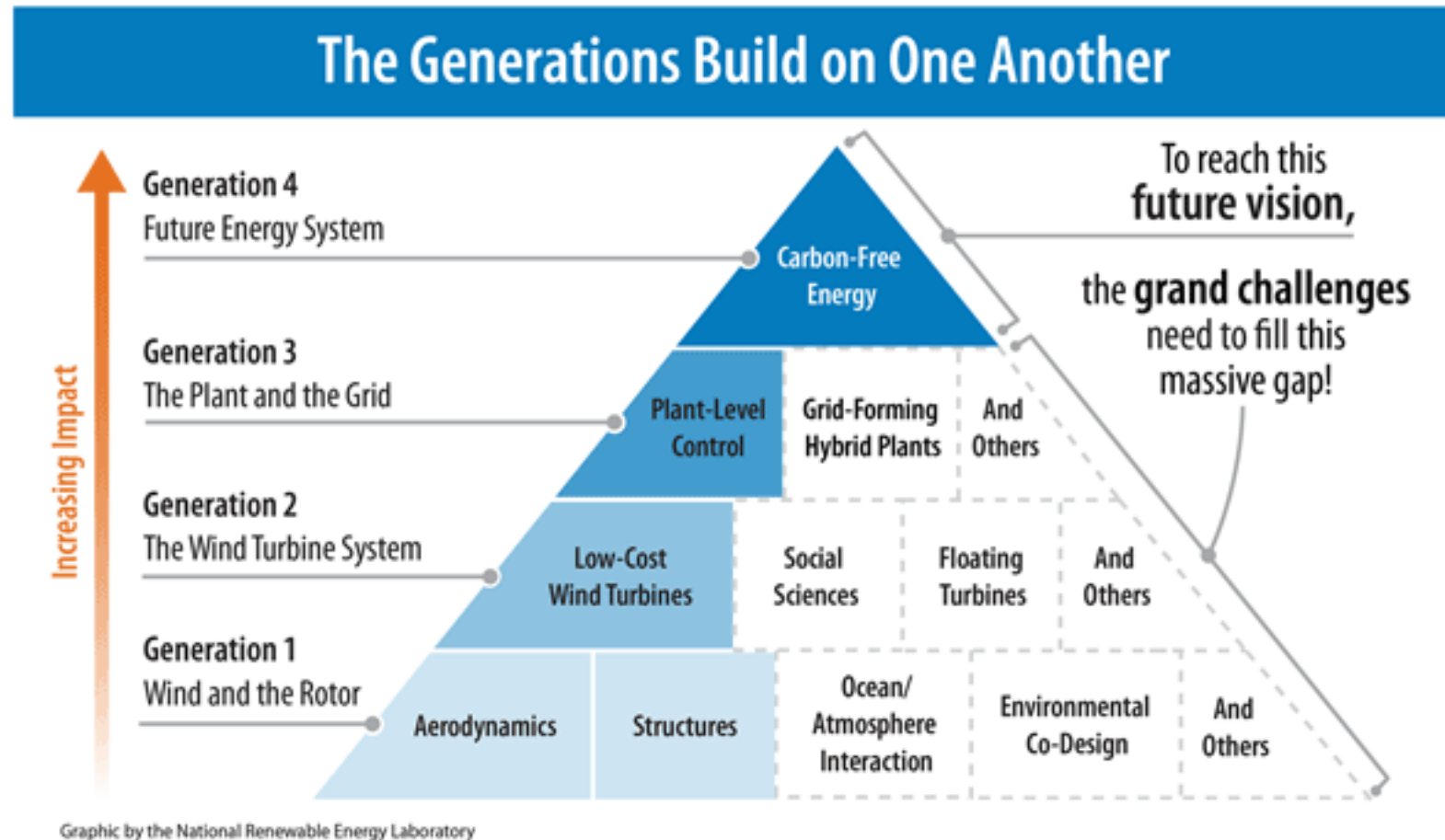
Phone +39 055 275 8773 (Office) + 39 055 275 8764 (Laboratory)

Agenda



- Introduction to offshore wind
- Metocean conditions
- Offshore wind turbines
- The Mediterranean Sea
- Offshore wind farms
- Hands-on exercise

The Veer's pyramid: wind energy still needs research



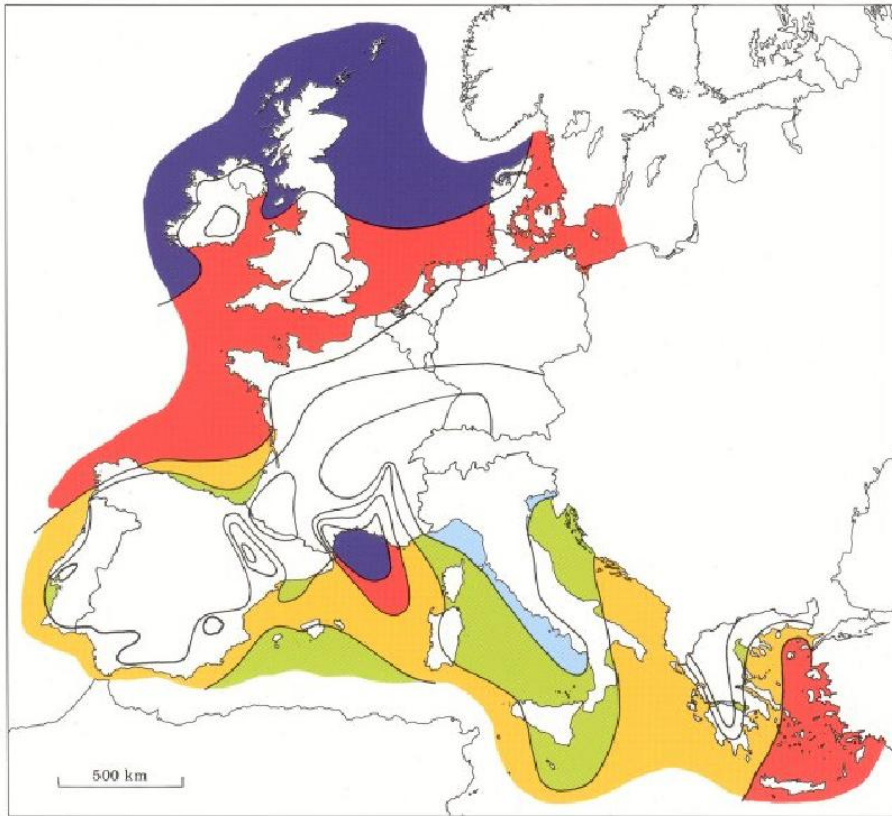
Veers, P., et al., 2023, "Grand Challenges: wind energy research needs for a global energy transition", Wind Energy Science, DOI: 10.5194/wes-7-2491-2022



1

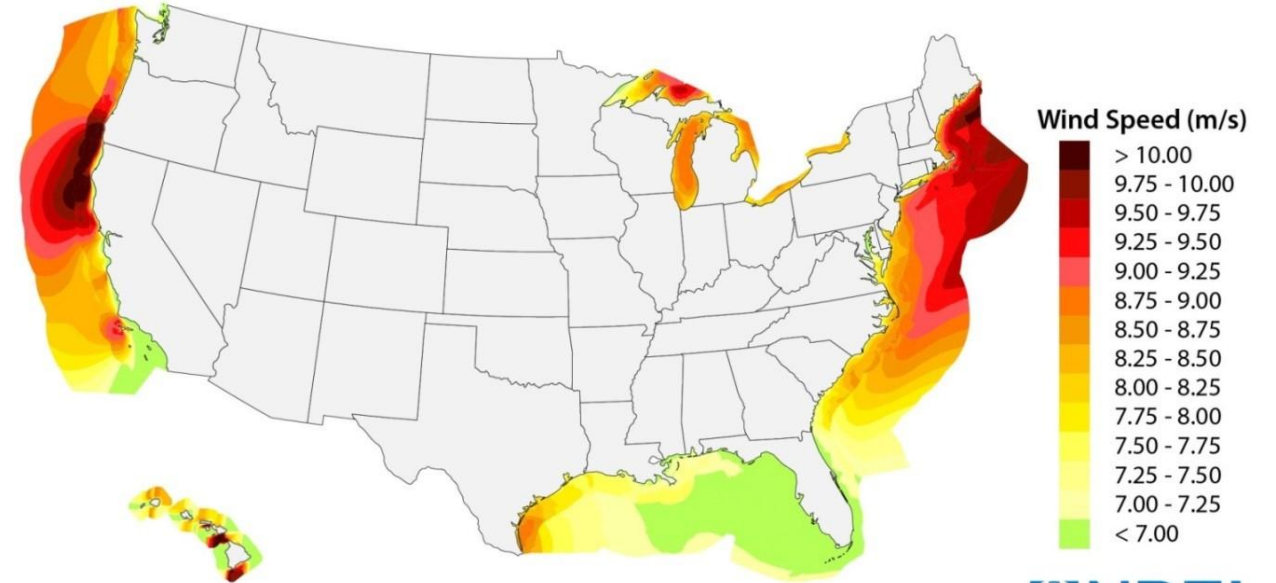
Offshore wind

Offshore wind: an unprecedented opportunity

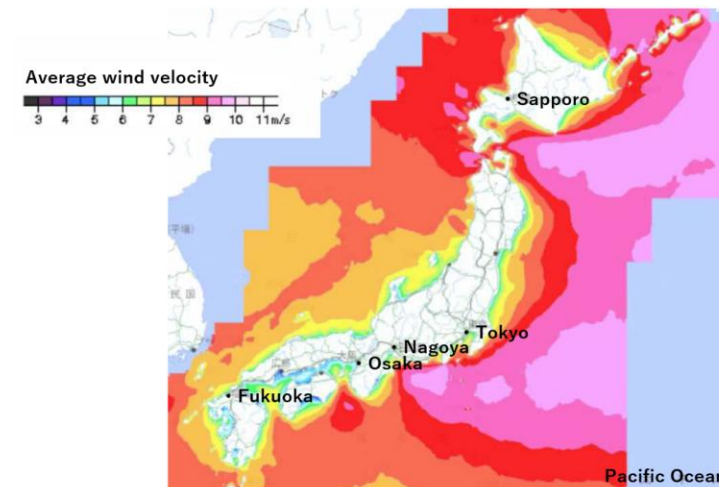


Wind resources over open sea (more than 10 km offshore) for five standard heights

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



Data Source: AWS Truepower 0-50nm; NREL WIND Toolkit beyond 50nm.



Floating is not an option, it is a necessity



About 80% of global offshore wind energy potential will require floating support structures

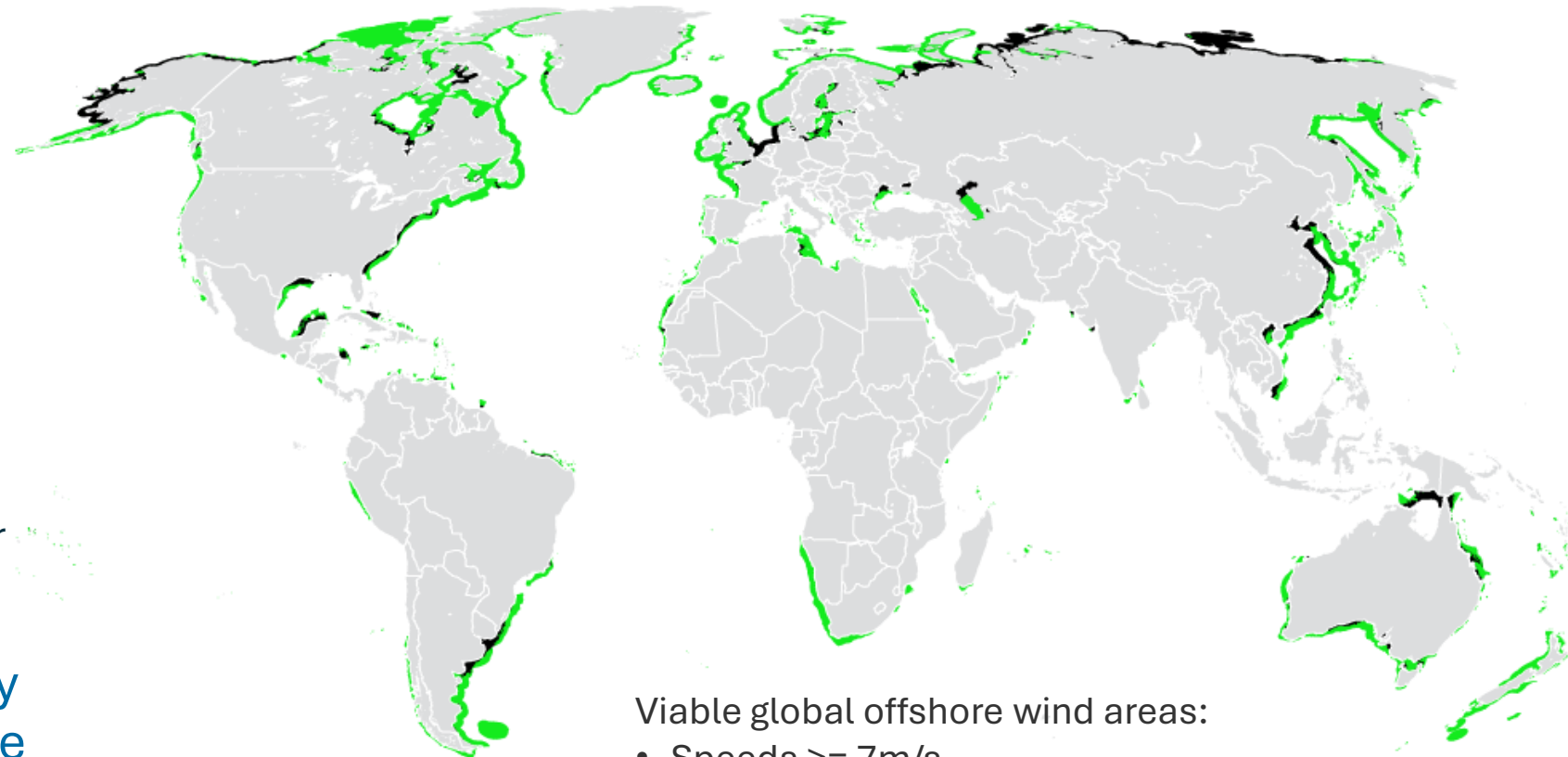
- ✓ waters deeper than 60-m

Fixed bottom ocean space is already becoming scarce

- ✓ floating wind enables sites farther from shore, out of sight, with better winds

The future floating wind energy market may be bigger than the fixed-bottom market

■ Floating (> 60 m depth) ■ Fixed-Bottom



Viable global offshore wind areas:

- Speeds $\geq 7\text{m/s}$
- Within 55km and 200km from shoreline

Image from: <https://www.bloomberg.com/news/features/2020-06-05/floating-wind-farms-could-supply-the-world-s-electricity-by-2040>

Wind megatrends (by WindEurope)



Offshore wind: highlights

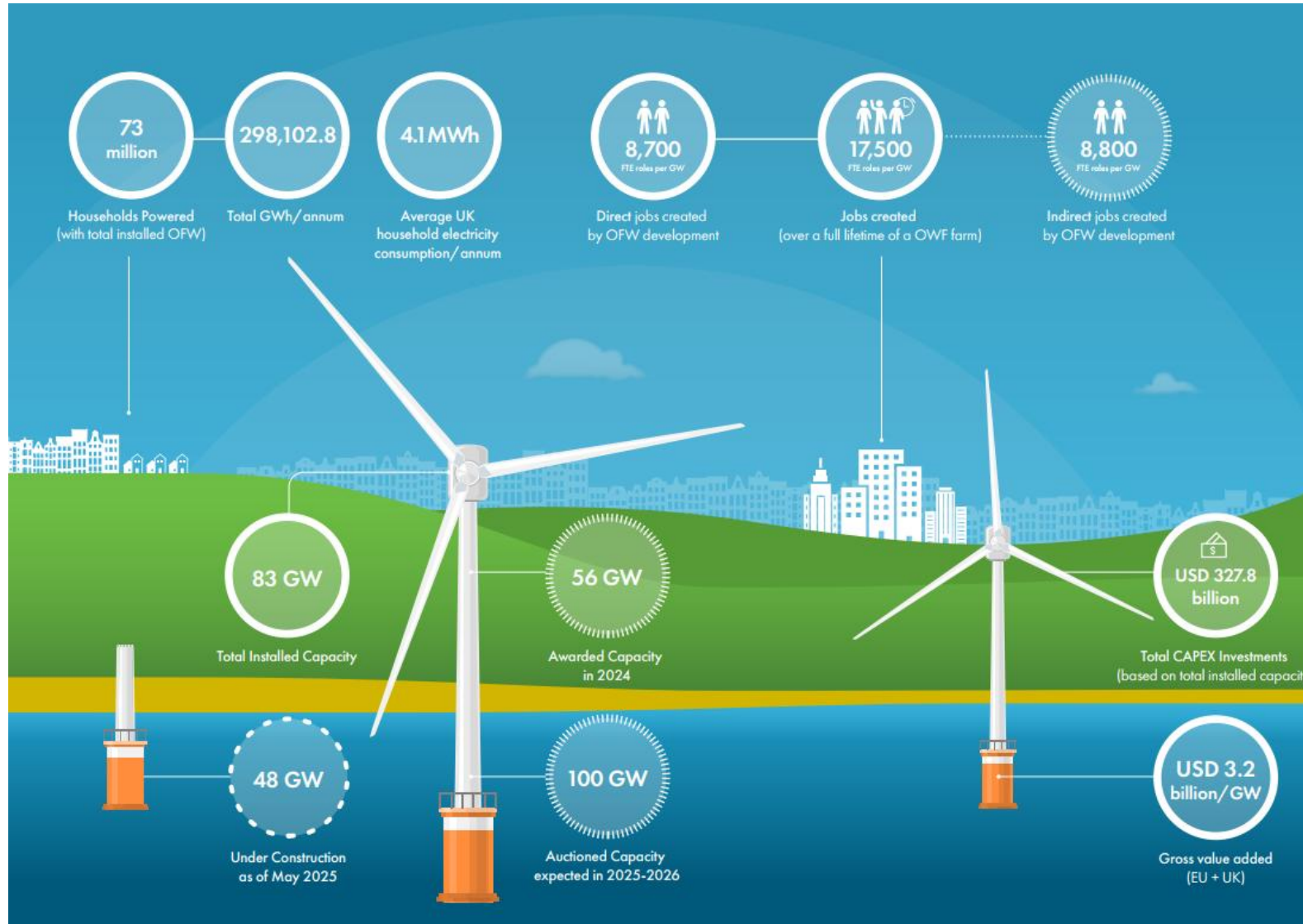


- Global installed offshore wind: ~83 GW by end-2024 (GWEC, 2025 report)
- 2024 additions: ~8 GW; 4th-highest year on record, but -26% wrt to 2023 (GWEC)
- 2030 outlook: ~212 GW installed globally; China ~50% of growth (IEA 2024)
- US first large-scale projects reached operation in 2024
 - ✓ more in the pipeline, but the new US administration is changing the scenario



Data mainly based on GWEC Global Offshore Wind Report 2025 (news release, 25 Apr 2025)

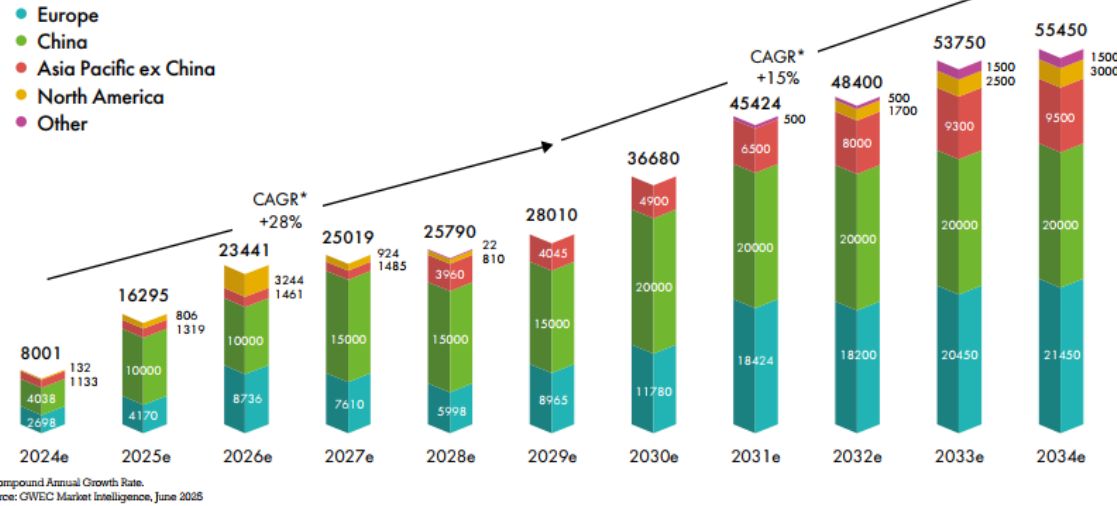
Offshore wind by numbers



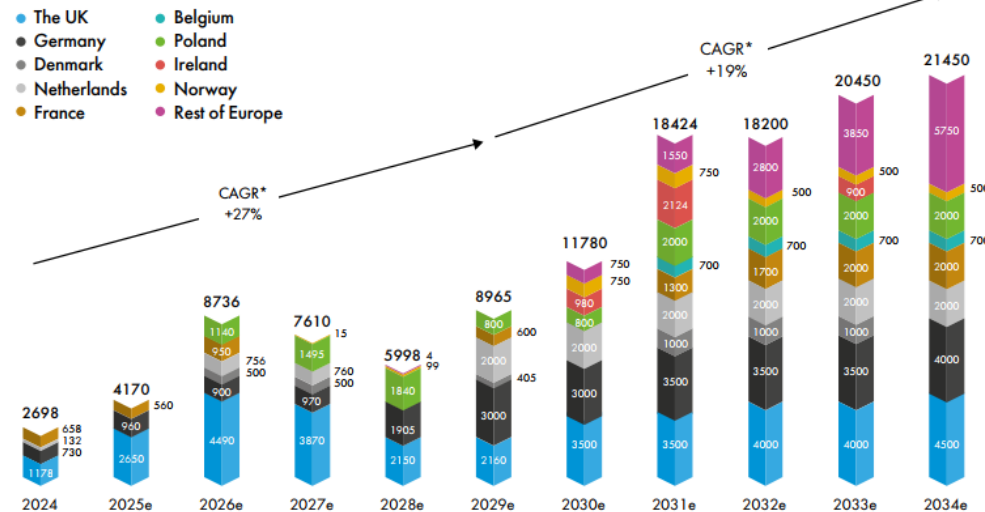
Trends: world and Europe



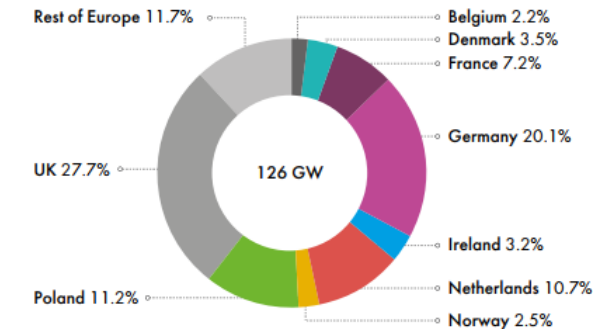
New offshore wind installations, global (MW)



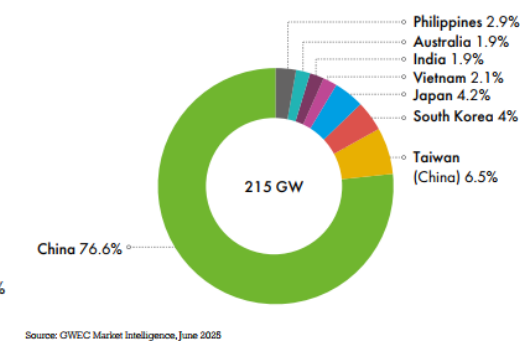
New offshore wind installations, Europe (MW)



Total offshore wind added between 2025 and 2034



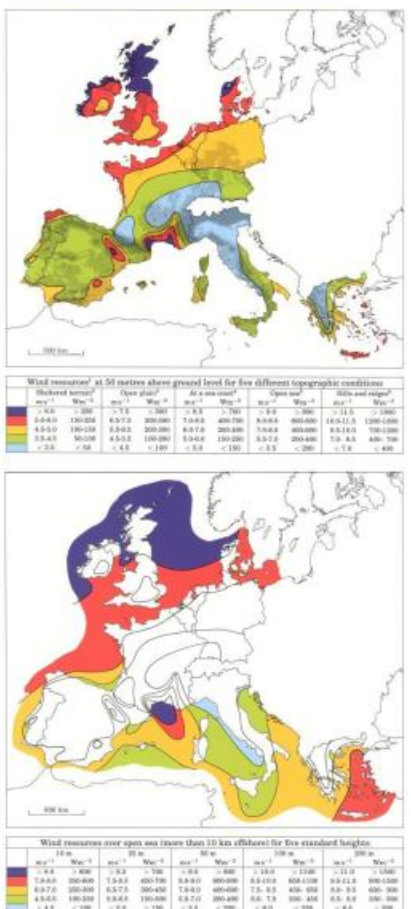
Total offshore wind added between 2025 and 2034



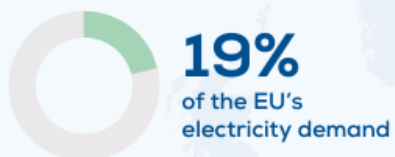
Trends: world and Europe



Wind resource in Europe



The EU's wind energy generation 2023



17%
of EU electricity demand met by onshore wind

24%
average onshore wind capacity factor*

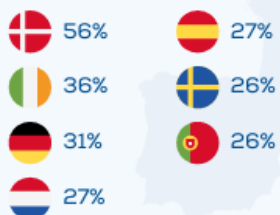
466 TWh
EU wind energy generation



2%
of EU electricity demand met by offshore wind

34%
average offshore wind capacity factor*

Highest wind energy shares



22 December
Record in wind production

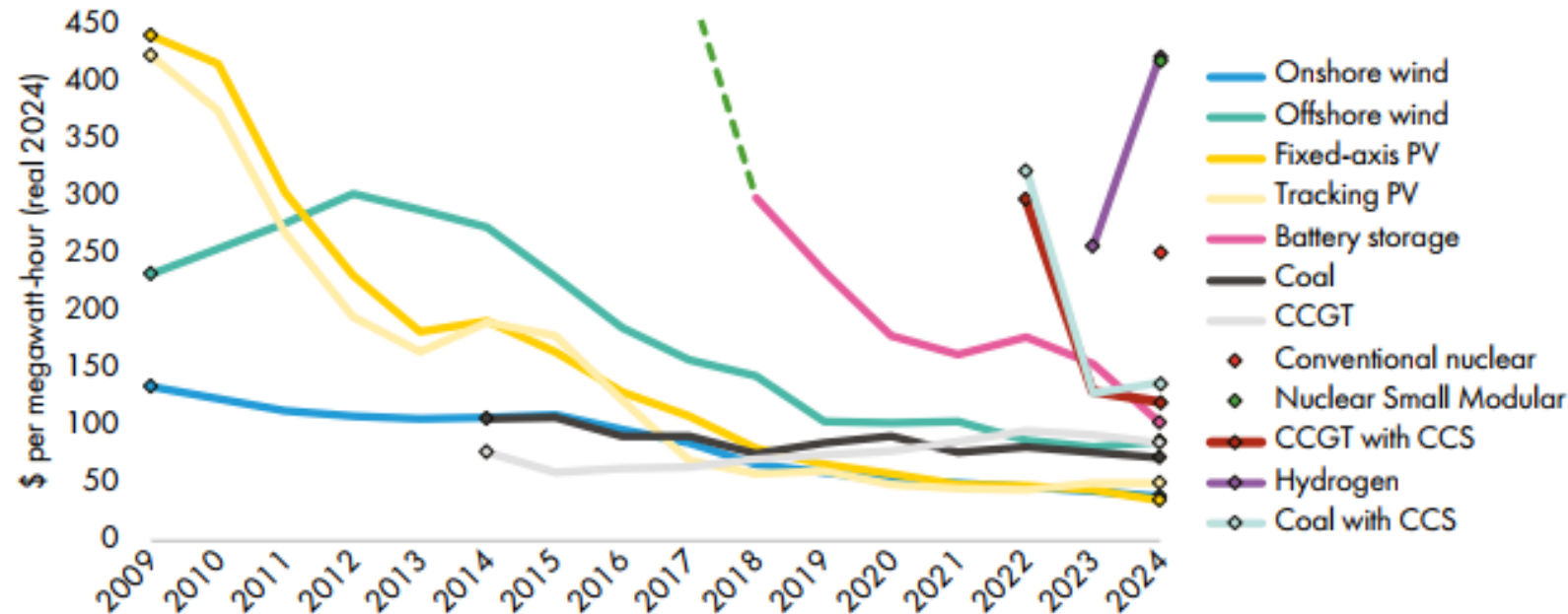


*Capacity factors of entire fleet including old turbines

LCOE of offshore wind (mainly bottom-fixed)

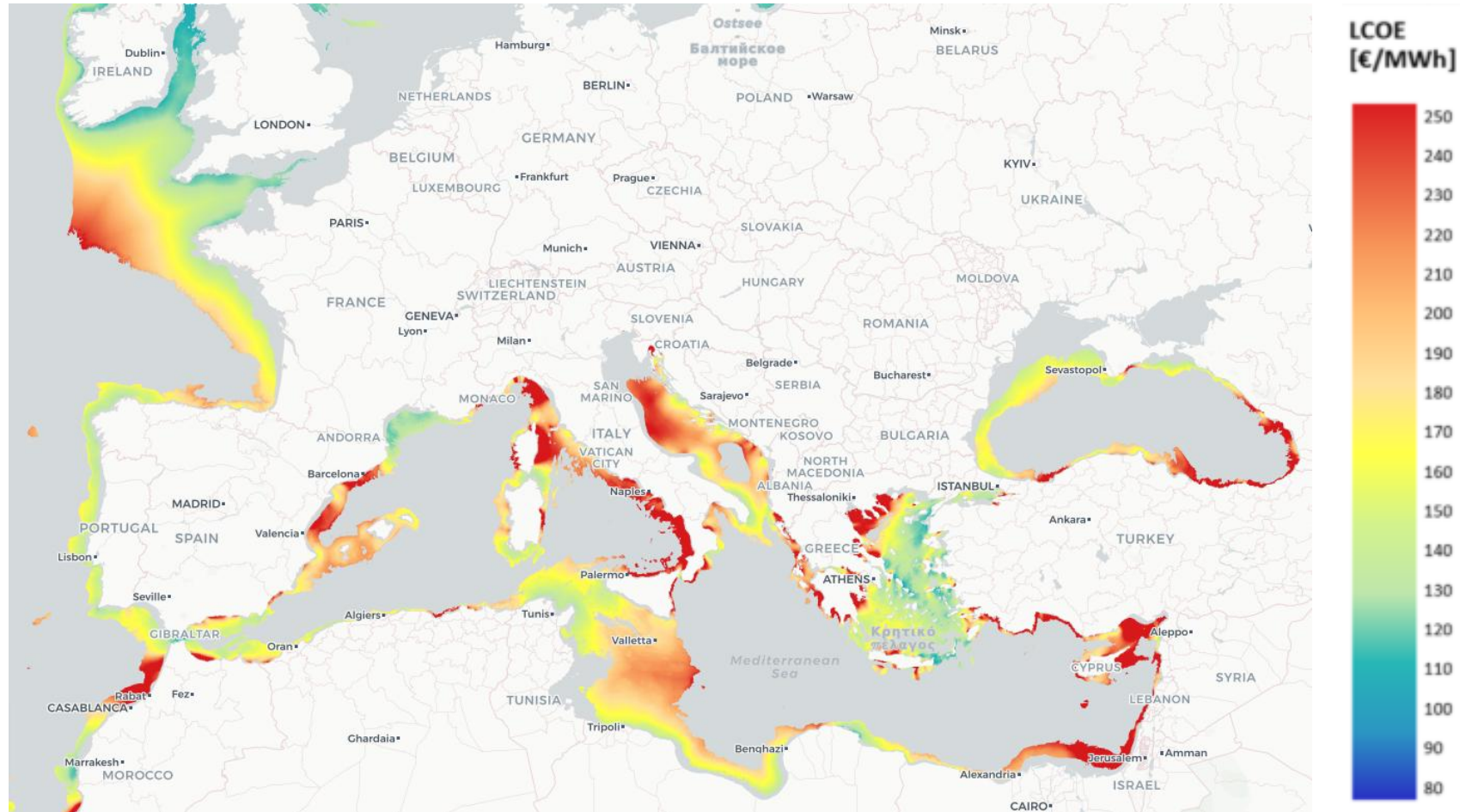


LCOE Benchmark



- Bottom-fixed LCOE (2024): ~55–120 €/MWh (DK/DE/NL/FR ranges)
- Recent inflation and rates pressured project economics made within 02021–2024
- Longer-tenor CfDs (e.g., UK 20 years) aim to reduce financing cost
- Auction strike prices adjusted upward in 2025 (UK AR7 guidance)

