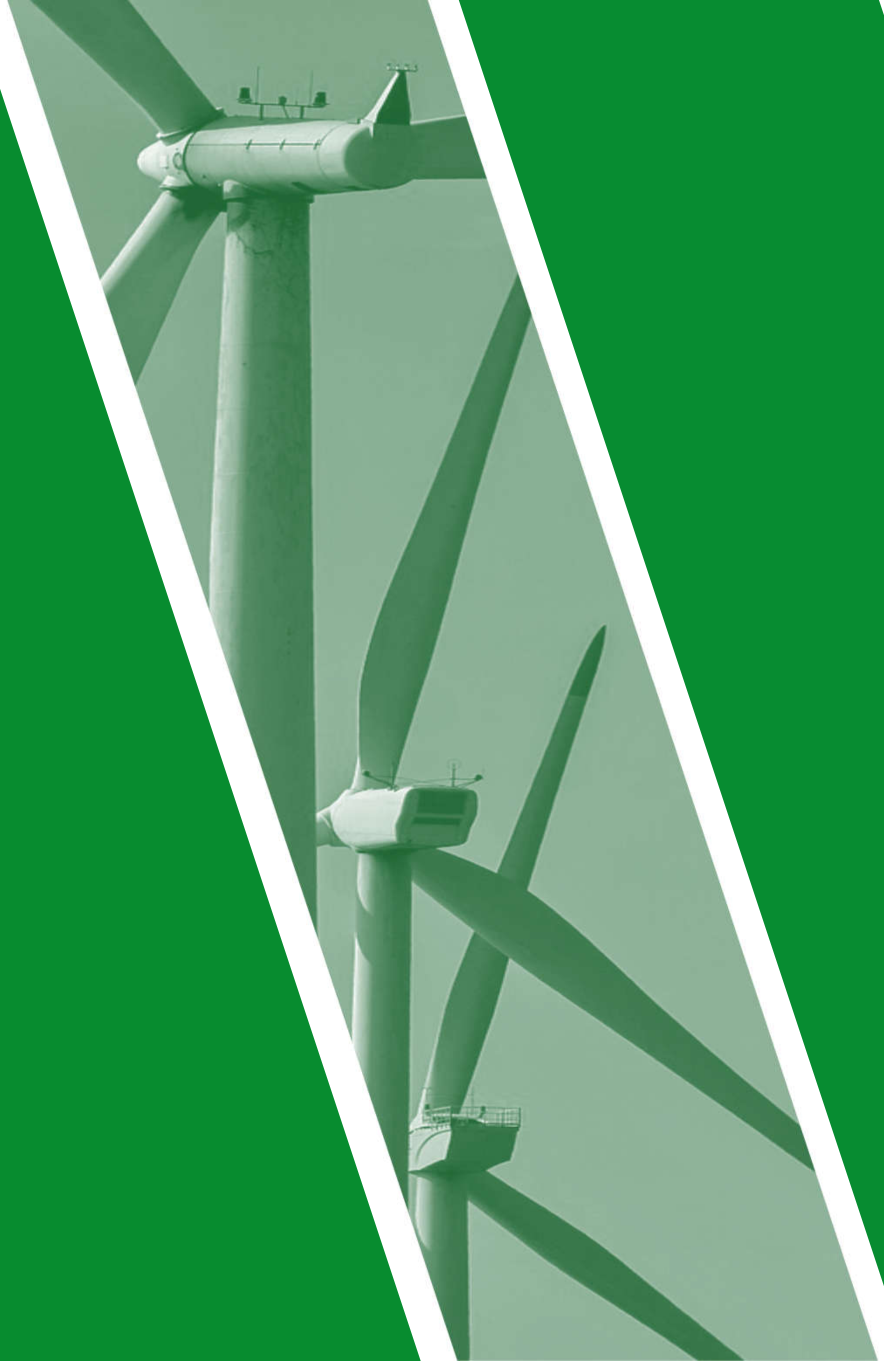

# Offshore Wind


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# Speakers

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# Outlook of the webinar



**Part 1 - An introduction to wind energy, with focus on offshore wind**

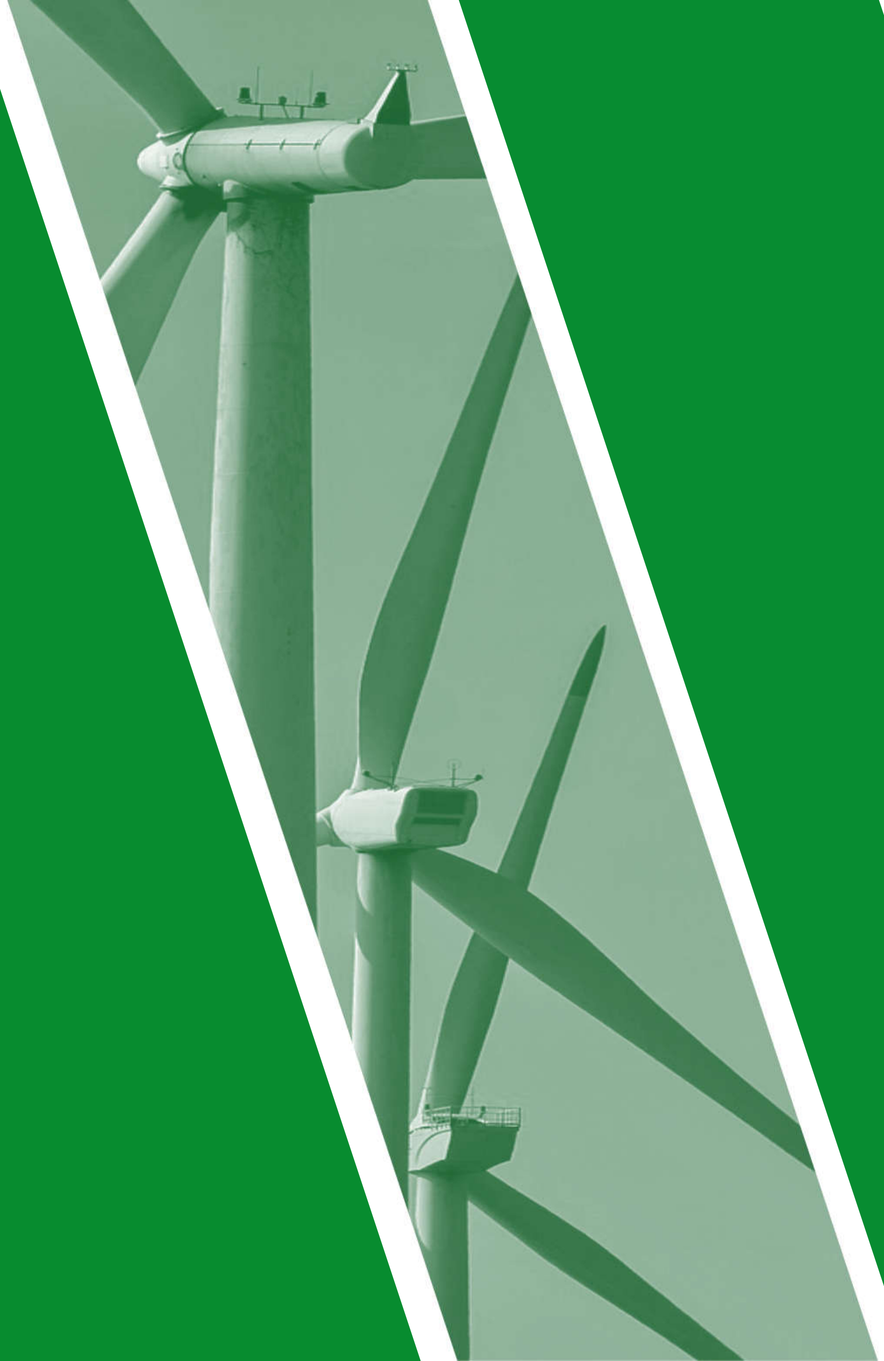
- Wind energy today
- Main features of modern wind turbines
- Wind turbines and the atmosphere
- Prospects of offshore wind

**Part 2 - Wind turbine design & operation**

- Basics of wind energy
- Wind turbine design
- Performance and loads

**Part 3 - Floating Offshore Wind Turbines: concepts, technical challenges and modelling**

- Why FOWTs?
- Technologies for floating wind



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# An introduction to wind energy, with focus on offshore wind

# Agenda.

**01** **Rotating giants**
Features of the largest rotating machines on Earth

**02** **How did we get there?**
A century of wind turbine development

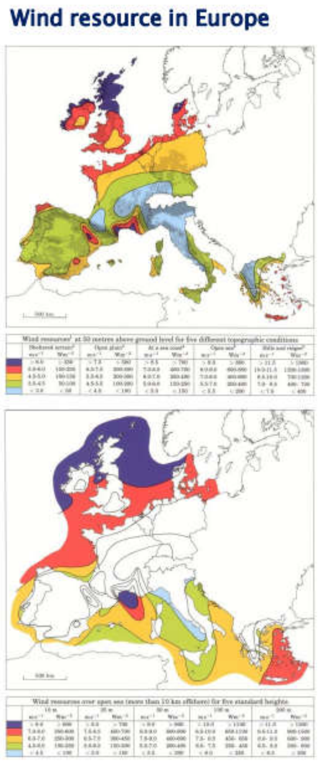
**03** **Wind resource**
Operating in the atmospheric boundary layer – onshore vs. offshore

