DIPARTIMENTO DI

INGEGNERIA INDUSTRIALE

Wind power

Renewable Energy Conversion Systems

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A.Y. 2024-2025

UNIVERSITÀ DI TRENTO

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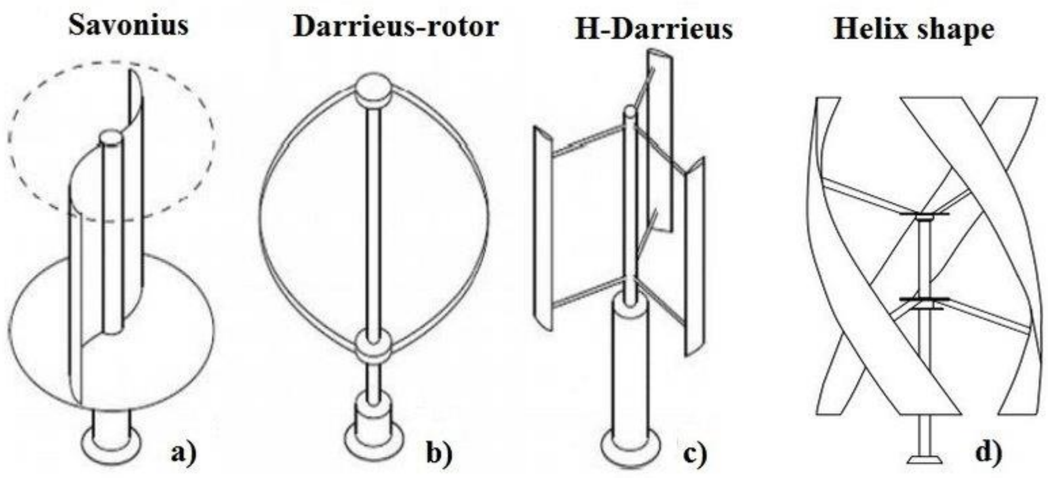
VERTICAL AXIS WIND TURBINES

Vertical axis wind turbines

Vertical axis wind turbines (VAWT) can be divided into two main categories, depending by which aerodynamic load (lift or drag) induces the torque:

- **Drag-based** wind turbines: Savonius turbine
- **Lift-based** wind turbines: Darrieus turbine
- **Drag + lift-based** turbines: Hybrid Darrieus-Savonius turbines



Drag-based

Lift-based

Savonius

Darrieus

Hybrid

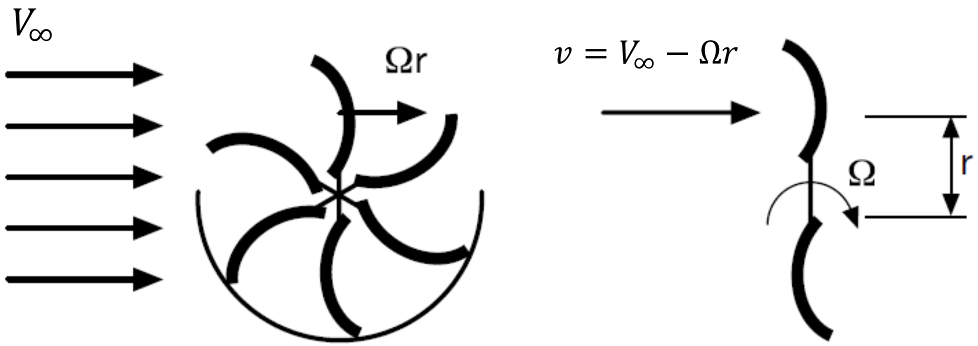
Savonius wind turbine

Savonius turbine is **drag-based** and represents the simplest among wind turbine concepts.
It consists of multiple vertical *scoops* curved in a semi-circular shape, with no airfoils. Its main features are:

- Low speed (tip speed ratio λ is <1)
- Low aerodynamic efficiency, suitable for the exploitation of mild wind
- High mechanical torque fluctuations
- Low-noise
- Requires speed control to maintain efficiency within acceptable ranges
- Inability to reduce the aerodynamic surface area at higher-than-rated-speed due to fixed blades, therefore needs mechanical braking devices for stopping;
- Need for a robust structure to withstand extreme winds (given the large surface area of the blades exposed);
- Adaptable to wind direction variations, with no need for yaw control mechanisms
- Used only in small-power applications

Savonius wind turbine

Because of the curvature, the scoops experience less drag when moving against the wind than when moving with the wind. The differential drag causes the Savonius turbine to spin.



Let us assume, as an optimal limit case, that only the scoop moving with the wind is subject to a drag force (let us thus neglect the opposite torque contribution from the scoop moving against the wind):

Drag force (top scoop): $F_D = C_D \frac{1}{2} \rho (V_\infty - \Omega r)^2 A$

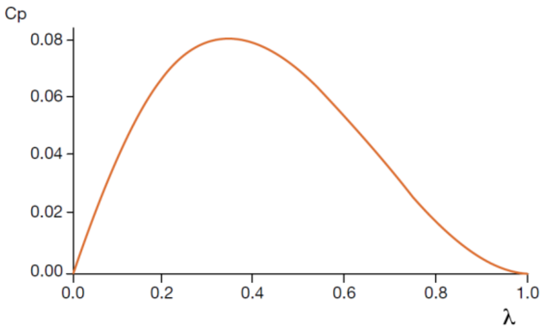
Power extracted:

$$P = C_D \frac{1}{2} \rho (V_\infty - \Omega r)^2 A \, \Omega \, r = C_D \frac{1}{2} \rho V_\infty^3 (1-\lambda)^2 \lambda \, A = C_p \frac{1}{2} \rho V_\infty^3 A$$

Tip-speed ratio: $\lambda = \frac{\Omega r}{V_\infty}$

C_D:scoop drag coefficient; $C_p = C_D (1-\lambda)^2 \lambda$: power coeff. of Savonius turbine

$$C_{p,max} = C_p \left(\lambda = \frac{1}{3} \right) = \frac{4}{27} \approx 0.15$$