LCOE of floating (expected for today's projects)

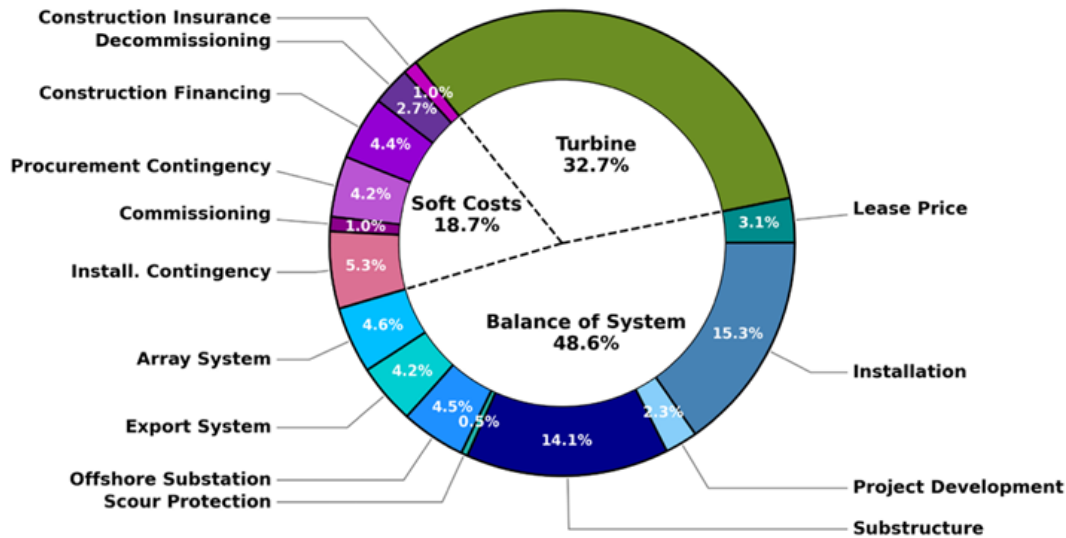


Floating wind remains higher cost but on a learning curve (source, NREL)

Different environment, new challenges



Fixed-Bottom Offshore Wind System CapEx Component Cost Breakdown



Parameter	Value (2023\$/kW)
Turbine	1,770
BOS	2,629
Array system	251
Export system	227
Offshore substation	243
Scour protection	25
Substructure	764
Project development	123
Installation	830
Lease price	167
Soft Costs	1,012
Construction insurance	55
Decommissioning	145
Construction financing	240
Procurement contingency	228
Commissioning	55
Install. contingency	289
Total CapEx	5,411

NREL

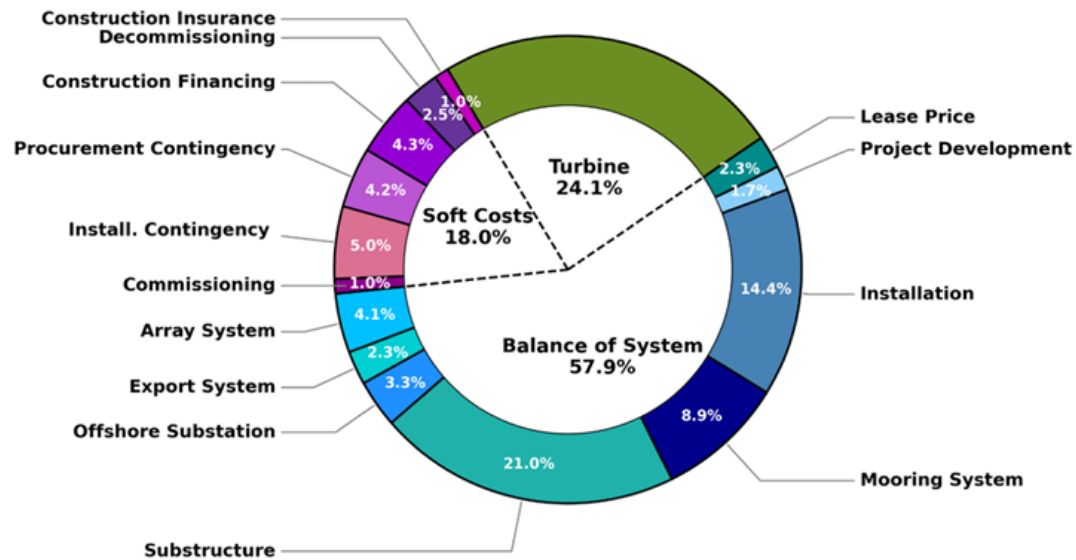


BOS and soft cost estimates are obtained with the Offshore Renewables Balance of System and Installation Tool (ORBIT) (Nunemaker et al. 2020). Refer to <https://github.com/WISDEM/ORBIT>. Note: Values rounded to the nearest dollar, and "Install." indicates installation.

Different environment, new challenges



Floating Offshore Wind System Component Cost Breakdown



Parameter	Value (2023\$/kW)
Turbine	1,770
BOS	4,254
Array system	301
Export system	171
Offshore substation	243
Substructure	1,541
Mooring system	651
Installation	1,058
Project development	123
Lease price	167
Soft Costs	1,325
Construction insurance	74
Decommissioning	184
Construction financing	319
Procurement contingency	307
Install. contingency	368
Commissioning	74
Total CapEx	7,349

NREL



BOS and soft cost estimates are obtained with ORBIT (Nunemaker et al. 2020). Refer to

<https://github.com/WISDEM/ORBIT>.

Note: Values rounded to the nearest dollar, and "Install." indicates installation.

Critical overlook: we are at a crossing point



Since first offshore WTs installed in 1991 in Denmark, offshore wind has been a story of success

Despite the growing strategic importance of offshore wind, the sector now faces a perfect storm of macroeconomic factors, geopolitical tensions and industry specific challenges

- ✓ the pipeline of development has been inconsistent and uncertain, resulting in a lack of effective investment signals
- ✓ In 2024, new installations totaled 8 GW – down 26% wrt to 2023 and -24% in the short-term forecast for 2025

Main issues

- ✓ slow permitting
- ✓ poor auction design in mature markets (failures seen in DK and UK)
- ✓ increasing policy instability in some markets (US)
- ✓ grid transmission delays in the EU



Suggested critical actions for the future (1/2)



1. Redefining auctions

- ✓ better risk sharing, based on collaborative government-industry effort to ensure clarity over auction volumes and pipelines
- ✓ using mechanisms such as two-sided Contracts for Difference (CfDs), which help balance risk by providing long-term predictable revenues to developers and investors

2. Fast-tracking permitting

- ✓ governments must enact clear deployment mandates, centralize permitting reviews, embed “overriding public interest” in national law and facilitate early stakeholder engagement

3. Making finance fit for purpose (high CAPEX)

- ✓ encourage lenders to provide longer-tenor loans, more flexible repayment schedules and inflation indexed revenue contracts
- ✓ multilateral development banks should support initial projects in EMDEs through concessional capital



Suggested critical actions for the future (2/2)



4. Strengthening supply chains through cooperation and standardization

- ✓ regional trade and industrial policy coordination to balance supply chain efficiency, sustainability and resilience

5. Enabling grid and transmission readiness

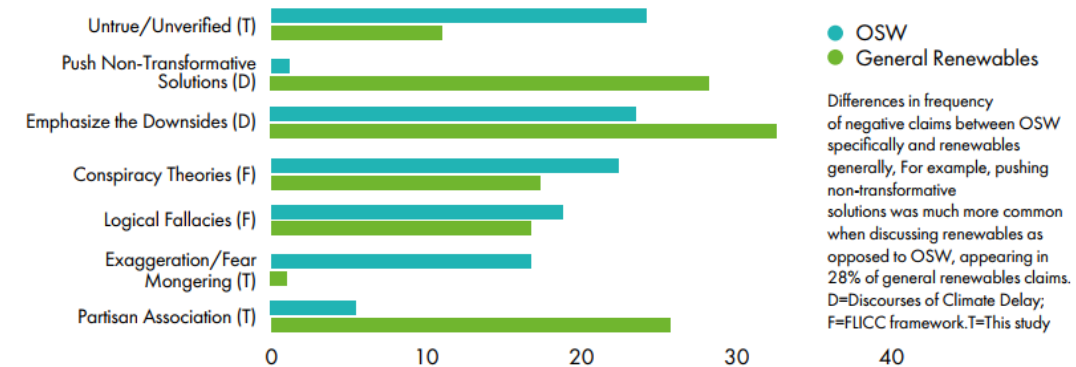
- ✓ delays in grid development risk derailing deliver projects that are even auctioned, permitted and ready to build
- ✓ adopting anticipatory, centralized grid planning – as seen in Germany – for de-risked investments
- ✓ defining clear grid connection responsibilities and aligning offshore hubs with future interconnection needs

6. Reclaiming the public narrative on offshore wind energy

- ✓ misleading claims about offshore wind have proliferated, swaying public opinion and complicating project development



Frequency of Negative Claims About Offshore Wind in U.S. Congress⁴⁸



Source: Brown University Climate & Development Lab, "Spinning Negativity Discourses of Delay on Offshore Wind in the 118th Congress," Feb 2024, <https://drive.google.com/file/d/1OUC27FPi37fxcETotueXKN5-TaNO06BP/view>



2

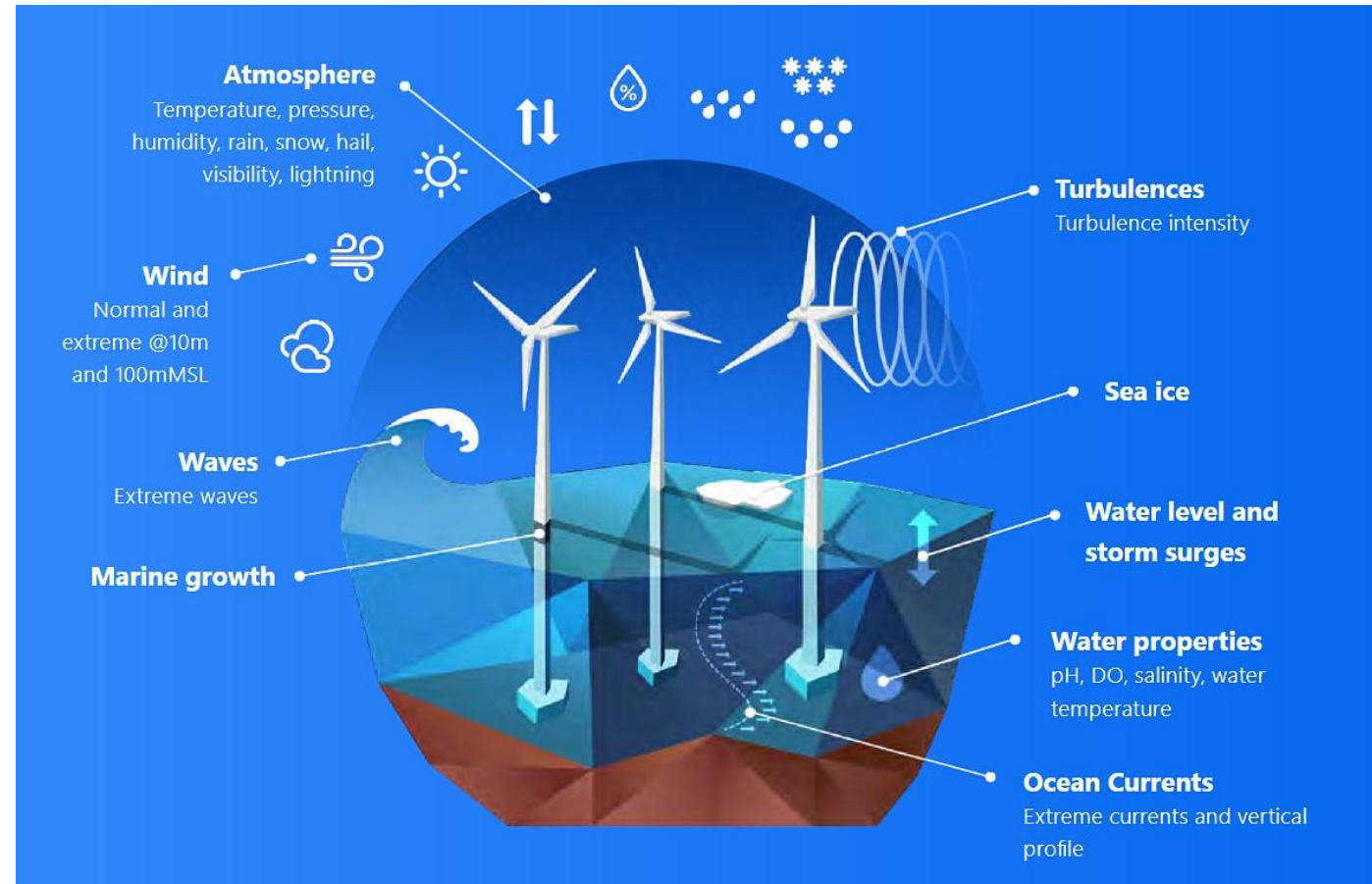
Metocean conditions

The ocean environment



As any other offshore structure, offshore wind turbines are subject to complex **metocean conditions**, i.e., combinations of different meteorological and oceanographic conditions

- ✓ local surface wind
- ✓ wind-generated local waves
- ✓ swell (long-period waves) generated by distant storms
- ✓ surface current generated from local storms
- ✓ energetic deep water currents associated with low frequency, large basin circulation
- ✓ non-storm-related currents, which are site-specific, such as loop current in the Gulf of Mexico
- ✓ water properties



Atmospheric stability



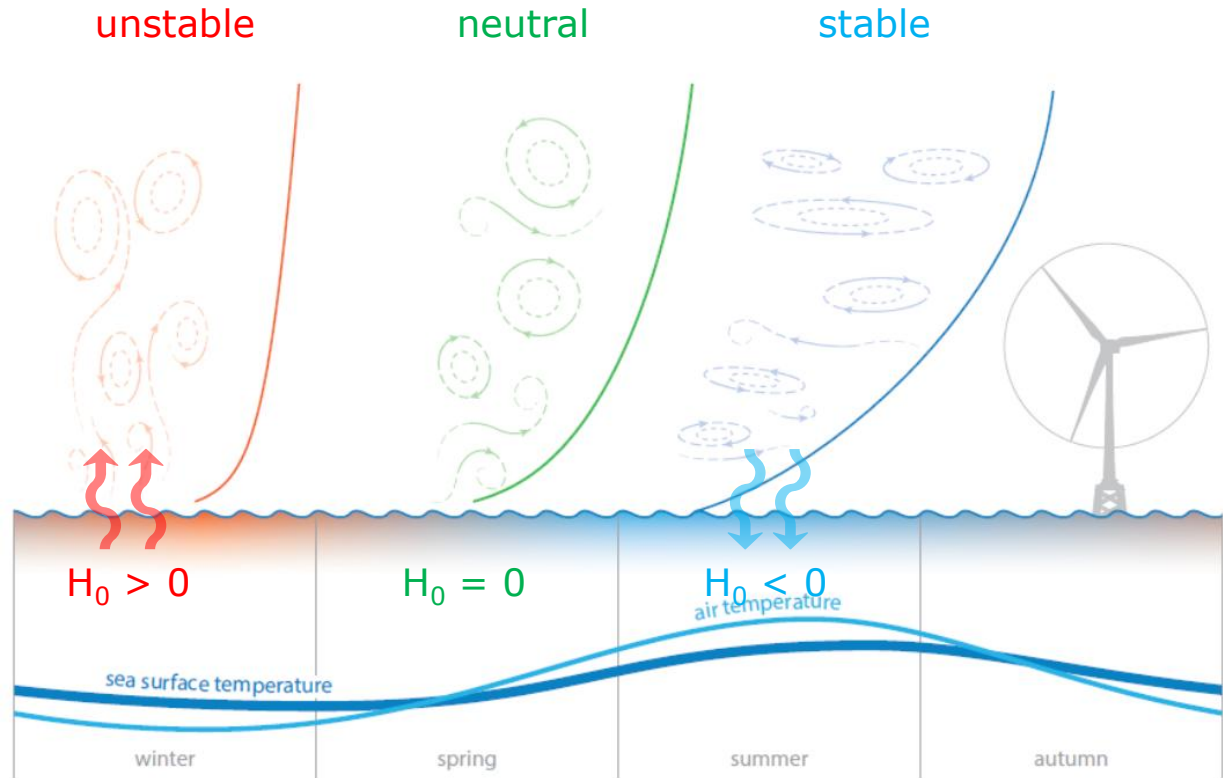
The Atmospheric Boundary Layer (ABL) is modelled with a logarithmic law:

$$V(z) = \frac{u_*}{k} \left[\ln \left(\frac{z-d}{z_0} \right) - \psi \left(\frac{z}{L} \right) \right]$$

ψ – Empirical function of the Monin-Obukhov length:

$$L = \frac{T_0}{kg} \cdot \frac{c_p u_*^3}{H_0}$$

Labels for the equation: T_0 is ground temperature, c_p is air heat capacity, u_*^3 is the cube of friction velocity, and H_0 is heat flux.



Source: Maarten Holstag, The wind farm in its environment, 2016

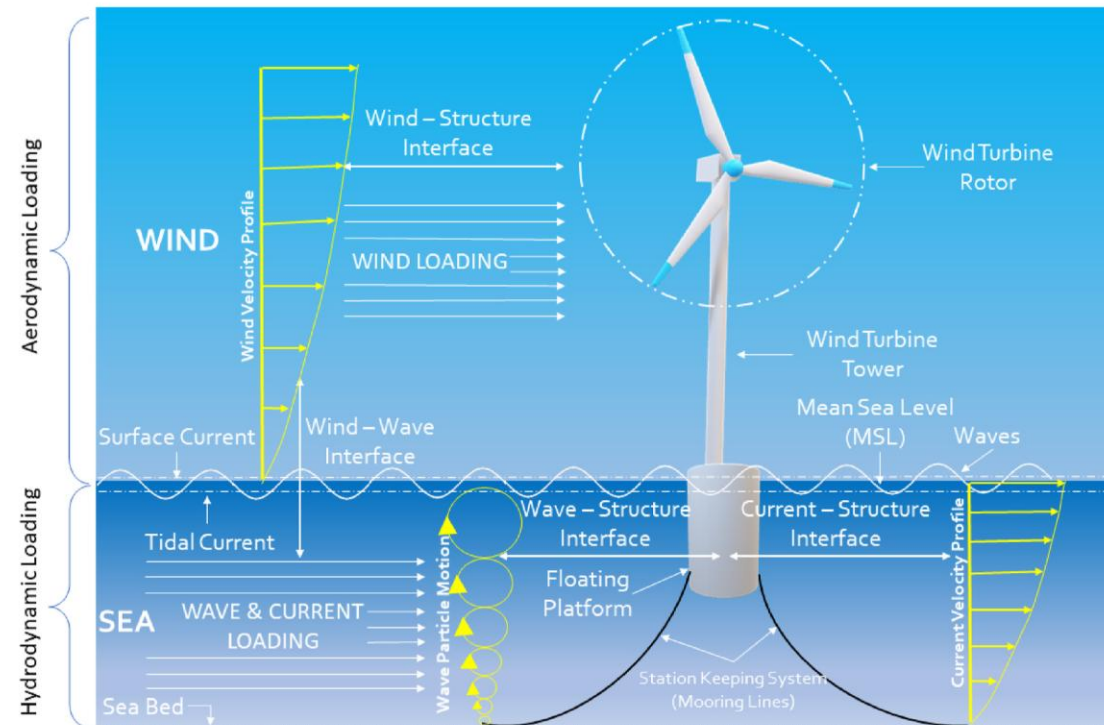
What about offshore ABL?



- Almost no roughness → more favorable wind shear profile
- No obstacles (except other WTs) → less shadowing effects

...however...

- different forcing sources arise...



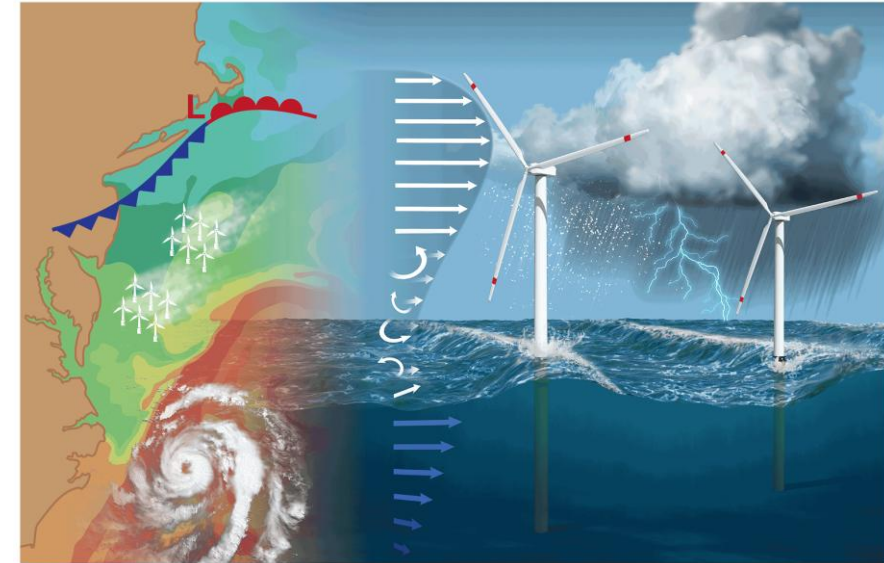
Upscaling and inflow offshore



Future wind turbines will extend beyond the top of the atmospheric surface layer and experience inflow characteristics never encountered by smaller machines

Atmospheric flow phenomena at these scales are complex

- ✓ hurricanes, tornadoes, microbursts, nocturnal and marine jet flows, and gravity waves must also be considered
- ✓ exact nature of atmospheric turbulence is not well characterized at the length scales and resonant frequencies of the modern wind turbine structure
- ✓ turbulence at these scales ($\sim 10^2$ m) is known to be non-Gaussian, nonstationary, and nonhomogeneous

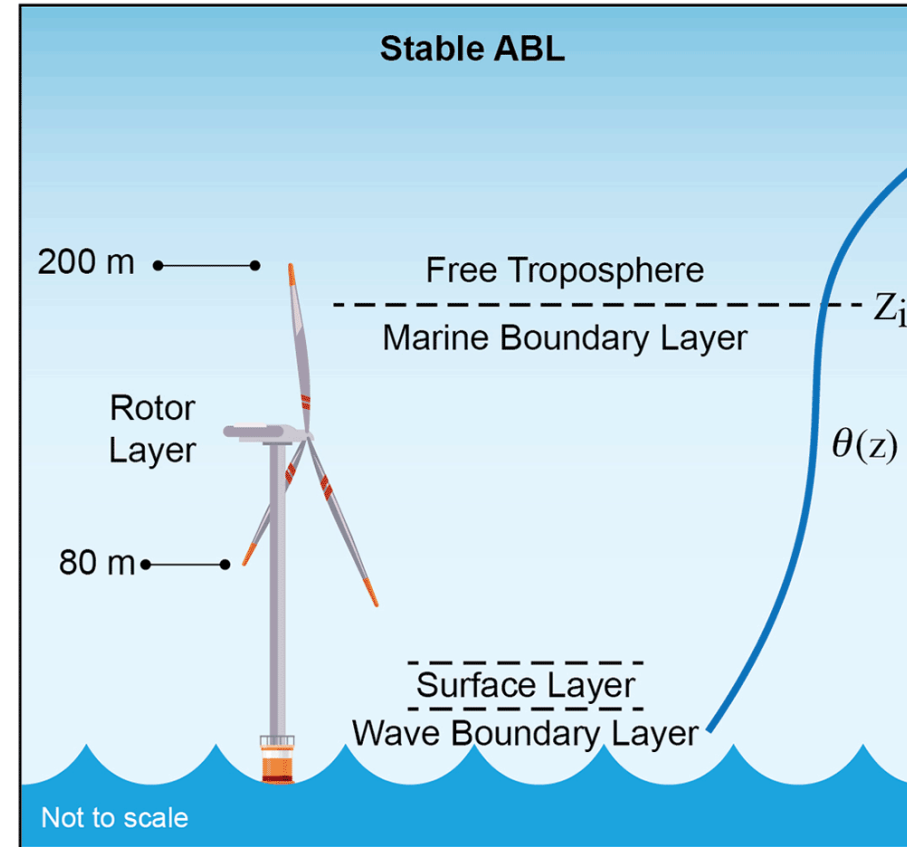
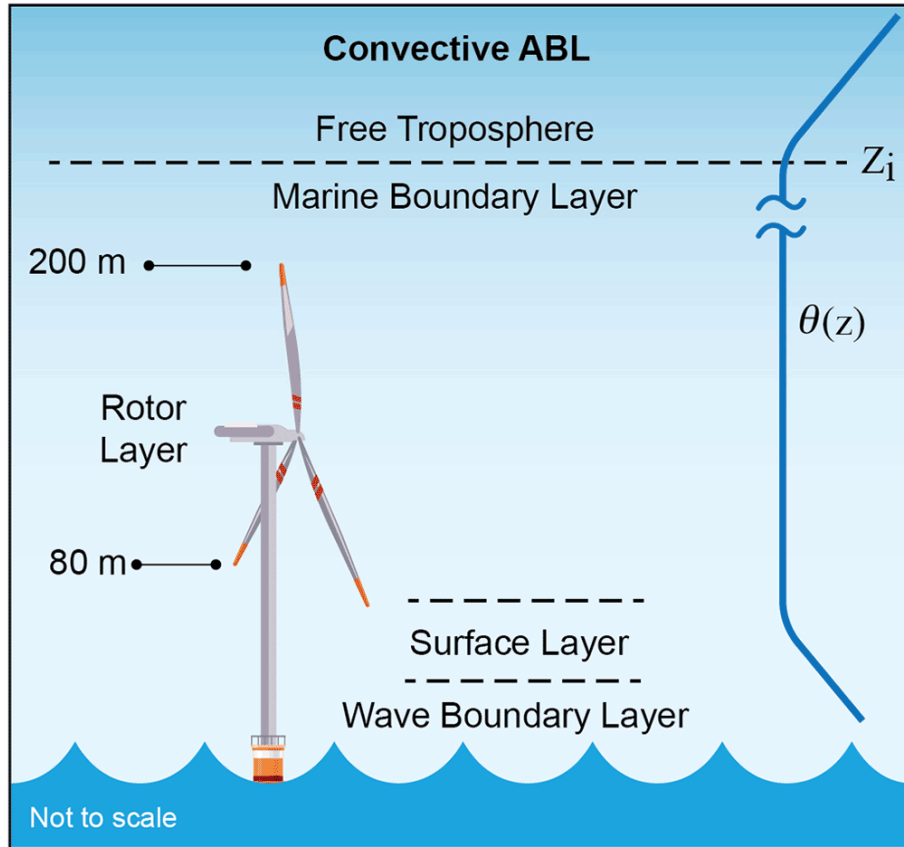


<https://doi.org/10.5194/wes-7-2307-2022>

The current design standards often fail to capture these new underlying physics (e.g., inflow turbulence models) and modern computational tools are not able to simulate specific atmospheric dynamics and configuration changes

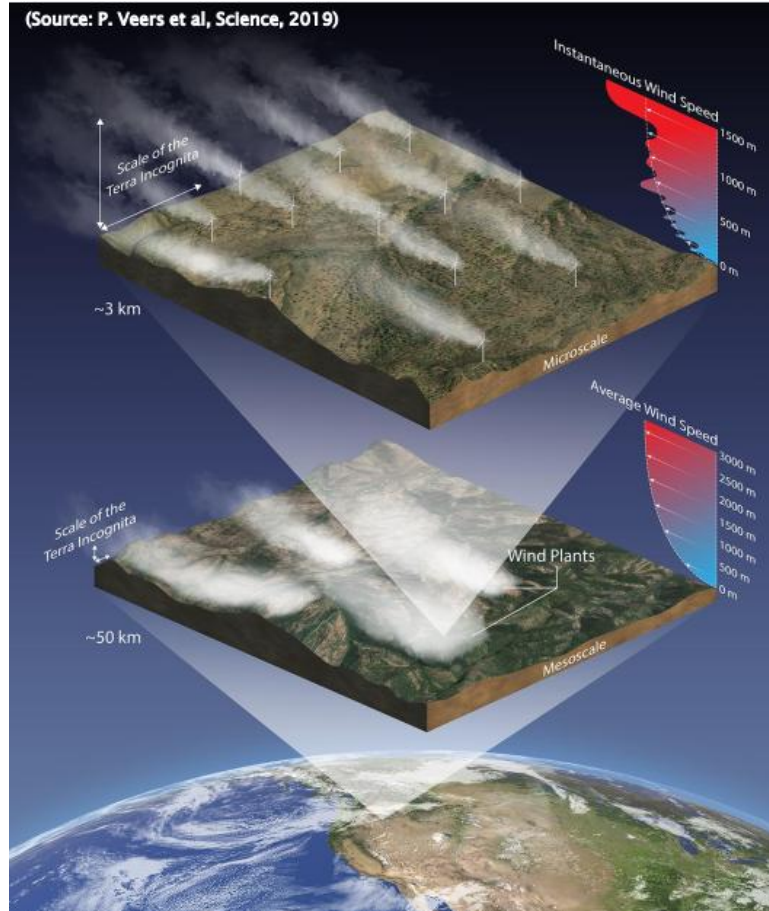
- ✓ design and certification standards must evolve