**04** **Floating wind energy**
A significant opportunity

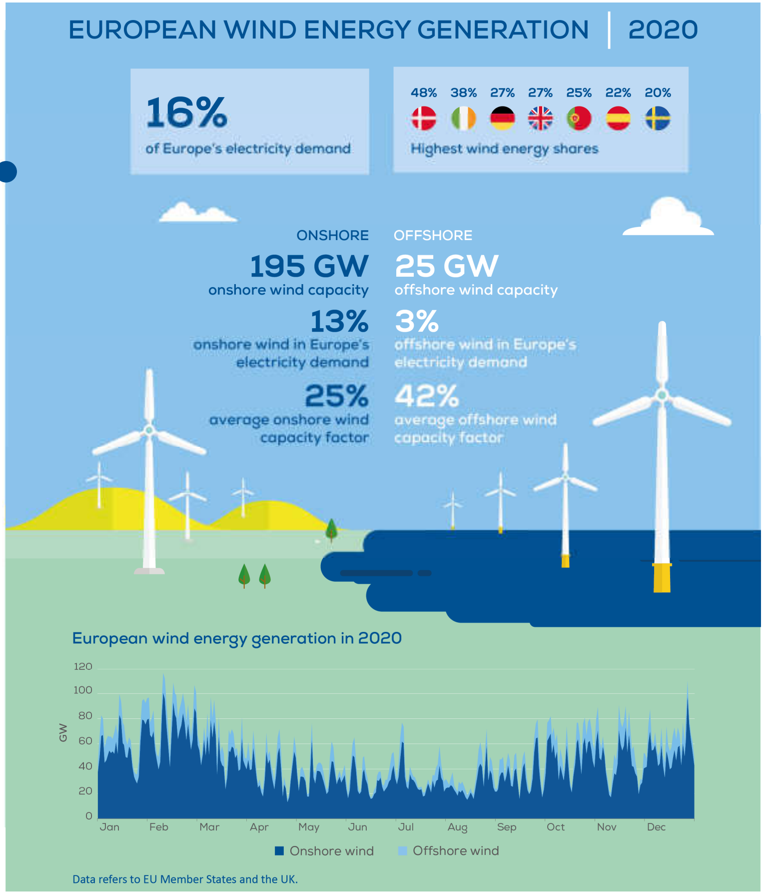
# Rotating giants

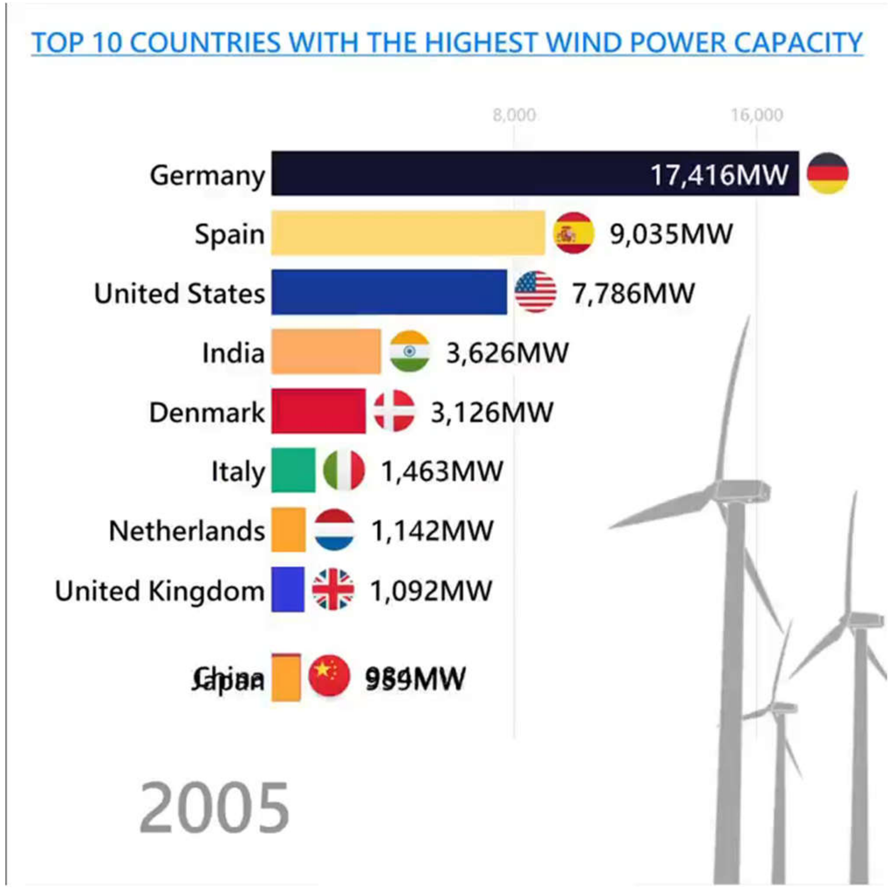
01

# Wind energy today



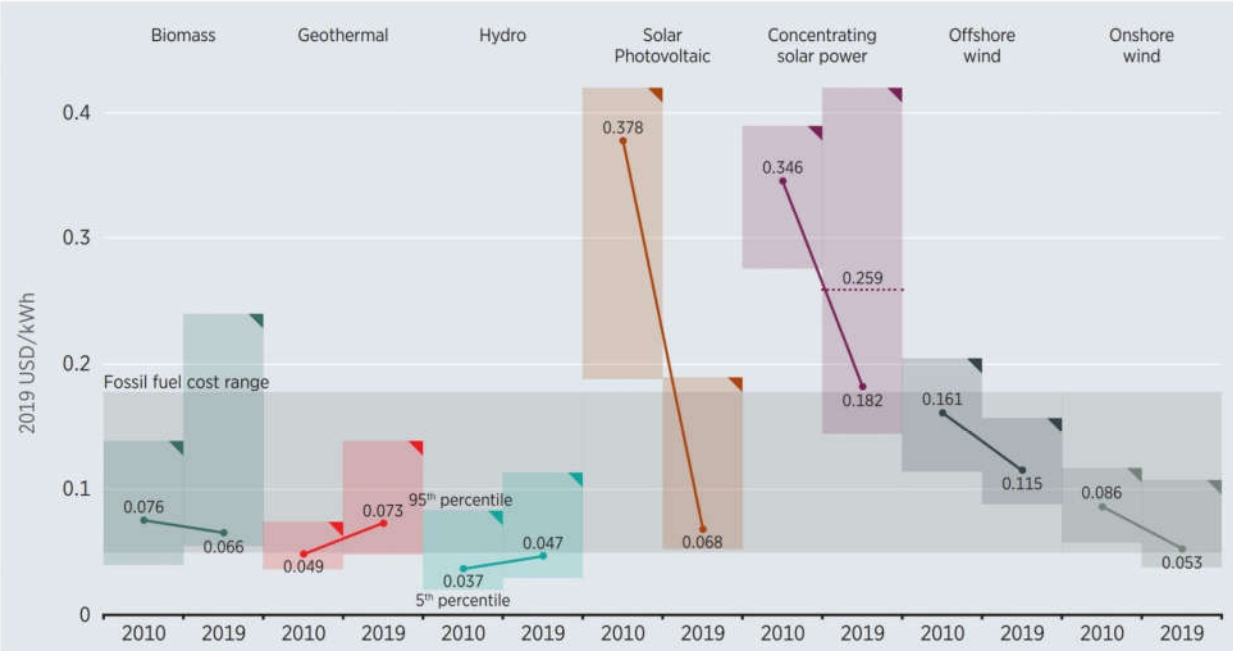

Source: WindEurope

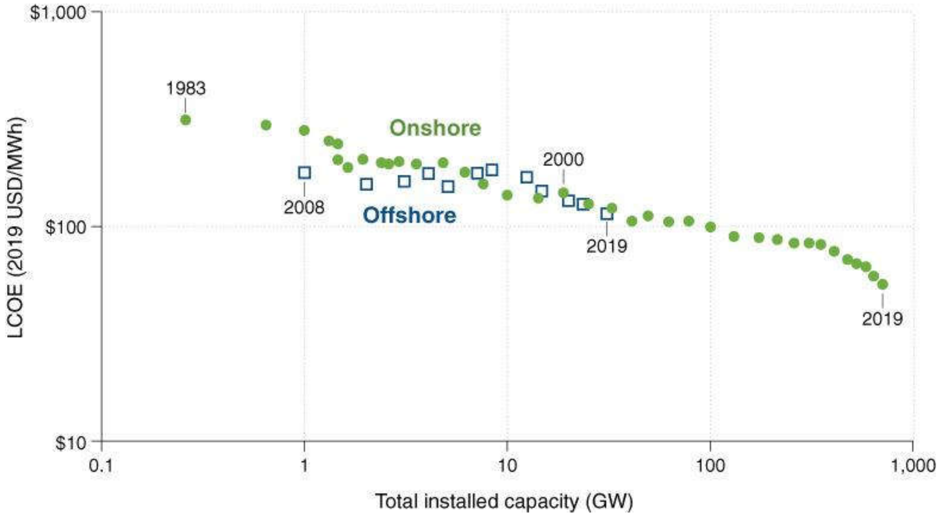


# Prices and LCOE



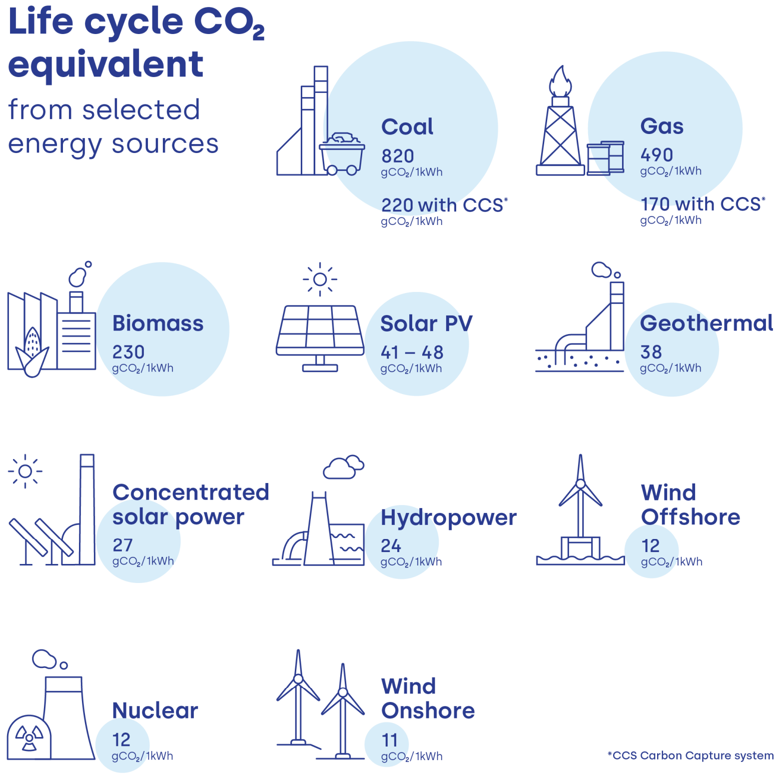


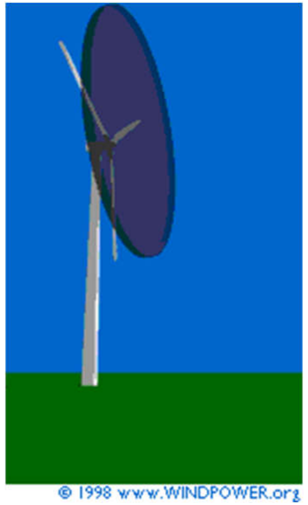



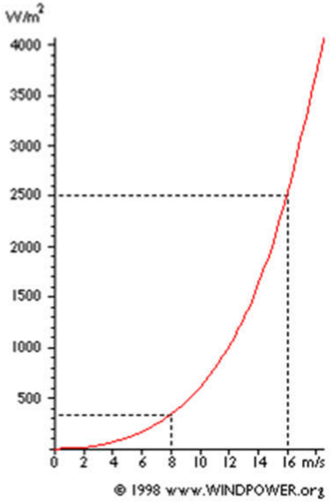

Source: IRENA 2019

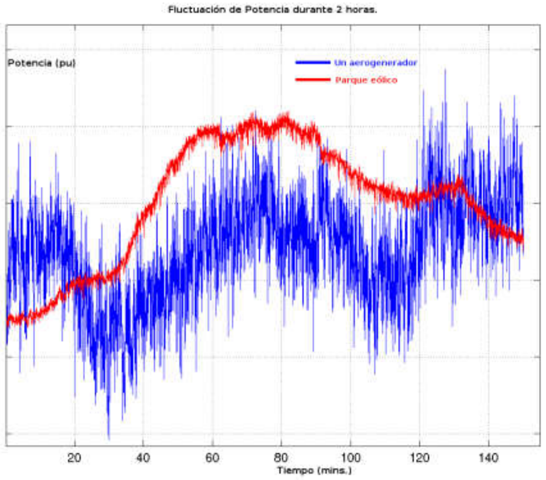
# The cleanest among renewables, but strongly intermittent






$$P = \frac{d}{dt}\left(\frac{1}{2}mU^2\right) = \frac{1}{2}\frac{dm}{dt}U^2 = \frac{1}{2}\rho A U^3$$

$\rho$ = air density (approx. 1.184 kg/m$^3$)

$A$ = rotor swept area

$U$ = wind speed [m/s]

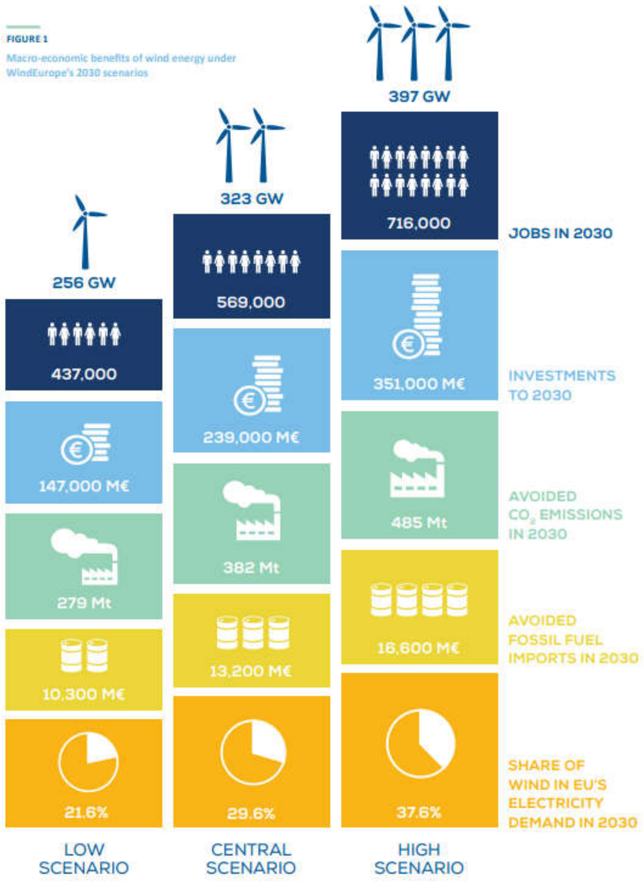
# What about tomorrow?

3 scenarios for EU*

**HIGH** – 397 GW installed = 38% of the energy demand

**CENTRAL** – 323 GW installed = 30% of the energy demand

**LOW** – 297 GW installed = 21.6% of the energy demand





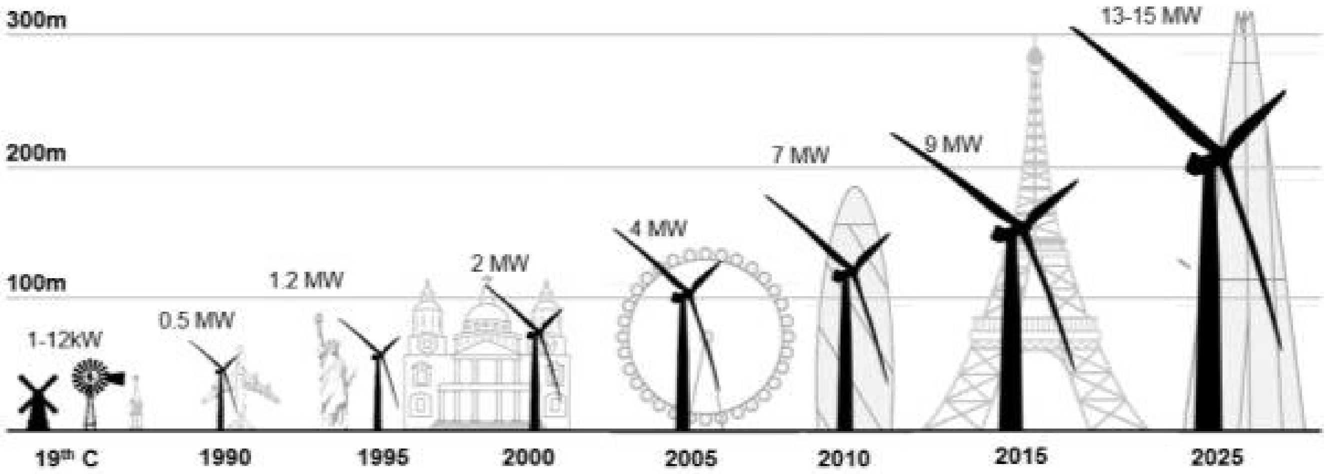
* WindEurope – "Wind energy in Europe: Scenarios for 2030"

Source: GWEC 2021

# How are we doing this?

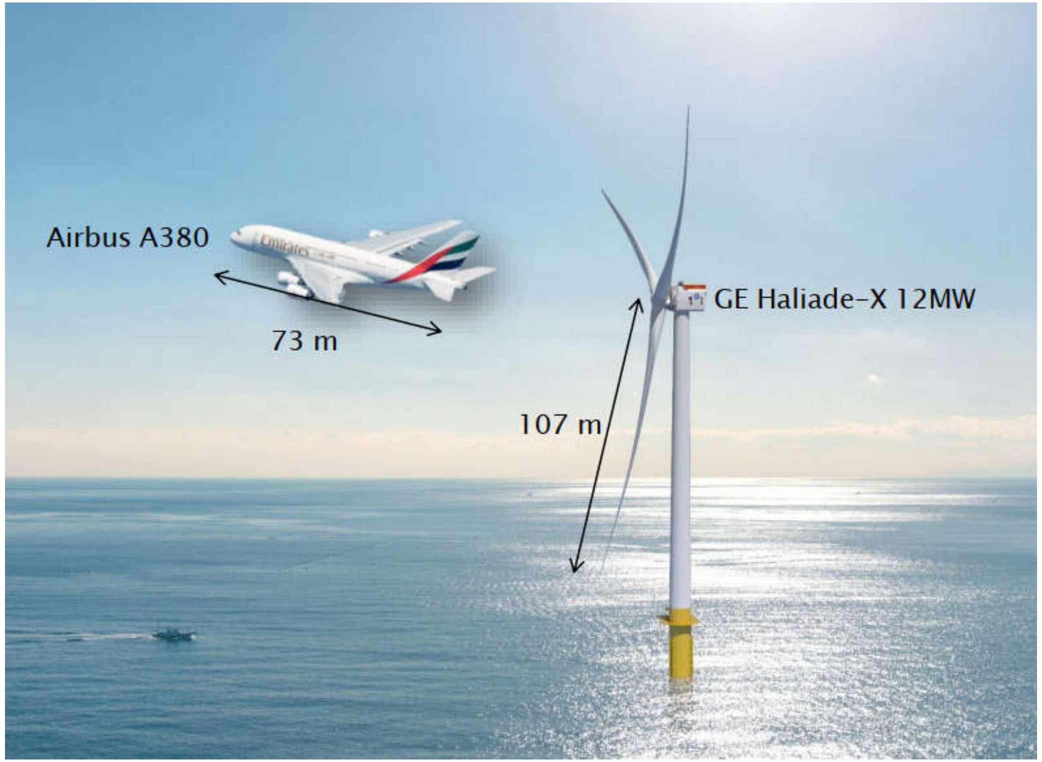
Larger and larger machines, clustered into arrays or farms

- ✓ standardized upwind configuration with three blades on a monopile tower

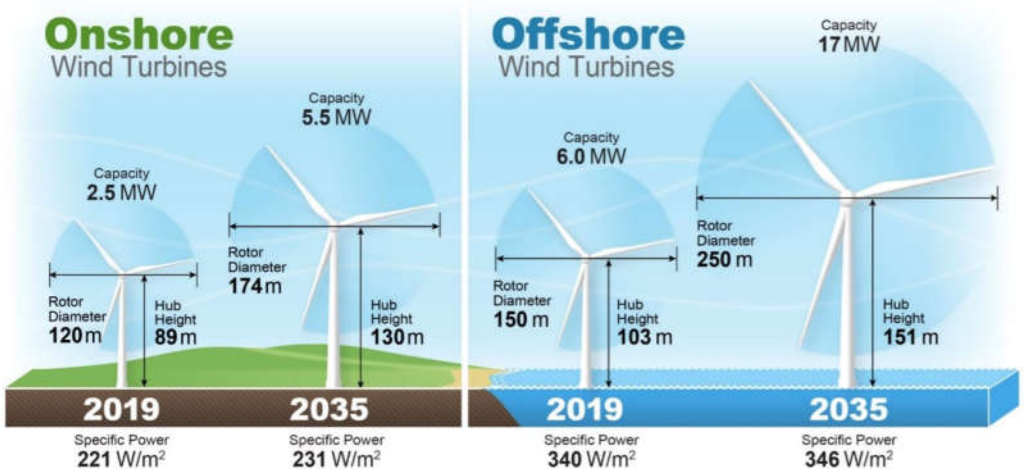



Source: Bloomberg New Energy Finance, 2019

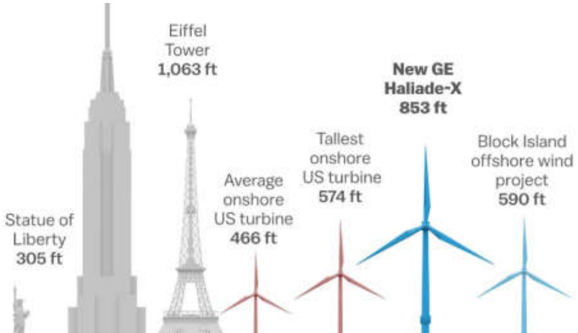
# The largest rotating machines on Earth