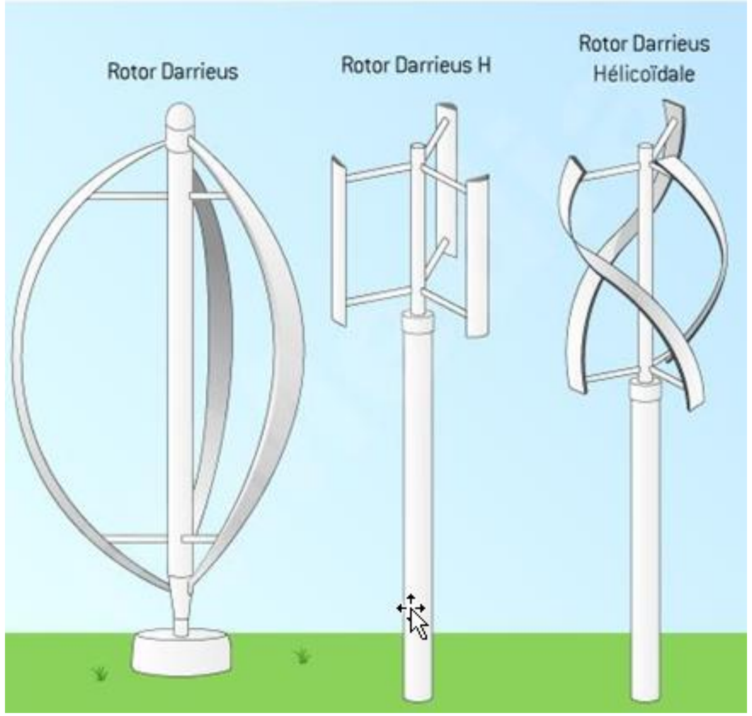


In practice, typical maximum values of C_p are below 0.1

Darrieus wind turbine

Darrieus-type turbines are vertical-axis lift-based turbines, consisting of number of curved airfoil blades mounted on a rotating shaft. Main features include:

- Highly fluctuating torque
- Traditional Darrieus rotors (with curved blades) offer structural advantages, but have low efficiency because a significant portion of the airfoil surface lies close to the axis
- Space occupancy is large as compared to HAWTs
- Performance is affected by low wind speeds close to ground
- Requires speed control to maintain efficiency within acceptable ranges
- Because of fixed blades, cannot reduce the aerodynamic surface at higher-than-rated-speed, therefore needs mechanical braking devices for stopping;
- Lower structural requirements compared to Savonius turbines
- Has **no self-start-up ability**. This is why it is sometimes combined with a Savonius turbine, which allows for self-start-up
- Adaptable to wind direction variations, with no need for yaw control mechanisms
- Generator and gear can be installed at ground level
- Low noise