Atmospheric stability and ABL offshore

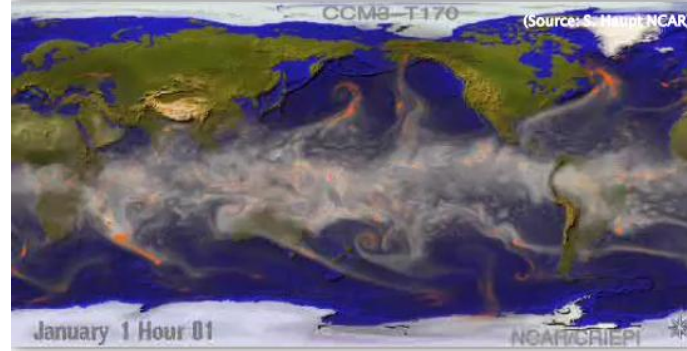


<https://doi.org/10.5194/wes-7-2307-2022>

Large wind farms and the atmosphere



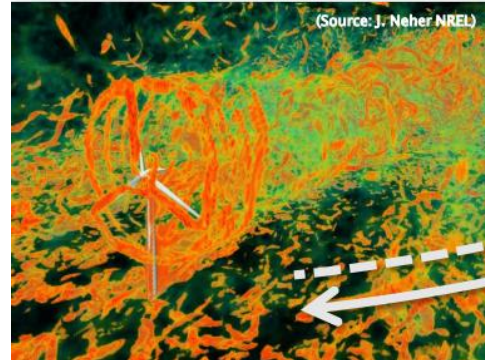
▼ Global scale



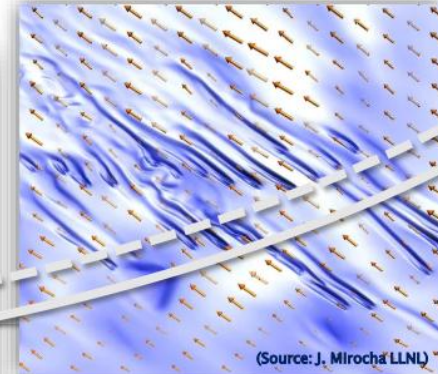
▼ Regional scale



▼ Wind turbine scale



▼ Wind plant scale

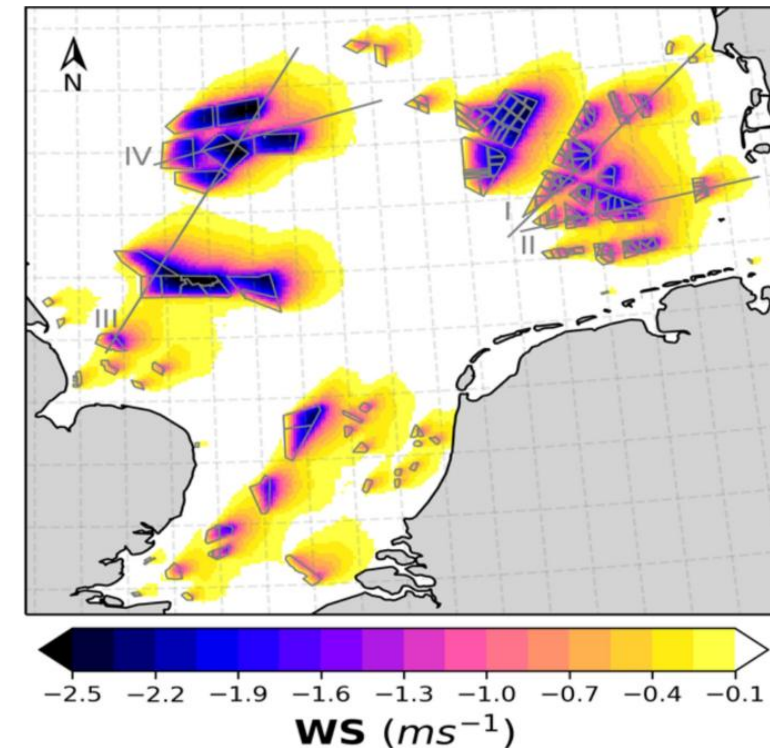
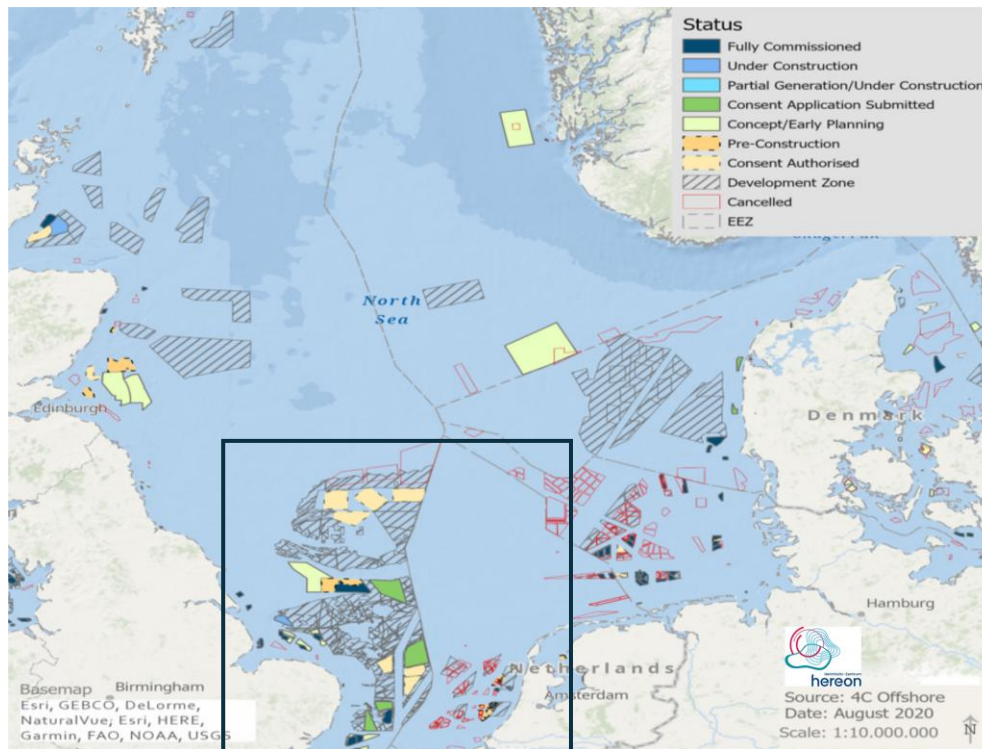


Two-way couplings

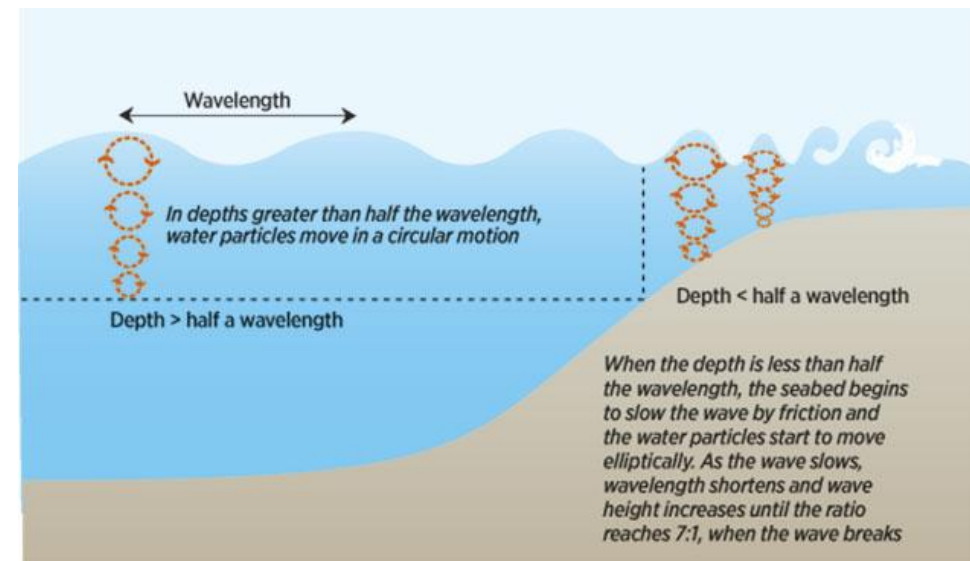
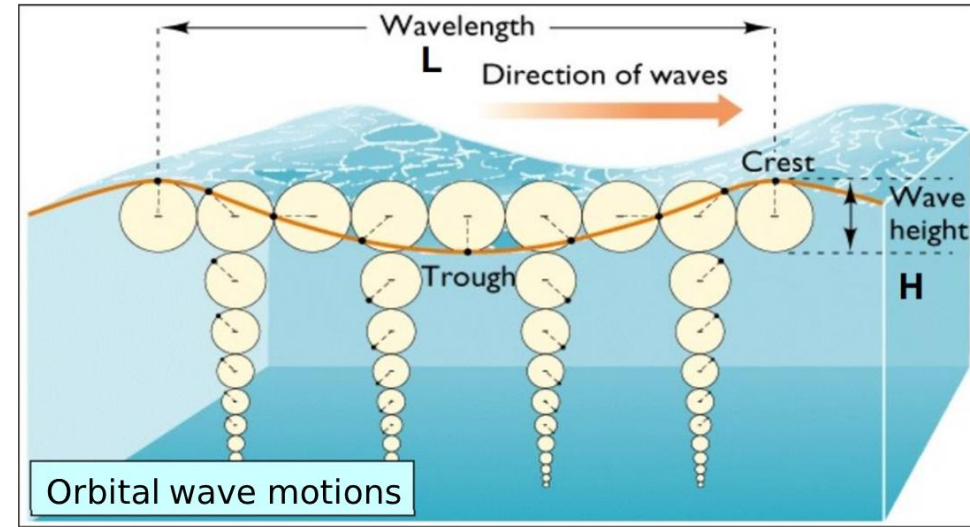
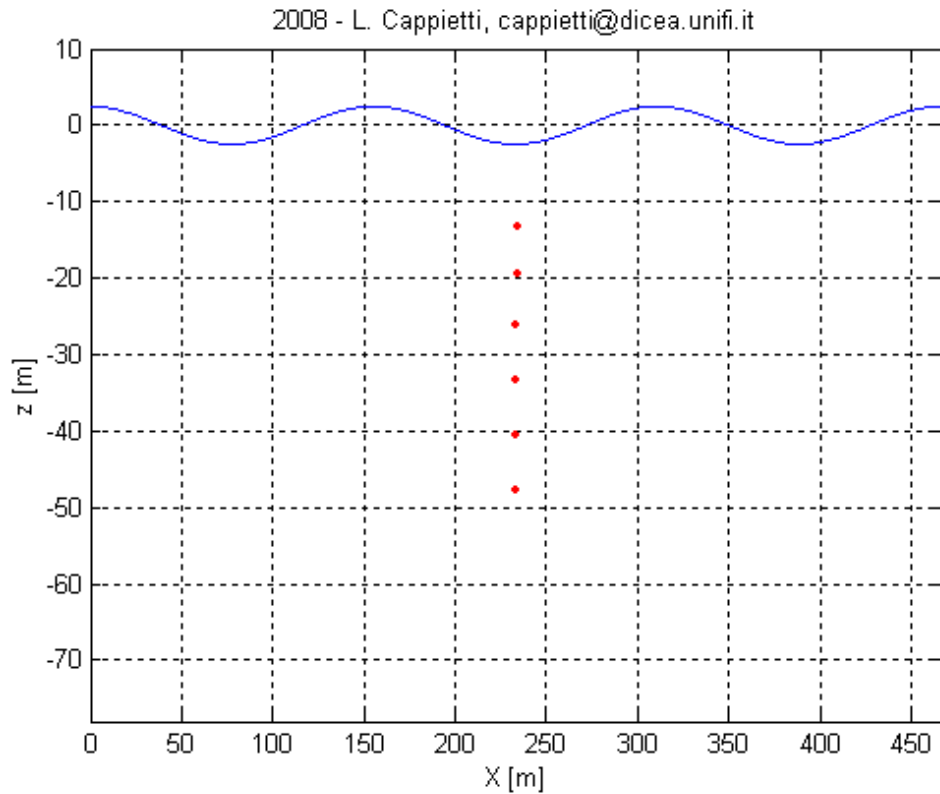
Interaction of large offshore wind farms



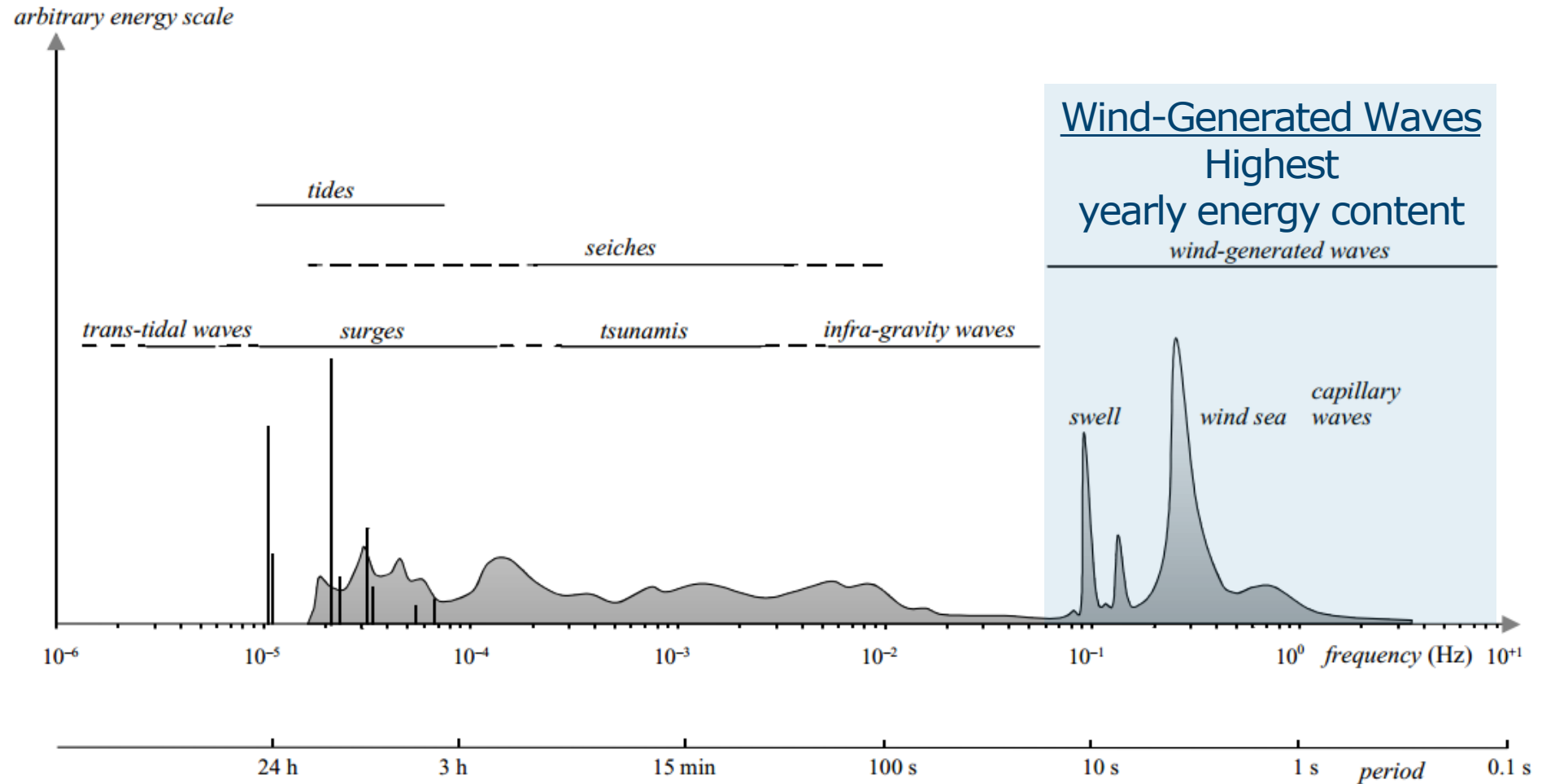
Science needs to progress since accelerating deployment of offshore wind energy could alter wind climate and reduce future power generation potentials and/or lead to too high cost



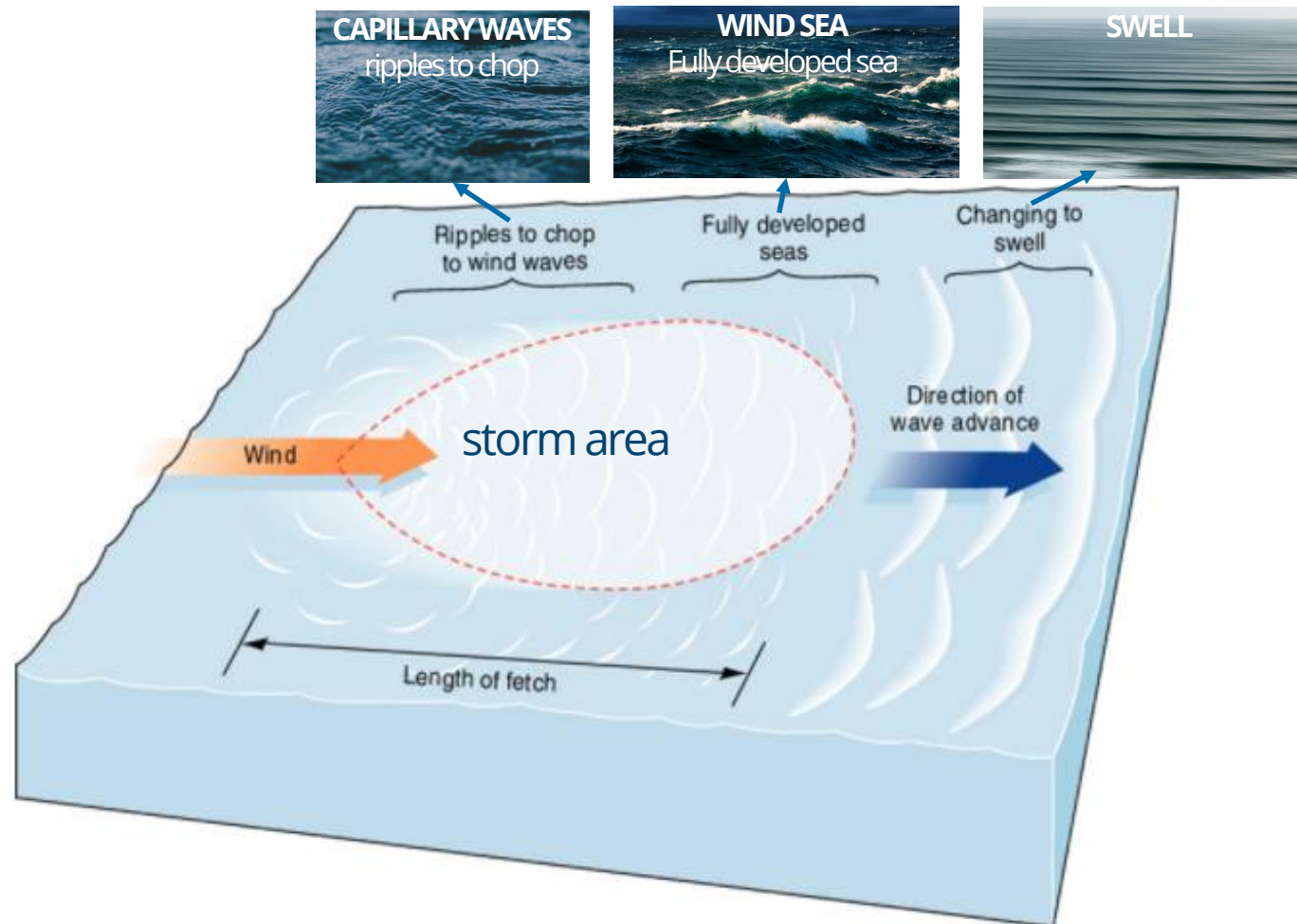
Waves



Types of waves and generation mechanisms



Wind-generated waves ($t < 30s$)



Wind-generated waves ($t < 30s$)



$T > 1/4s \rightarrow$ surface gravity waves
dominated by gravity

$T < 1/4s \rightarrow$ capillary waves
dominated by surface tension

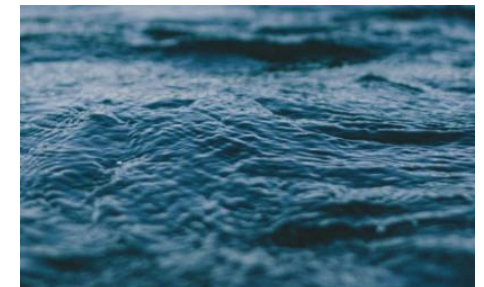
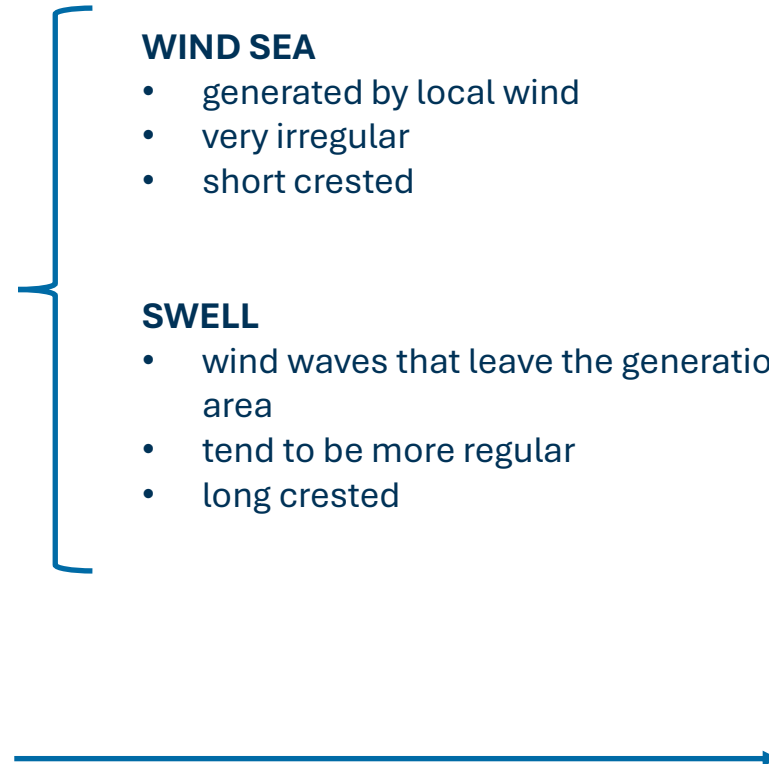
WIND SEA

- generated by local wind
- very irregular
- short crested



SWELL

- wind waves that leave the generation area
- tend to be more regular
- long crested



Linear Wave theory



The simplest way to model deep bottom ocean waves is through linear wave theory (**Airy theory**)

$$\zeta_a(t) = \zeta_a \sin(\omega t)$$

With adequate hypothesis (linearization helps) the potential flow problem can be solved and velocity fields can be found.

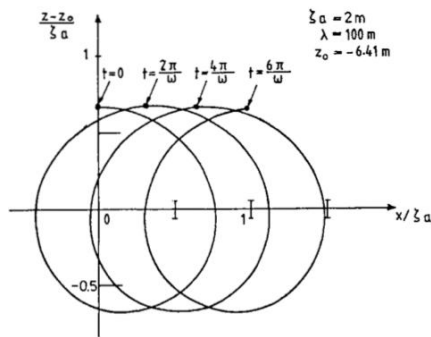


Fig. 2.4. Trajectory of a fluid particle in sinusoidal waves computed from first-order (linear) velocity potential (ζ_a = wave amplitude, λ = wavelength, z_0 = z -coordinate of fluid particle at rest.) (Ogilvie, 1983.)

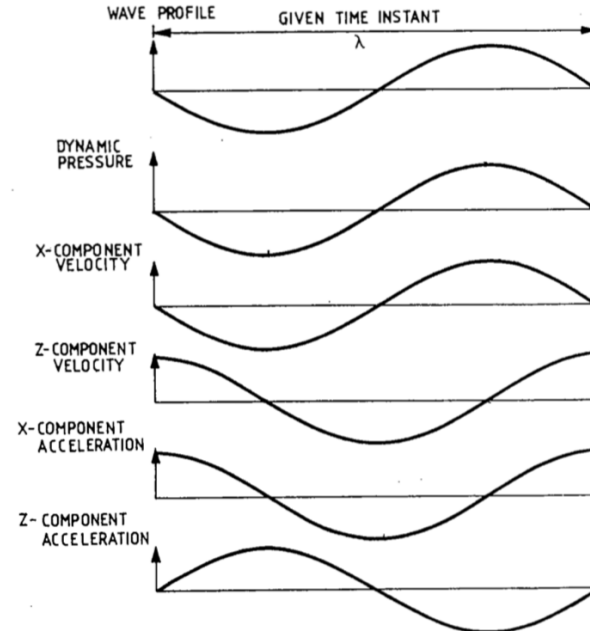


Fig. 2.1. Wave elevation, pressure, velocity and acceleration in long-crested sinusoidal waves propagating along the positive x -axis (see Table 2.1).

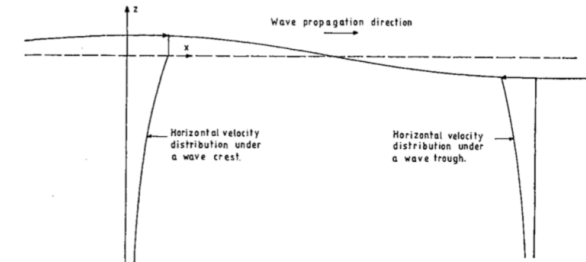


Fig. 2.2. Horizontal velocity distribution under a wave crest and a wave trough according to linear wave theory. (The x - and z -axis have different scales).

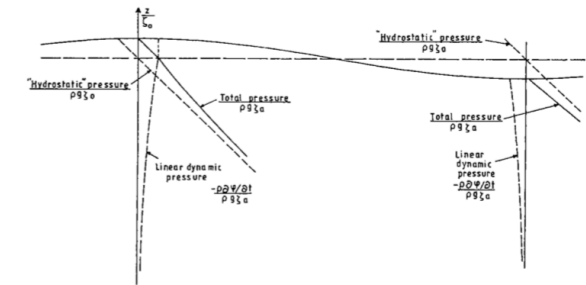


Fig. 2.3. Pressure variation under a wave crest and a wave trough according to linear wave theory.

Irregular linear waves

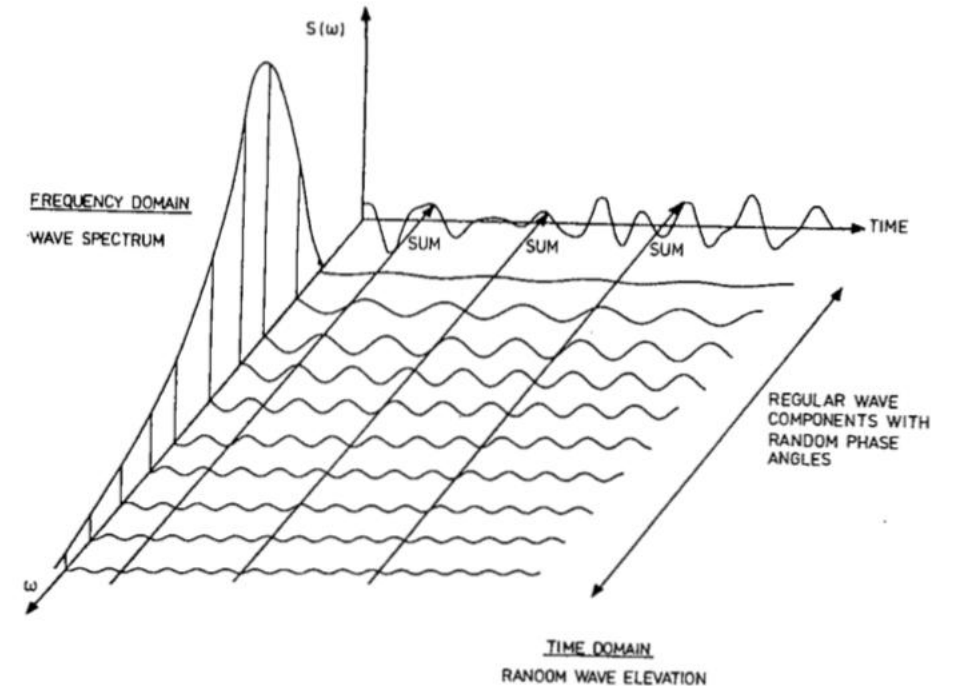


Since the wave theory is linear, to obtain an irregular wave field we can combine linear waves with different frequencies and phases:

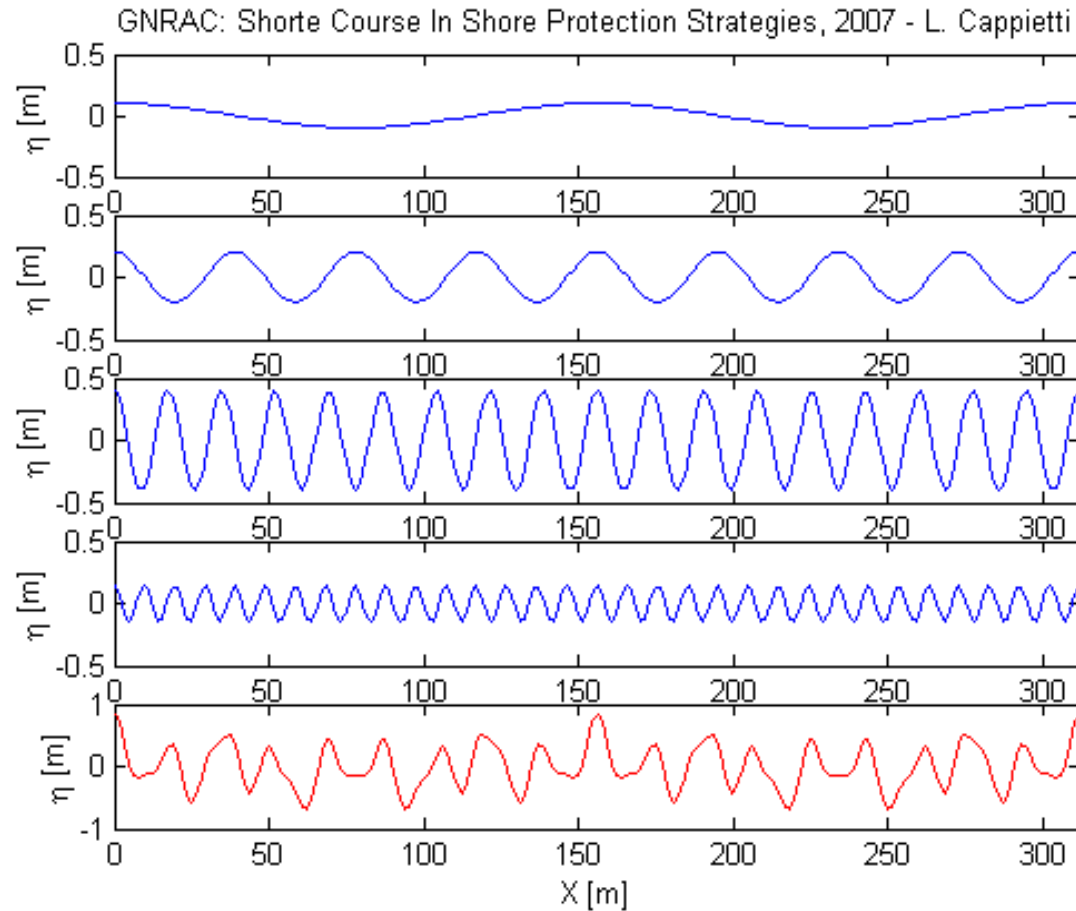
$$S(t) = \sum_i A_i \sin(\omega_i t + \varphi_i)$$

The amplitude A_i of each wave frequency is given by a spectrum, typically the Jonswap spectrum. By randomizing the phases φ_i we can obtain an infinite number of irregular wave timeseries with a give spectrum

For potential flow solutions, we only need to know the wave amplitude to obtain diffraction forces



Wave modelling: the random-phase and amplitude wave model



$$\eta_1 = a_1 \cos(2\pi f_1 t + \alpha_1)$$

$$\eta_2 = a_2 \cos(2\pi f_2 t + \alpha_2)$$

$$\eta_3 = a_3 \cos(2\pi f_3 t + \alpha_3)$$

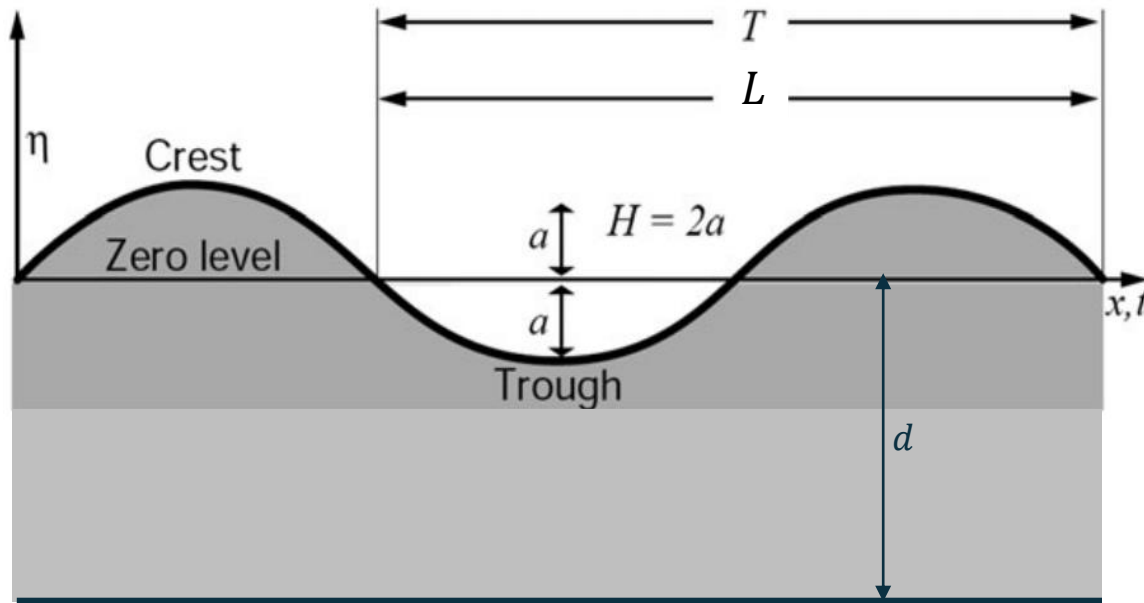
$$\eta_4 = a_4 \cos(2\pi f_4 t + \alpha_4)$$

wave
components

$$\eta(t) = \sum_{i=1}^N a_i \cos(2\pi f_i t + \alpha_i)$$

resulting
wave motion

Wave characteristic parameters of a harmonic wave component



Wave frequency

$$f = \frac{1}{T}$$

Angular frequency

$$\omega = \frac{2\pi}{T}$$

Wave Number

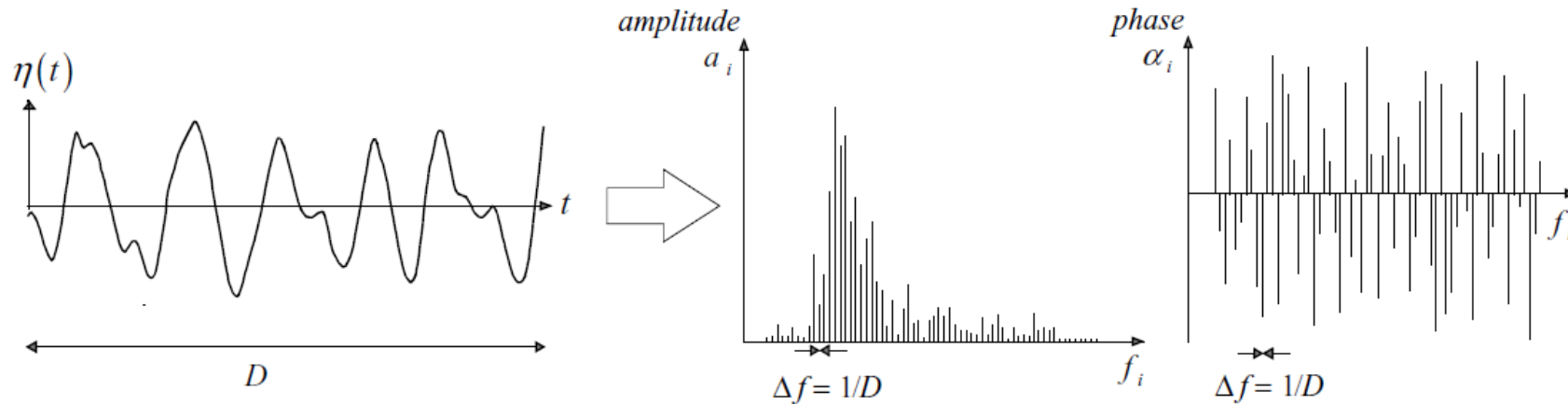
$$k = \frac{2\pi}{L}$$

dispersion relationship

$$\omega^2 = kg \tanh(kd)$$

Having T and d then this relationship provides L , as such L is no longer a necessary parameter