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

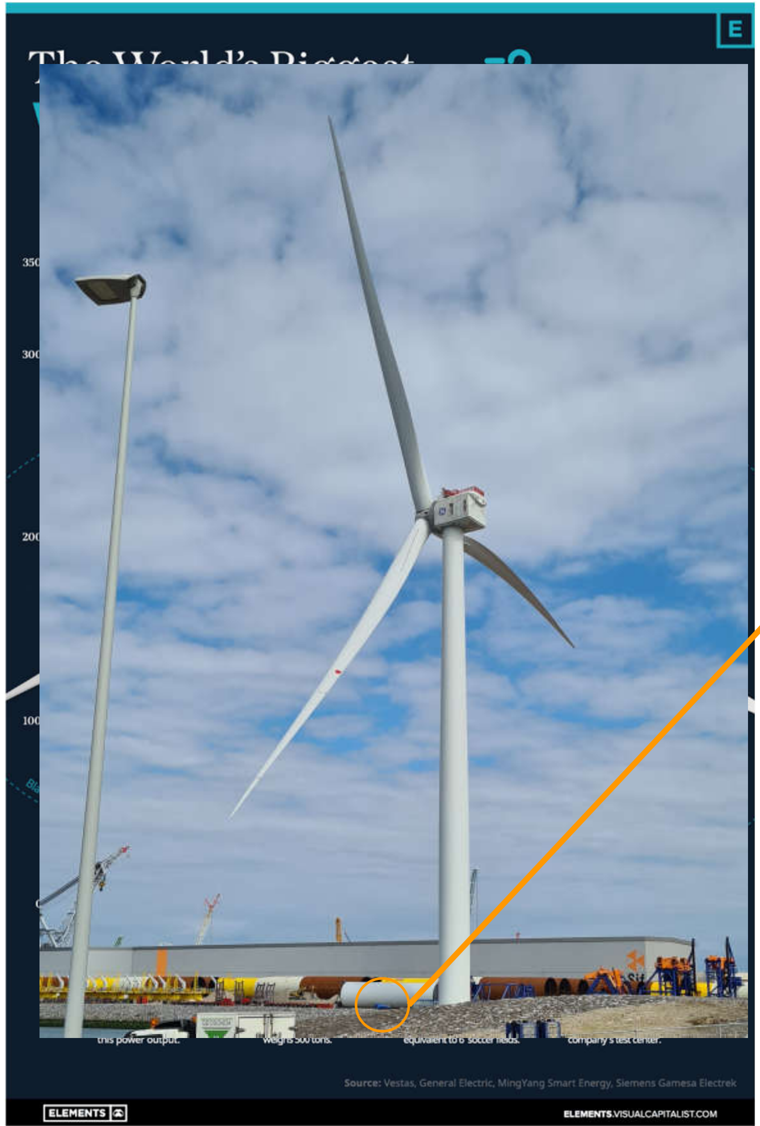



Source: Berkeley Lab



# ..just to get a clearer idea..



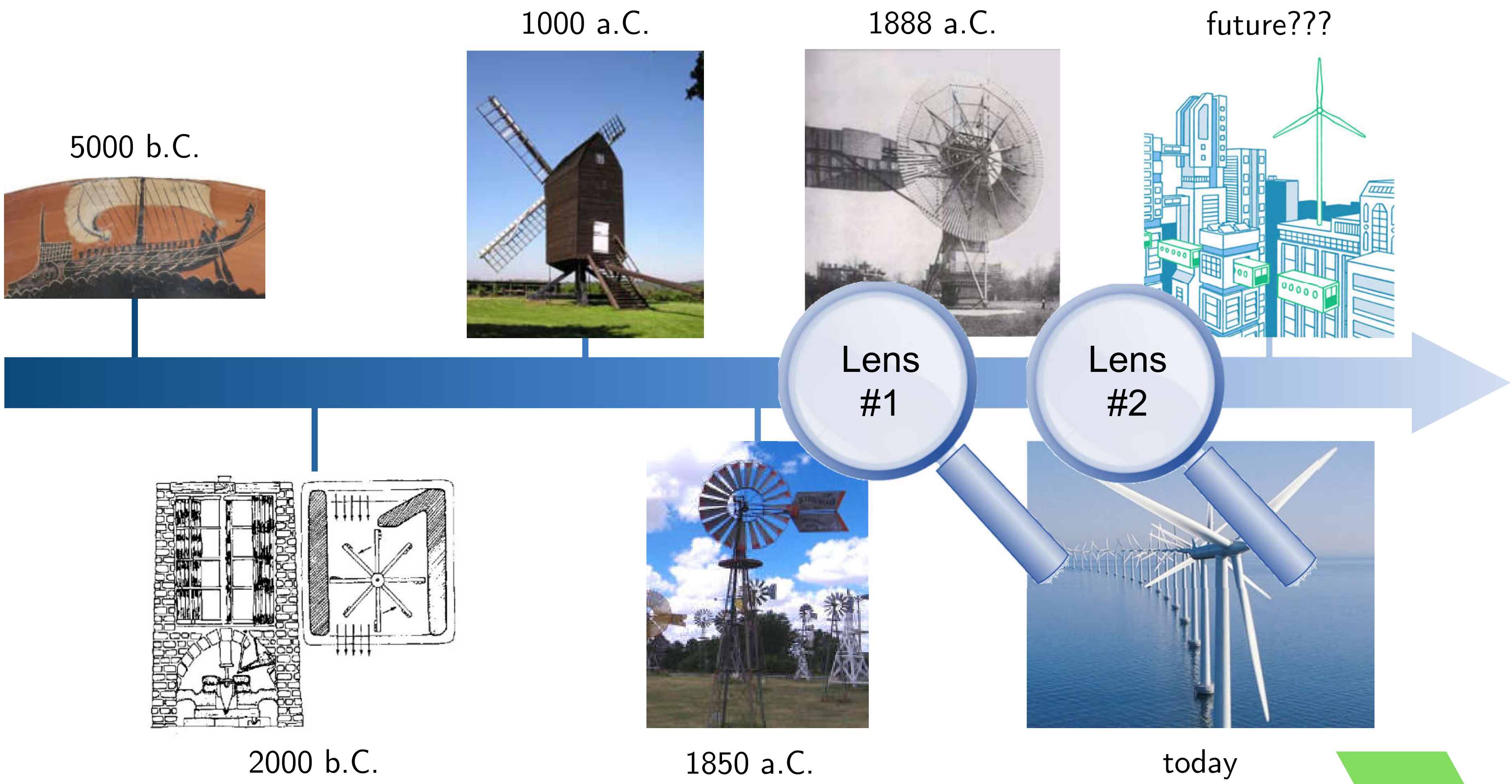



x10 zoomed view – NISSAN Quasquai

# How did we get there?

02

# Wind power through history



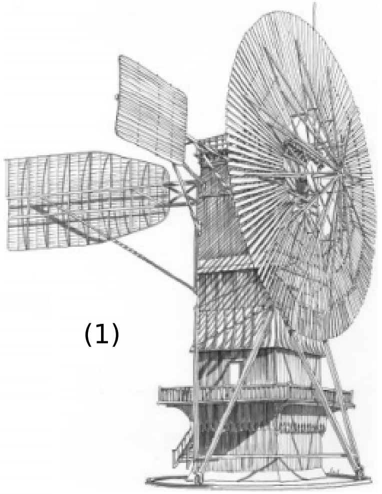
# Lens #1 – Wind energy pioneers

1887 → Very first "wind turbine". Prof. James Blyth (Glasgow) combined a traditional vertical-axis windmill to an electric generator

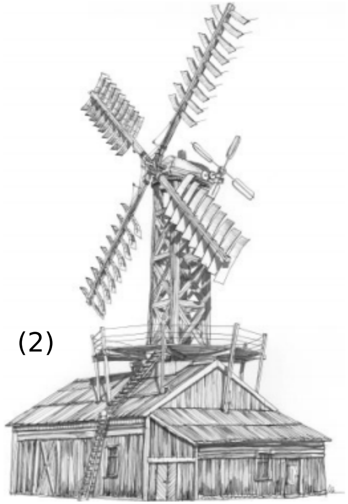
1887 → American inventor Charles F. Brush built a wind generator (1) installed in his backyard in Cleveland – 12kW with batteries to feed 350 incandescent lamps and three motors

1891 → Meteorologist Paul La Cour built Denmark's first wind turbine (2) – 9 kW DC electric generator with the very first attempt for a constant speed rotor (generator to 2nd shaft with pulleys)

'30s → Start thinking about "big wind". German engineer H. Honnef envisioned the development of a series of wind turbine 300m tall with rated capacities of 20 MW each. He figured out some solutions that foreshadowed the future of wind power technology like the first direct-drive turbine and power conversion to AC. The same aspiration to getting larger showed up also in the Soviet Union, with the creation of the first 100kW turbine "Bakalava" (3)



(1)



(2)

(3)

Credits: Brandon N. Owens, "The Wind Power Story", IEEE Press, Wiley, 2019

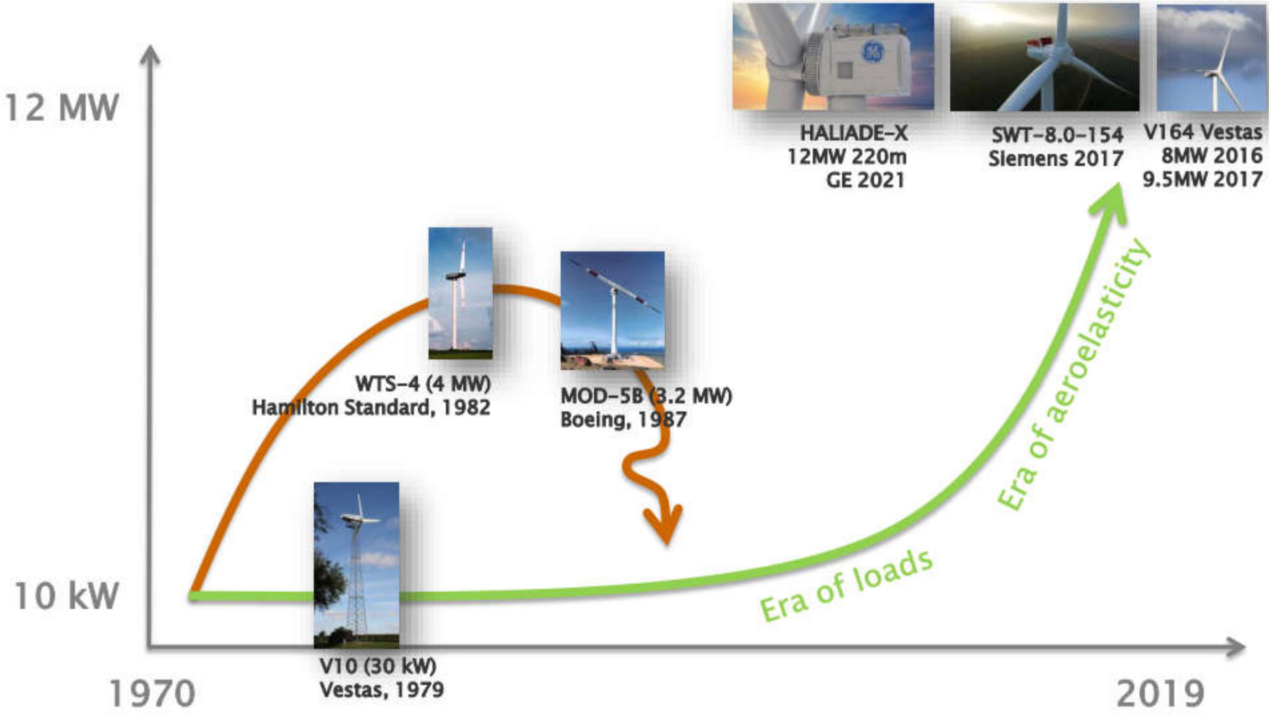
# Lens #2 – The rush starts

Wind power had mixed fortunes in the first 70 years of the last century, exploring different solutions and ideas, often destroyed by the impacts of World Wars

Curiously, the most authoritative voice in favor was that of Pope John XXIII in his speech from Castel Gandolfo in summer 1961 on “new source of energy”

The story changed after 1973, when the OPEC crisis suddenly showed to the world that the dependency on oil was critical (price of oil x4)

At that time, two very different paths started




Partially taken from G. van Kuik (TU Delft) and C. Bottasso (TUM)

# The American way

In 1973, “Federal Wind Energy Program” (FWEP) in US by Nixon

NASA led that program, which started in Ohio, 60 miles far from Brush’s first turbine, with the 100 kW MOD-0 turbine (1). It was a downwind rotor, with aluminum blades and the hub had no chance to teeter → blades bended too much

Despite several improvements, the philosophy remained the same, with bulky and heavy “airplane wings” connected to a tower in downwind configuration (e.g. the 2.5 MW MOD-2 built by Boeing (2))

This approach rapidly came to a dead end, especially when in 1981 Reagan’s administration halted many programs on renewables in US after the oil crisis had waned

(1)


(2)

Credits: Brandon N. Owens, “The Wind Power Story”, IEEE Press, Wiley, 2019

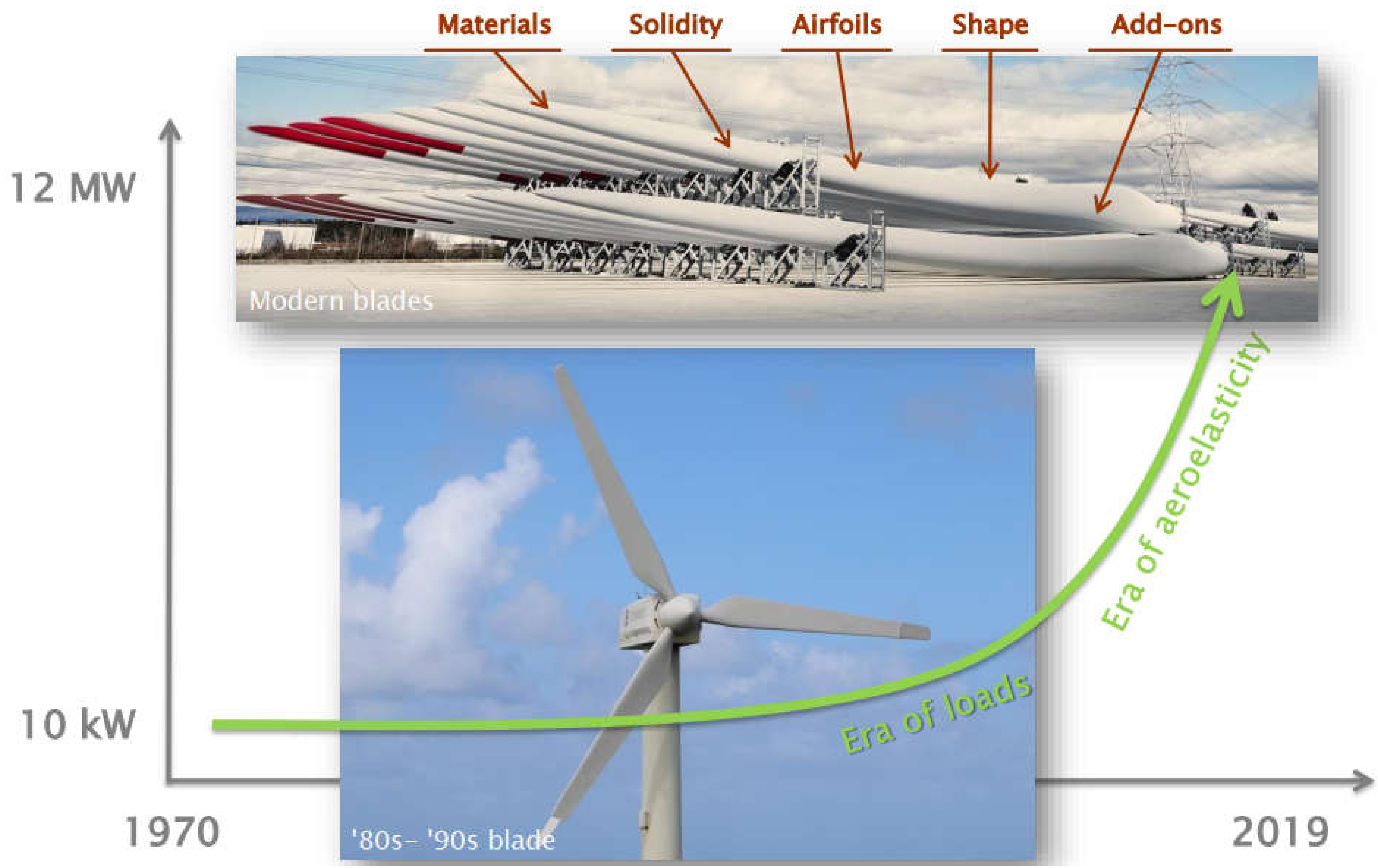
# Denmark reinvents wind power

Oil crisis posed an existential threat to Denmark, because oil was widely used for space heating. Massive research programs in wind energy were launched in 1974 and the Danish Nuclear Laboratory (Risø) and DTU were both tapped to conduct that research. Before their first (excellent) results came in 1978, a strong commitment from individuals and entrepreneurs flourished.