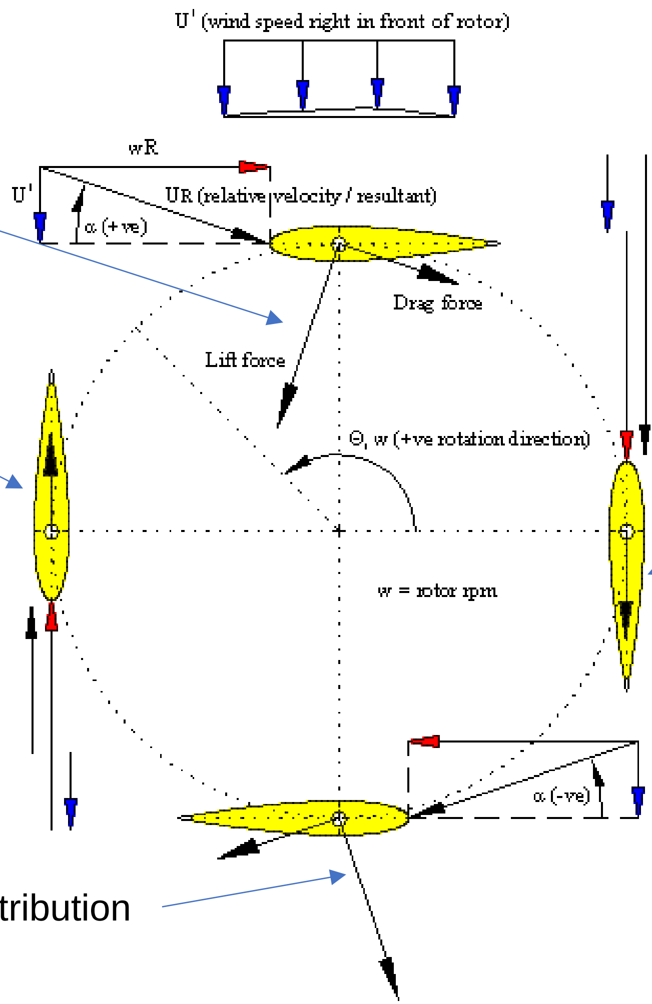


Darrieus wind turbine

<u>Positive</u> torque contribution

No torque contribution

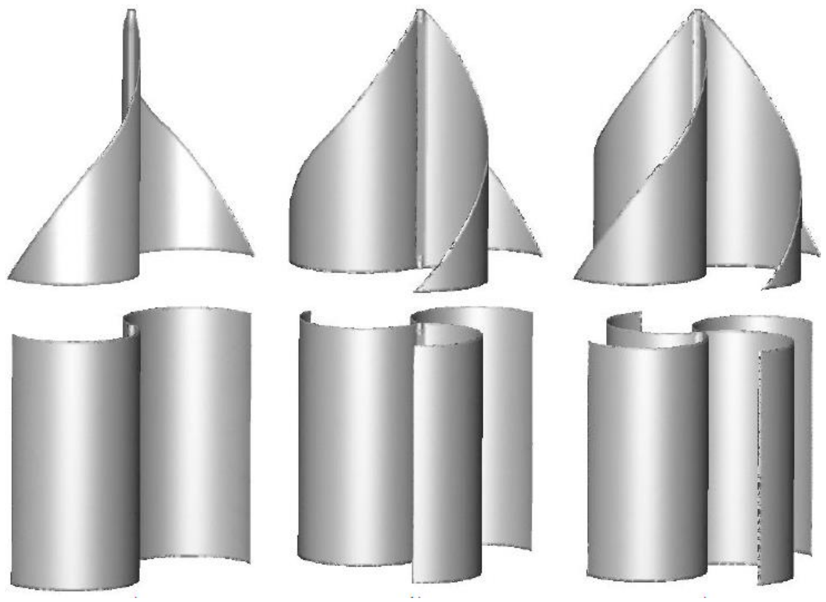
No torque contribution

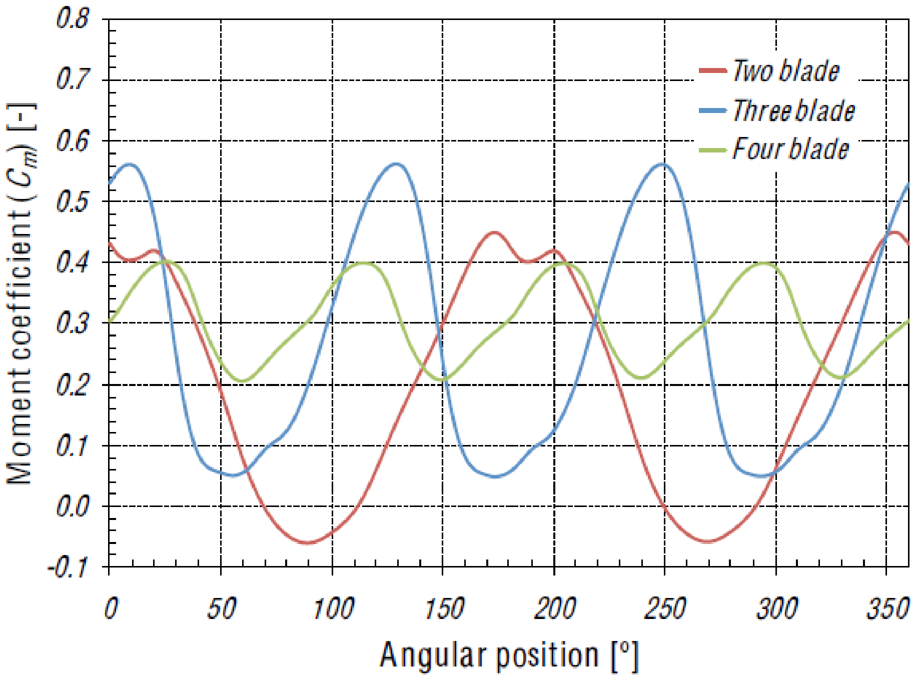


<u>Positive</u> torque contribution

Torque fluctuations in VAWTs

VAWTs, both drag and lift based, are characterised by variable torque as a function of the angular position instantaneously assumed by the rotor. The case of various Savonius rotor configurations is given below as an example. Variability decreases as the number of blades increases, but on the other hand, the cost/complexity of the machine increases, and so do aerodynamic losses

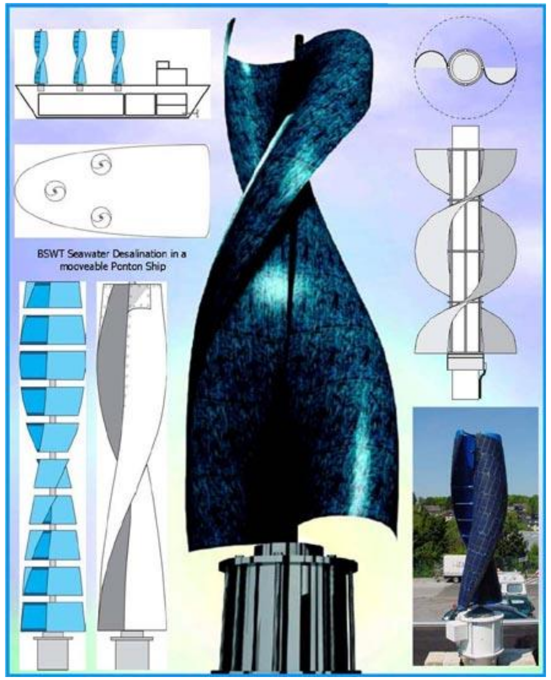




Variation of moment coefficient (C_m) for two bladed, three bladed and four bladed Rooftop rotors.

Torque fluctuations in VAWTs

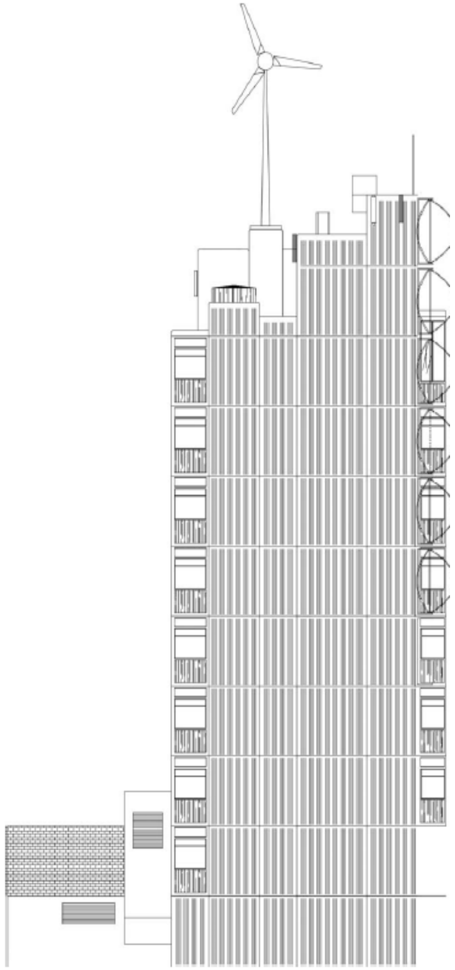
In order to reduce the variability of torque, without increasing the number of blades, helical blade geometries are used:



Helical drag-based turbine

Helical lift-based turbine

Integration of VSWTs onto buildings



Wind turbines comparison

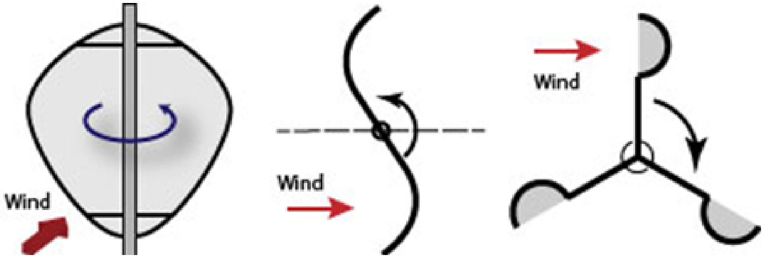
Vertical

The rotor axis is perpendicular to the wind direction. Some designs use draf, others use lift forces.

The most widely used application is the wind anemometer with its moving cups. Small-scale roof-top turbines are also often with a vertical axis to avoid gear box.