Realistic waves can be described with the **random-phase and amplitude wave model**



where a_i and α_i are the amplitude and phase for each frequency $f_i = i/D$ and the frequency interval is $\Delta f = 1/D$. The Fourier analysis provides values a_i and α_i for each frequency, and this would give us **the amplitude and phase spectrum for a given wave record**

Experimental measurements proved that:

- ✓ the **phase** at each frequency is **uniformly distributed**
- ✓ the **amplitude** phase at each frequency is **Rayleigh distributed**

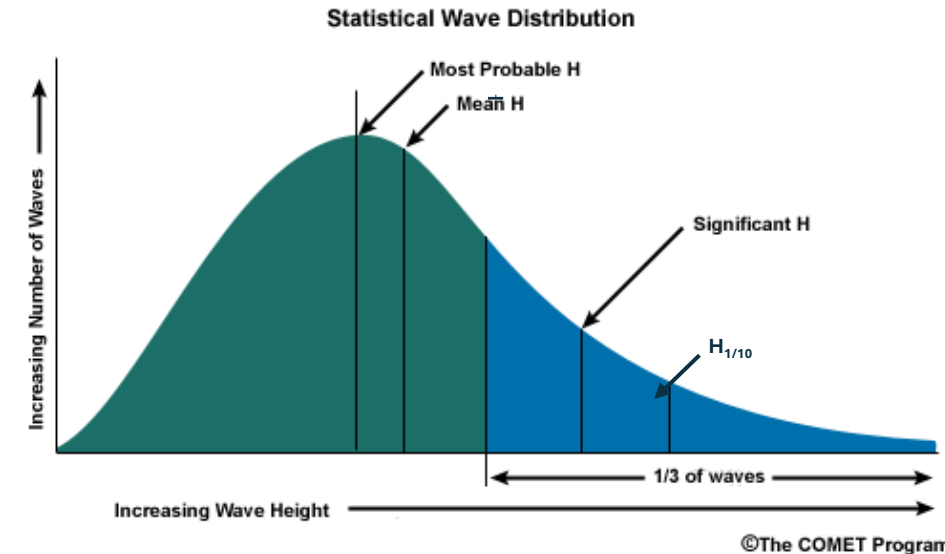
Wave height



H is the most probable or the most frequent wave height, this is not displayed in the forecast. The most frequent wave height is approximately half the value of the significant wave height

\bar{H} is the average wave height. This is not displayed in the forecast. The average wave height is estimated to be about 5/8 the value of the significant wave height

H_s is the **significant wave height**. This is the average of the highest one third of waves. This is currently what is displayed in the forecast



$H_{1/10}$ is the average of the highest 10% of waves observed. This is what is newly being displayed in our forecast. This is indicated by "Waves occasionally to xx m"

Sea state



Another important variable is the **peak spectral period (T_p)**, i.e., the wave period (in s) associated with the most energetic waves in the total wave spectrum at a specific point

To define a complete set of **METOCEAN CONDITIONS**, we can rely on 4 variables only (plus eventually currents): **U** (wind speed, m/s), **H_s** (significant wave height, m), **T_p** (s), **M_{ww}** wind-wave misalignment (deg)



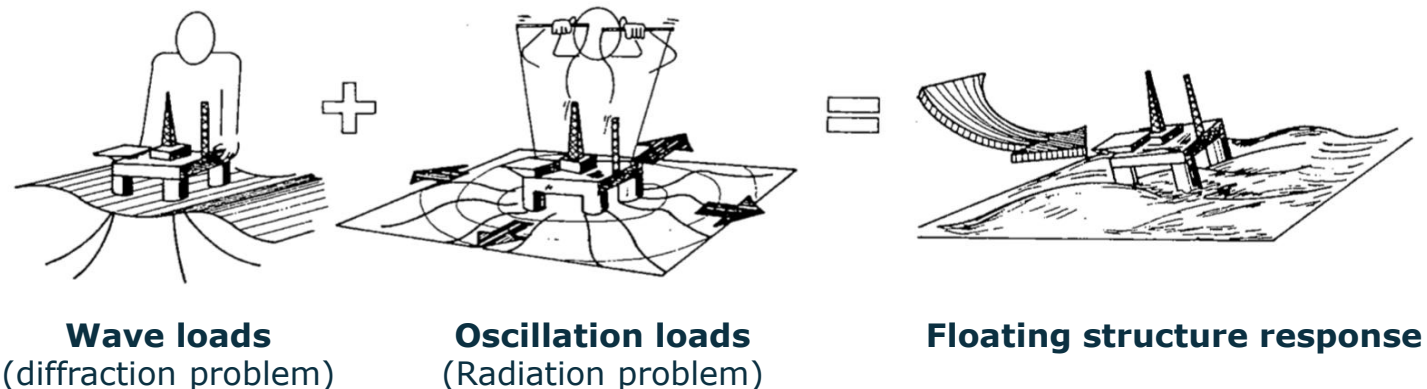
Potential Flow - Hydrodynamics



In offshore wind, we typically want to find the loads on a structure that is oscillating around its equilibrium position (e.g. a floating wind turbine on a floater)

The current state of the art approach is to linearize the problem around the structure's equilibrium point. If the problem is linear the superposition principle is valid and we can decompose the problem into two more simple problems:

- ✓ Diffraction problem: loads on the structure when it is locked in place and the waves are infringing upon it
- ✓ Radiation problem: loads on the structure when it is oscillating and there are no waves



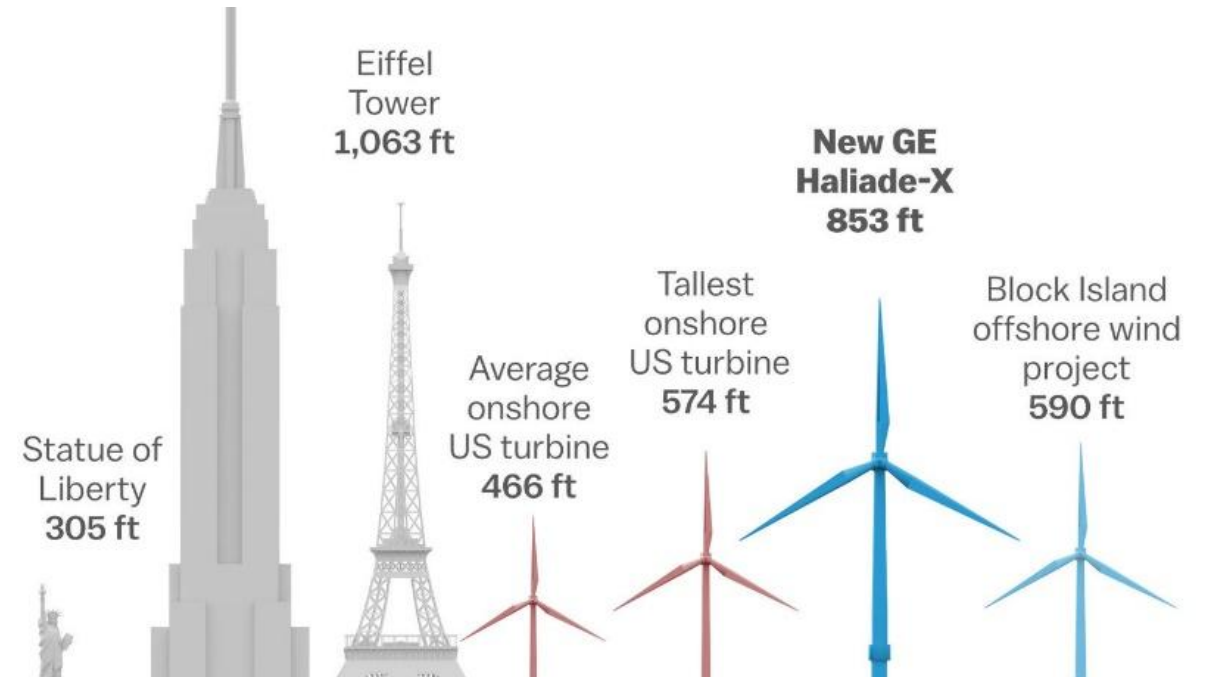
Curious? You will learn more in 2026!



3

Offshore wind turbines

The largest rotating machines on Earth (and in the sea)



Source: Haliade-X rendering from www.ge.com
A380 rendering from www.airbus.com

To better convince you...



x10 zoomed view - NISSAN Quasquai

A few numbers...



Blade

glass- and carbon-fiber composite
can weigh 70-100t each
can reach 120 m in length
maximum deformation $\approx 25\%$ of length

Nacelle

Gearless or geared generator
 $\approx 600-800$ t in total weight

Tower

Hollow steel shell
 $\approx 800-1400$ t in total weight

idling – no wind



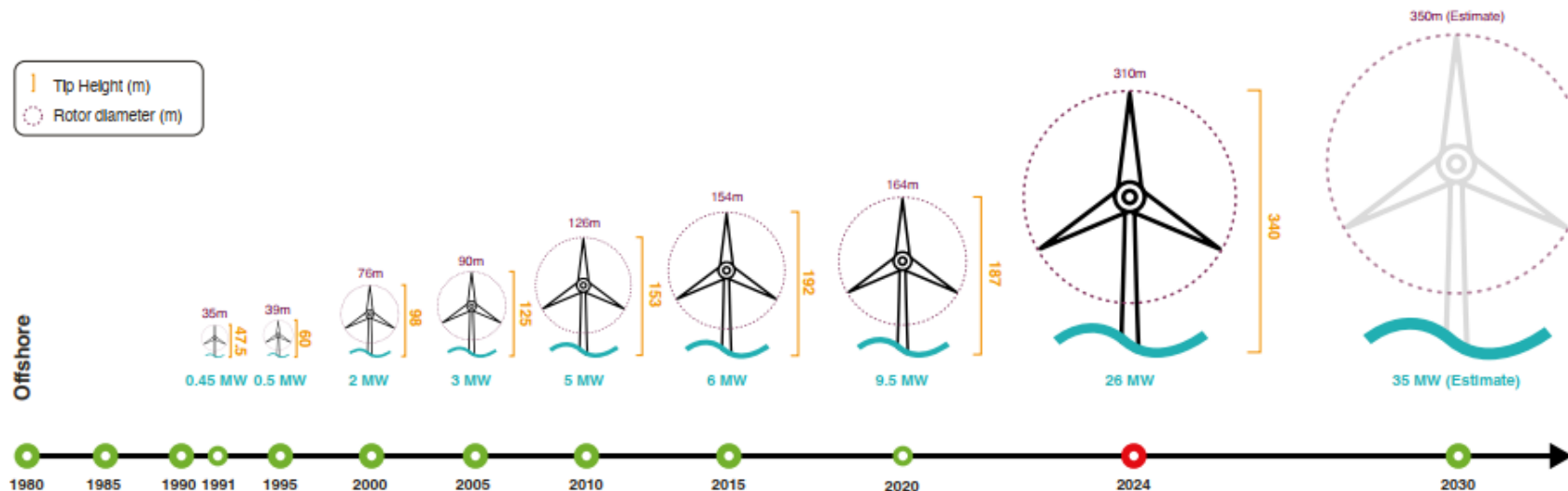
power production



Expected trends



Trend of Offshore turbine size, 1980-2030



Source: GWEC Market Intelligence

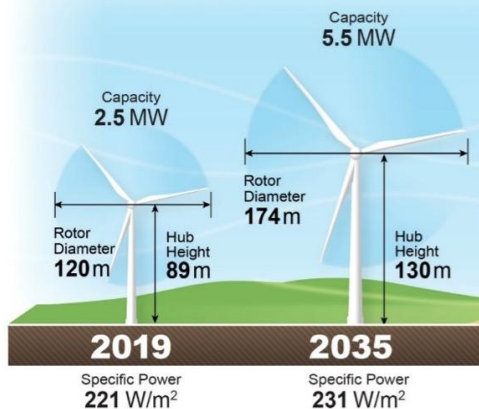
Source: GWEC, 2025

diameter +45% - tower +46%

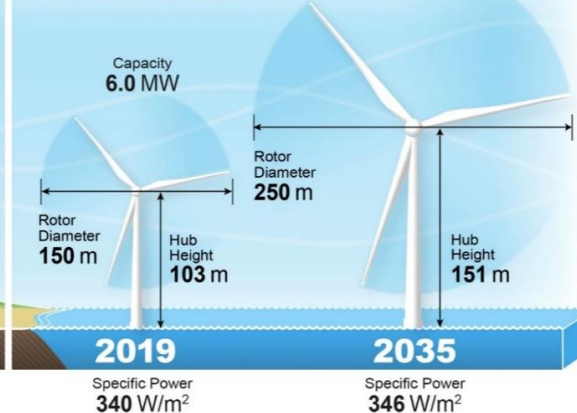
diameter +66% - tower +46%



Onshore Wind Turbines



Offshore Wind Turbines



Source: Bloomberg, 2023

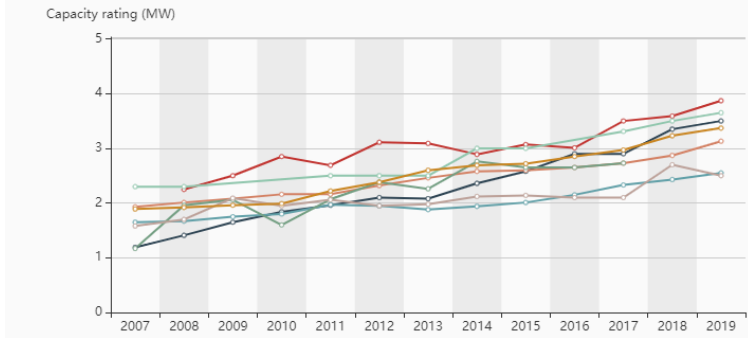
Underlying trends



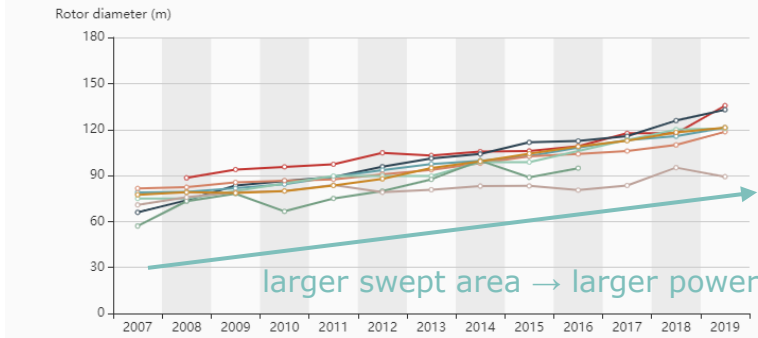
Data from IEA Task 26 – “Cost of Wind Energy” - <https://iea-wind.org/task26/>

- Denmark -○-
- Sweden -○-
- United States -○-
- EU-28 -○-
- Norway -○-
- Ireland -○-
- Germany -○-
- Japan -○-

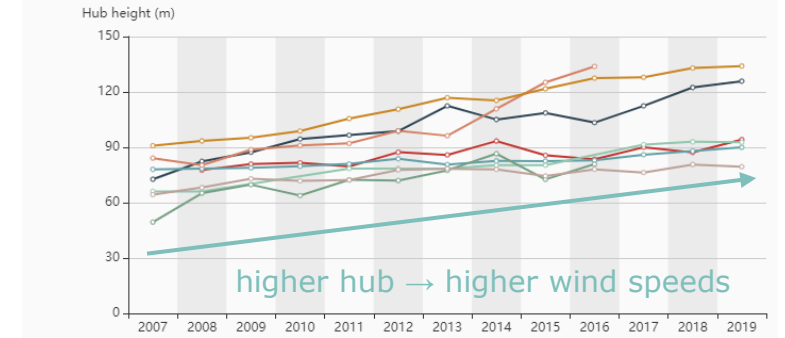
Wind Turbine Nameplate Capacity Rating



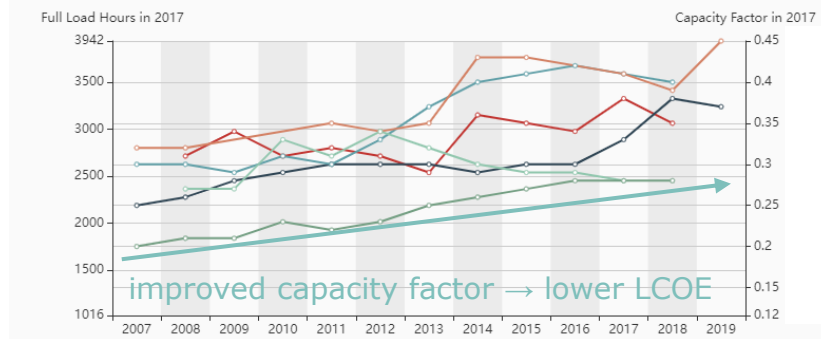
Turbine Rotor Diameter



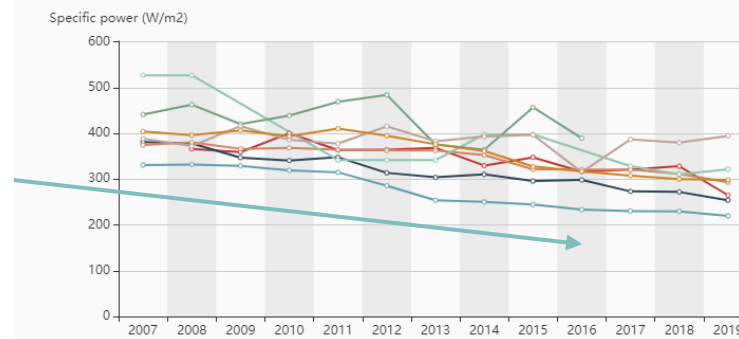
Wind Turbine Hub Height



Full Load Hours



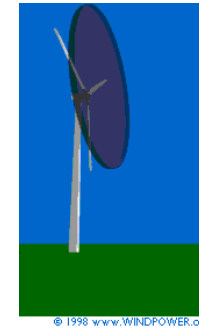
Wind Turbine Specific Power



Why less specific power?



Rated wind speed $\rightarrow v_{rated} = \sqrt[3]{\frac{P_{rated}}{A \cdot \frac{1}{2}\rho C_{P_{max}}}}$



$$P_{theor} = \frac{d}{dt} \left(\frac{1}{2} m v^2 \right) = \frac{1}{2} \frac{dm}{dt} v^2 = \frac{1}{2} \rho A v^3$$

ρ = air density (approx. 1.184 kg/m³)

A = rotor swept area

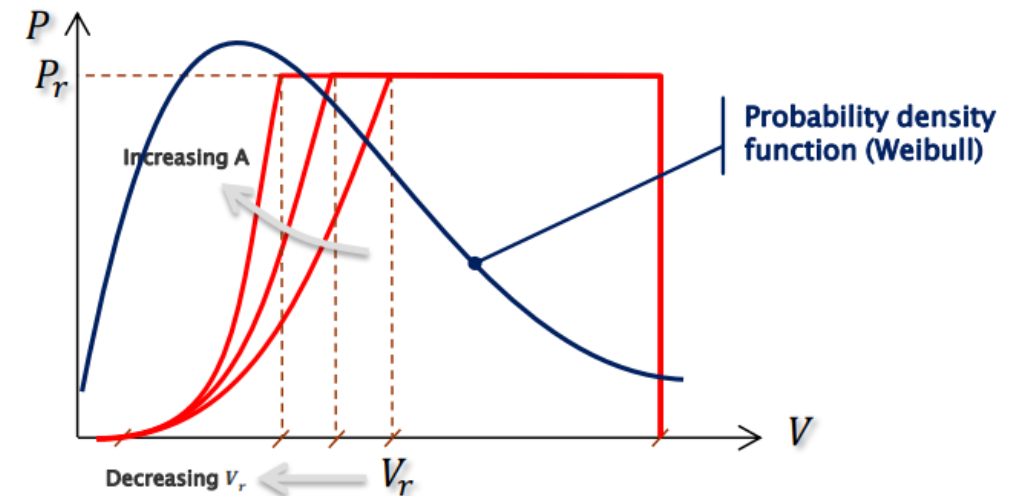
v = wind speed [m/s]

$C_{P_{max}}$ is limited by physics

- ✓ wind turbines already reached an aerodynamic efficiency comparable to that of internal-flow turbines

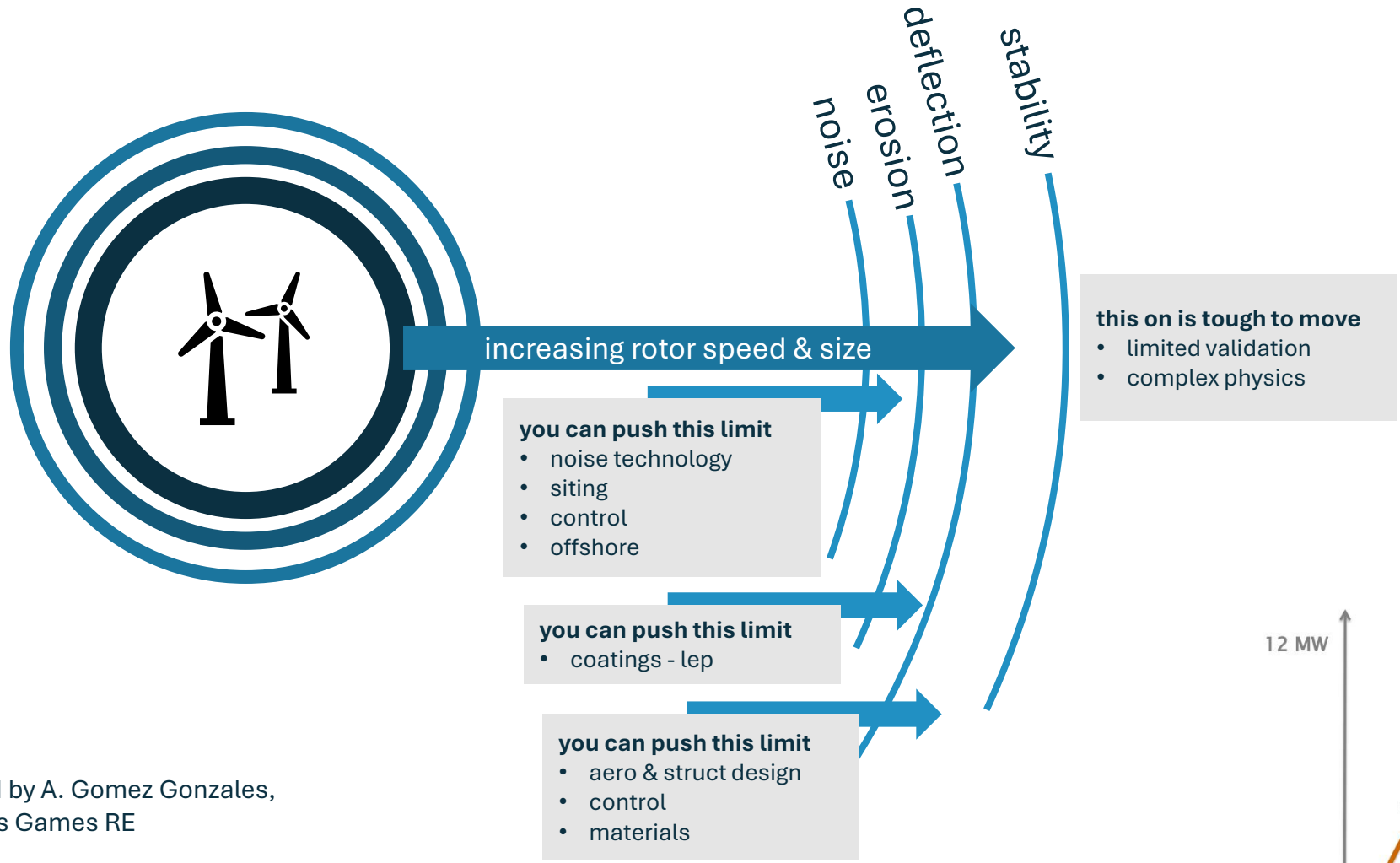
To increase the capacity factor, we need to better exploit lower (and more frequent) winds

The only way is to reduce the specific loading P_{rated}/A

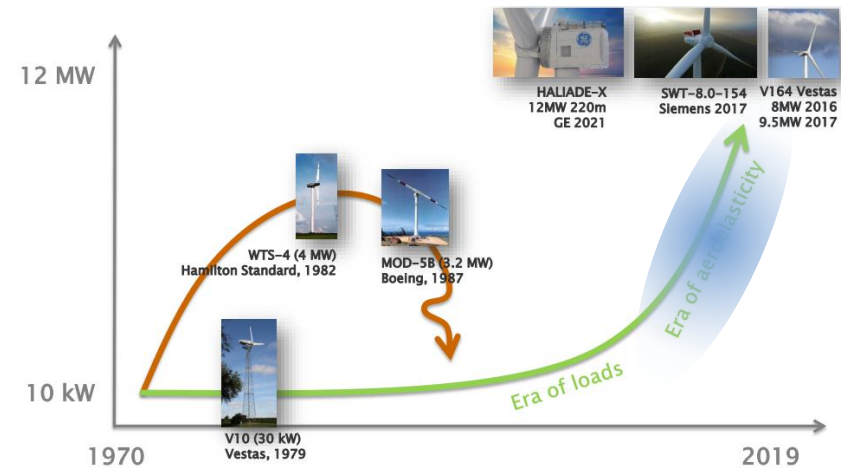


Credits to Prof. Carlo Bottasso, TUM

Design drivers



Inspired by A. Gomez Gonzales,
Siemens Games RE

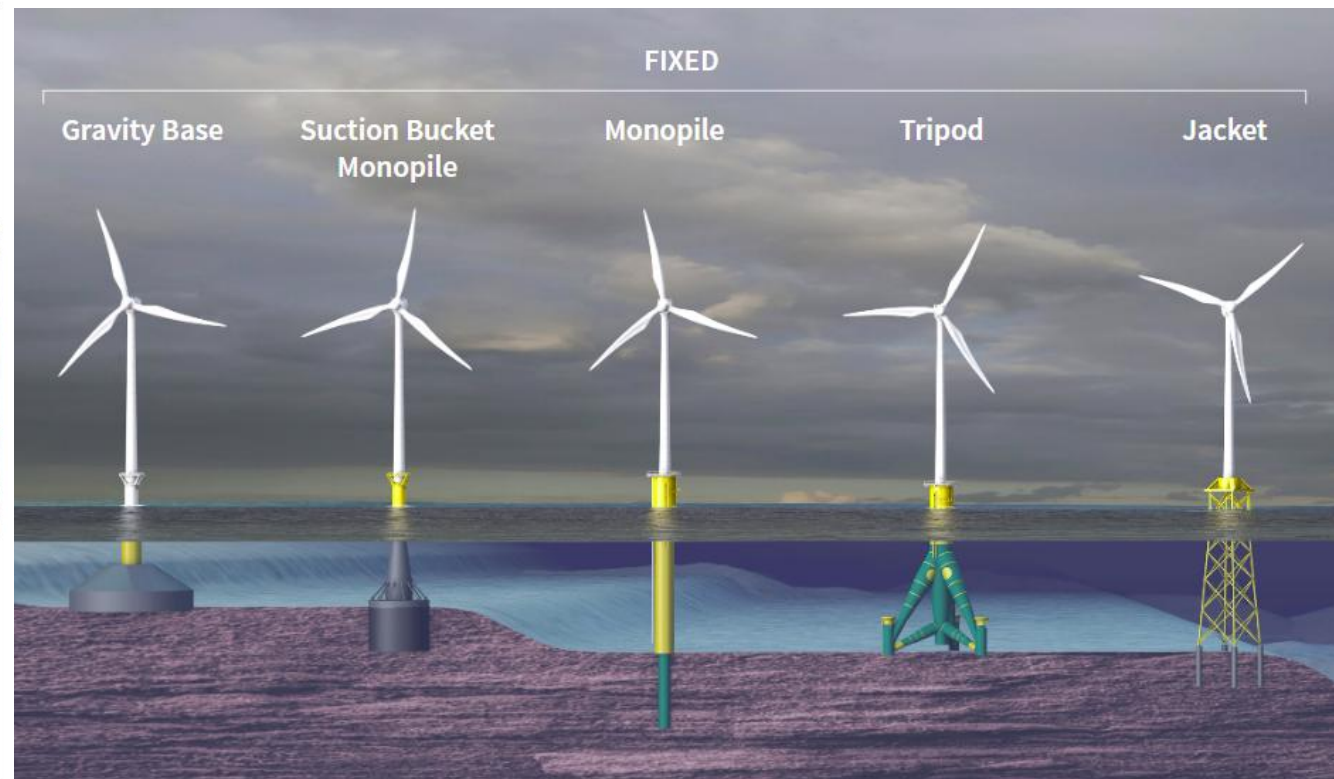
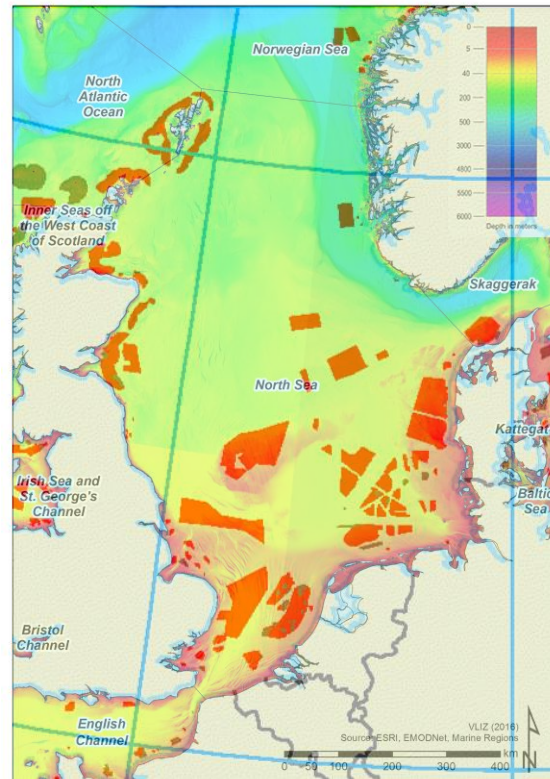


Bottom-fixed foundations



Fixed-bottom OWTs are established technology. Have proven to be able to operate in harsh sea environment, despite having their own problems

- ✓ limited access for maintenance
- ✓ corrosive conditions
- ✓ high winds
- ✓ rain (erosion)