A prime example of wind power's reinvention is the work of a carpenter from Jutland named Christian Riisager, who developed, built and sold a 22 kW wind turbine, which costed less to produce than all other smaller models available at the time and became the standard for European small wind turbines


Make no mistake: the global wind power industry was born in Denmark with the release of the Vestas's V-10 in 1979. It introduced the "Danish concept", i.e. upwind rotor with three fixed blades and a lower solidity. The V-10 is the forefather of modern rotors

# A new era




Partially taken from G. van Kuik (TU Delft) and C. Bottasso (TUM)

# Wind resource and siting

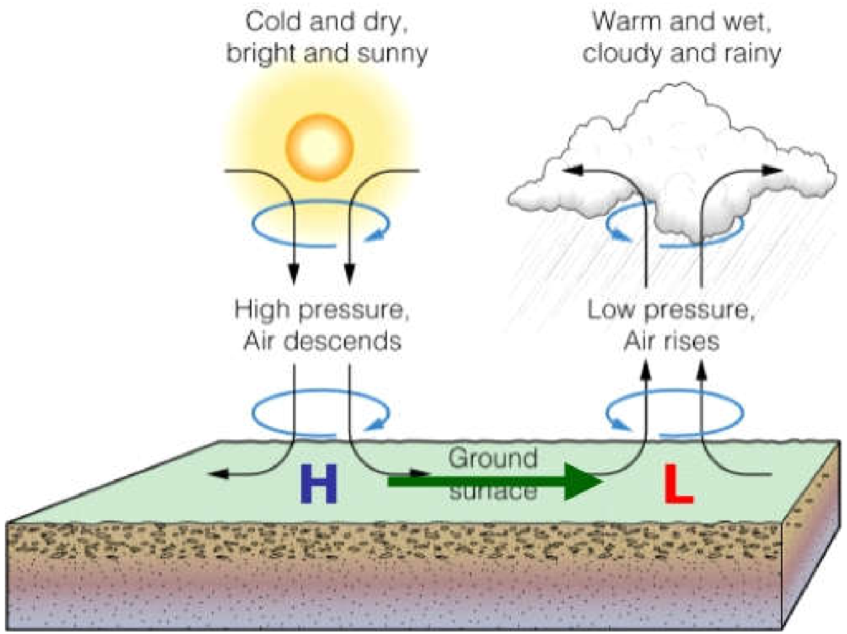
03

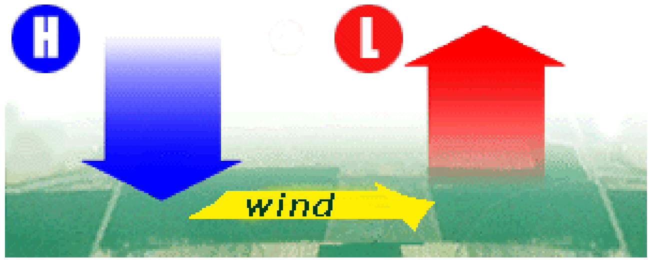
# The origin of wind



Wind is nothing else than a movement of an air mass. It is originated by a pressure difference due to a different solar irradiation between two zones

- ✓ hot (lighter) air rises toward the higher atmospheric layers and is replaced by the cold air (denser)
- ✓ the same effect takes place globally (hot air rises at the equator) and is replaced by air from the poles



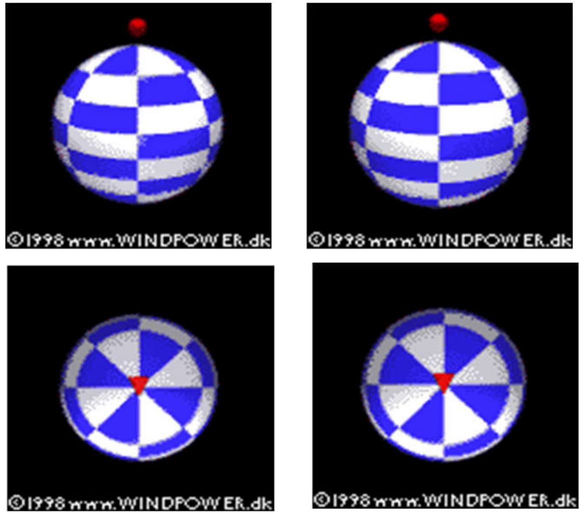



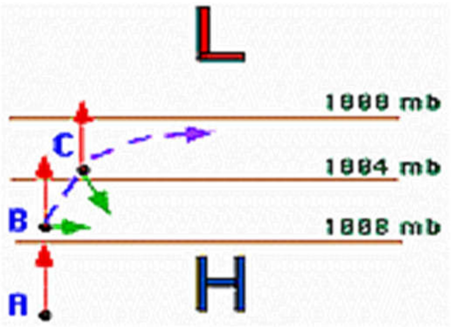
# The Coriolis force

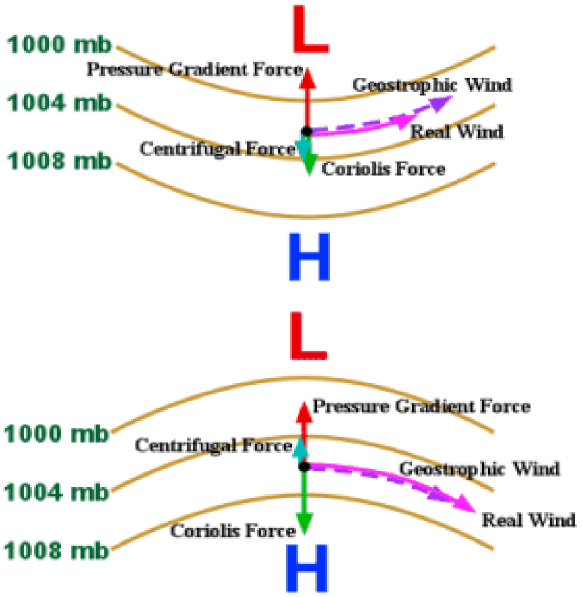


Since the Earth is rotating around its axis, the Coriolis force generates a deflection of each linear motion (with respect to an observer integral with the soil)

- ✓ the deflection is on the right in the northern hemisphere and on the left in the southern hemisphere
- ✓ geostrophic winds flow parallel to isobars. If isobars are curved, the centrifugal force must be included in the force balance



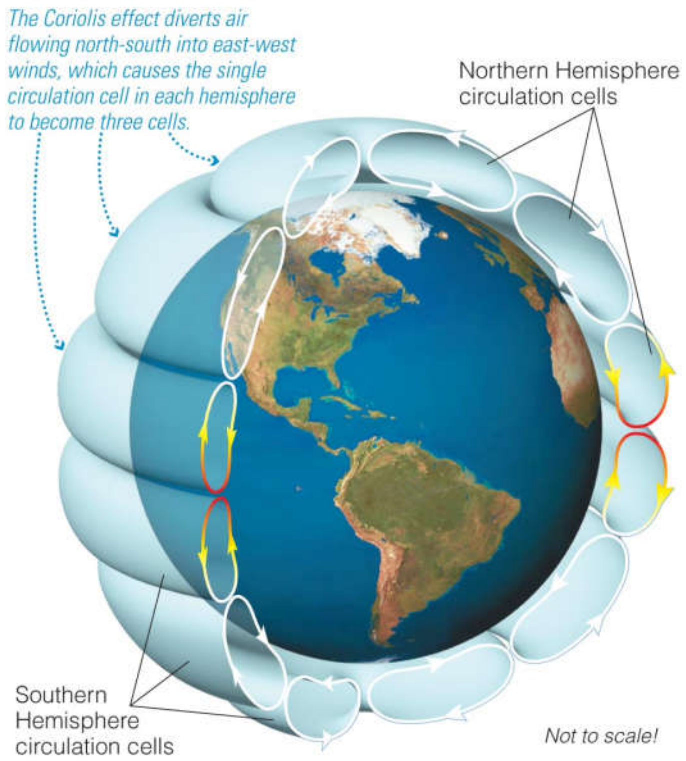



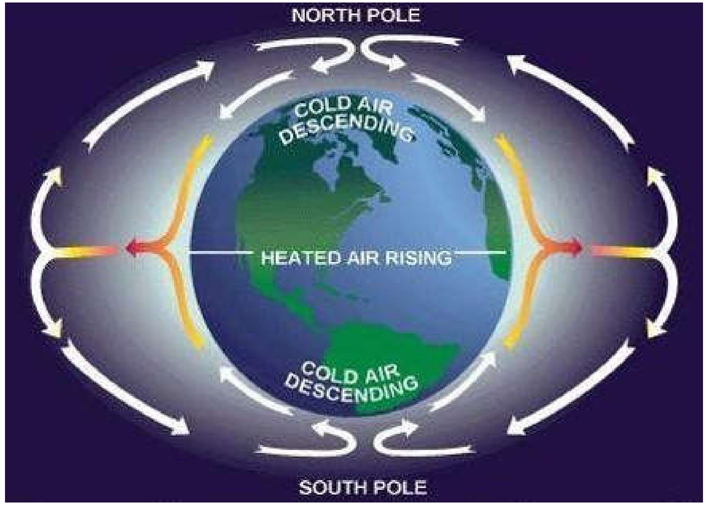
# Geostrophic winds

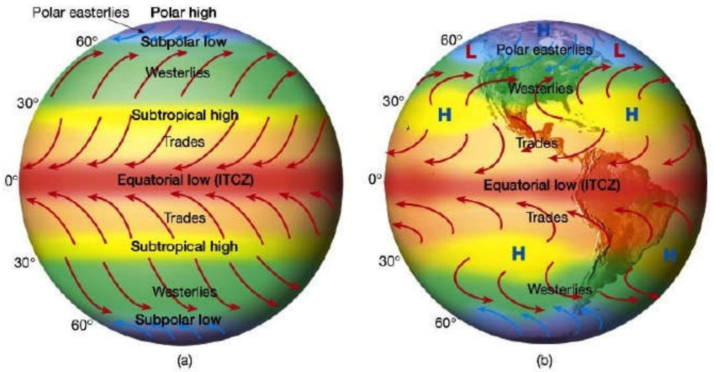


Due to temperature and pressure differences between different zones of the planet

✓ not influenced by the orography of the soil (h > 1000 m)



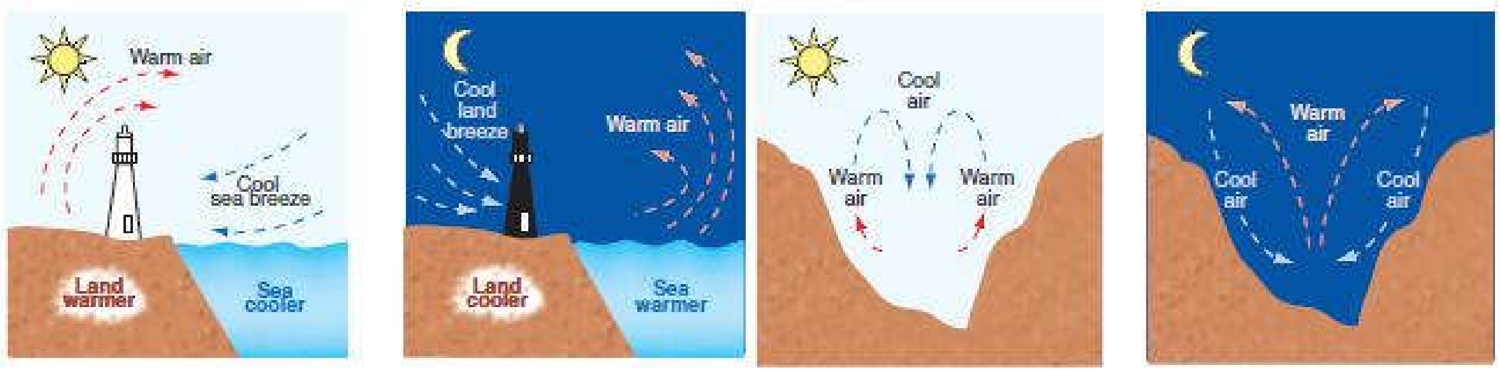



# Local winds

As soon as the considered altitude decreases (h<100 m) the orography of the soil, its roughness and the effects of obstacles become not negligible

- ✓ wind turbines always operate in LOCAL WINDS
- ✓ local winds are over-imposed on the global winds and can be predominant in a specific site
- ✓ global winds are generally considered in wind atlas but the local conditions of each installations can be substantially different

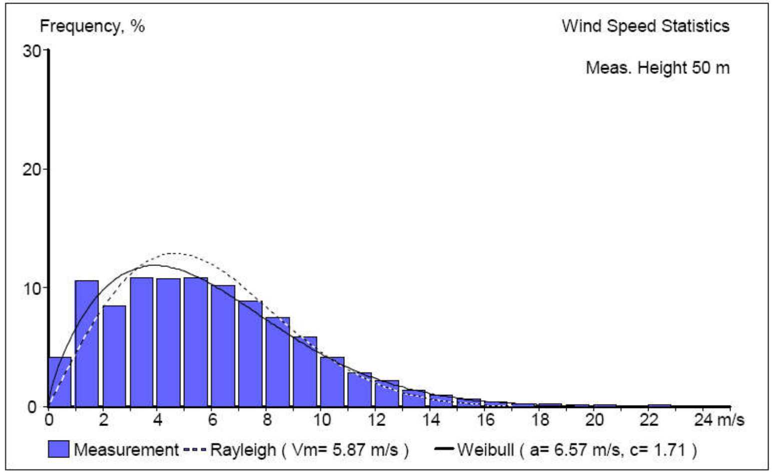


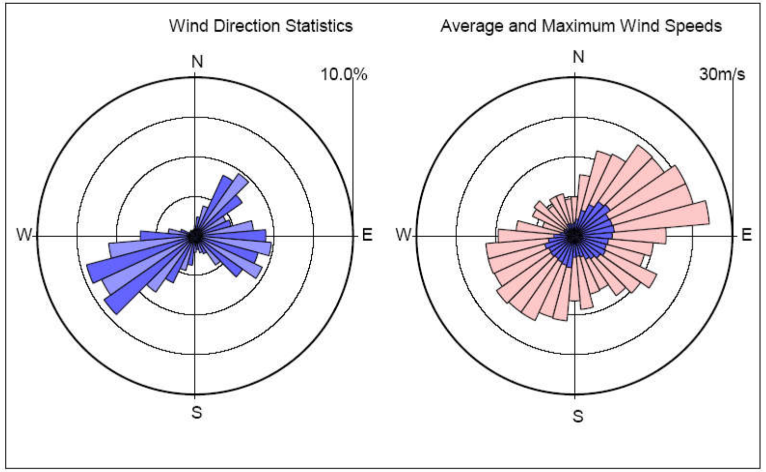
# Anemometry: the importance of measuring the wind



Anemometry = measurement of **local** wind characteristics

- ✓ frequency distribution
- ✓ wind rose
- ✓ daily variations
- ✓ calms
- ✓ turbulence



# Anemometry: the importance of measuring the wind



"Cup anemometers" are the most common solution. Recently, massive use of ultrasonic anemometers (based on the signal delay between two receivers in each direction)

- ✓ A RIGOROUS CALIBRATION IS NEEDED!
  - <u>A 3% error on the velocity measurement can lead to an overestimation of attended power up to 10%!!!</u>
  - $\Delta P=1.03^3-1=0.1$
- ✓ "icing" may represent a serious issue
- ✓ importance to account for height variation