Lift | Drag

Darrieus | Savonius | Wind Anemometer



tip speed ratio: 4 | tip speed ratio: <1

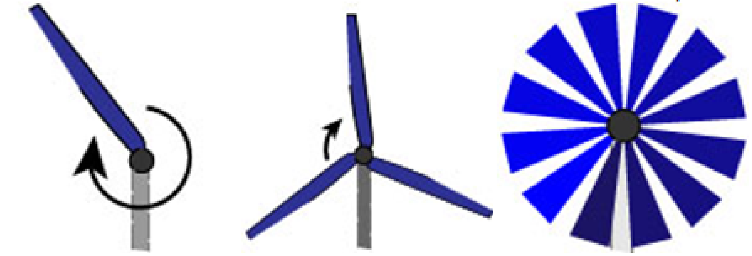
- Omni-direction - wind may come from any direction
- Easy to mount at ground level, no tower needed
- Low rotation speed - no gearbox needed - less noise
- Generally near the ground with low wind speeds
- Self-starting problems
- Drag devices capture only ~15% of energy, Darrieus ~40%.
- No large-scale commercial application

Horizontal

The rotor is parallel to the wind direction. All devices use lift forces rather than drag.

Horizontal axis is the most common design for turbines, and is also the design of the traditional wind mills. For electricity generation, mostly 3 blades or less.

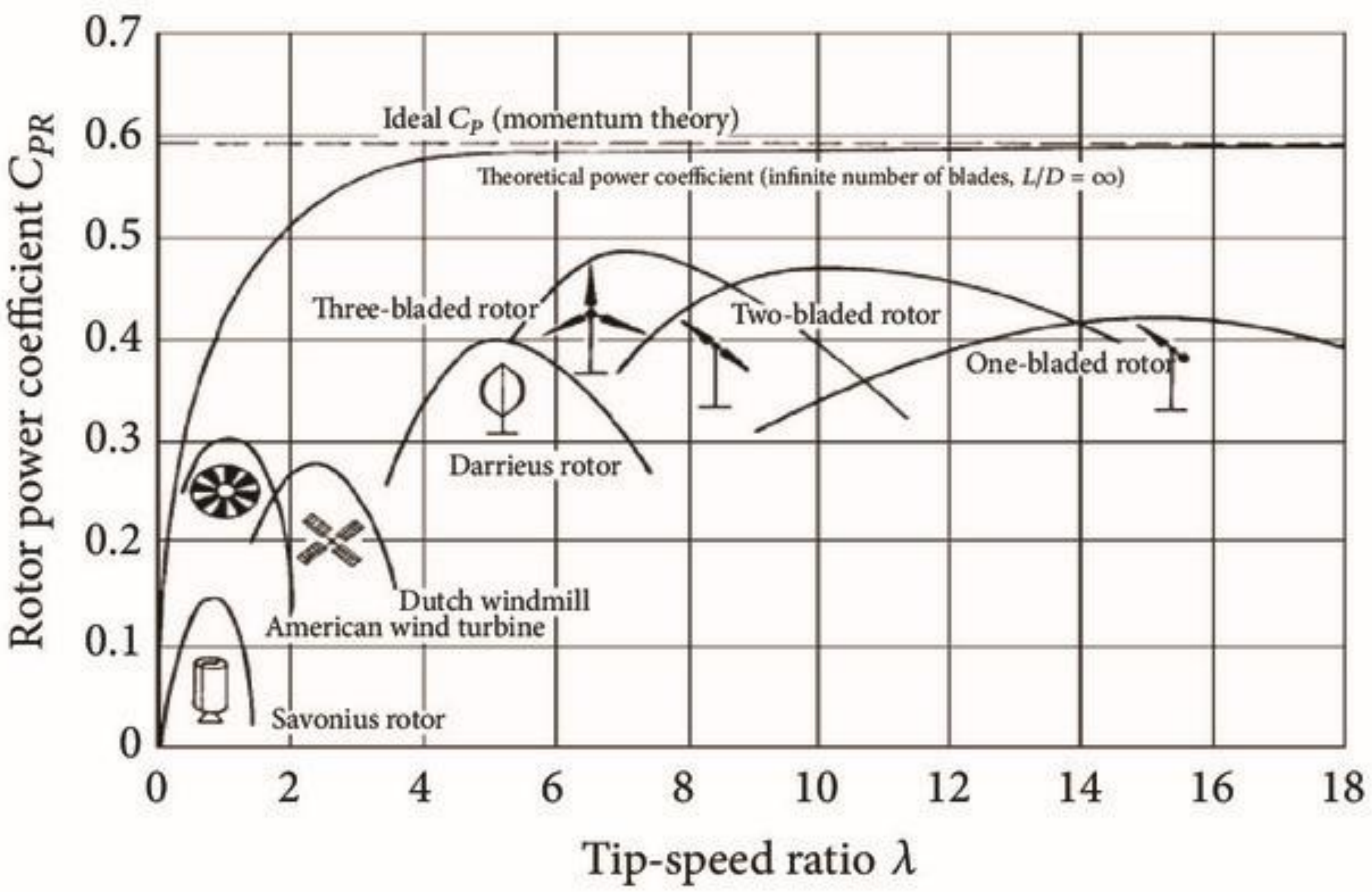
1 Blade | 3 Blades | Water Pumps



Tip speed ratio:12 | Tip speed ratio: 6 | Tip speed ratio: 1

- Tip speed ratio is the ratio of the tangential velocity of the blade (at the tip) to the undisturbed wind speed. Fewer blades means higher tip speed. The optimum tip speed ratio that maximises the lift-to-drag force ratio is around 8. With more than 4 blades, less efficiency because each blade operates in the wake of others.
- Efficiencies up to 50%
- Lower cut-in wind speeds than vertical turbines

Wind turbines comparison



Tipo di turbina	TSR ottimale λ	Velocità tangenziale V_t [m/s]	Raggio rotore R [m]	Velocità angolare Ω [giri/min]
VAWT Savonius	1	7	1	67
VAWT Darrieus	5	35	1.5	223
HAWT bipala	10	70	28	24
HAWT tripla	7	49	45	10