Floating foundations



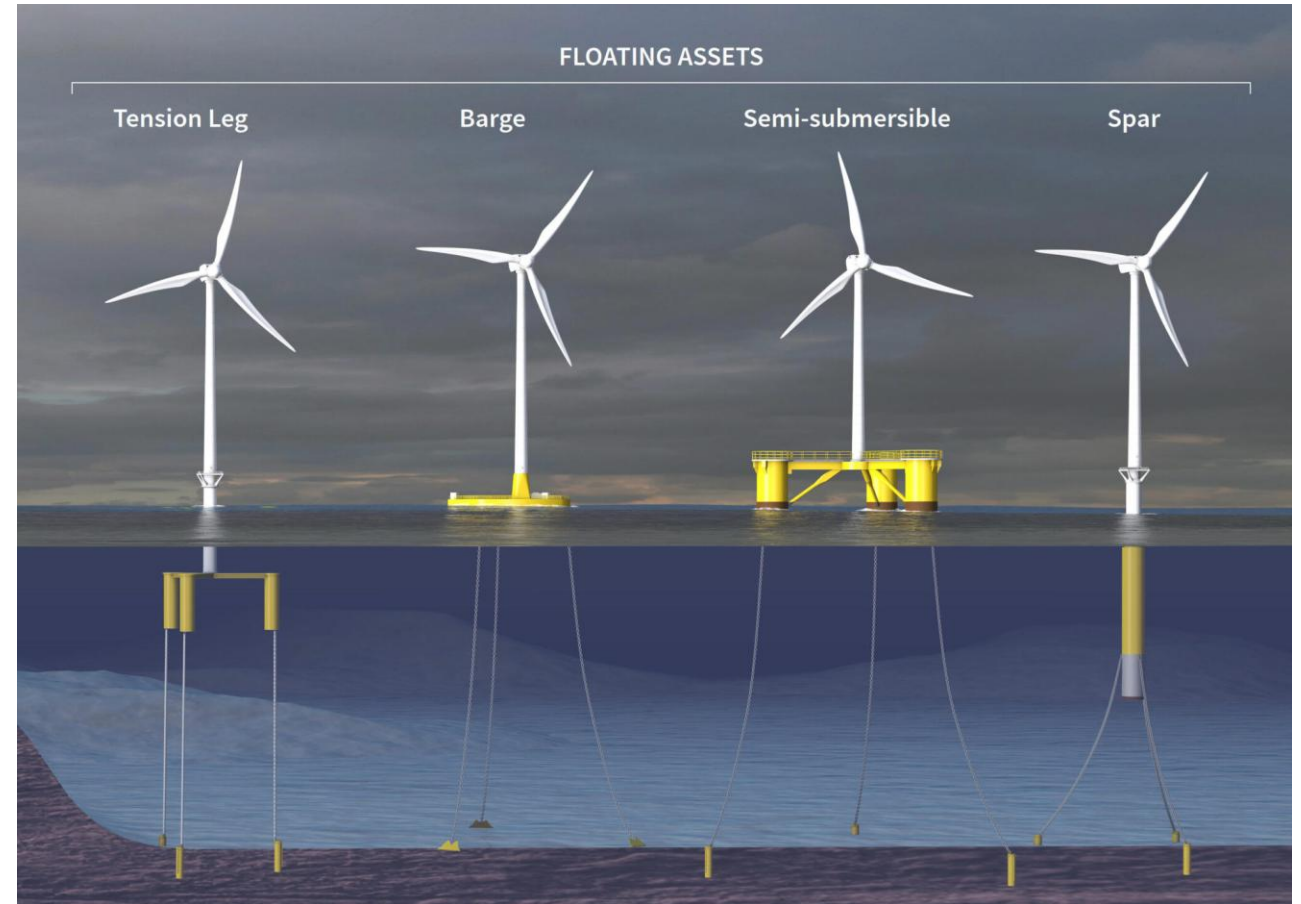
For installation in medium to deep waters (150-1000m) floating wind is the only solution

At this early stage several concepts of platforms have been proposed

- ✓ tension leg (TLP), barge and Semi-sub are adapted from oil&gas industry

The concepts differ in how stability is achieved

- ✓ each concept has its own advantages
- ✓ nowadays the semi-sub is the most promising concept followed by spar



Floating wind turbines – current projects in water



SMALL FARMS



DEMOS (snapshot)



A complex design space



Floating designs are bringing together two industries: land-based wind and Oil & Gas, but with distinct differences

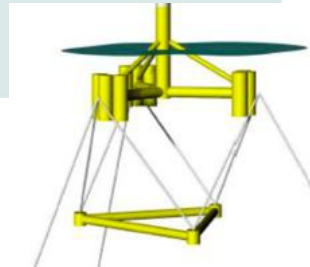
Aerodynamics

- large motion
- bigger turbines
- optimized control for performance + stability
- wake behavior, including turbine going in/out of its own wake



Hydrodynamics

- higher center of gravity
- large thrust force from the turbine
- hydro-elasticity
- operational design drivers
- more optimized designs (cost vs risk focus)
- deployment methods



Metocean

- different wind than on land, and limited measurements
- extreme conditions: hurricanes and breaking waves
- sea ice loading
- wind/wave interaction



Loads



Loading conditions are complex even if onshore applications

Floating additions

✓ Metocean conditions

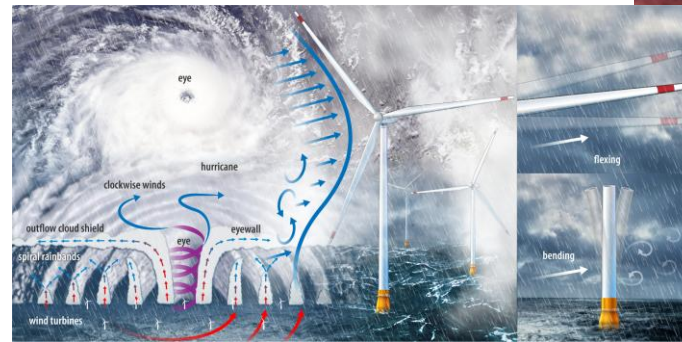
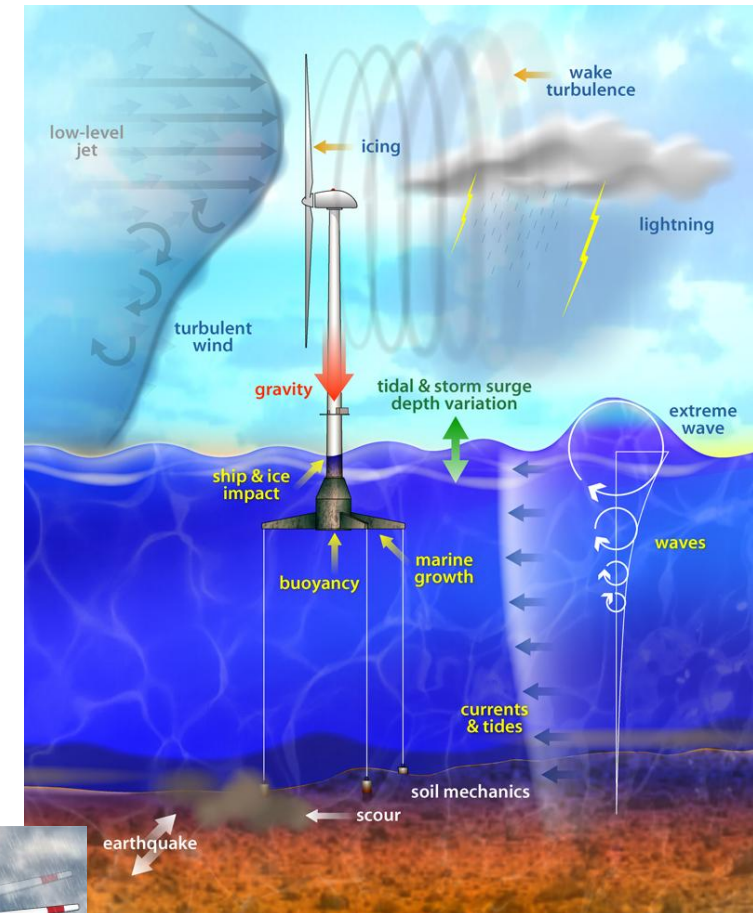
- offshore: waves, currents, tides
- wind/wave interaction – properties, direction
- marine growth
- floating ice

✓ Components

- moorings
- seabed

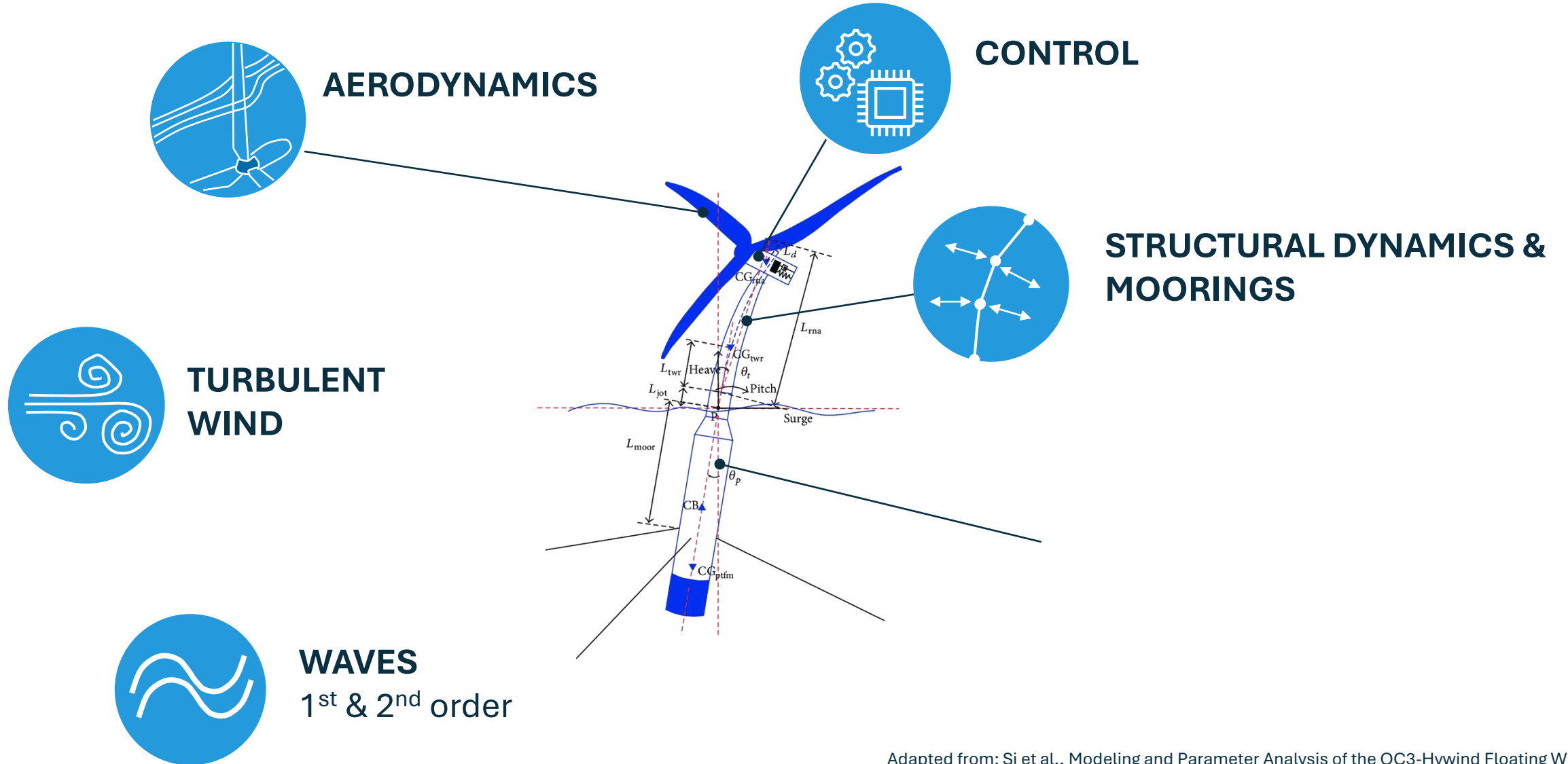
✓ Extremes

- hurricanes/typhoons!
- 500-yr robustness check
- phasing of motion with extreme events



Courtesy of NREL

Fully coupled aerodynamics

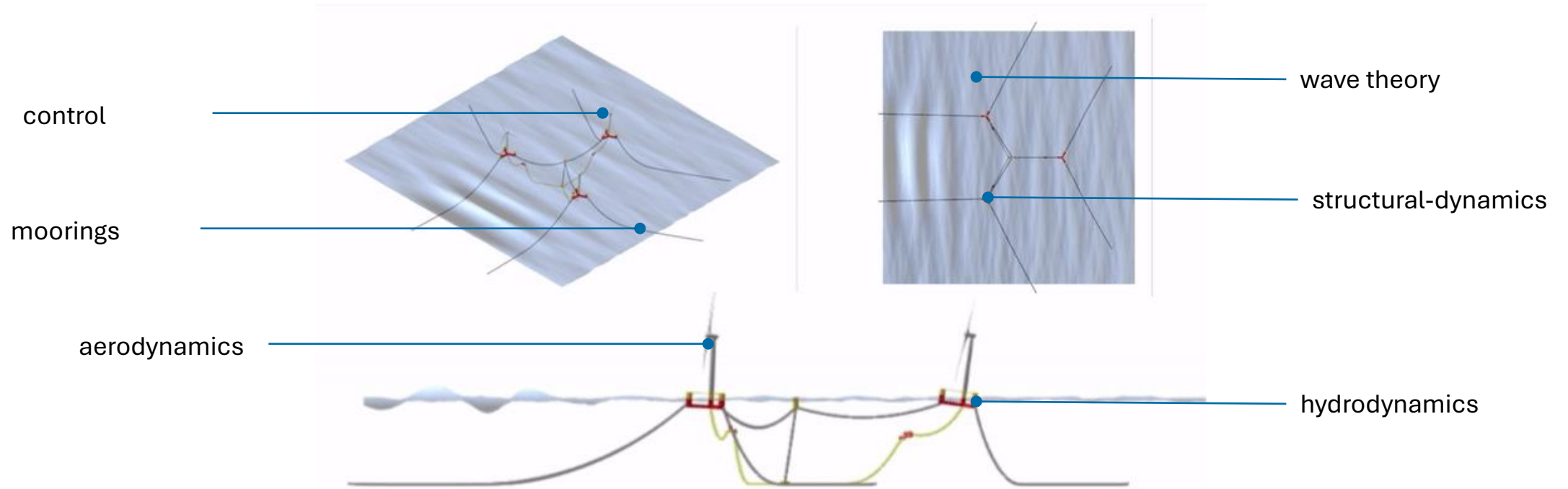


Adapted from: Si et al., Modeling and Parameter Analysis of the OC3-Hywind Floating Wind Turbine with a Tuned Mass Damper in Nacelle

Fully coupled dynamics

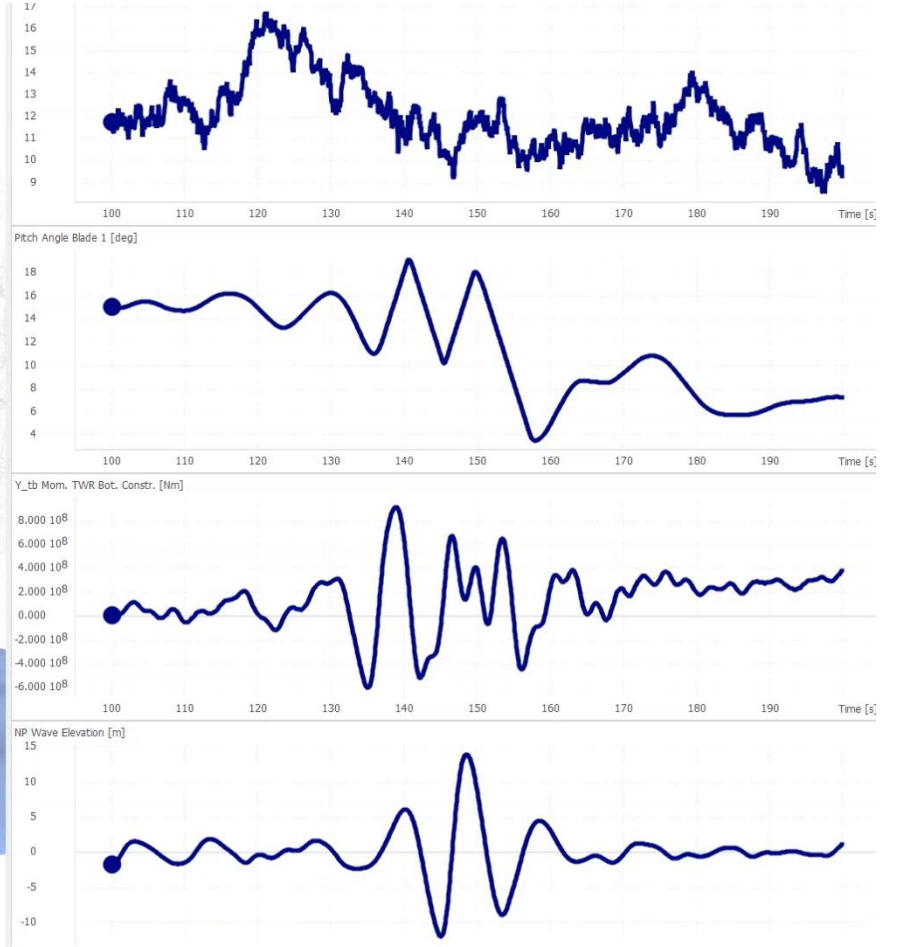
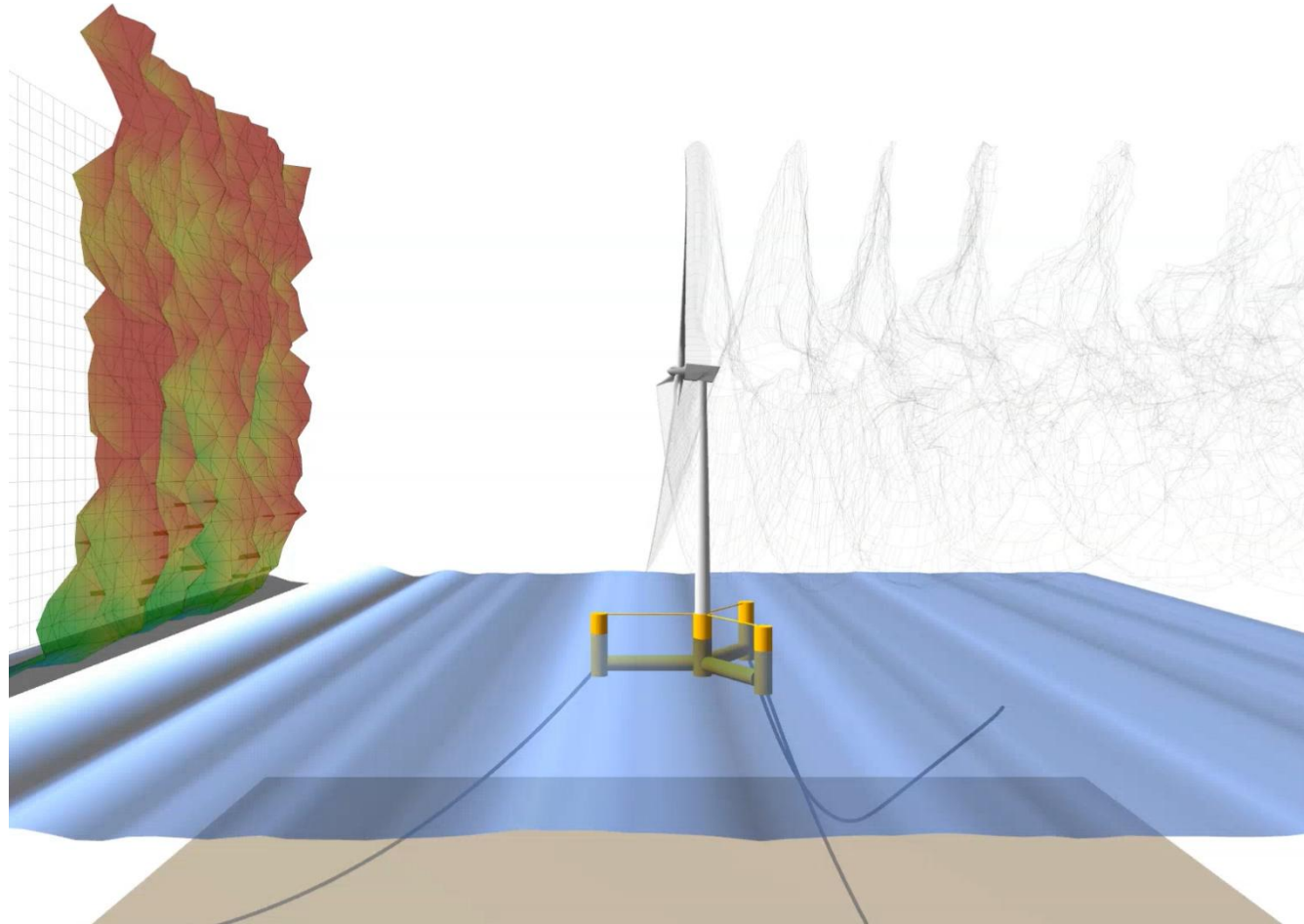


Coupled physics need to be solved simultaneously



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

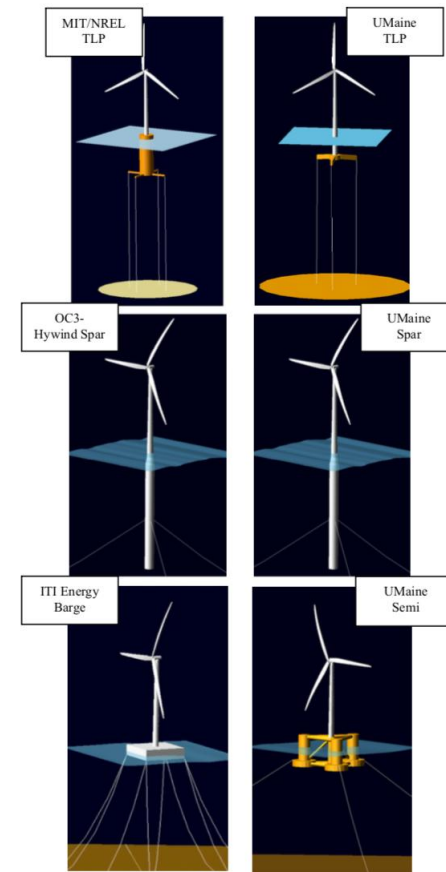
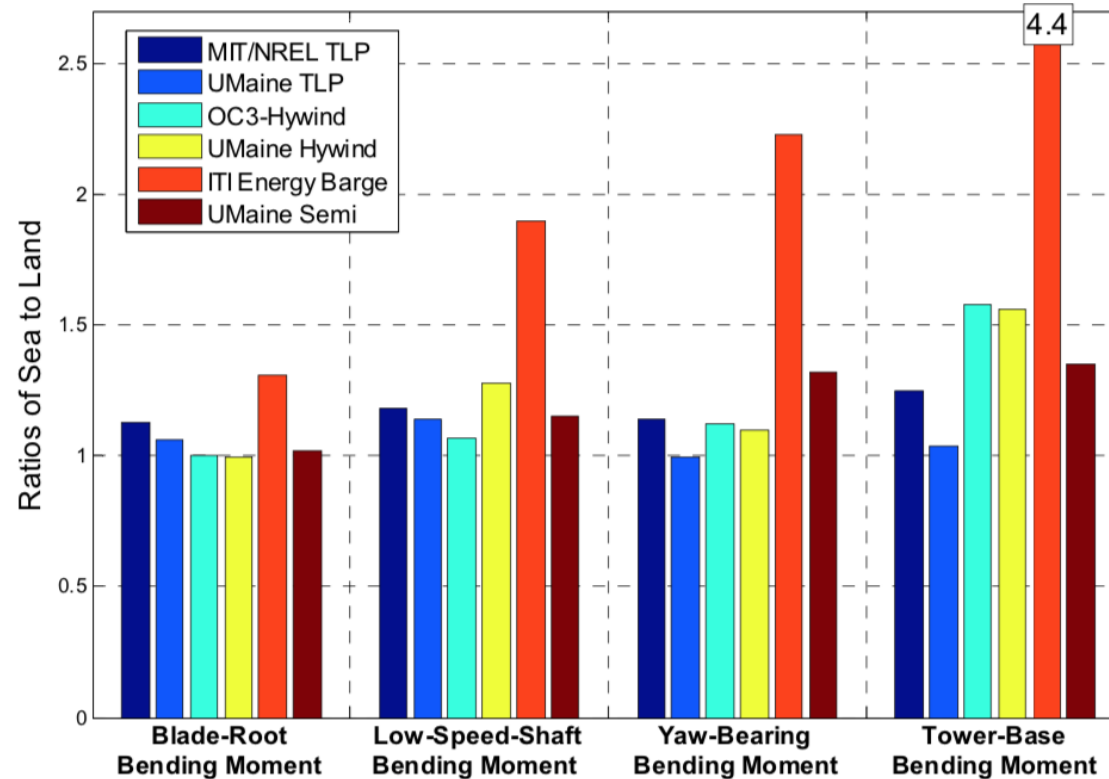
Fully coupled dynamics



Loads in FOWTs

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



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

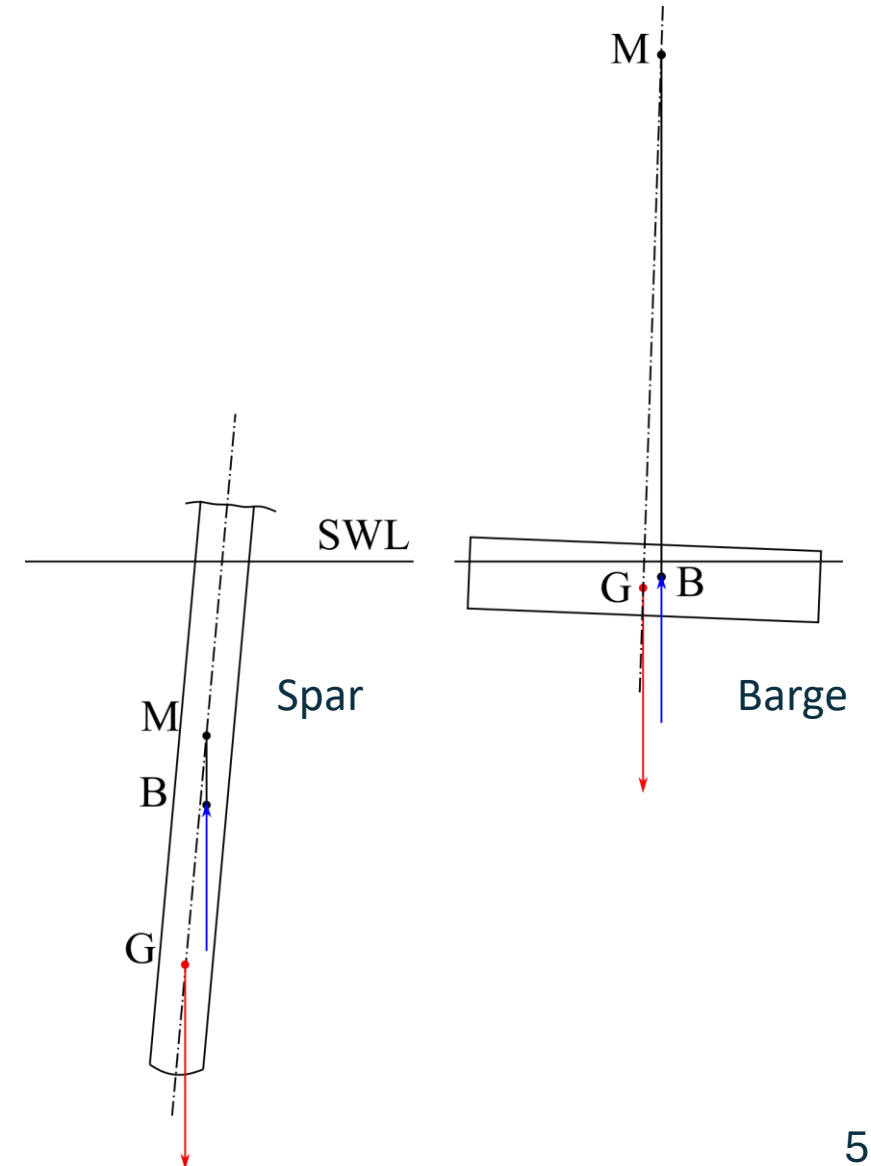
G = Center of mass

M = intersection between buoyancy force and symmetry axis

$BM = I_{xx}/V$

I_{xx} = moment of inertia of waterplane area

STABILITY FOR $GM > 0$

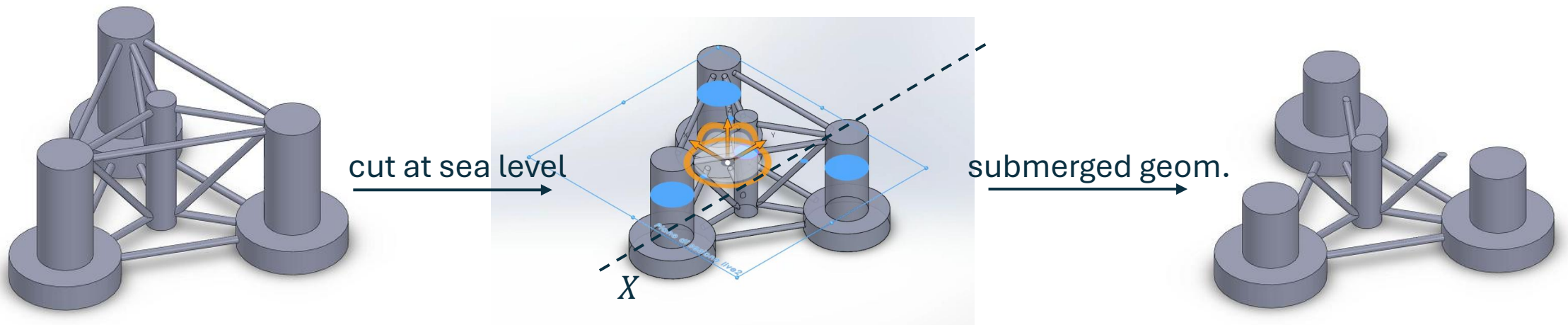


Waterplane moment of inertia



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

$$I_{XX} = \iint y^2 dx dy$$



Floater stability: comparison



Barge: Buoyancy, stability through large waterplane area

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

Spar: Ballast, stability through low CoG

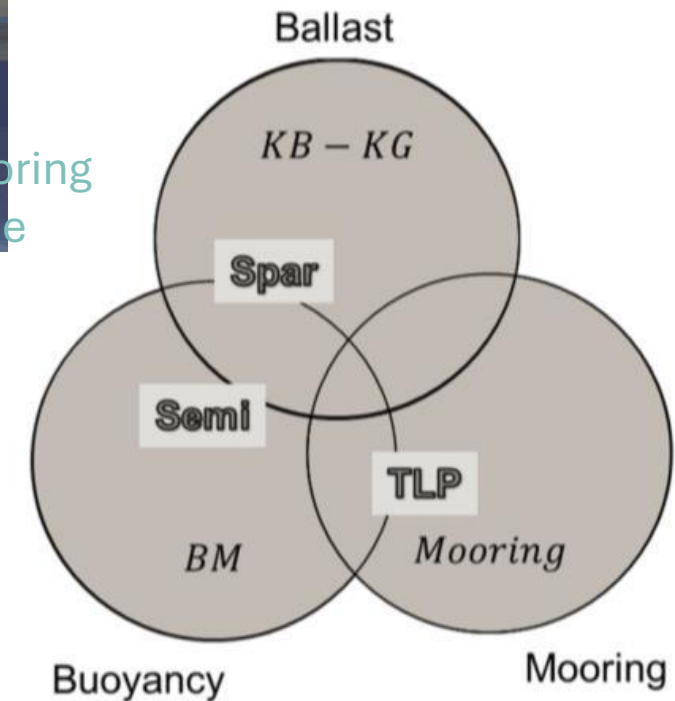
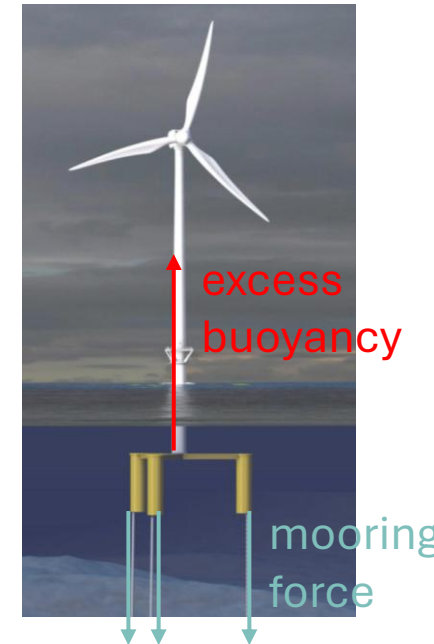
- ✓ transparent to waves due to small projected surface in wave direction but typically aerodynamic loading induces larger motions