# Siting onshore

Location of a wind turbine has a strong influence on its Annual Energy Production Energy (AEP), as it affects:

**local wind**
large variability of the wind characteristics with the selected installation site

**turbine design**
matching of the machine with the site conditions

**wind farm layout**
arrangement of the machines according to the local wind map and wake interference effects

field

ocean cliff

snowy mountain

desert

# Siting onshore - challenges



**different length scales**
wind operates from the global to the local scale

**different time scales**
the period of wind fluctuations spans from years to minutes (gusts)

**multi-physics problem**
several concurrent effects such as thermal forcing or icing

**multi-disciplinary problem**
wind farm layout is affected by different constraints of heterogeneous nature (e.g., social acceptance)

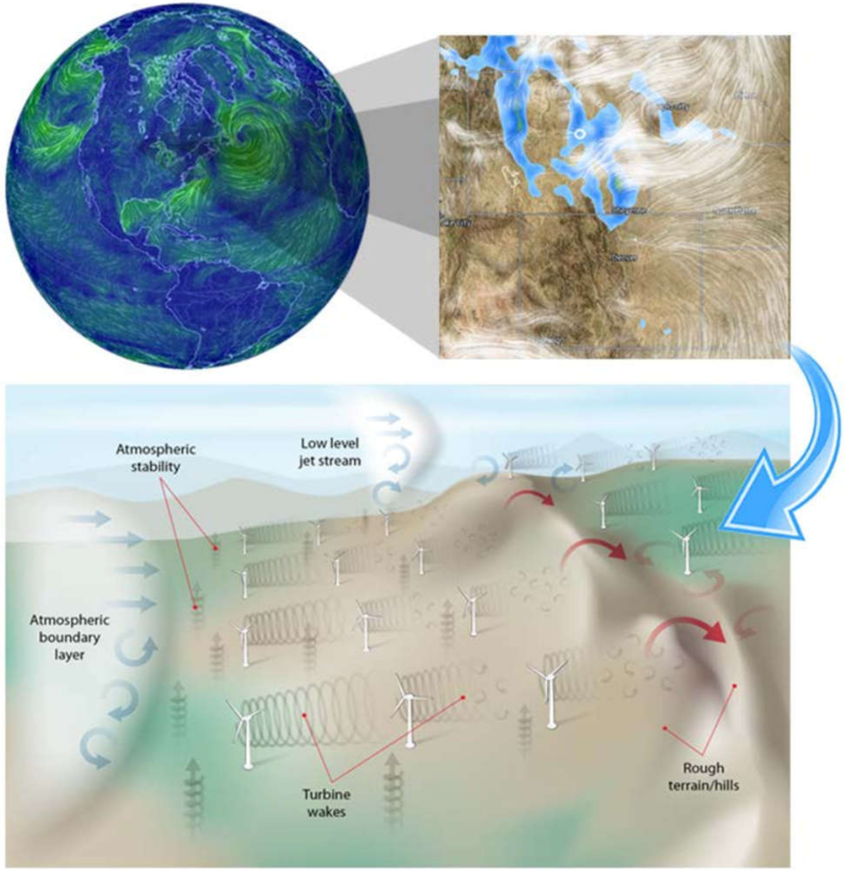



Illustration by Josh Bauer and Al Hicks, National Renewable Energy Laboratory (NREL)

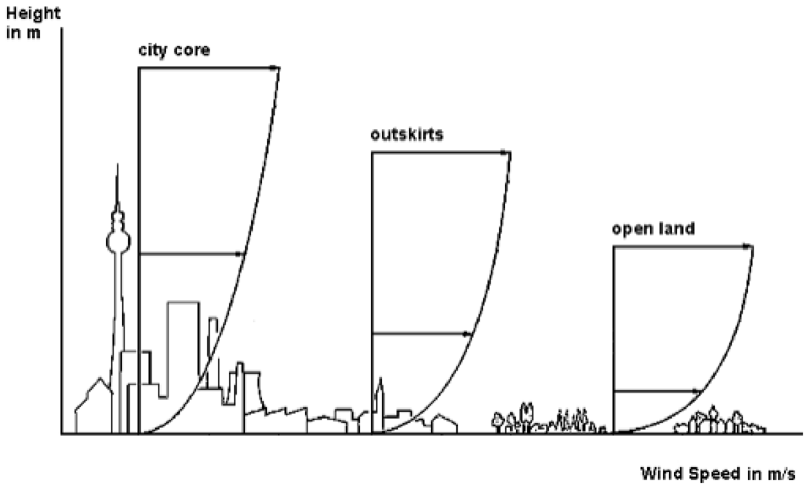
# Surface roughness

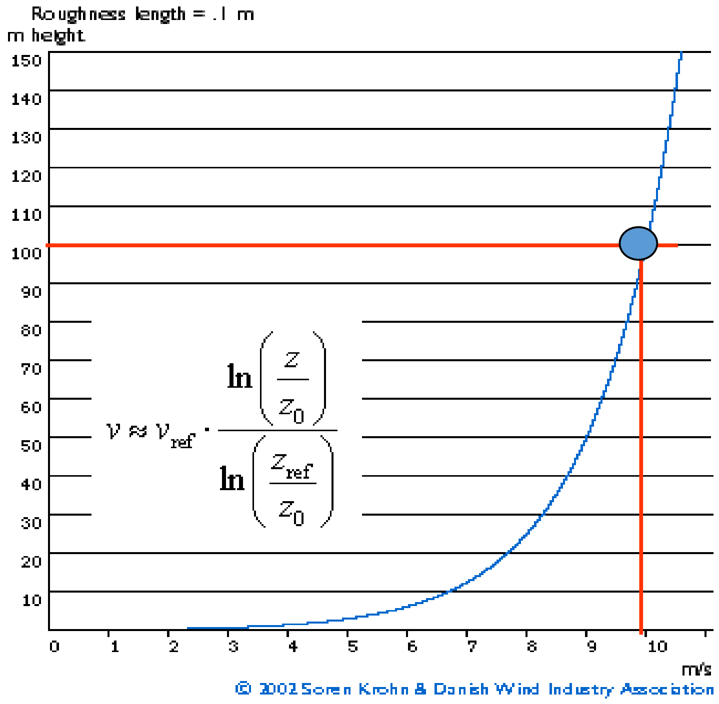
Near the soil, the effect of surface roughness on the wind profile becomes predominant

- ✓ the higher the roughness, the largest the wind speed decrease
- ✓ roughness (large scale!) can be due to trees, buildings, bushes, etc.

## Surface roughness length

- ✓ distance from the soil at which the wind speed becomes theoretically null



# Surface roughness - modeling

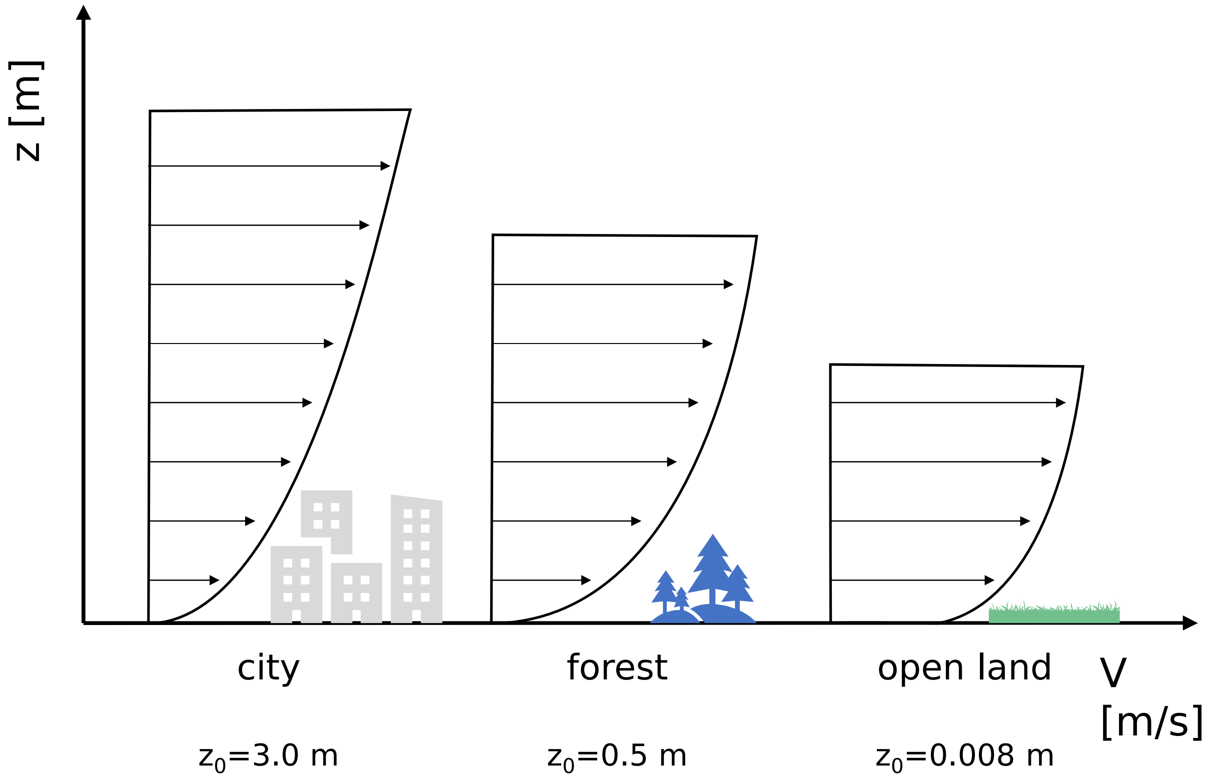


The Atmospheric Boundary Layer is modelled with a logarithmic law:

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

$z_0$ - roughness length, m

- quantifies the flow deceleration due to its interaction with the surface
- height above ground at which $V(z_0) = 0$
- depends on the terrain configuration



# Surface roughness - modeling

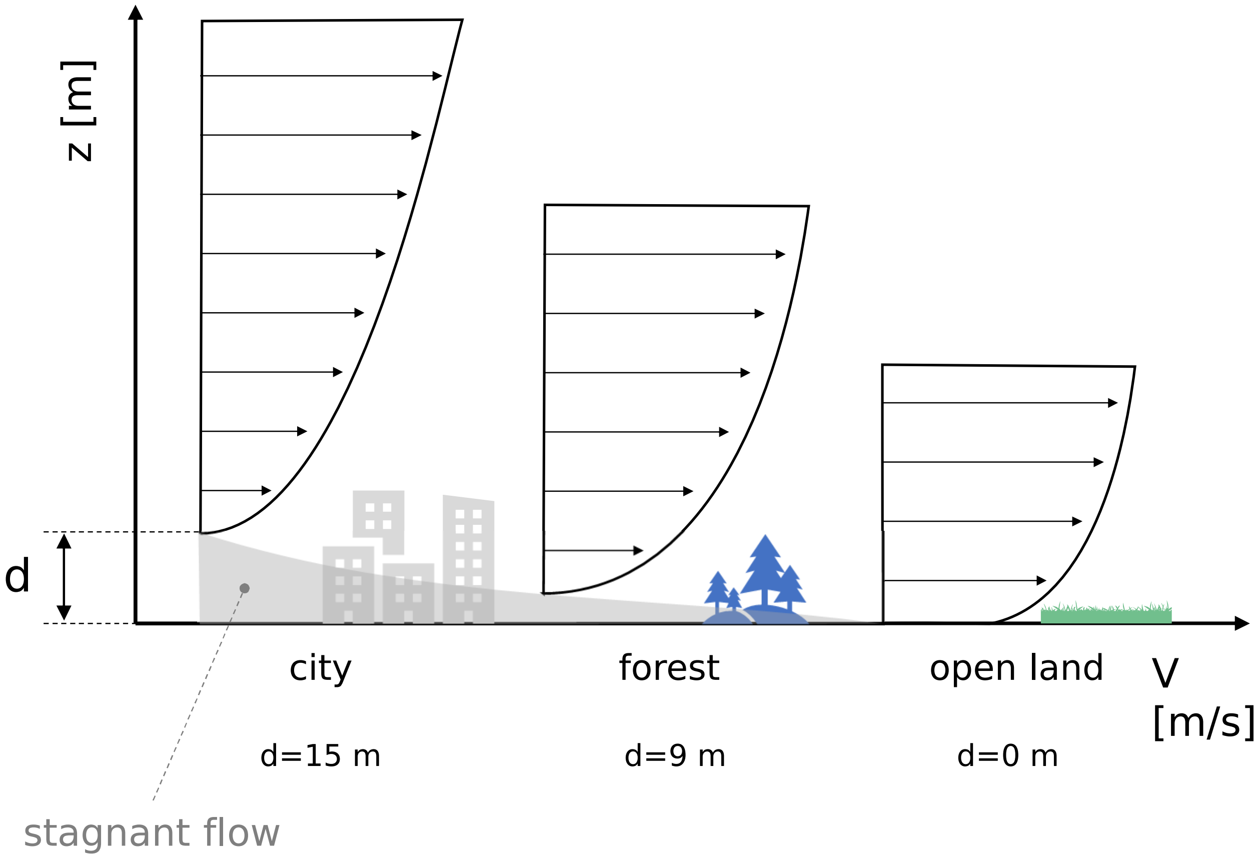


The Atmospheric Boundary Layer is modelled with a logarithmic law:

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

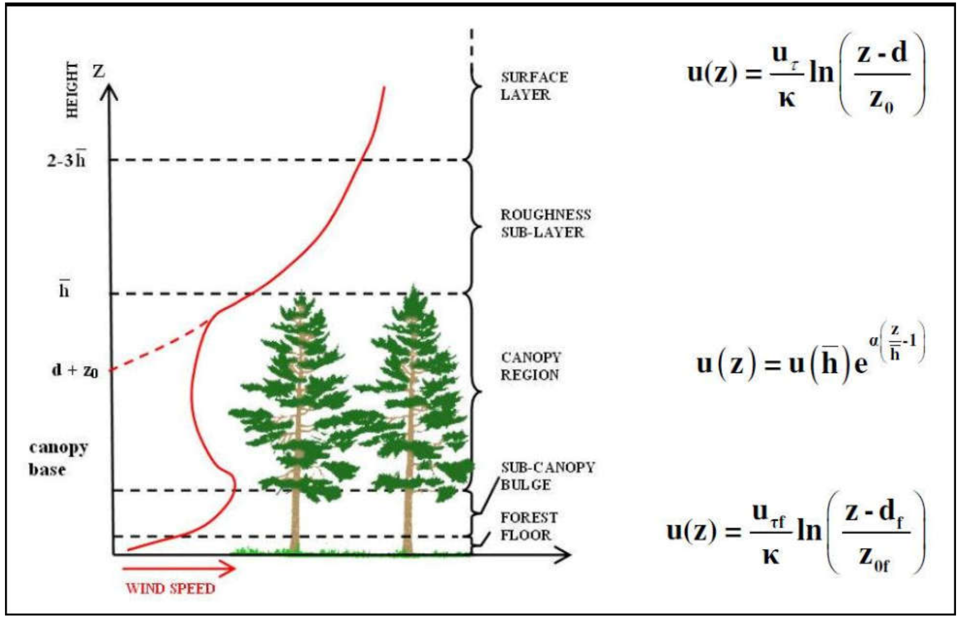
$d$ - displacement height, m

- deceleration of the flow due to high-density urban areas or forests is so high, that it is possible to assume $V(z \leq d) = 0$
- the whole ABL profile is displaced of a height d
- can be estimated from the obstacle characteristics