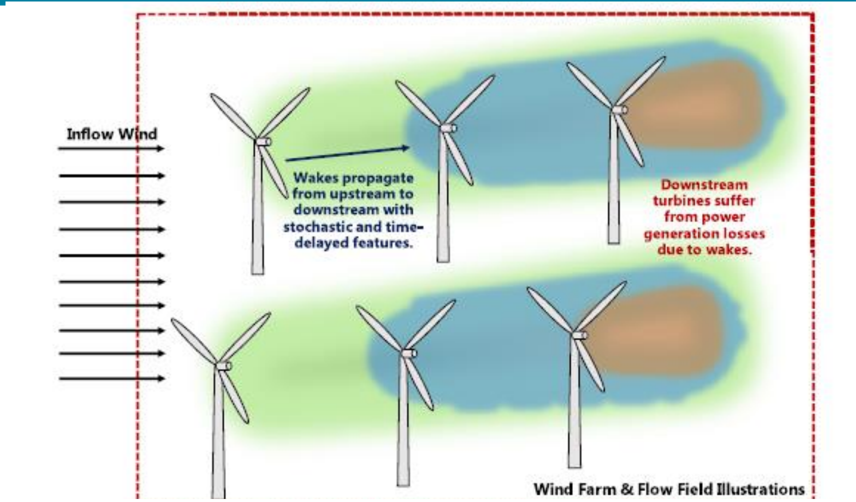
WIND FARMS

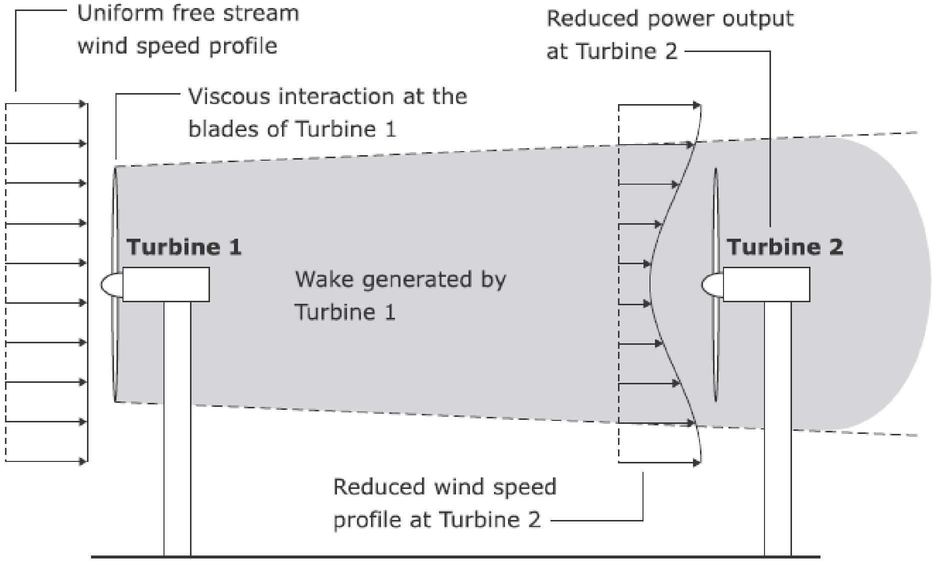
Wind farm generalities

Arranging multiple WTs in a farm involves the identification of trade-offs between
- the number of units that can be hosted within a site (i.e., the installable rated power)
- performance limitations due to aerodynamic interference between neighbour turbines

Specifically, after an upstream wind turbine in the farm extracts power from the inflow wind, downstream turbines will experience *wake effects* characterized by the following phenomena:
- Reduction of mean wind-speed: Since upwind turbines extract energy from wind, a lower wind-speed is experienced by downwind turbines. This reduces the energy captured by the downwind turbines significantly.
- Increase in turbulence: Since wind is inherently stochastic, there is always some amount of 'ambient' turbulence. Upwind turbines add to this turbulence through the rotation of their rotor-blades.

Wake effects are estimated to reduce the farm power capture in the range of 5 -15%.





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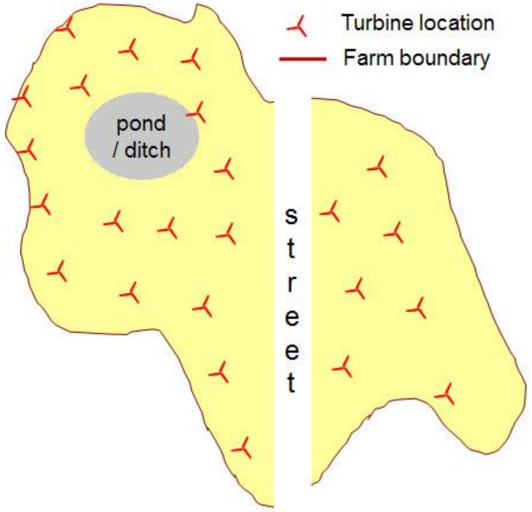
Design considerations



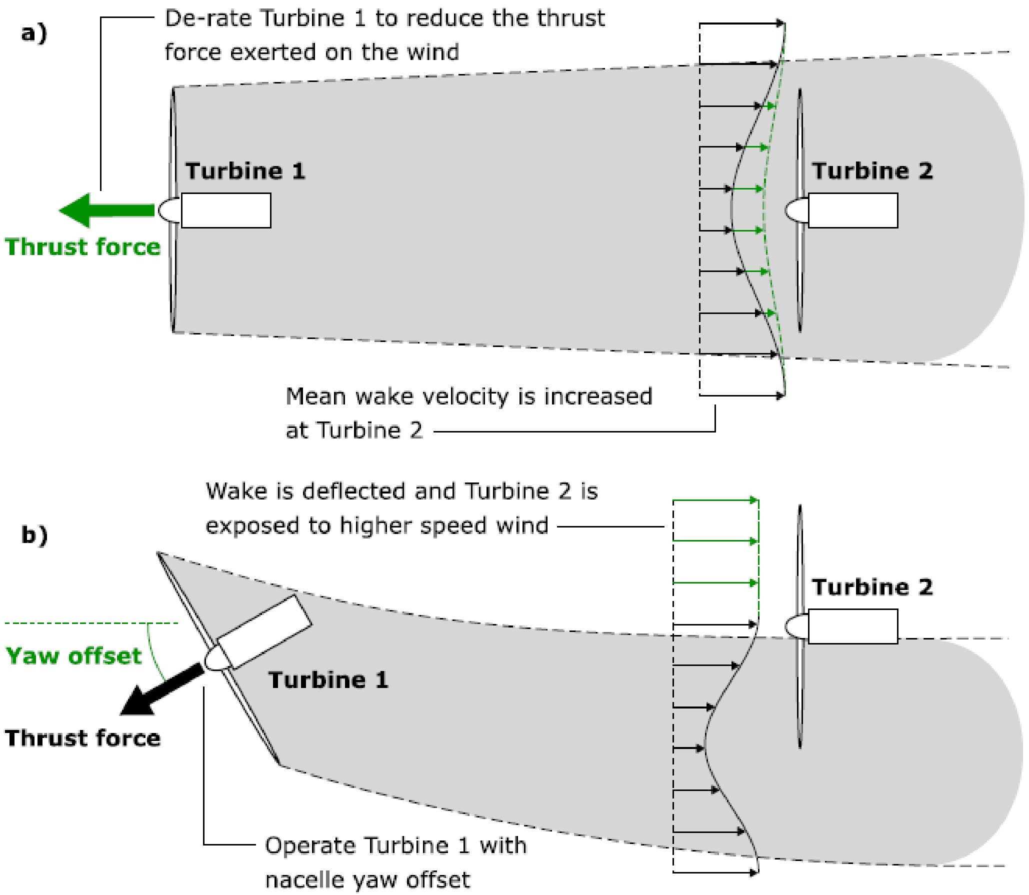
Micro-sitting (i.e., positioning of wind turbines within a pre-defined farm area) involves a number of design constraints, including:

- Topological constraints (e.g., presence of geographical obstacles) and forbidden zones (streets, ditches etc)

- Minimum spacing: farm developers typically enforce a pre-specified minimum spacing between turbines (typically, *3-5 rotor diameters* lateral distance, *5-7 diameters* axial distance between neighbor turbines)) in order to mitigate the impact of wake effects.

- Noise: The rotation of the turbine rotor generates frequencies in the audible range. When the wind farm is located close to a residential area, larger noise levels may not be acceptable. To operate turbines at reduced noise, some amount of captured energy typically needs to be given up.

Control approaches

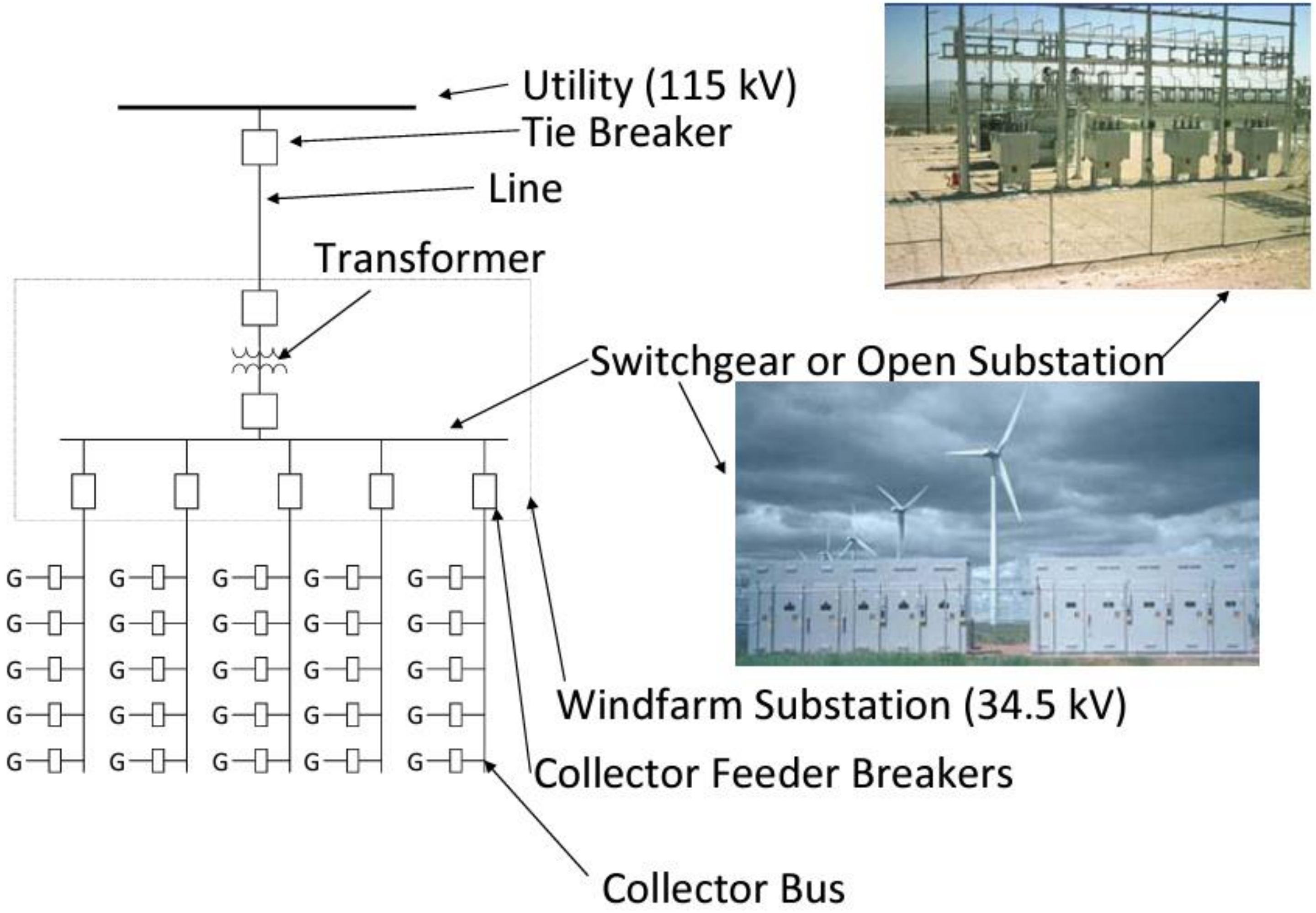


Two notable wind farm control concepts have been proposed for mitigating the effects of aerodynamic coupling within wind farms:

a) *Power de-rating* (also called *axial induction-based control*):the upstream turbine reduces its axial induction factor and, hence, its power output. The downstream turbine, which is located further downstream and aligned with the wake, is exposed to greater wind speed and outputs higher power compared to a baseline scenario in which Turbine 1 had not been de-rated

b) *Yaw-based wake redirection*. Operating Turbine 1 with a certain nacelle yaw offset causes the generated wake to be redirected in the direction of yaw. The overlapping area between this deflected wake and the rotor of Turbine 2 is reduced, and a portion of the rotor of Turbine 2 is exposed to higher speed. There exists an optimal nacelle yaw offset at which Turbine 2 experiences a power output rise that exceeds the power loss of Turbine 1