TLP: 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

Semi: Hybrid buoyancy-ballast

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



Degrees of Freedom



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

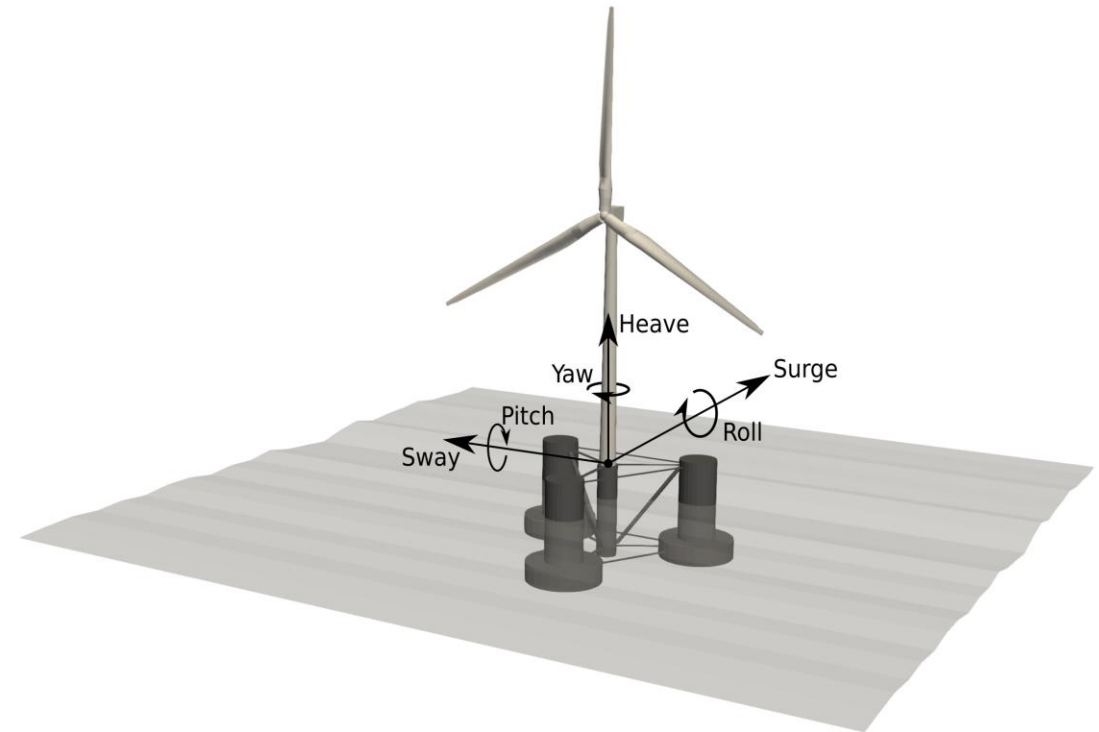
- ✓ 3 translations: Surge, Sway, Heave
- ✓ 3 rotations: Pitch, Roll, Yaw

Platform grants stability in Heave, Pitch and Roll

Moorings stabilize Surge, Sway and Yaw

- ✓ 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



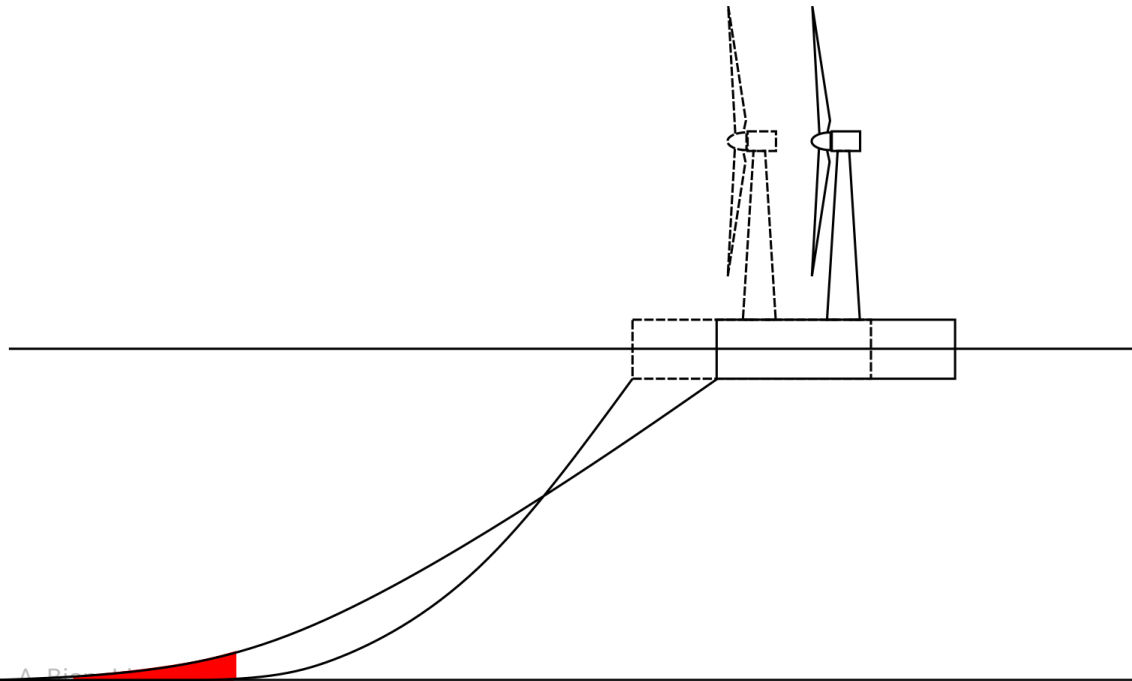
Mooring lines



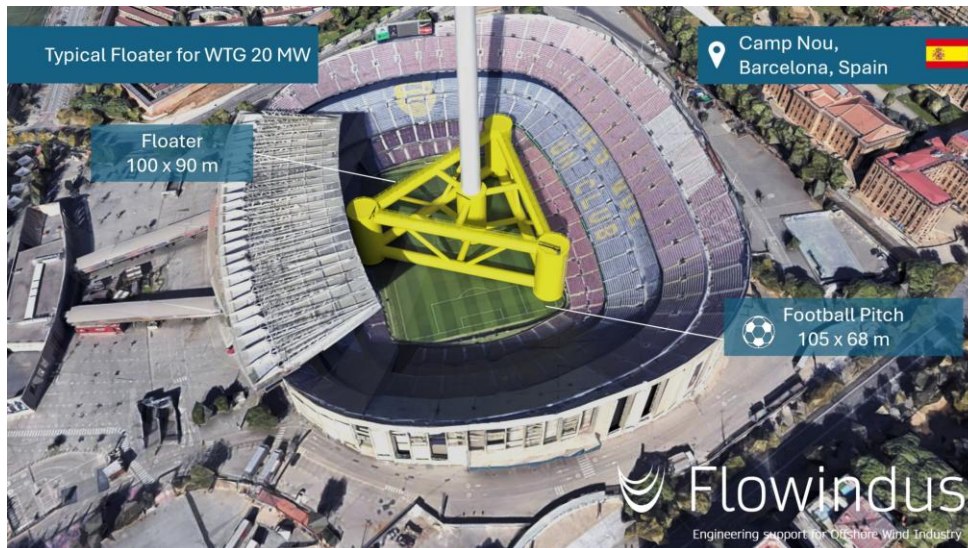
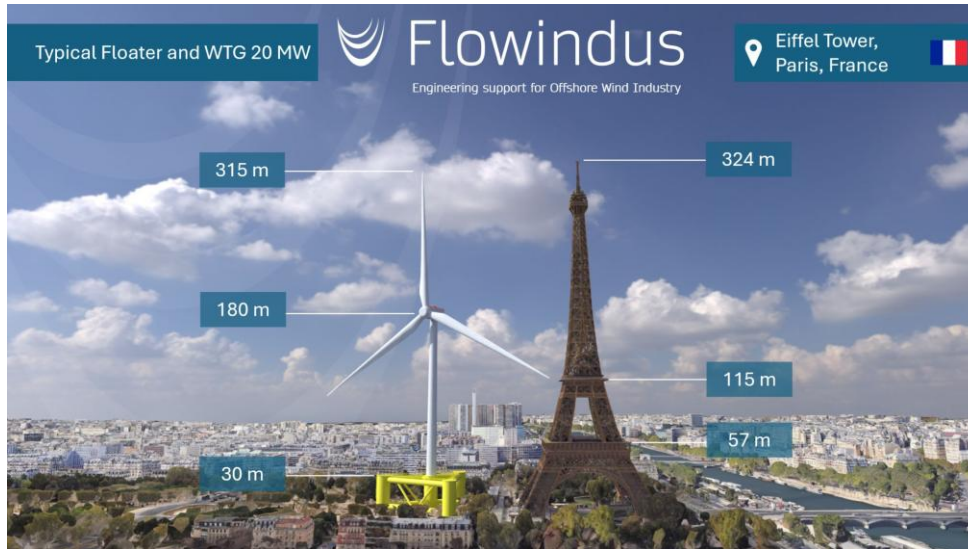
Catenary moorings rest on the seabed. As the floater moves, it has to lift the mooring line

- ✓ 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.



Floating foundations are huge!

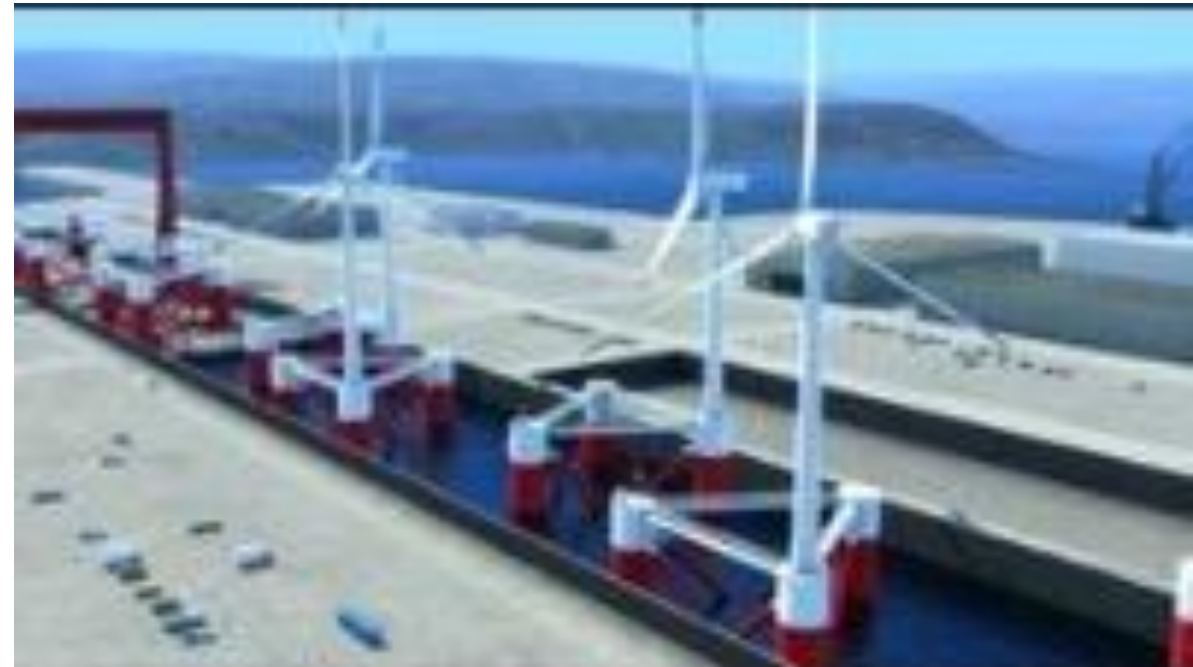


Installation and O&M



Floating wind has potential advantages in O&M

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



Standardization



Despite the above, wind turbines are an industrial product and require standardization and serial production to keep costs low

- ✓ not easy as they are subject to some of the same site-specific issues of civil engineering structures (bridges, skyscrapers), which are designed much more on a site-specific basis
- ✓ strong industrial IP protection
- ✓ **optimization is important!**





4

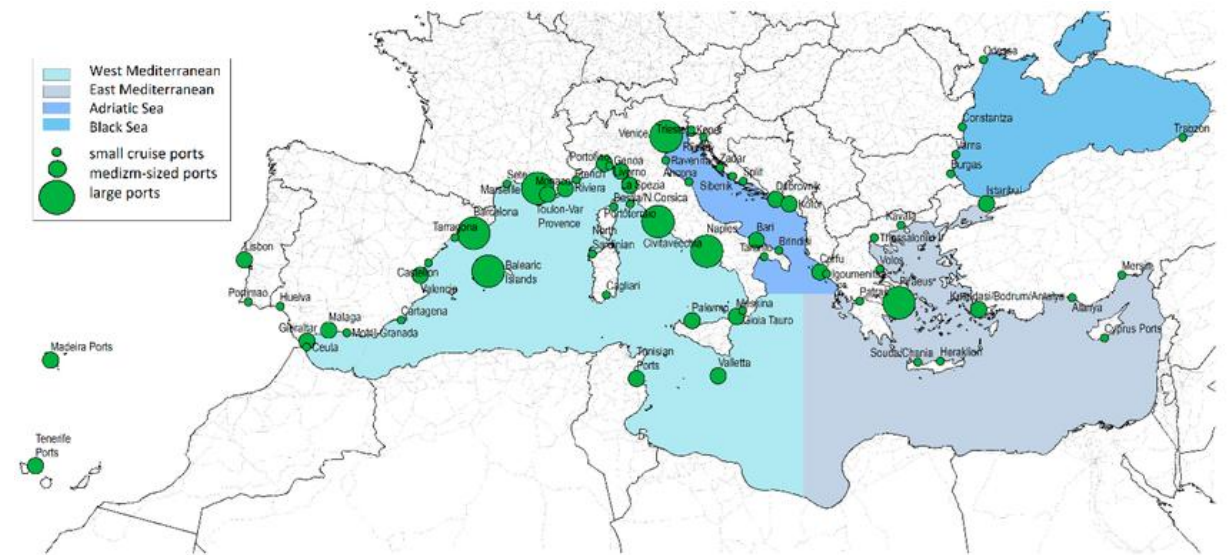
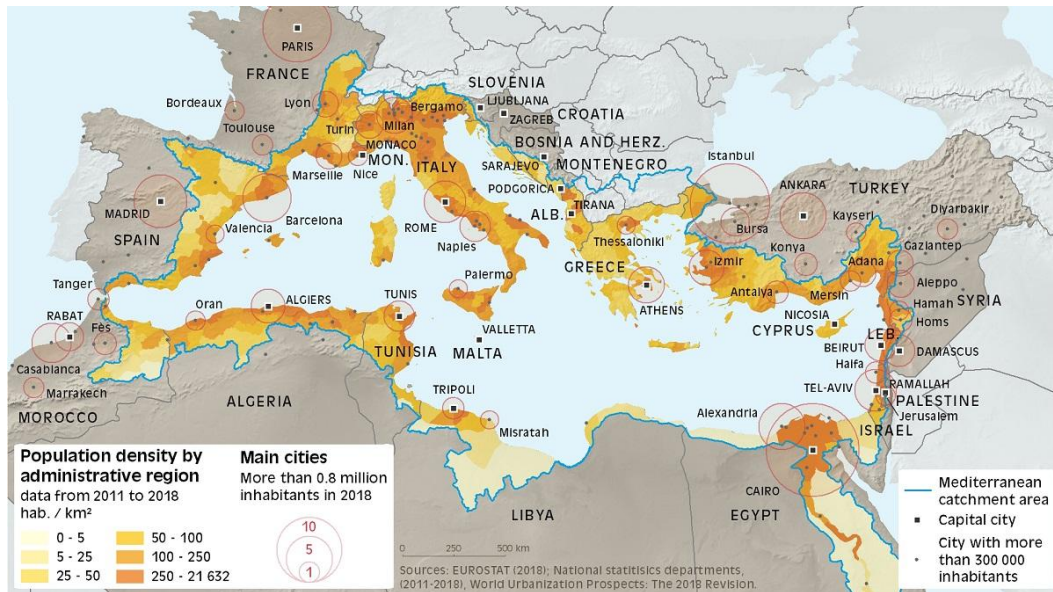
The Mediterranean Sea

Offshore wind in the Mediterranean Sea?



Offshore wind in the Med Sea is seen as a key driver for energy transition in Southern Europe

- ✓ densely populated area
- ✓ industrial areas facing the Sea (especially in France and Italy)
- ✓ several ports for shipping, tourism, and...wind turbines?



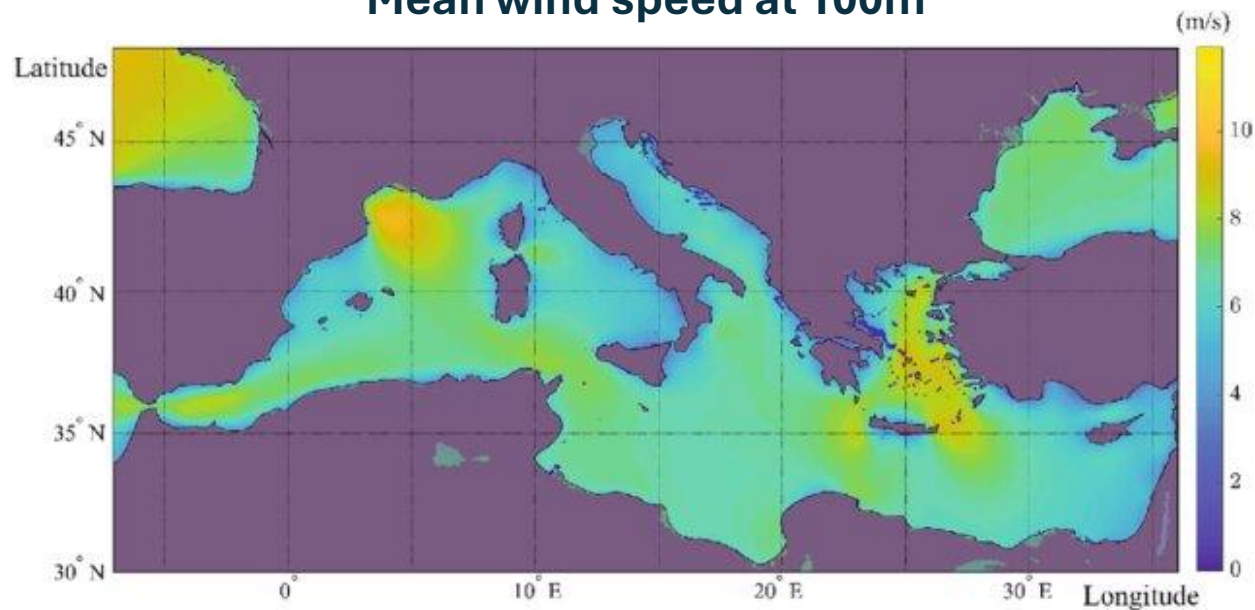
Metocean conditions in the Mediterranean Sea



Metocean conditions are different from engineers are used to deal with in the North Sea

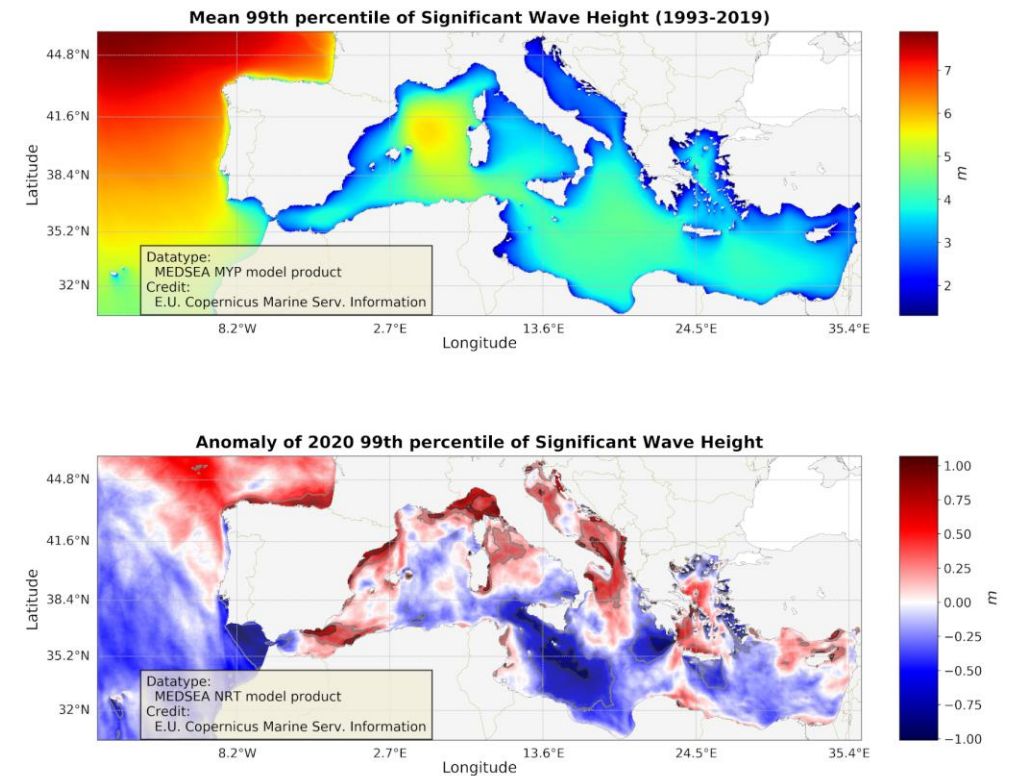
- ✓ wind and waves

Mean wind speed at 100m



DOI: 10.1016/j.enconman.2021.114416

Mediterranean Sea wave height extreme variability mean and anomaly.



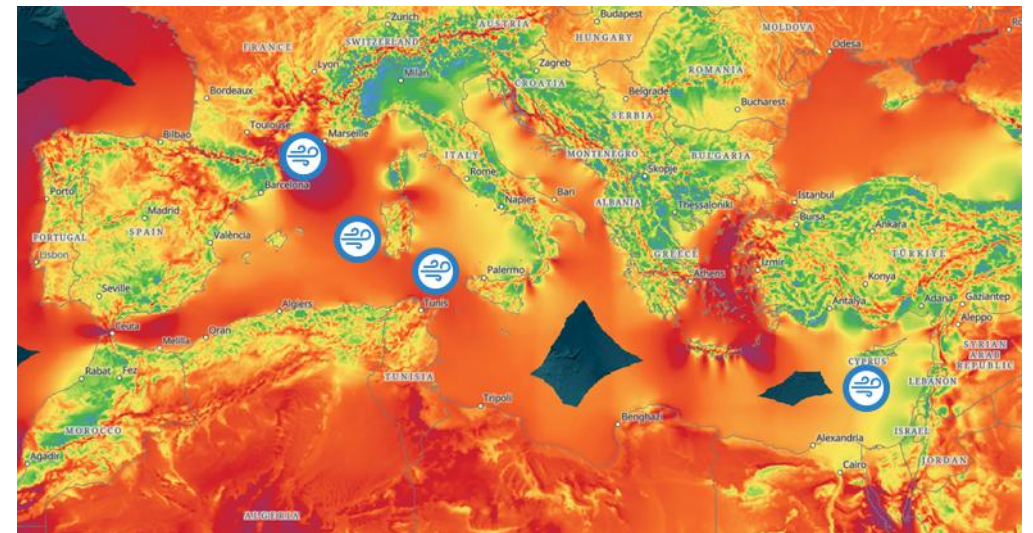
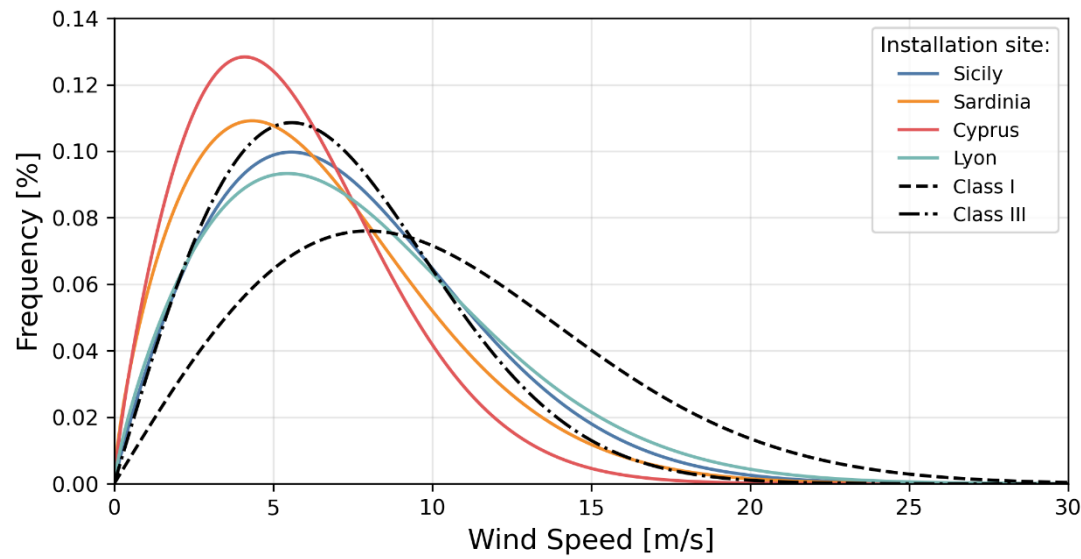
Wind energy potential



Several sites are promising, despite wind speeds much lower than those in the North Sea

- ✓ most of today's WTs are designed for such conditions (Class I)

WT designs for the Med Sea should be tailored for Class III



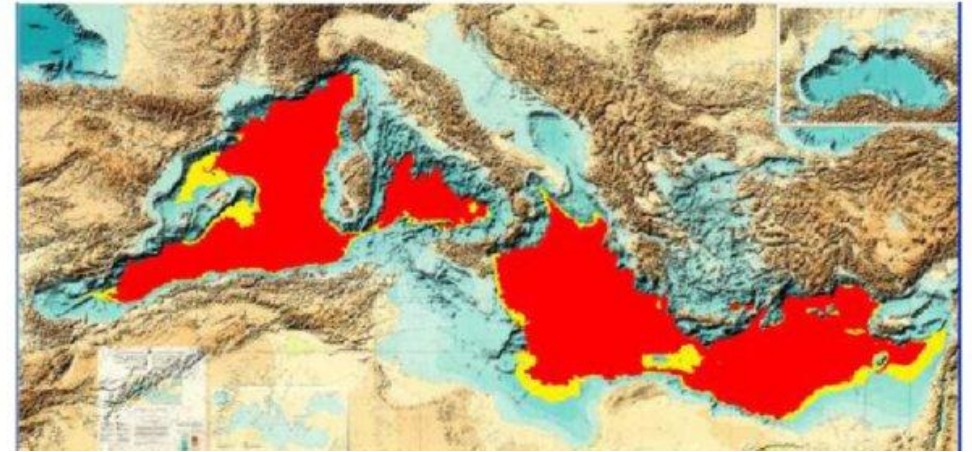
Seabed in the Mediterranean Sea



The seabed is also very complex

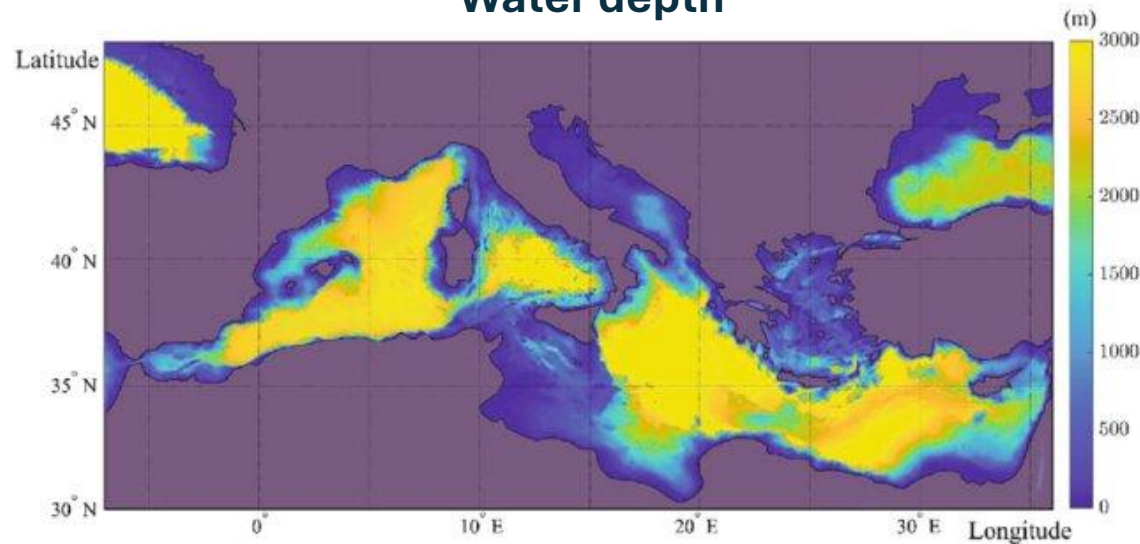
- ✓ high depths
- ✓ complex morphology (also within the same area)
- ✓ variable seabed types (relevant for anchoring)