# Typical surface roughness lengths

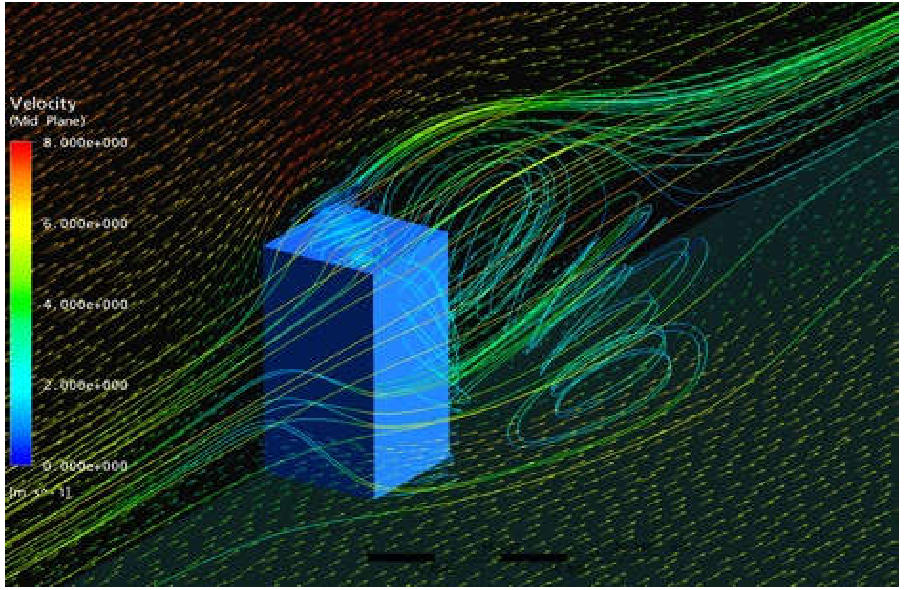
| Terrain Description | Surface Roughness Length, $z_0$ (m) |
| --- | --- |
| Very smooth, ice or mud | 0.00001 |
| Calm open sea | 0.0002 |
| Blown sea | 0.0005 |
| Snow surface | 0.003 |
| Lawn grass | 0.008 |
| Rough pasture | 0.01 |
| Fallow field | 0.03 |
| Crops | 0.05 |
| Few trees | 0.1 |
| Many trees, hedges, few buildings | 0.25 |
| Forest and woodlands | 0.5 |
| Suburbs | 1.5 |
| Centers of cities with tall buildings | 3.0 |



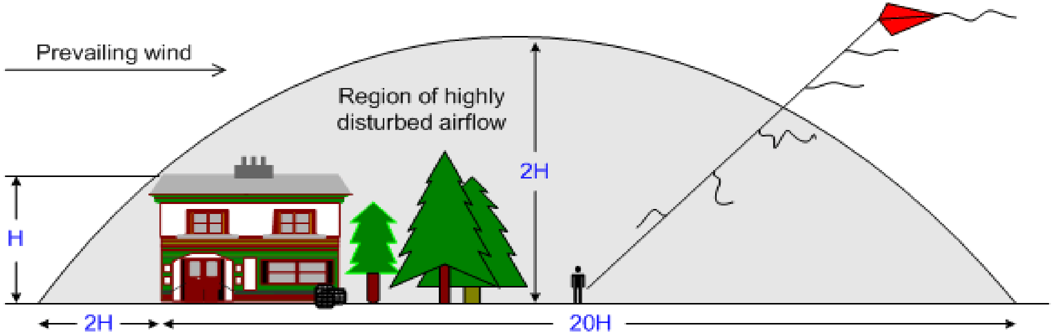
# Obstacles

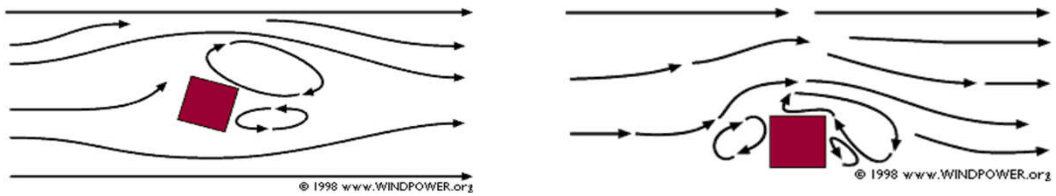
Obstacles, buildings, etc. can reduce the wind speed and create intense macro-turbulence in the surroundings

- ✓ their effects are dependent on the “porosity” of the obstacles, i.e. the permeability of the mean to wind
- ✓ e.g. a building has a porosity equal to 0 (no permeability), a deciduous tree has a variable porosity between summer (0,33) and winter (0,5).




**from the web**

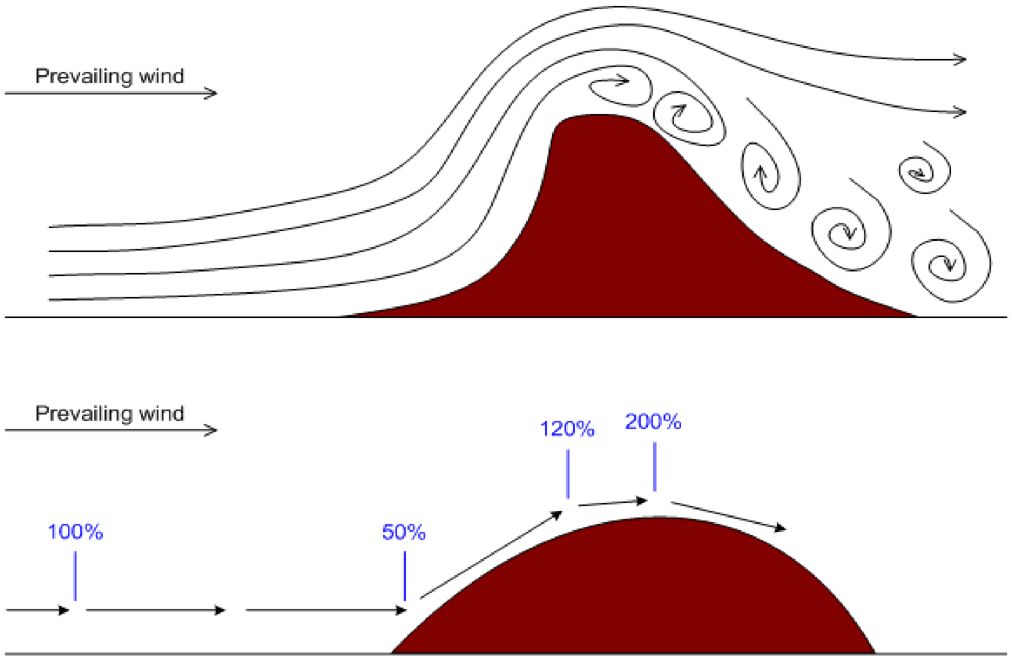


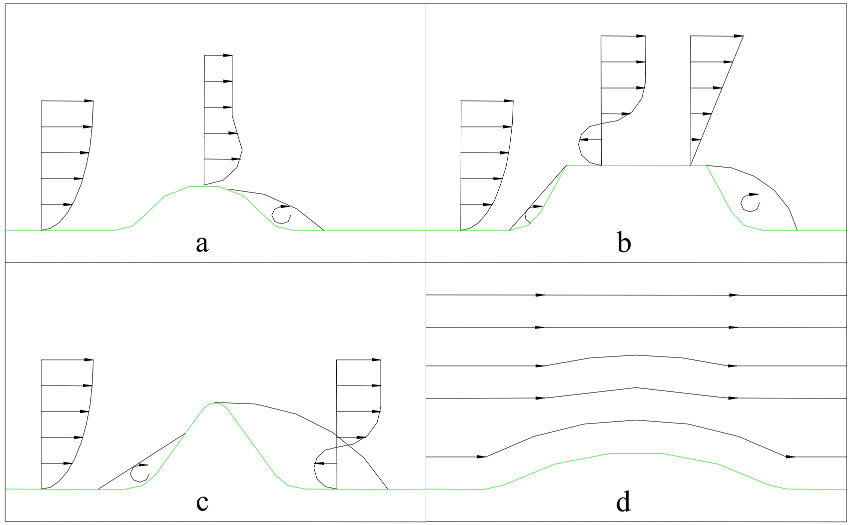



# Hill effects

A turbine placed at the top of a hill or slope may exploit an accelerated wind flow

- ✓ separated zones are again about to arise, being sometimes detrimental for the system




from the web

# Atmospheric stability



The Atmospheric Boundary Layer is modelled with a logarithmic law:

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

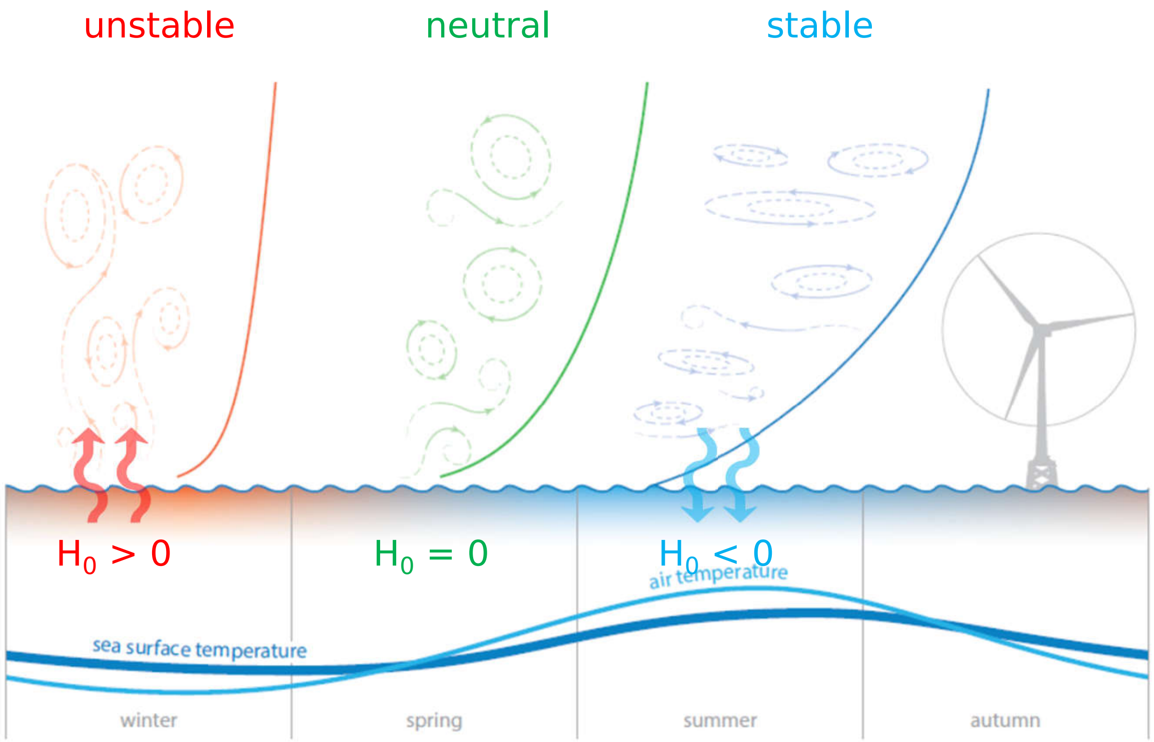
$\psi$ – Empirical function of the Monin-Obukhov length:

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

ground temperature

air heat capacity

heat flux



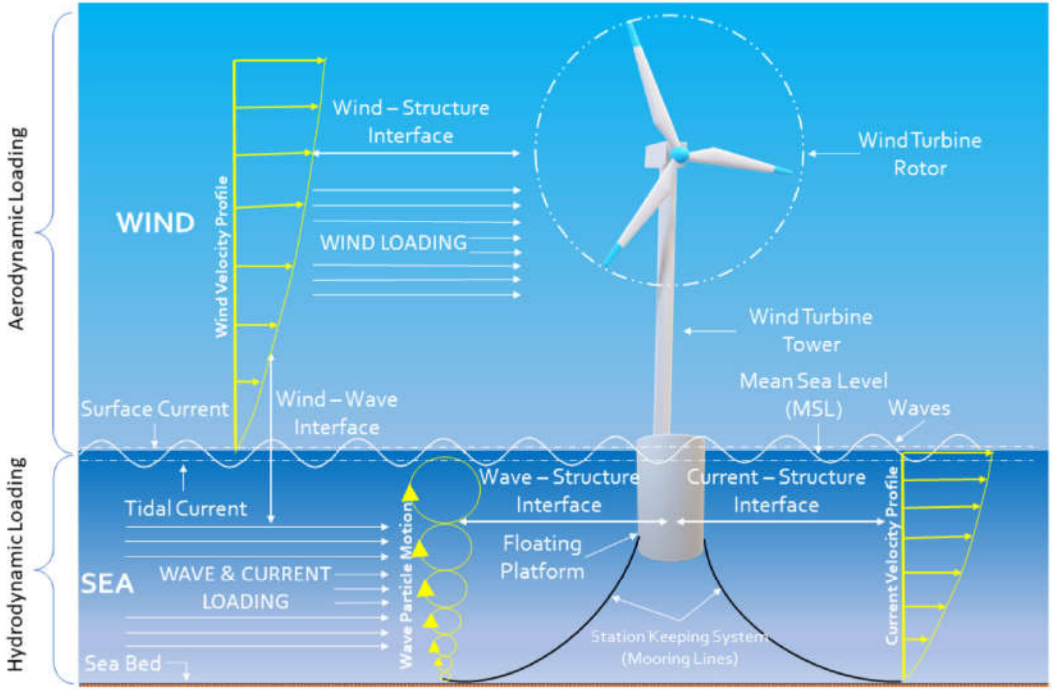

Source: Maarten Holstag, The wind farm in its environment, 2016

# What about offshore?

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

…however…

- different forcing sources arise…

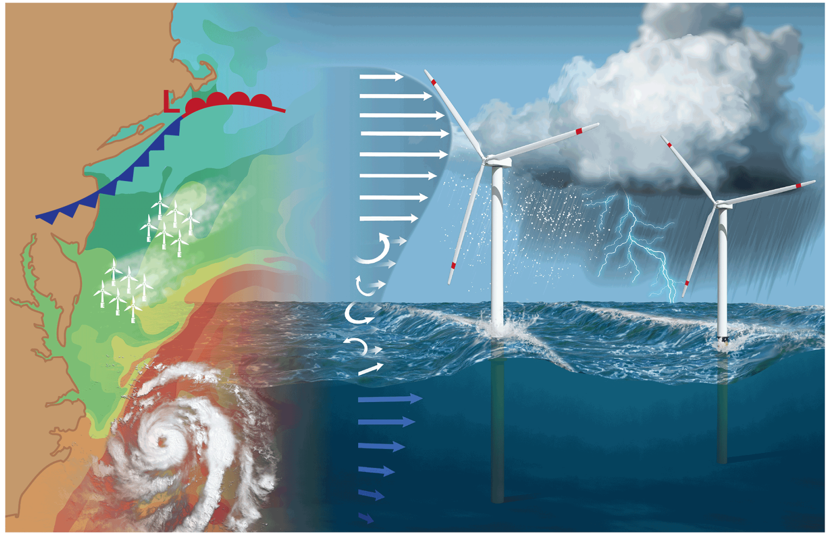



https://doi.org/10.3390/en16010002

# 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




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

Atmospheric flow phenomena at these scales are complex

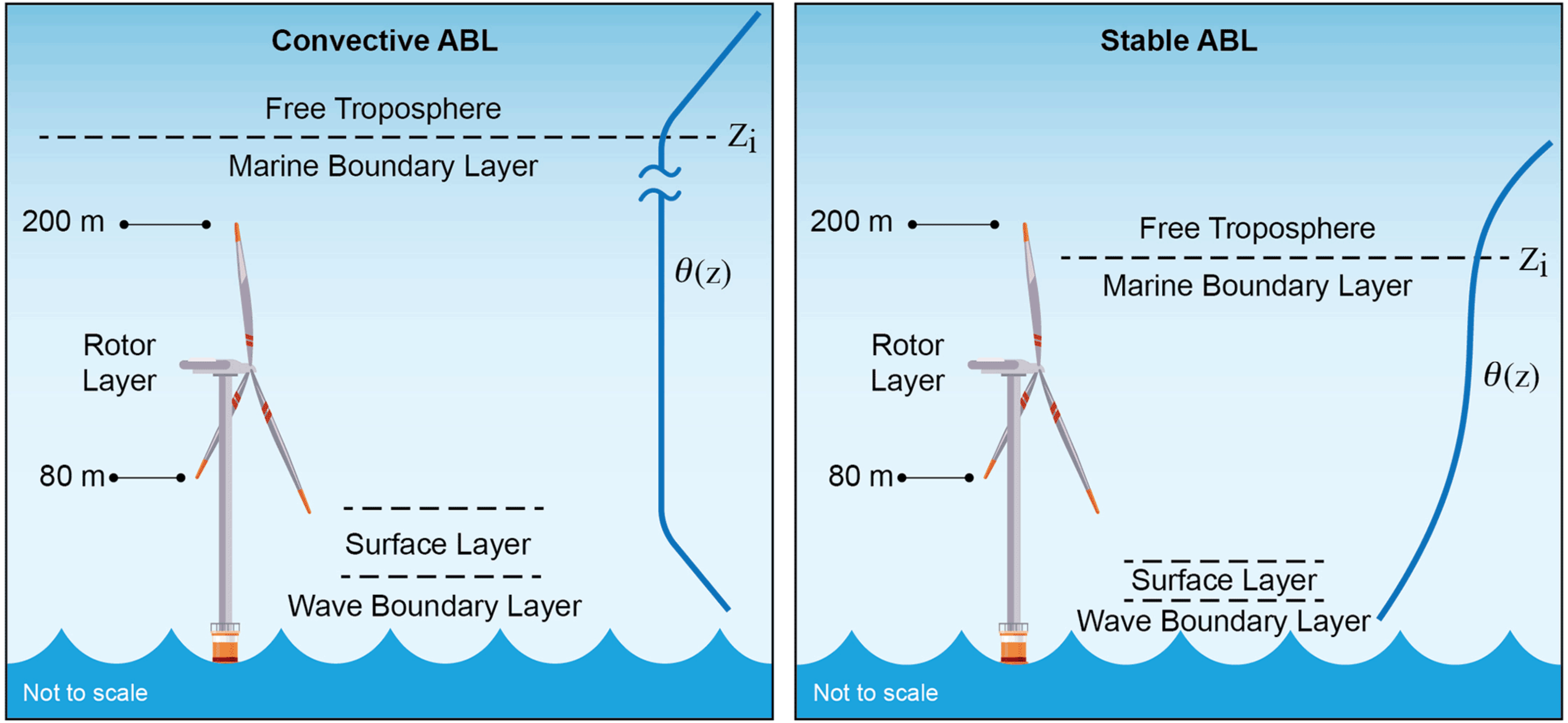
- ✓ hurricanes, tornadoes, microbursts, nocturnal and marine jet flows, and gravity waves must also be considered
- ✓ exact nature of atmospheric turbulence is not well characterized at the length scales and resonant frequencies of the modern wind turbine structure
- ✓ turbulence at these scales (~$10^2$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

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

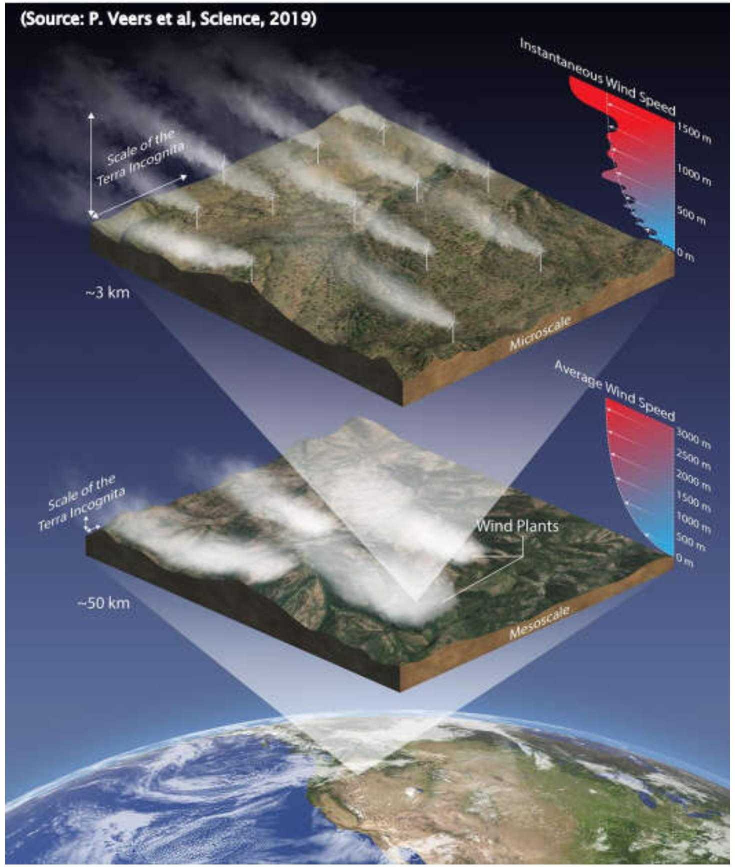


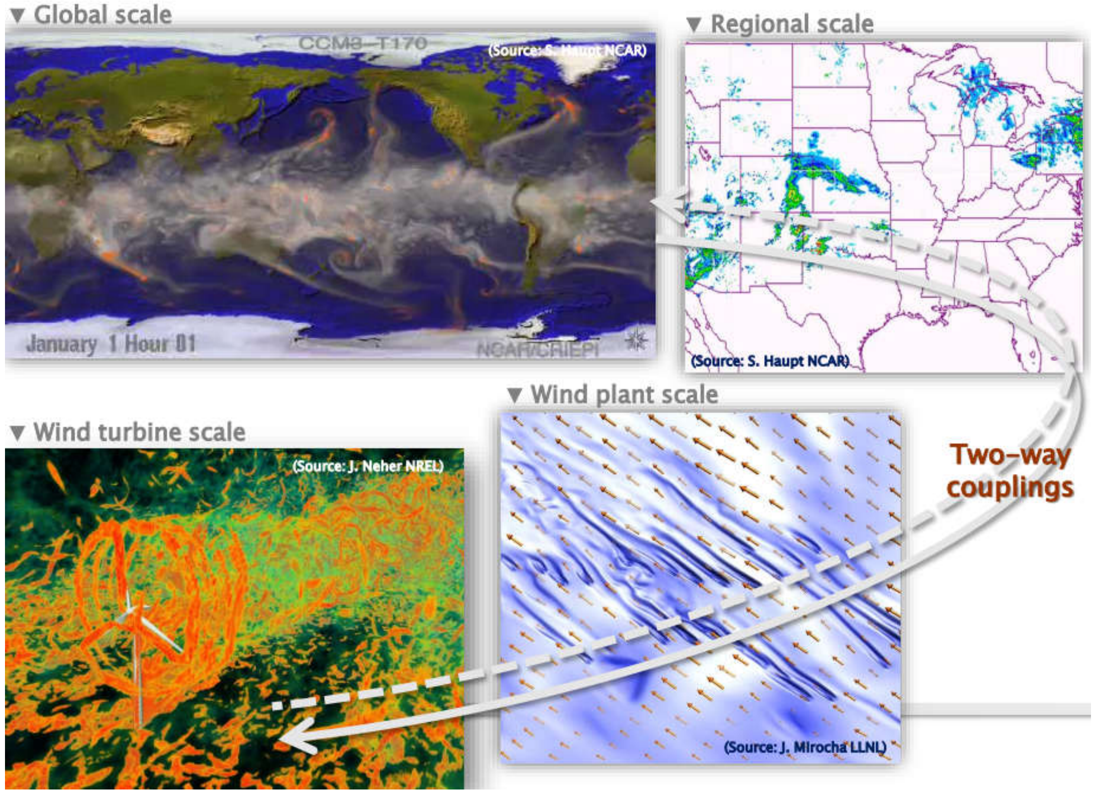



https://doi.org/10.5194/wes-7-2307-2022

# Large wind farms and the atmosphere



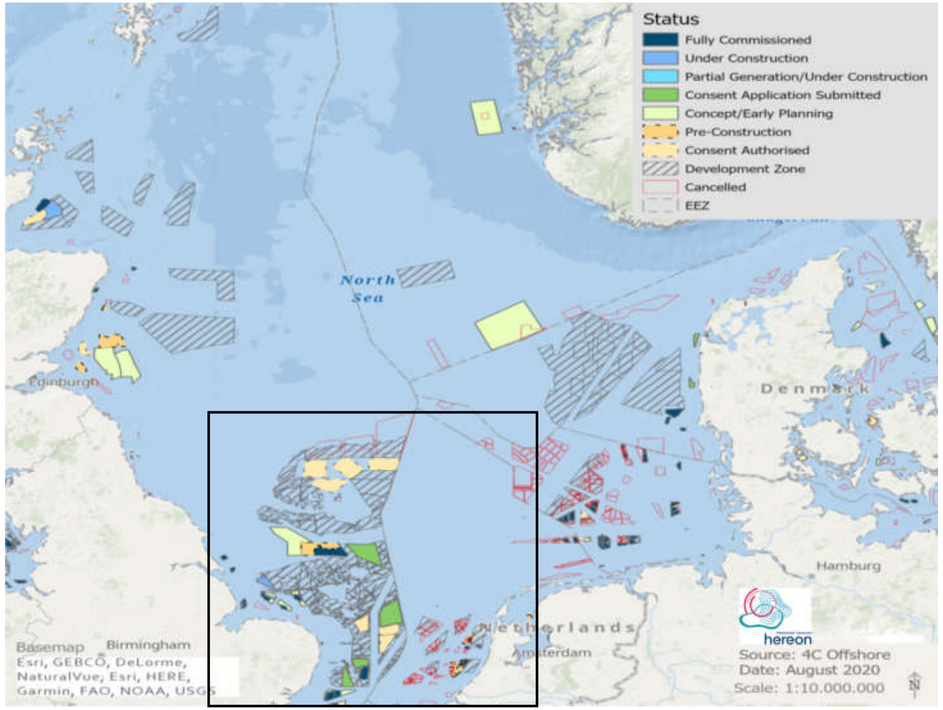


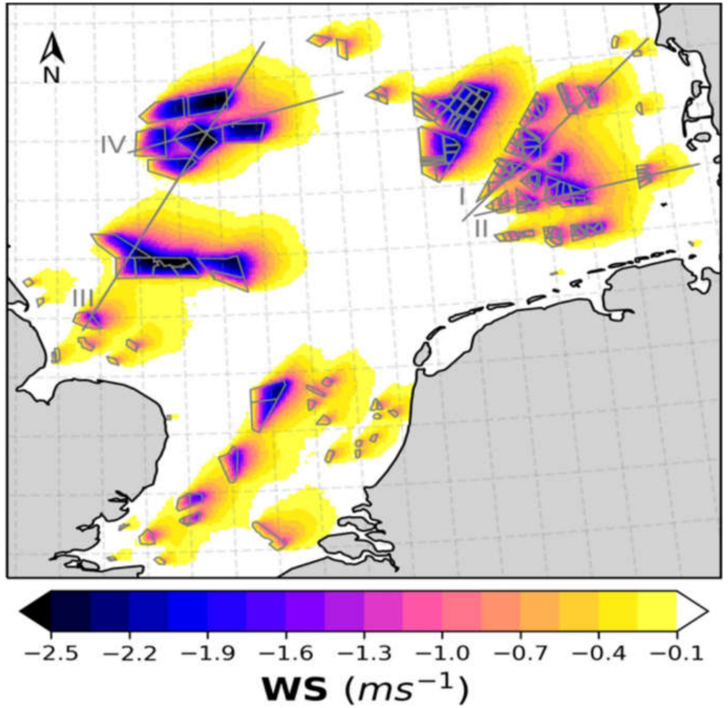



# Interaction of large offshore wind farms



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



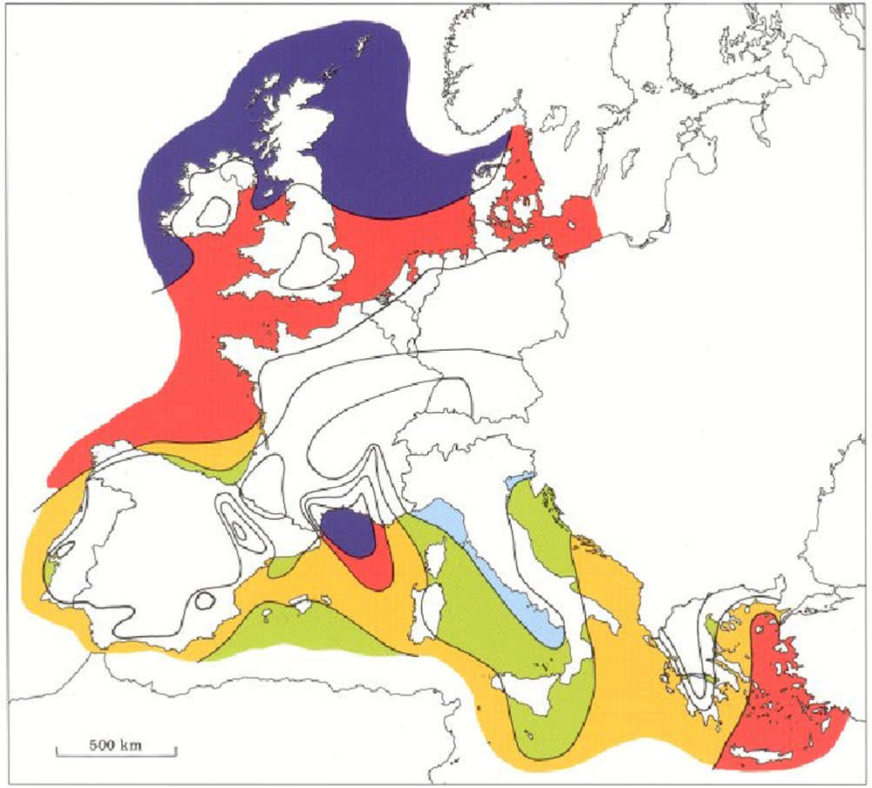
# Floating Wind

04

# An unprecedented opportunity



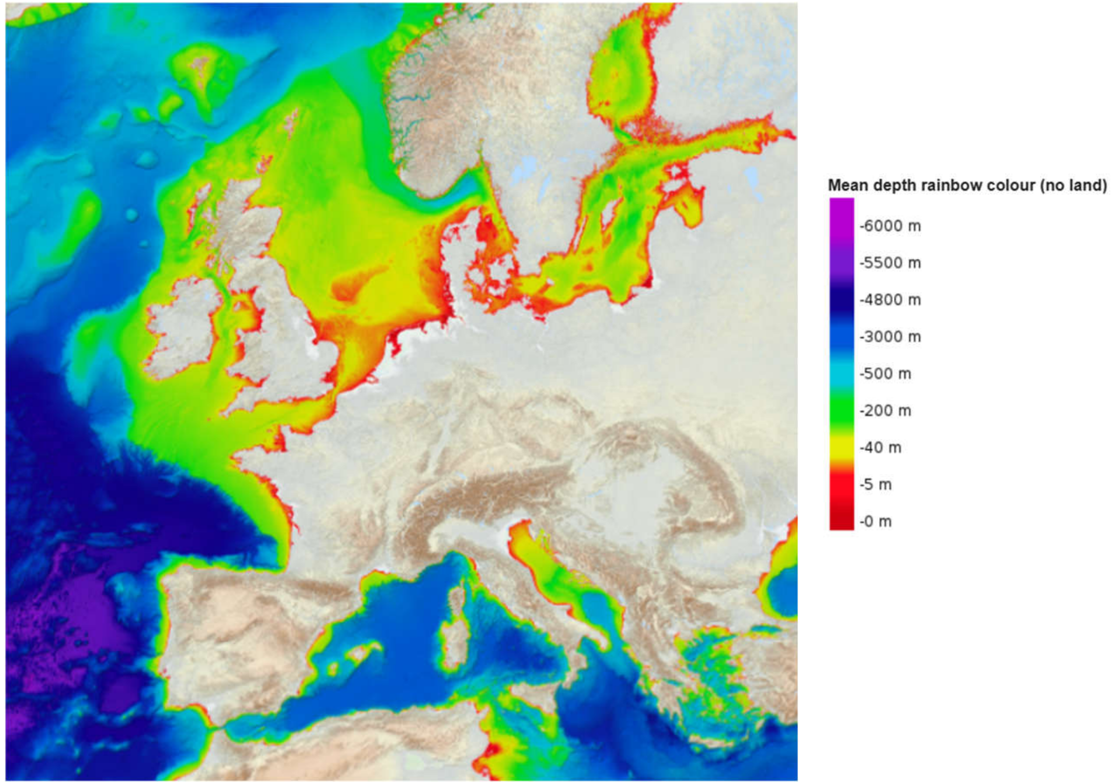
## Offshore wind speed




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

| | 10 m | | 25 m | | 50 m | | 100 m | | 200 m | |
|---|---|---|---|---|---|---|---|---|---|---|
| | $m s^{-1}$ | $W m^{-2}$ | $m s^{-1}$ | $W m^{-2}$ | $m s^{-1}$ | $W m^{-2}$ | $m s^{-1}$ | $W m^{-2}$ | $m s^{-1}$ | $W m^{-2}$ |
| | > 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 |