Electrical layout



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OFFSHORE WIND TURBINES

Offshore wind turbines – Motivation & Context

- The power output of a WT is proportional to the square of the rotor diameter and the cube of the incident wind speed → need for larger turbines, in regions where the wind speed is higher

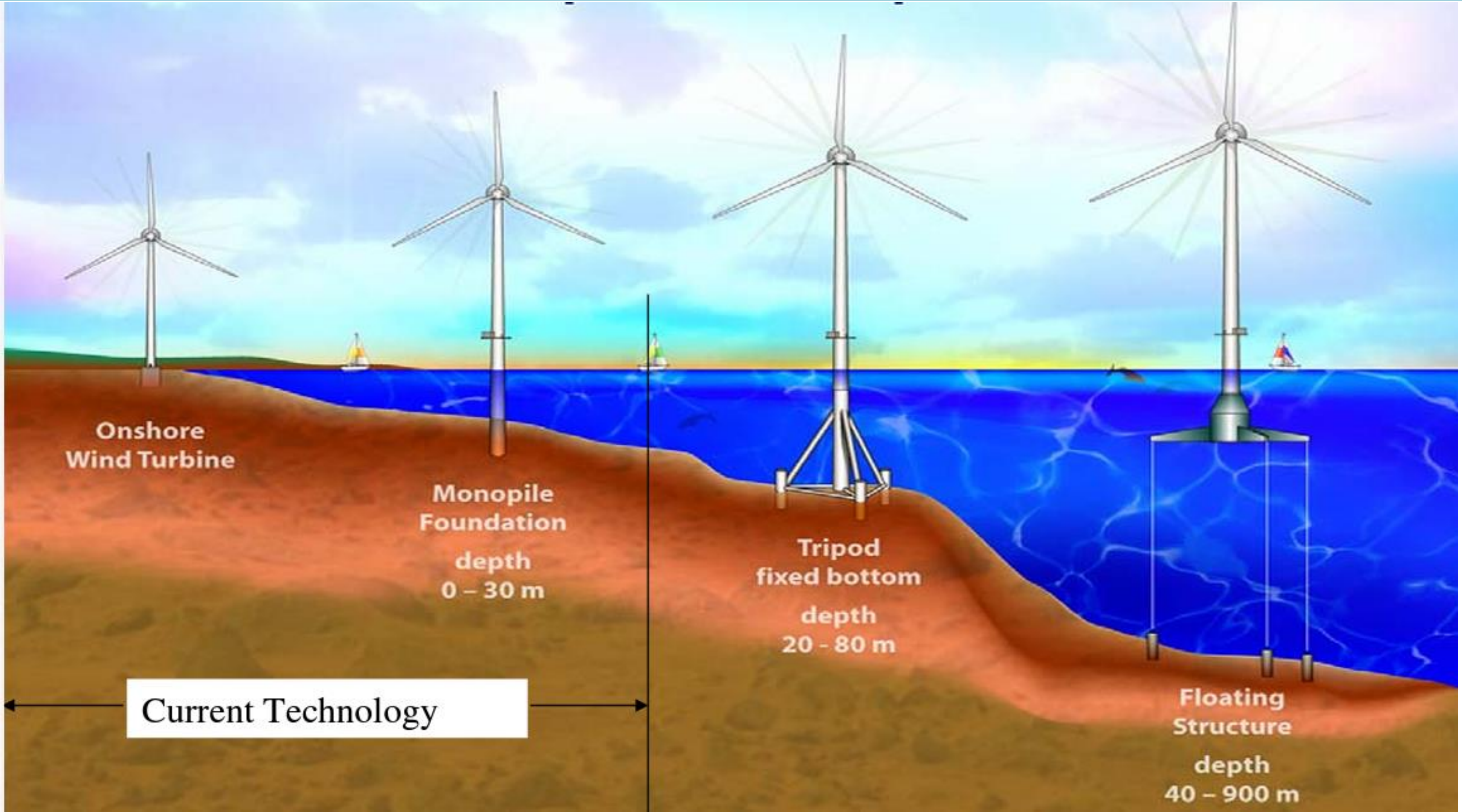
- The wind can be stronger up to 10 m/s and steadier over water due to the absence of topographic features

- Existing fixed-bottom wind turbine technology deployments have been limited to water depths of 30 m