Seabed morphology

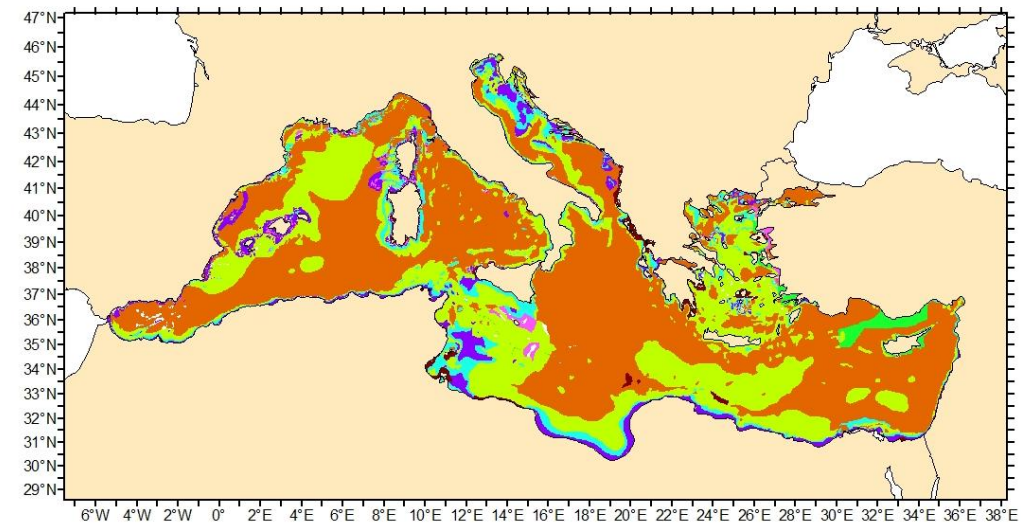


www.medemip.eu

Water depth

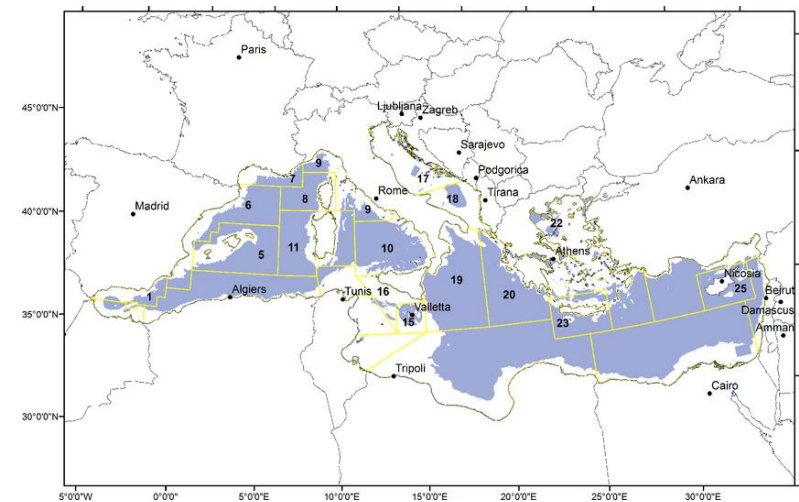
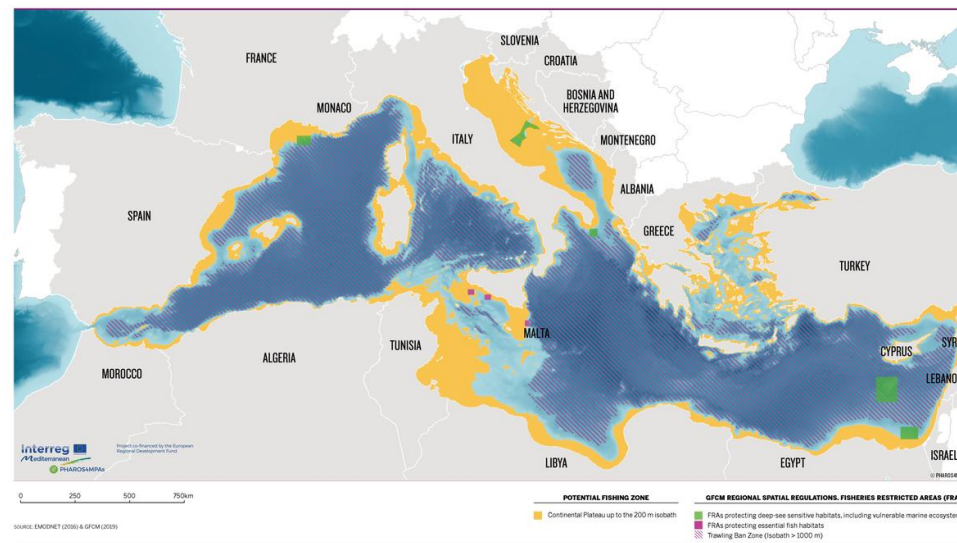
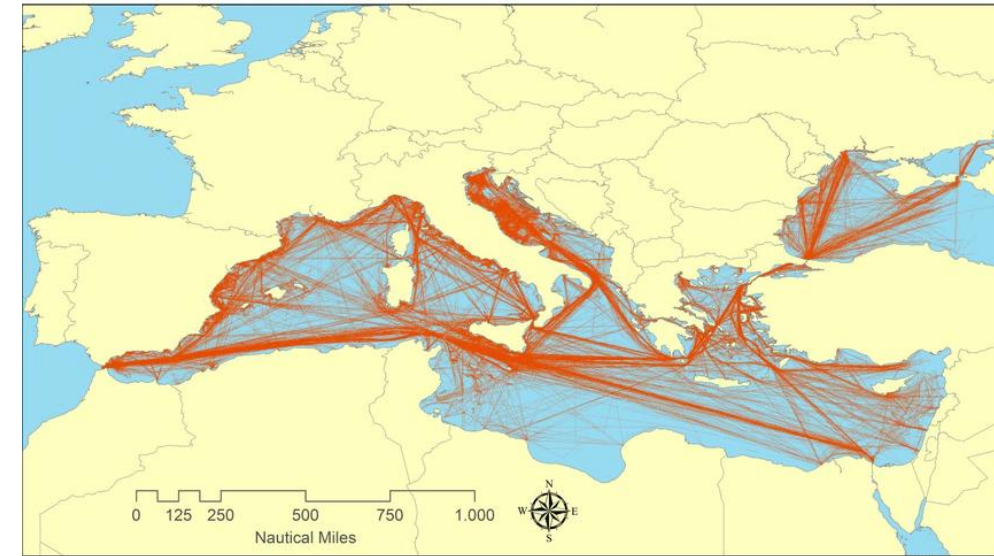
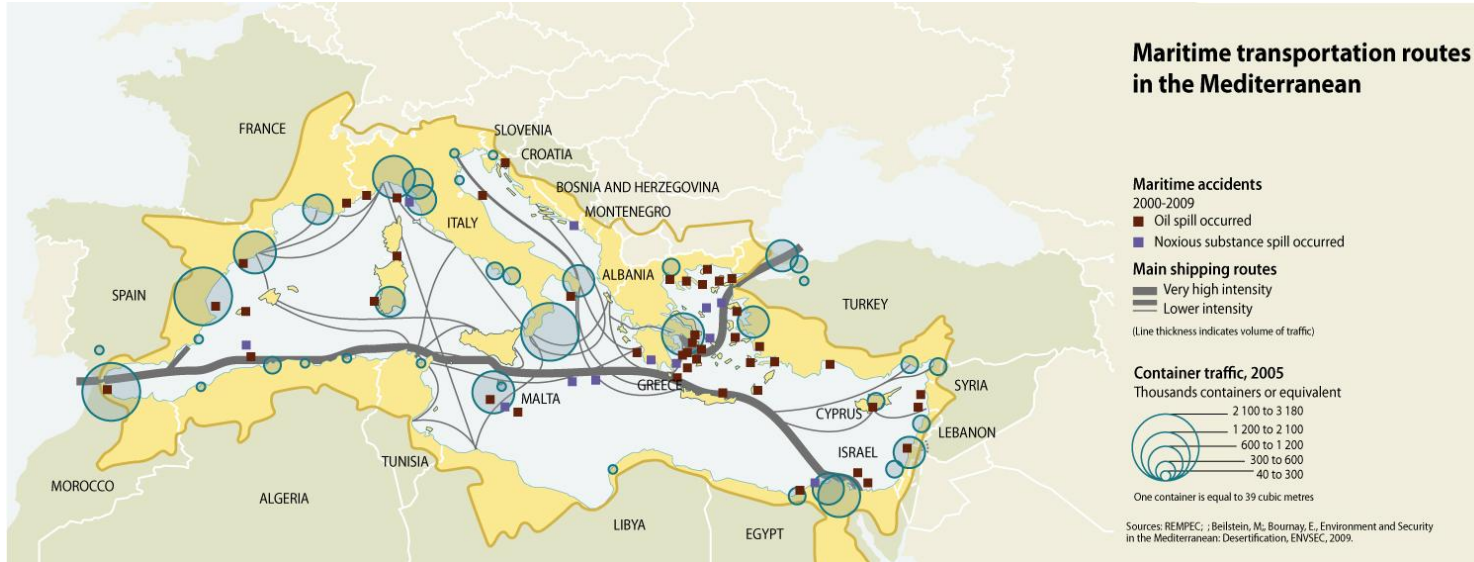


Seabed type (grain size)



DOI: 10.12770/522f867b-f8b0-412c-8e4a-5a49980856f8

A «crowded» sea



Continental plateau up to the 200m isobath, reflecting major potential fishing areas in the Mediterranean Sea, and spatial regulations adopted by the General Fisheries Commission for the Mediterranean (GFCM) between 2005 and 2018: the deep-sea trawling ban area under 1000m as well as nine Fisheries Restricted Areas.

Wind turbines for the Mediterranean Sea



By synthesizing the above for creating design guidelines for WTs in the Med Sea, two options may be spotted out:

1) FLOATING WIND TURBINES

- ✓ use of sea depths > 60m
- ✓ installed within the ports and towed to destination
- ✓ exploitable areas far from fishery, tourism and shipping
- ✓ novel technology, with high CAPEX and in turn LCOE

2) BOTTOM FIXED TURBINES IN THE ADRIATIC SEA

- ✓ easy and cheap to install
- ✓ lower CAPEX
- ✓ absolute need of tailored rotors because the energy potential is too low





5

Offshore wind farms

Why offshore farms?



Pros

- ✓ better wind source
- ✓ reduced visual and noise impact
- ✓ absence of land use conflicts
- ✓ reduced constraints on available lot size
- ✓ installation of larger aerogenerators

Cons

- ✓ high capital and operational expenditures
- ✓ difficult and expensive installation procedures
- ✓ harsh marine environment
- ✓ possible environmental constraints



Bottom-fixes vs floating wind turbines

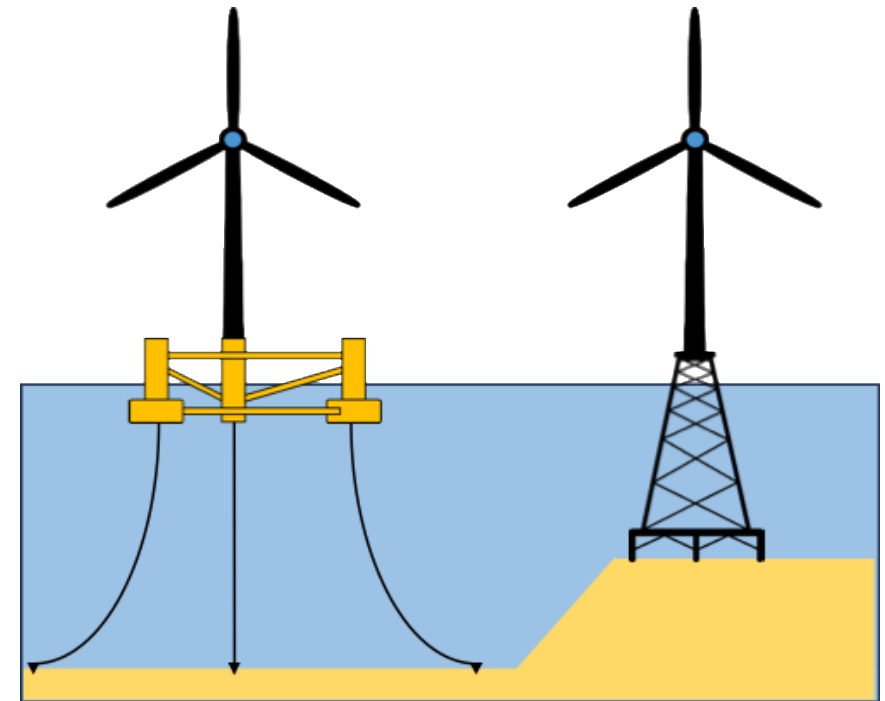


Bottom-fixed wind turbines

- ✓ water depth: <60-70 m
- ✓ current standard: 15 MW wind turbine installations
- ✓ lower CAPEX (1200-1800 €/kW) and OPEX
- ✓ lower design efforts (tower, rotor, foundation loads, ...)
- ✓ more challenging and expensive installation

Floating wind turbines

- ✓ water depth: 70-800 m
- ✓ current proposals: 18 MW wind turbine installations
- ✓ higher CAPEX (2000-3500 €/kW) and OPEX
- ✓ higher design efforts (tower, rotor, foundation loads, ...)



Bottom fixed wind turbines

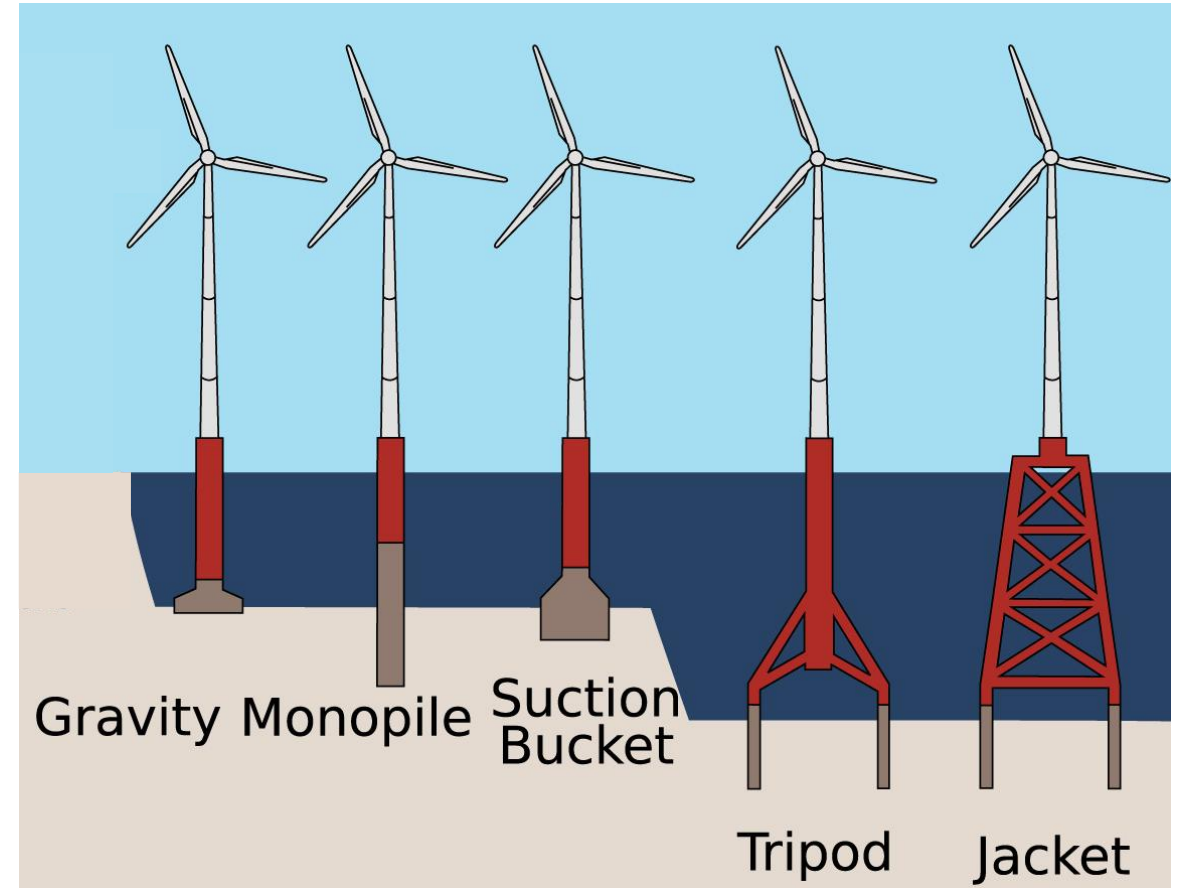


Installed capacity in MW (2022):

- ✓ Monopile 35502
- ✓ Jacket 6152
- ✓ Tripod 1060
- ✓ Gravity 815
- ✓ Suction bucket 4.3

Projections on installed capacity in MW (2030):

- ✓ Monopile 52660
- ✓ Jacket 16244
- ✓ Gravity 5230



Source: Ribeiro et al., 2025, <https://doi.org/10.1016/j.apenergy.2025.126294>

Floating wind turbines

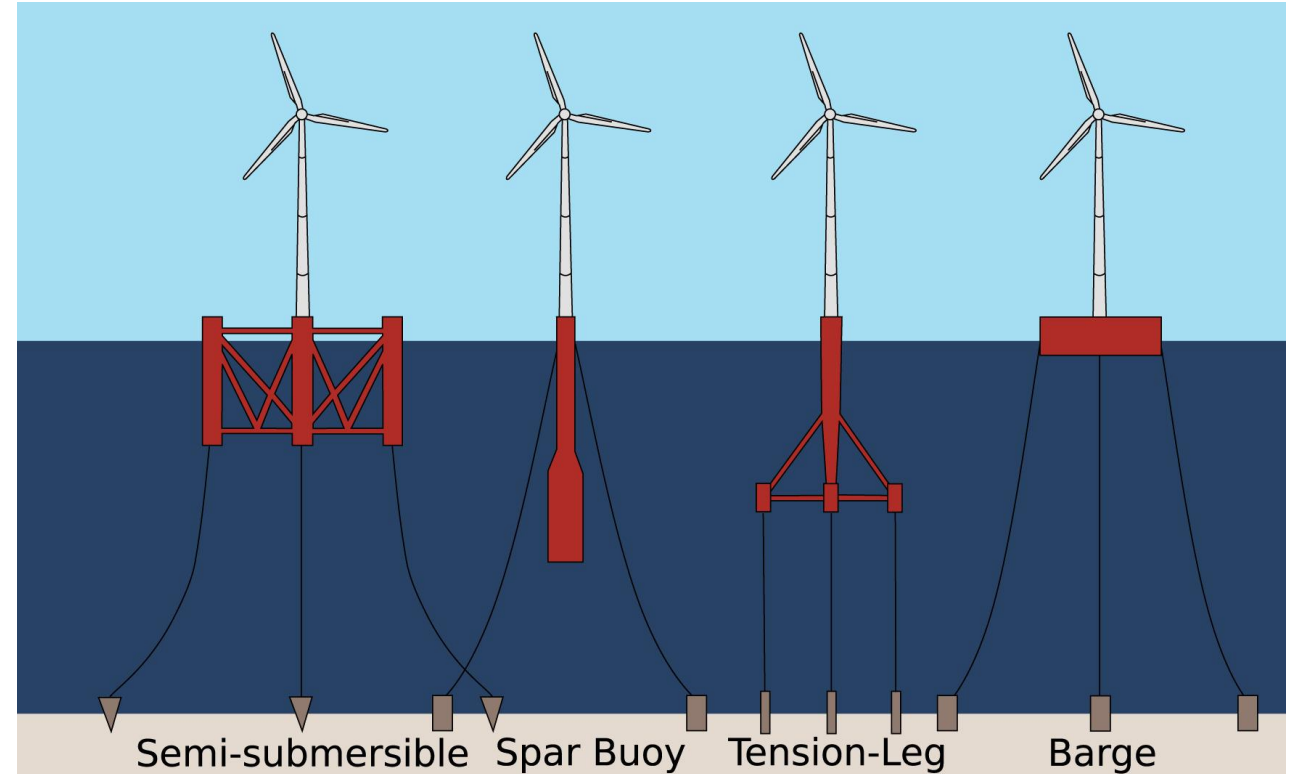


Installed capacity in MW (2022):

- ✓ Semisub 80.7
- ✓ Spar 37.9
- ✓ Barge 5

Projections on installed capacity in MW (2030):

- ✓ Semisub 28216.4
- ✓ Spar 3277.8
- ✓ Tension-leg 1972.7
- ✓ Barge 1542.0

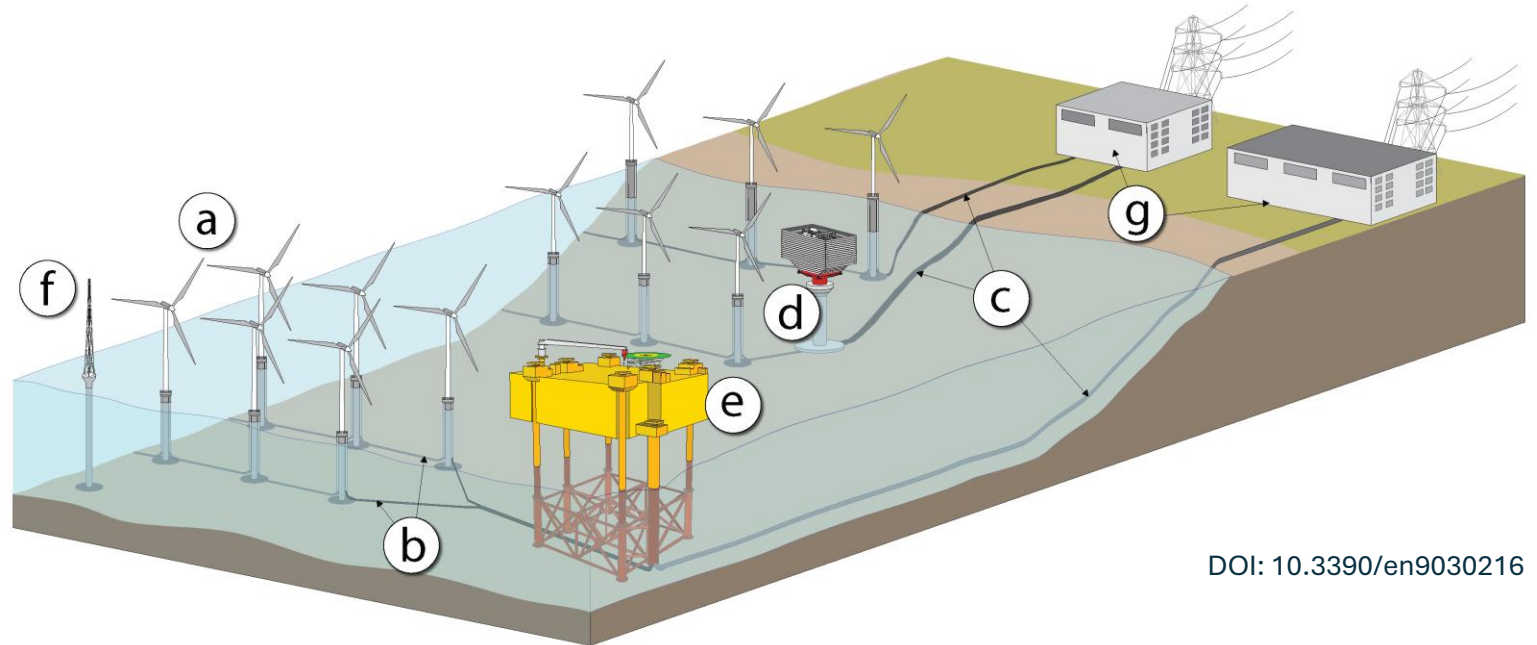


Source: Ribeiro et al., 2025, <https://doi.org/10.1016/j.apenergy.2025.126294>

Offshore wind farms

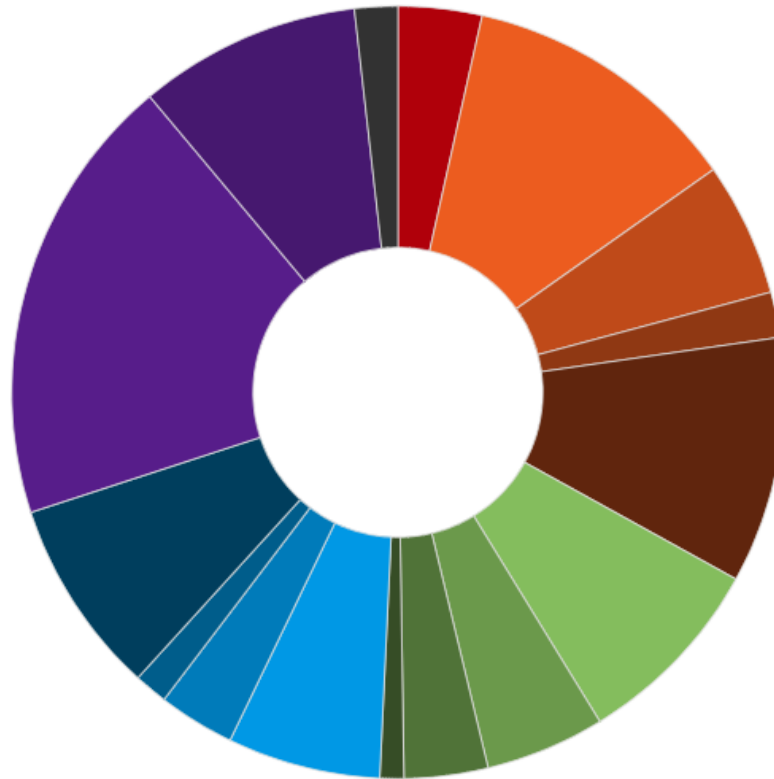


- a) Wind turbines
- b) Inter-array cables
- c) Export cables
- d) Transformer station
- e) Converter station
- f) Meteorological mast(s)
- g) Onshore station(s)



DOI: 10.3390/en9030216

Cost for offshore wind farms



Development and project management	3.5%	Nacelle	11.7%	Rotor	5.6%
Tower	1.9%	Other turbine	10.3%	Turbine foundation	8.2%
Cables	5%	Offshore substation	3.5%	Other BoP	1%
Offshore cable installation	6.4%	Foundation installation	3.2%	Turbine installation	1.4%
Other installation	8.2%	Maintenance & service	18.9%	Operations	9.3%
Decommissioning	1.8%				

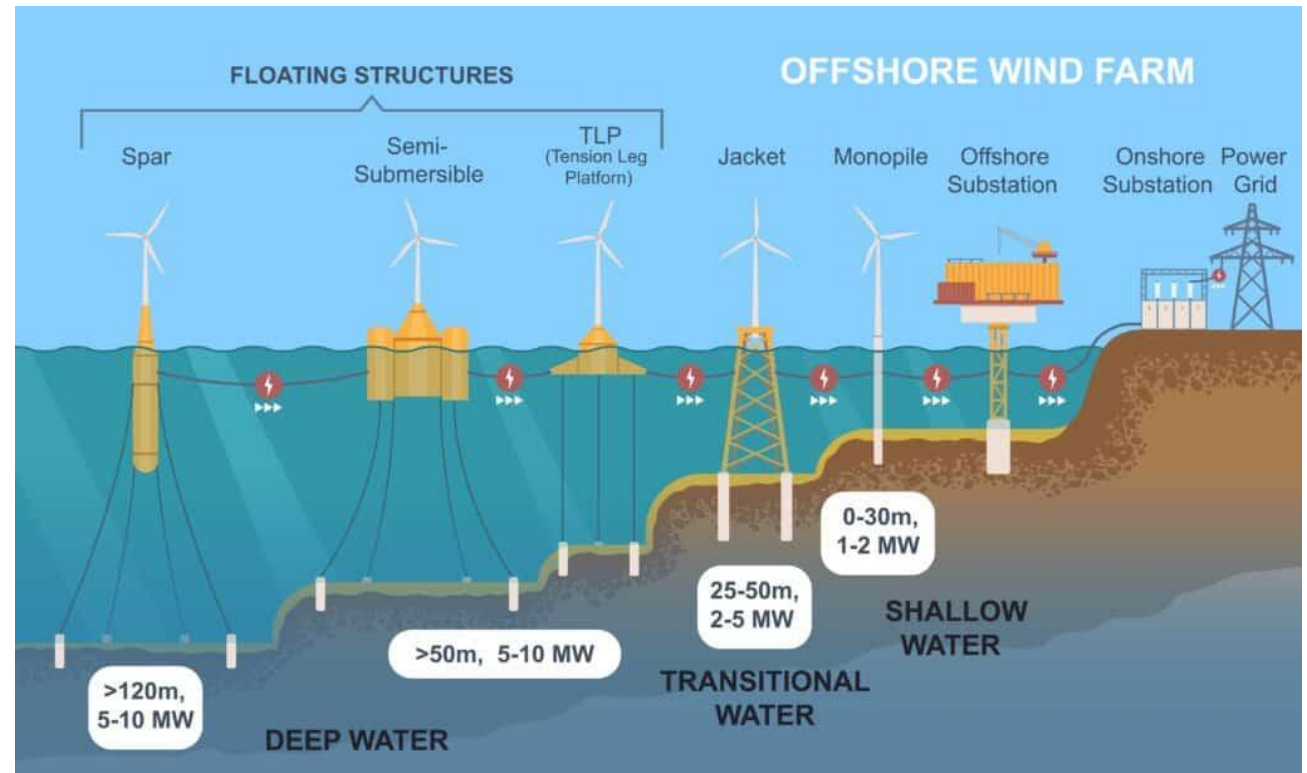
Balance of Plant (BoP)



The balance of plant includes all the components of the wind farm except the turbines. It also includes the transmission assets built as a direct result of the wind farm

- ✓ cables
- ✓ turbine foundations
- ✓ offshore substation
- ✓ substation foundation
- ✓ onshore substation
- ✓ operations base

The BoP cost approximately €1.3 billion for a 1 GW wind farm



<https://sinay.ai/en/what-is-floating-wind>

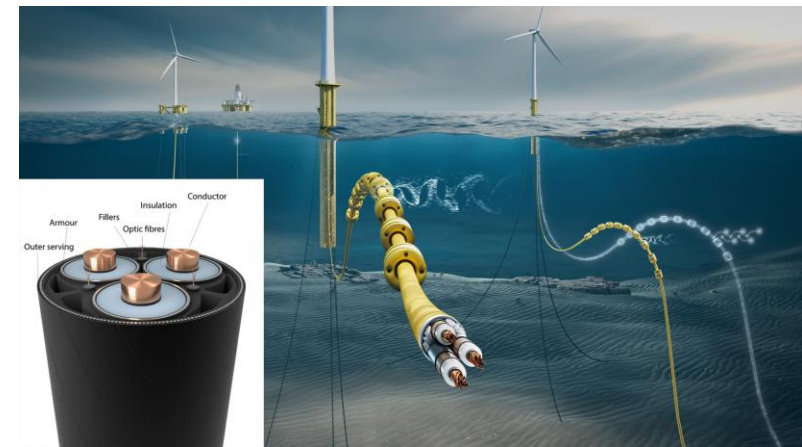
FUNCTION: cables deliver the power output from the wind turbines to the grid

COST: about €400 million for a 1 GW wind farm

KEY FACTS (1/2)

- ✓ Offshore wind farms use (definitions):
 - **inter-array cables** to deliver power from the wind turbines to the offshore substation
 - **export cables** to deliver power from the offshore substation to the onshore substation
 - **subsea cables** used for the array cables and the offshore section of the export cable
 - **onshore cables** used for the export cable section between the shore and the onshore substation

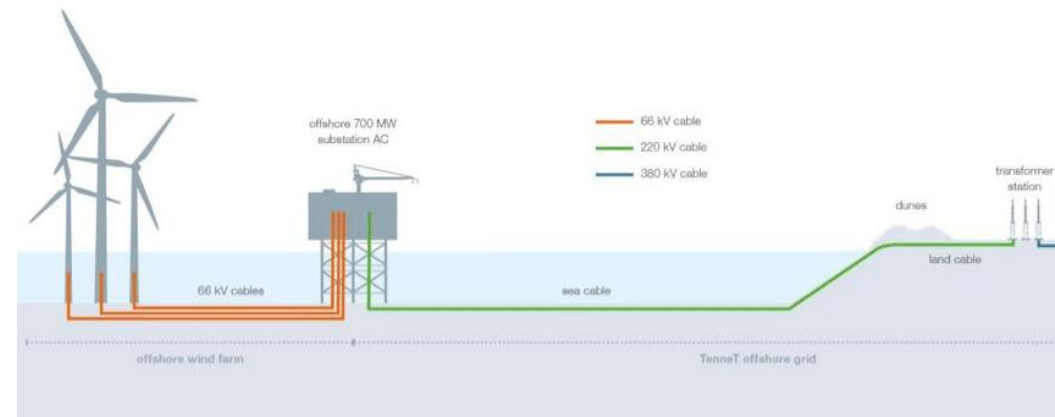
- ✓ A standard subsea cable used in offshore wind is made up of a stranded, profiled conductor with a combination of sealing layers, insulation, fillers, and protective armouring. Subsea AC cables have three cores (one for each phase). Onshore AC cables have single cores and are laid in groups of three. DC cables (land and subsea) have single cores (two, one positive and one negative, for each circuit)





KEY FACTS (2/2)

- ✓ There are three main insulated power core design types:
 - **Dry**, with an extruded lead sheath over the insulation
 - **Semi-wet**, with a polyethylene sheath over a non-fully impervious metallic screen
 - **Wet**, without a sheath over a non-fully impervious metallic screen
- ✓ Wet designs have the advantage of being lighter and more flexible. Currently, cables with voltages above 66 kV are only available as dry designs
- ✓ The terms for voltage ratings are not formally defined by the industry: **Low voltage (LV)** typically refers to cables rated up to 11 kV, **medium voltage (MV)** typically refers to cables rated up to 66 kV, **high voltage (HV)** typically refers to cables rated up to 220 kV and **extra high voltage (EHV)** typically refers to cables rated higher than 220 kV
- ✓ HV and EHV cables are generally associated with transmission networks and export cables, whereas MV is associated with array cables. The wind turbines generate at LV with a transformer at the base of the tower stepping up exported power to MV



Export cables



Deliver energy to shore using electricity as an energy vector

Depending on the distance, two different technologies can be adopted:

✓ HVAC

- Used for small distances to shore < 70 - 90 km depending on installed power
- Lower fixed cost (0.129 M€/MW) but higher cost per unit length (0.0059 M€/MW/km)
- High electricity losses per unit length 3-4% per 50 km

✓ HVDC

- Used for long export distances > 90 km
- Higher fixed cost (0.39 M€/MW) but lower cost per unit length (0.0018 M€/MW/km)
- Lower electricity losses per unit length 1-2% per 100 km

Electrical substation



Offshore substation

FUNCTION: The offshore substation connects the array cable system to the export cables

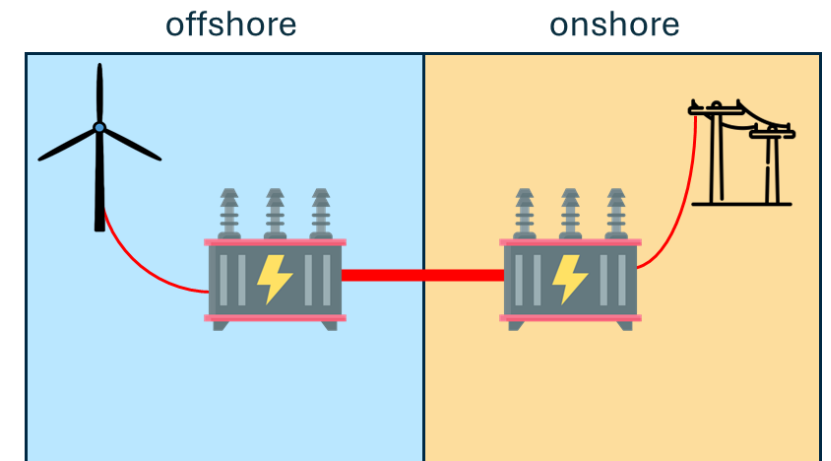
COST: about €275 million for a 1 GW wind farm