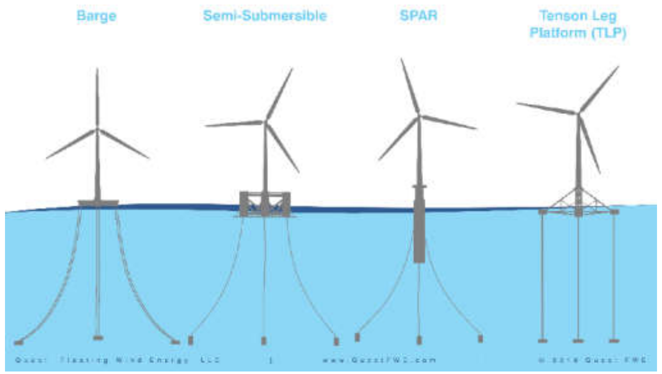
## Bathymetry

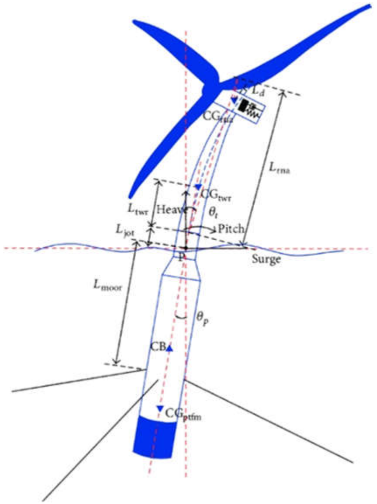


# Floating Offshore Wind Turbines

## Great interest in floating offshore wind (FOWT)

- ✓ outstanding potential, also for social acceptance
- ✓ still a relatively new technology with a lot of unknowns and improvement margins
- ✓ to date, turbines are “adapted” to floating conditions
- ✓ no clear consensus on the right floater for each application
- ✓ excitation of the floating substructure results from:
  - the direct wave interaction
  - the rotor loads, which are transferred to the floater through the tower. These, in turn, depend on the velocity and position of the system. Hence, the problem is fully coupled




## Many additional issues:

- ✓ floater cost/production
- ✓ installation
  - depth
  - seabed characteristics
  - distance

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

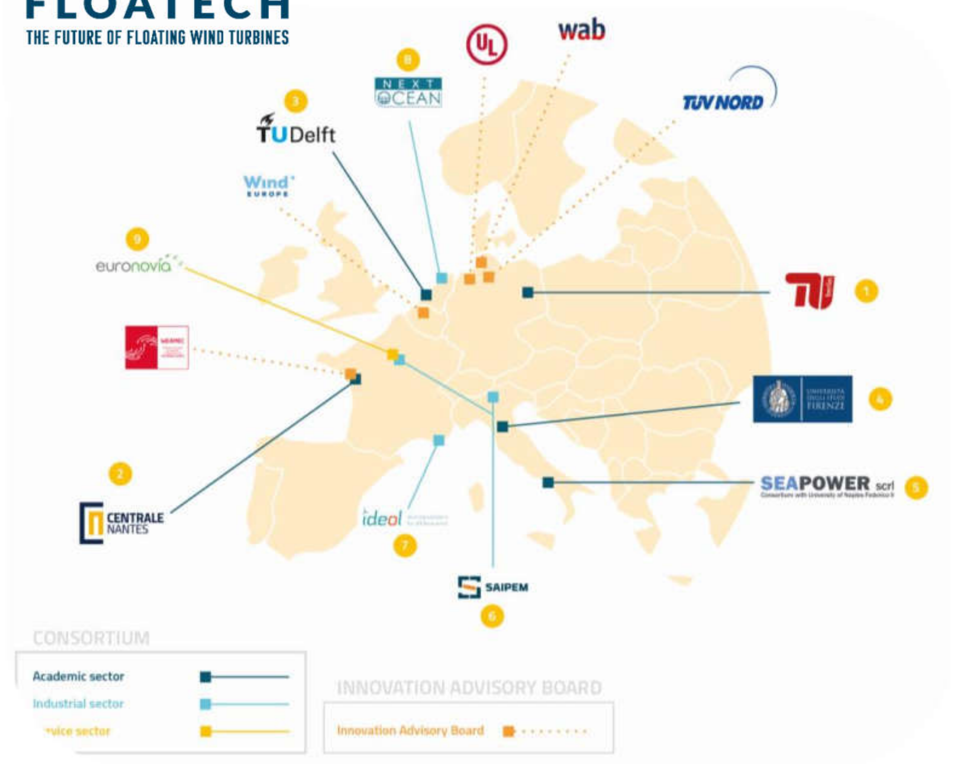
# An example from my own research: the FLOATECH project

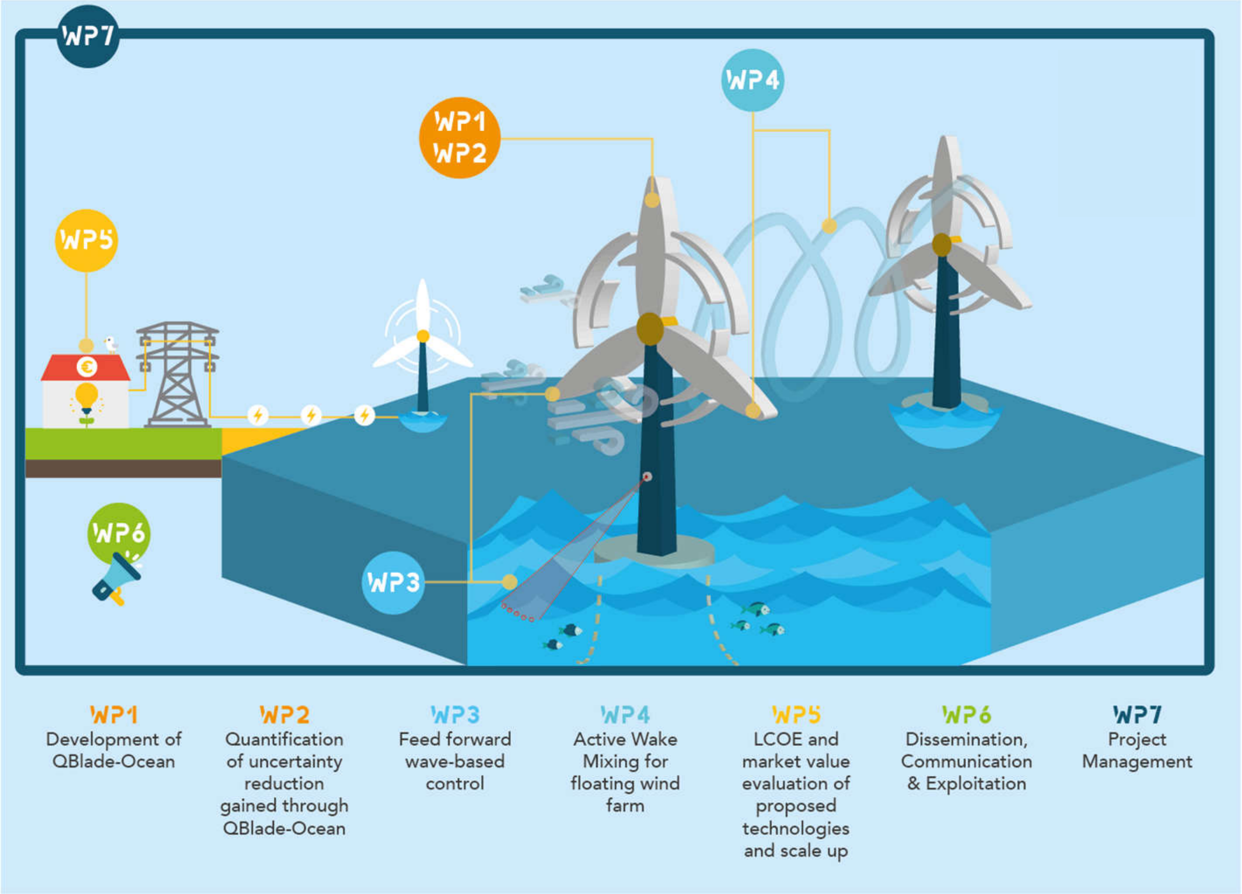


FLOATECH
THE FUTURE OF FLOATING WIND TURBINES

Jan 2021 – Dec 2023

https://www.floatech-project.com



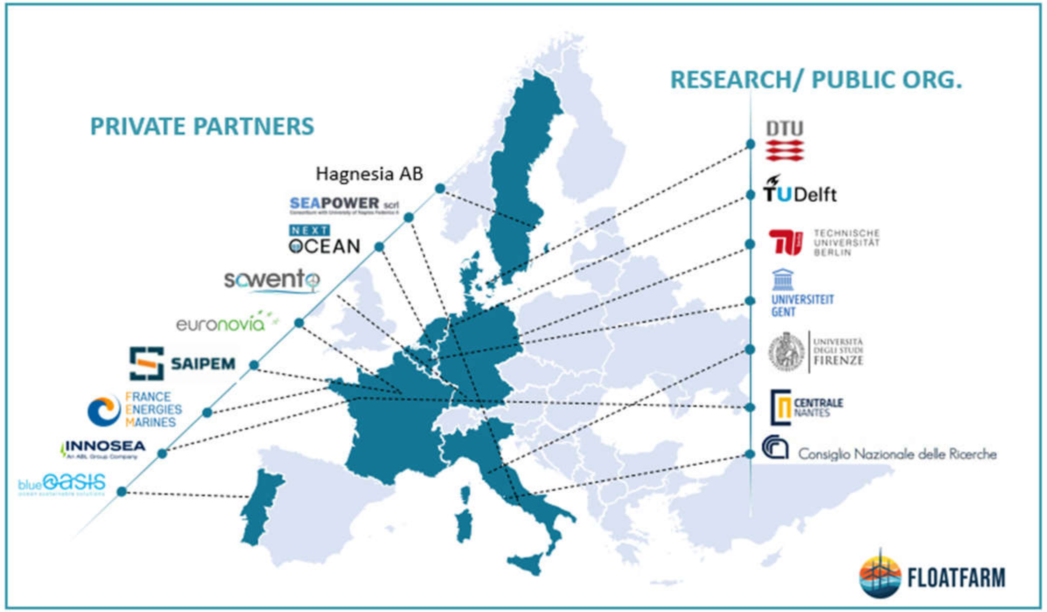



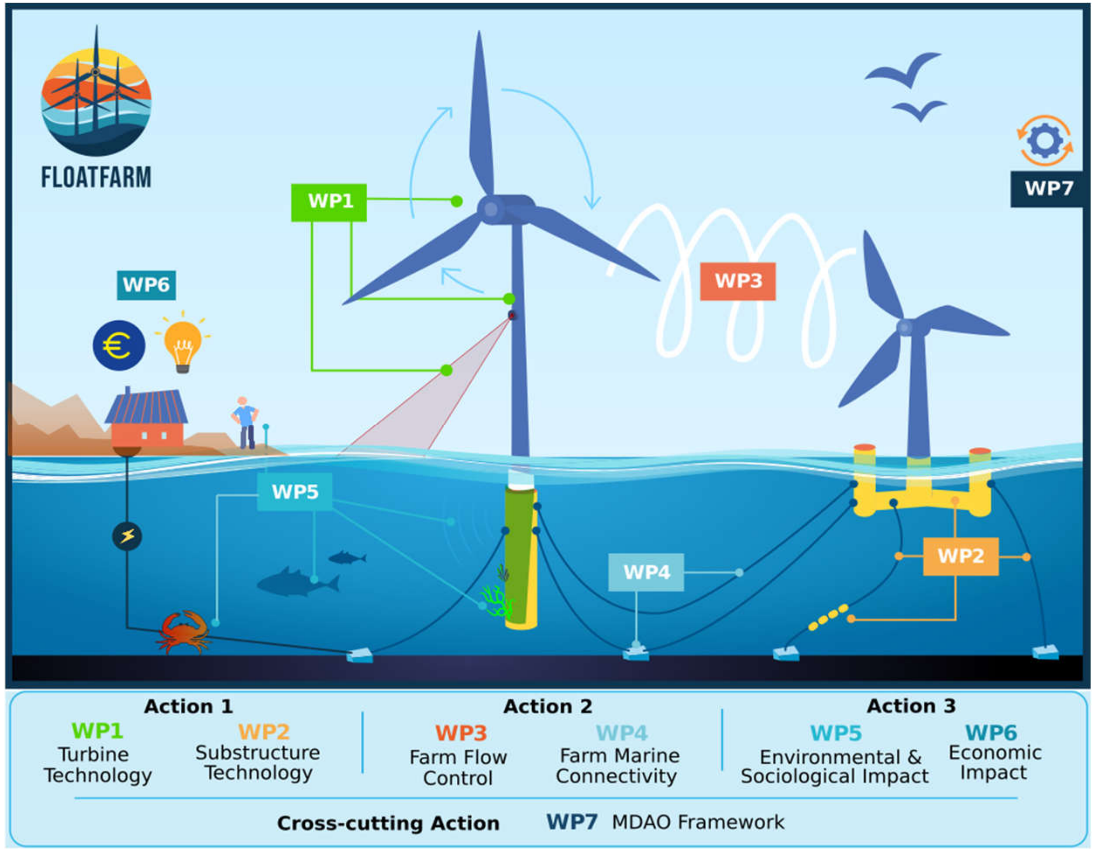
# ..and the next to come: FLOATFARM



FLOATFARM

Jan 2024 – Dec 2028



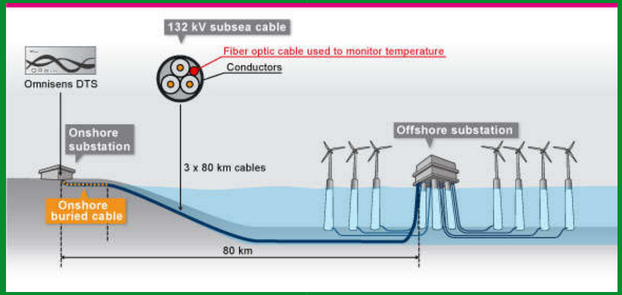
# New installations: offshore

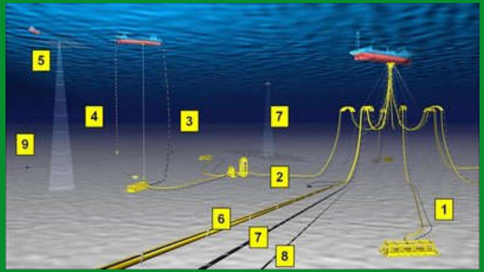
TETHYS – 1st webinar

Offshore WT systems need to operate in harsh conditions, with turbine structures being excited by strongly coupled aerodynamic and hydrodynamic forces

To increase the penetration of offshore wind in the energy market, more cost-effective designs and installation methods are needed

- ✓ consider overall lifetime costs, including manufacturing, installation, O&M and decommissioning
- ✓ get a thorough understanding of the stochastic metocean climate and how it impacts structural loading on these systems
- ✓ develop a multi-fidelity toolset to accurately represent the physics, as well as a design process that integrates these capabilities in a way that is tractable
- ✓ put in place extensive validation campaigns to ensure that these design practices are accurate across the diverse design space and metocean environments including full-scale campaigns



SIDE TOPIC

SUBSEA CABLES