- ✓ hosts the power electronic components used for AC-DC conversion
- ✓ connection point between inter-array and export cables
- ✓ floating or bottom fixed, depending on the sea depth
- ✓ can host pv panels or electrolysis facilities in hybrid plants



Onshore substation

- ✓ represents the point of delivery of electricity
- ✓ connects the wind farm with the transmission grid or the demand
- ✓ critical for land occupation





6

Hands-on case study: a Mediterranean wind farm

Riccardo Travaglini
Alessandro Bianchini



Cyprus, 03/09/2025

Offshore Wind Energy

Prof. Alessandro Bianchini

alessandro.bianchini@unifi.it





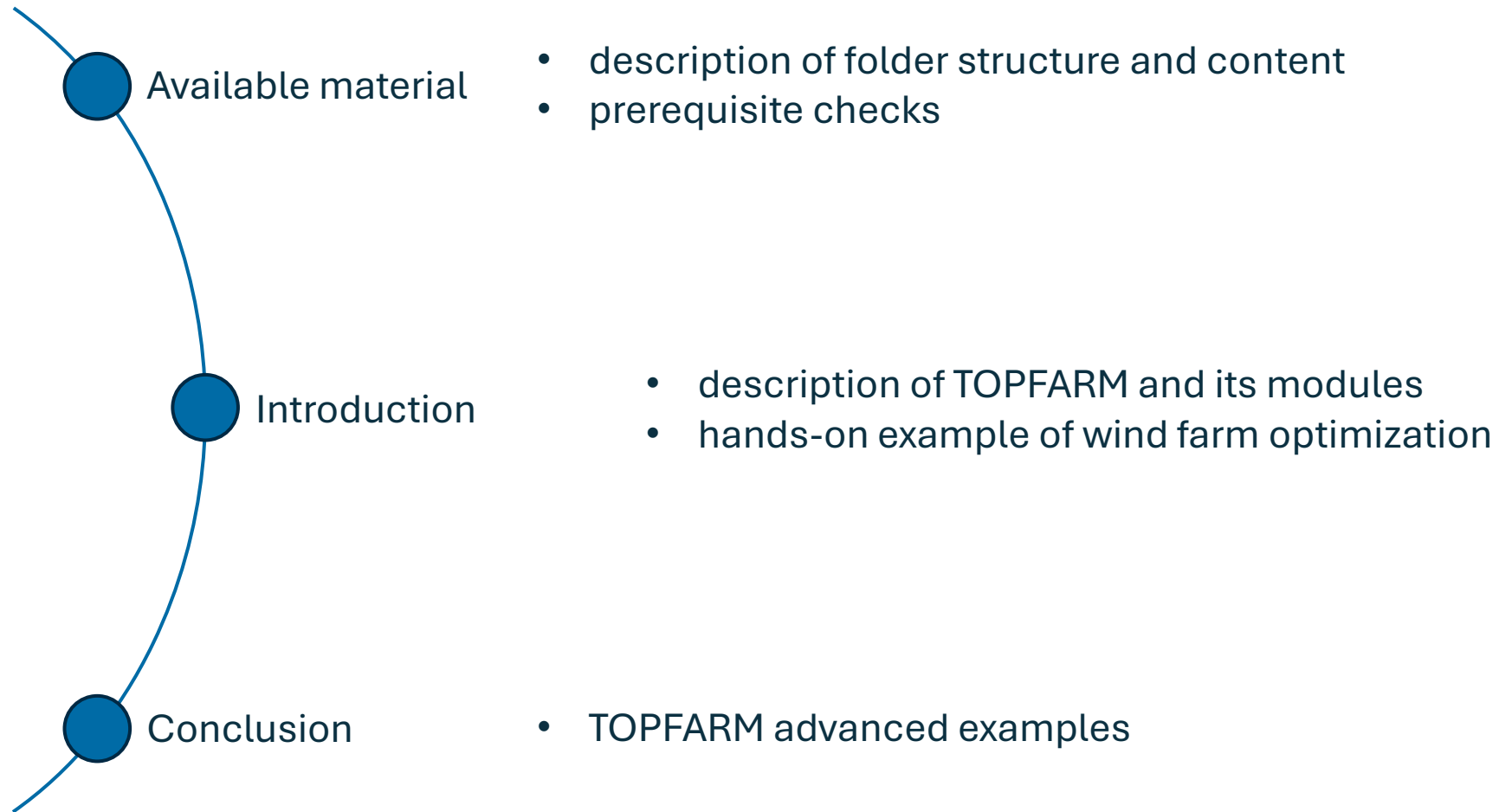
Cyprus, 03/09/2025

Offshore wind farm optimization

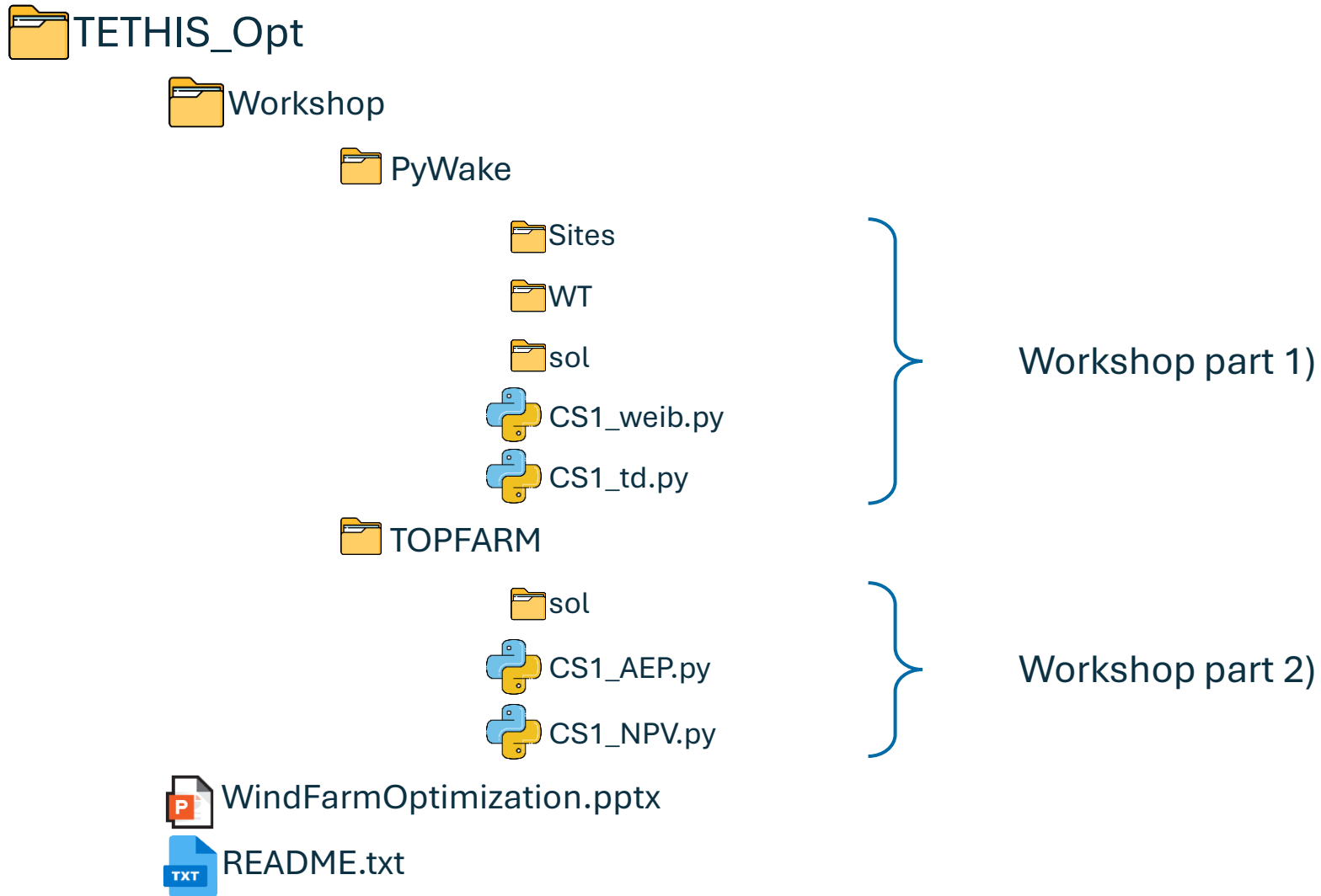
R. Travaglini, A. Bianchini



Workshop agenda



Available material



Package checks



In order to go ahead with the workshop, please check the version of the libraries installed on your device in the topfarm conda environment

Activate the conda environment:

```
conda activate topfarm
```

python version (should be 3.11)

```
python -V
```

numpy version (should be <2.0)

```
pip show numpy
```

topfarm version (should be 2.5.3.post2)

```
pip show topfarm
```

edwin version (should be 0.0.1)

```
pip show ed_win
```



Introduction

Integrated wind farm model

- uses OpenMDAO for farm optimization
- wraps PyWake for the computation of AEP
- able to optimize onshore and offshore (fixed-bottom) farms

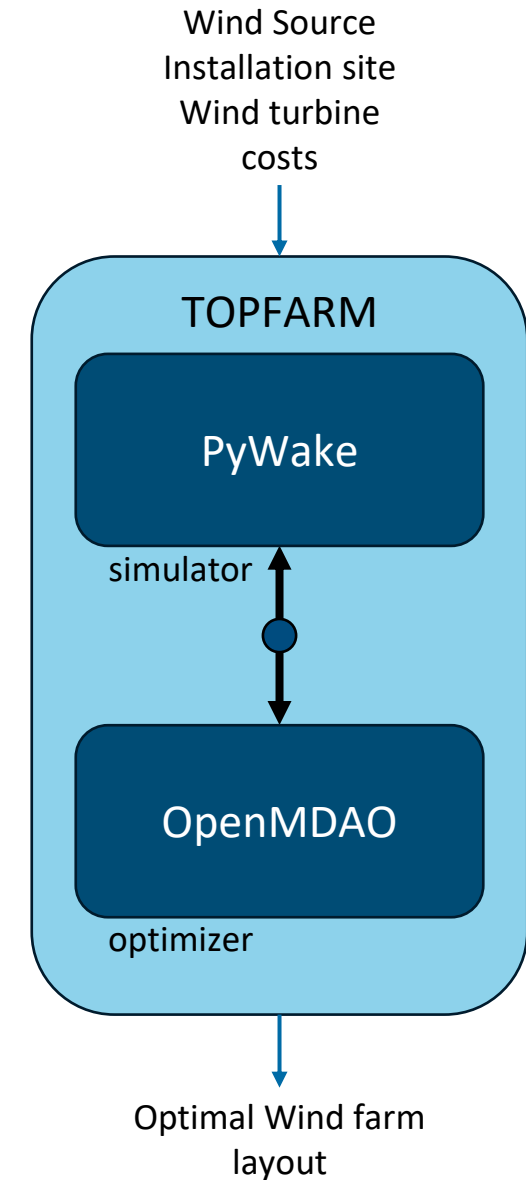
Input

- Weibull distribution of wind speed and direction
- installation site (bathymetry, available sea lot)
- wind turbines
- costs

Output

- optimal layout according to the objective function

<https://topfarm.pages.windenergy.dtu.dk/TopFarm2/index.html>





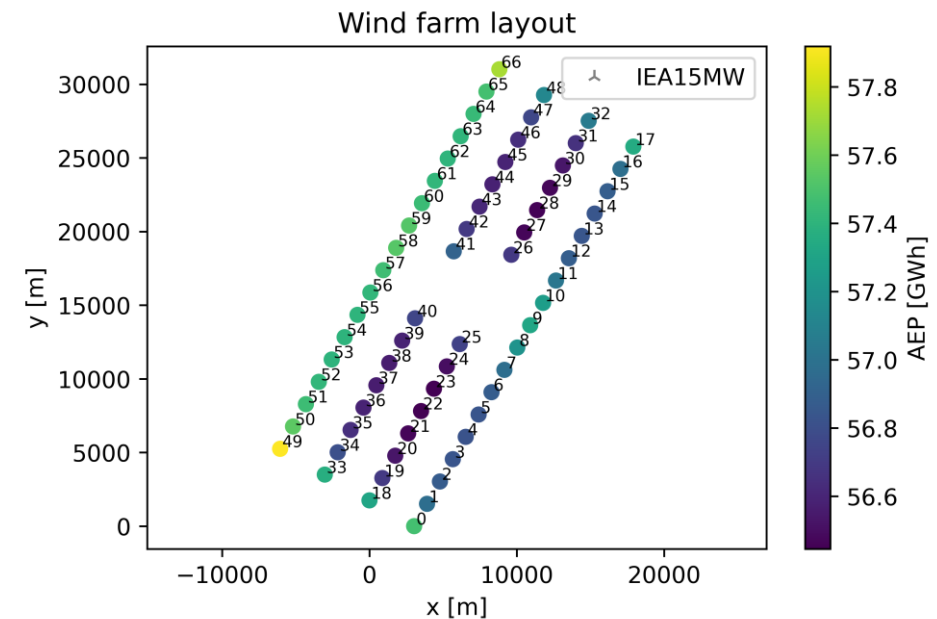
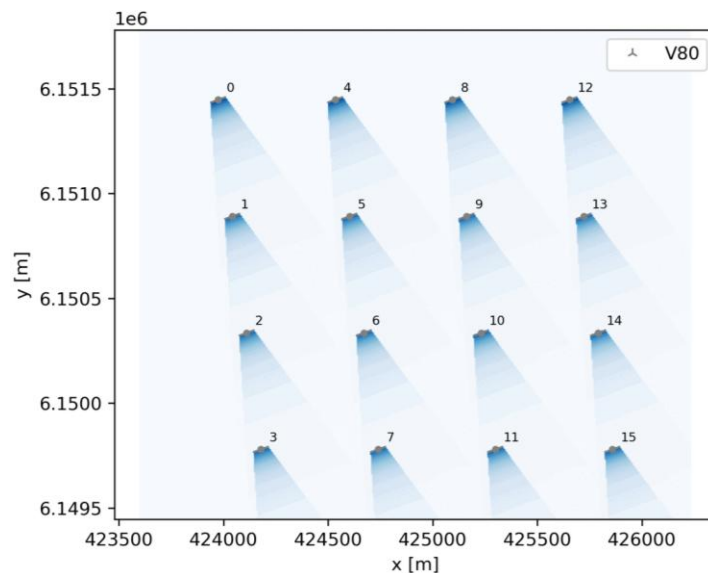
Introduction

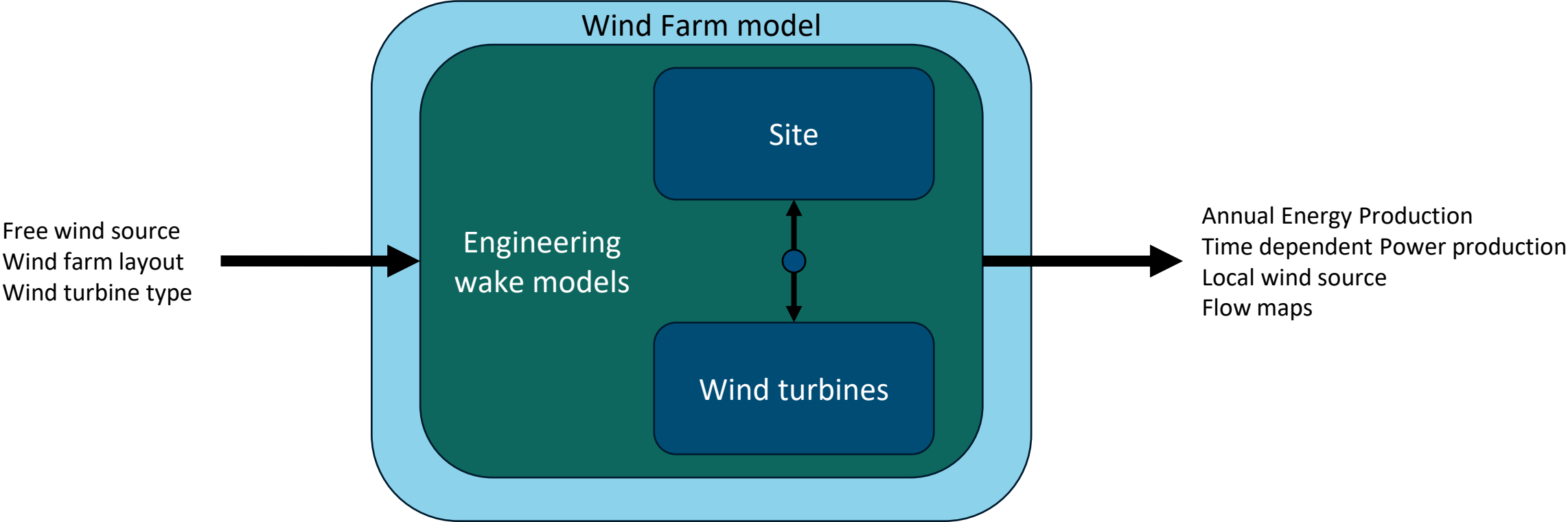
What can do

- wake interaction in a wind farm (low computational time)
- use of user-defined wind turbines
- evaluation of the single wind turbine production
- time-dependent Power production / AEP
- wind turbine optimization in TOPFARM



<https://topfarm.pages.windenergy.dtu.dk/PyWake/>

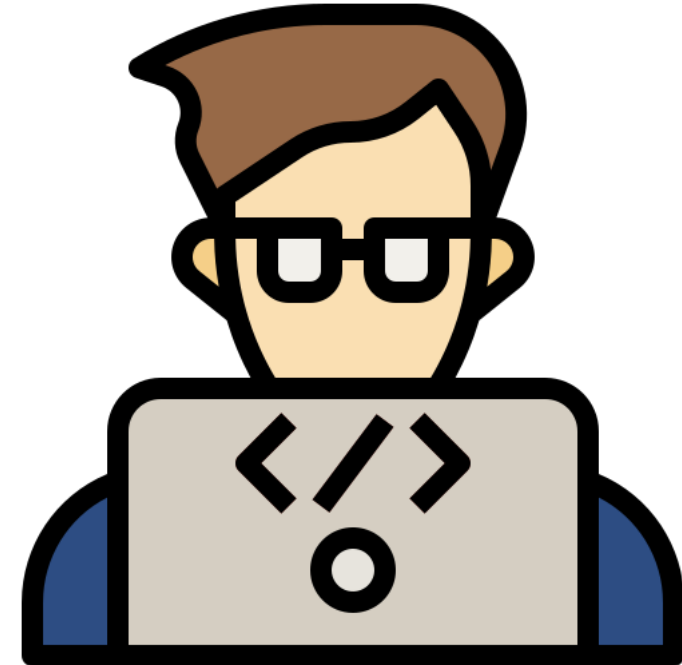




Let's do some coding

- Guided example:
 - CS1_weib: wind farm power production (Weibull)
 - CS1_td: wind farm power production (time-dependent)
- Try yourself, play around with:
 1. wind turbines (CS2_weib)
 2. installation sites (CS3_weib)
 3. wake model (CS4_weib)

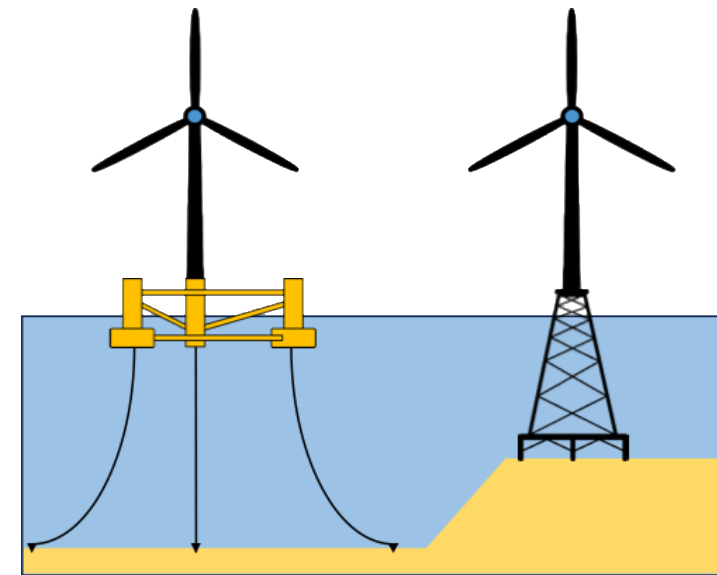
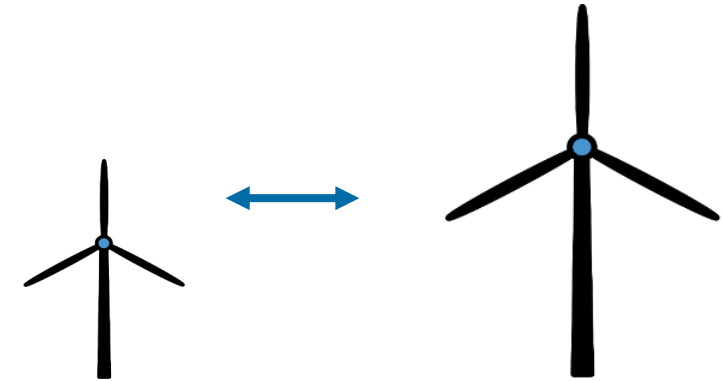
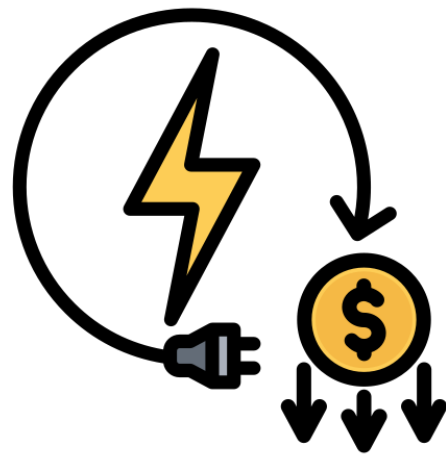
(solutions available in sol folder)



Introduction

What can do

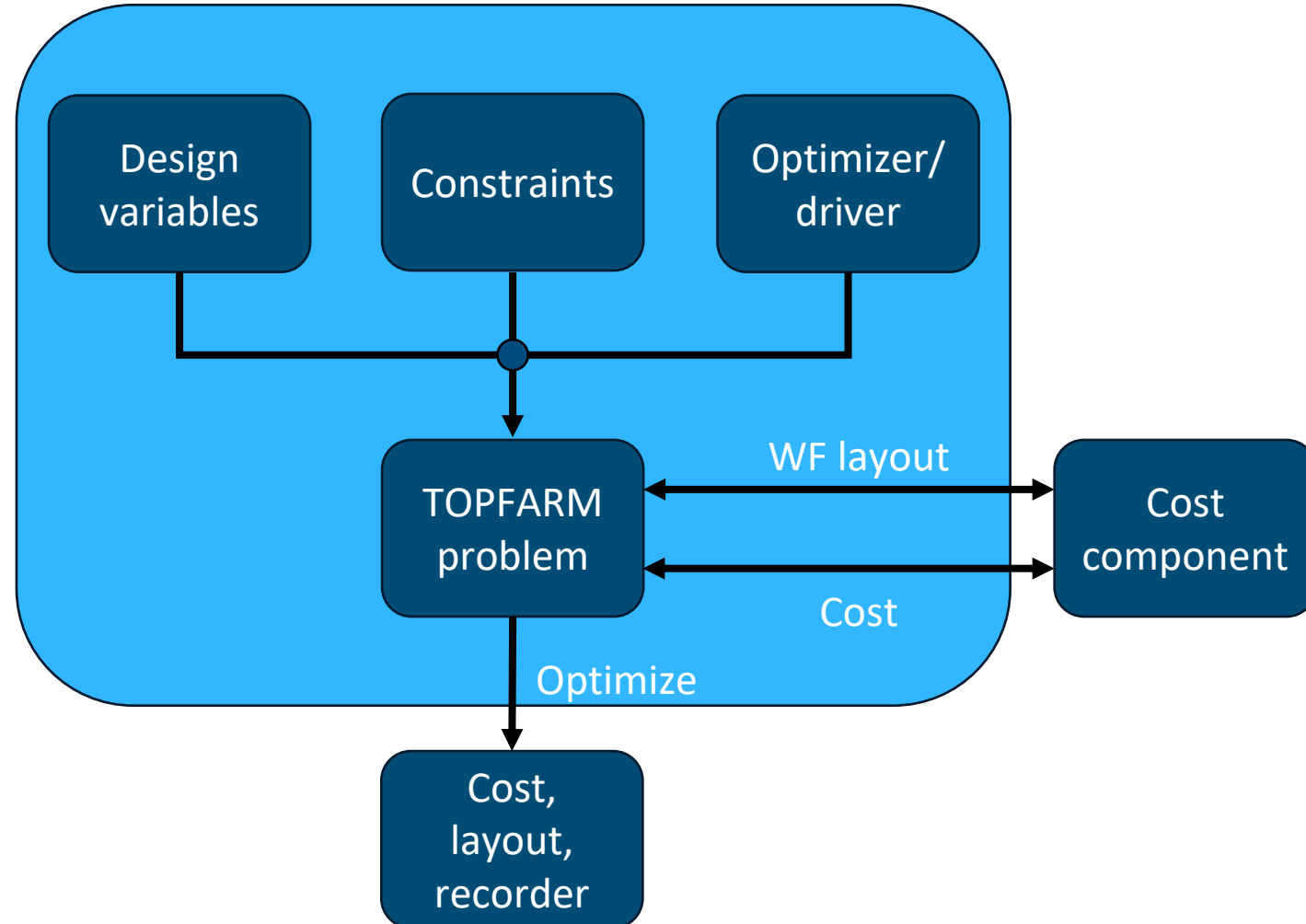
- wind farm layout optimization for different turbine types
- wind farm layout optimization for different turbine hub heights
- load-constrained layout optimization
- wind farm layout optimization including bathymetry
- cost/revenue-based layout optimization





How it works

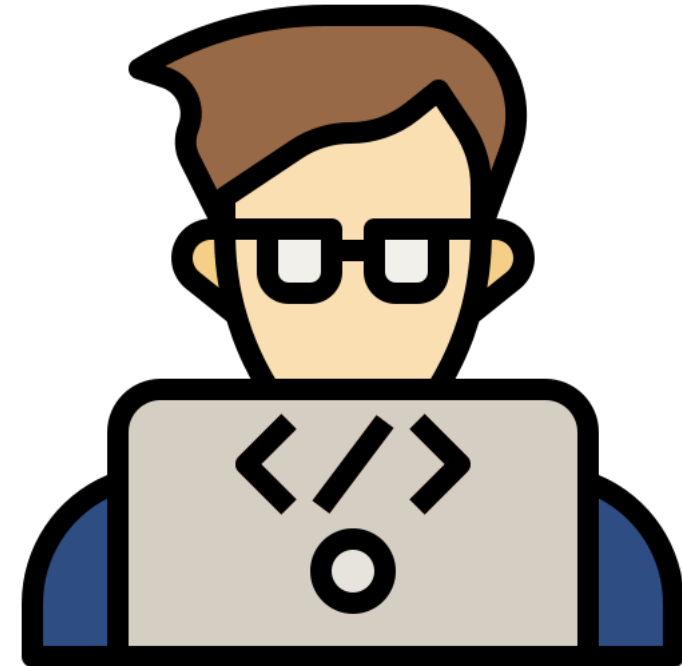
- ✓ **design variables:** during the optimization, the design variables are changed while influencing the objective function. E.g., turbine position, type, hub height
- ✓ **cost component:** topfarm's core, defines component costs and optimization function
- ✓ **drivers:** define the optimization algorithm
- ✓ **constraints:** ensure that the optimization results represent feasible/realistic solutions. E.g., minimum distance between turbines, allowed sea/land lot
- ✓ **cost, layout, recorder:** final optimization result. E.g., LCOE), final result of design variables, optimization history



Let's do some coding

- Guided example:
CS1_AEP: Wind farm optimization AEP driven
- Try yourself, play around with:
 1. available sea lot shape, minimum WT distance (CS2_AEP)
 2. driver (genetic, random search algorithms) (CS3_AEP)
 3. wake model (CS4_AEP)

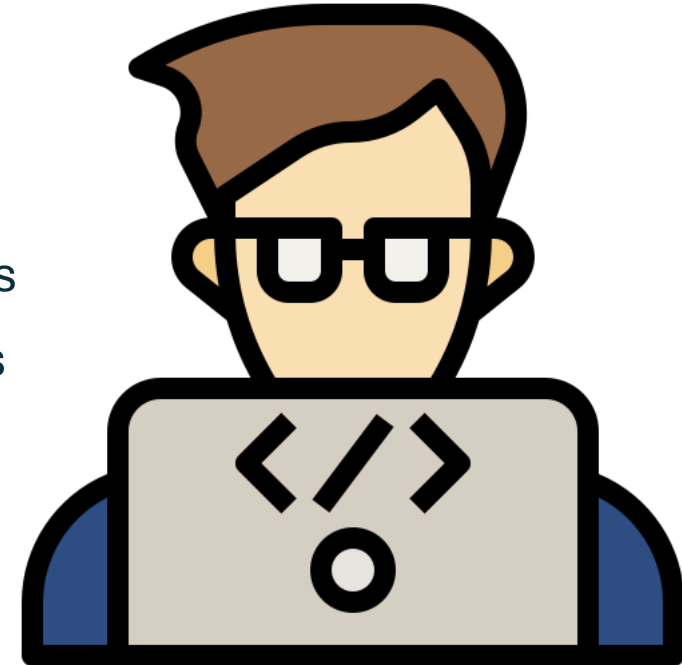
(solutions available in sol folder)



Let's do some coding

- Guided example:
 - CS1_NPV: Wind farm optimization NPV driven
 - CS2_NPV: Wind farm optimization NPV driven + IA cables
 - CS3_NPV: Wind farm optimization NPV driven + IA cables
- Try yourself, play around with:
 1. cable cost

(solutions available in sol folder)



Advanced examples

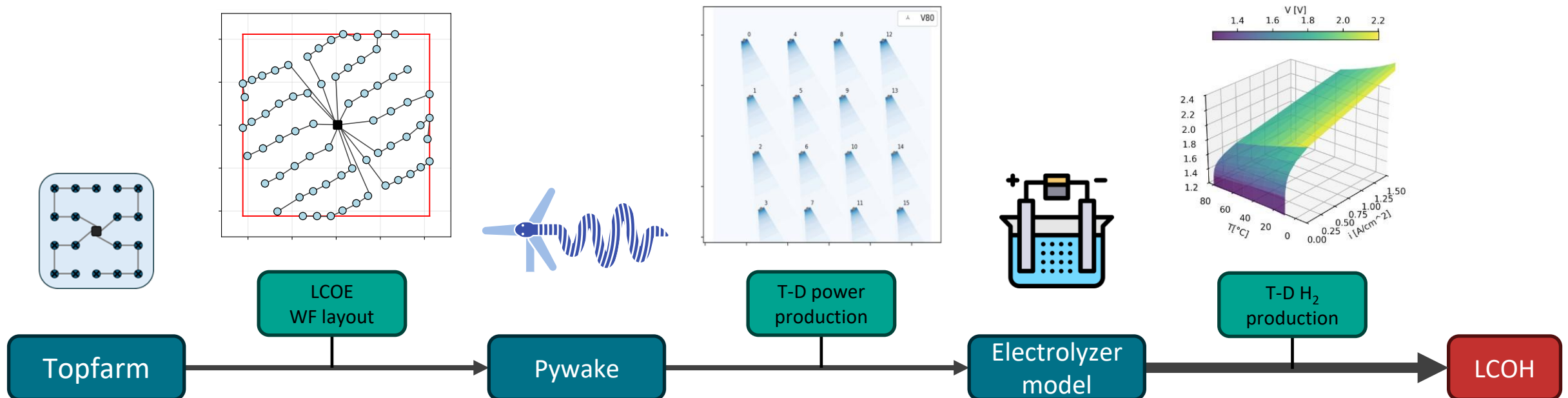


Wind farm customization:

- floating wind farm -> new cost model

Hydrogen integration:

- multi-step procedure for hydrogen production evaluation





Cyprus, 03/09/2025

Offshore wind farm optimization

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