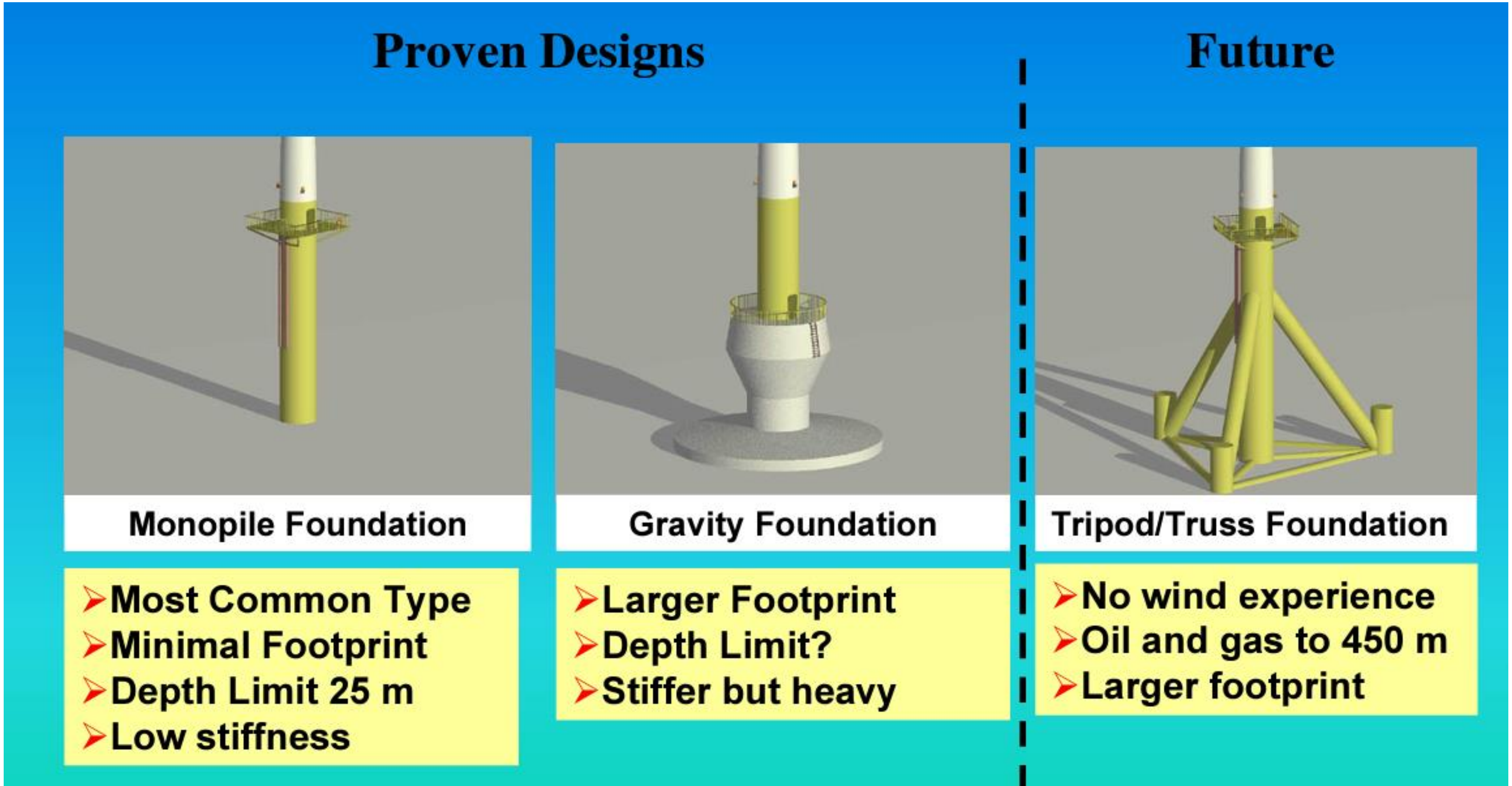
- Worldwide wind resources are abundant over deep-waters

- Noise and visual pollution created by fixed turbines near the coastal areas are to be avoided

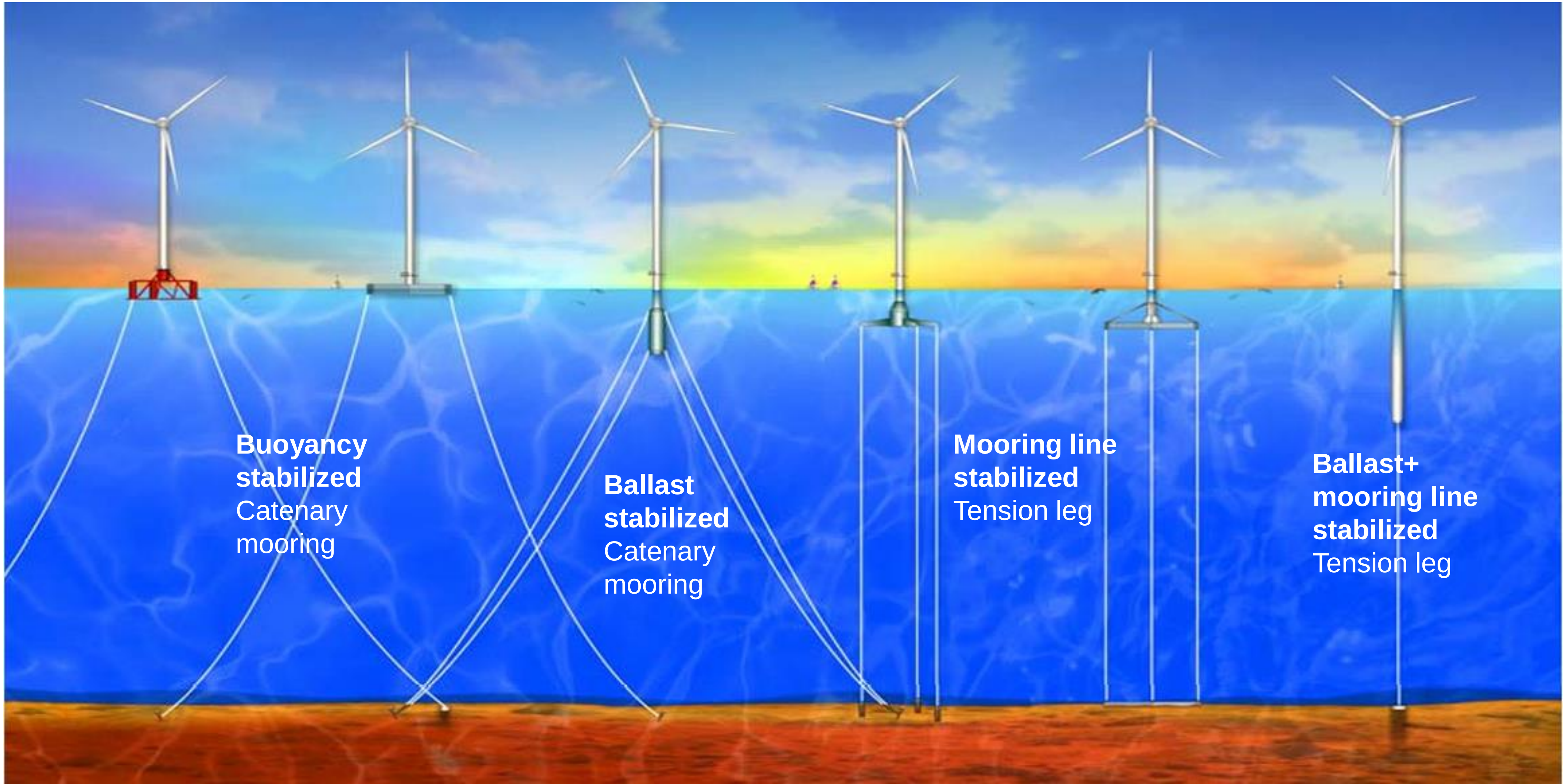
Offshore wind turbines



Offshore wind turbines – bottom fixed concepts



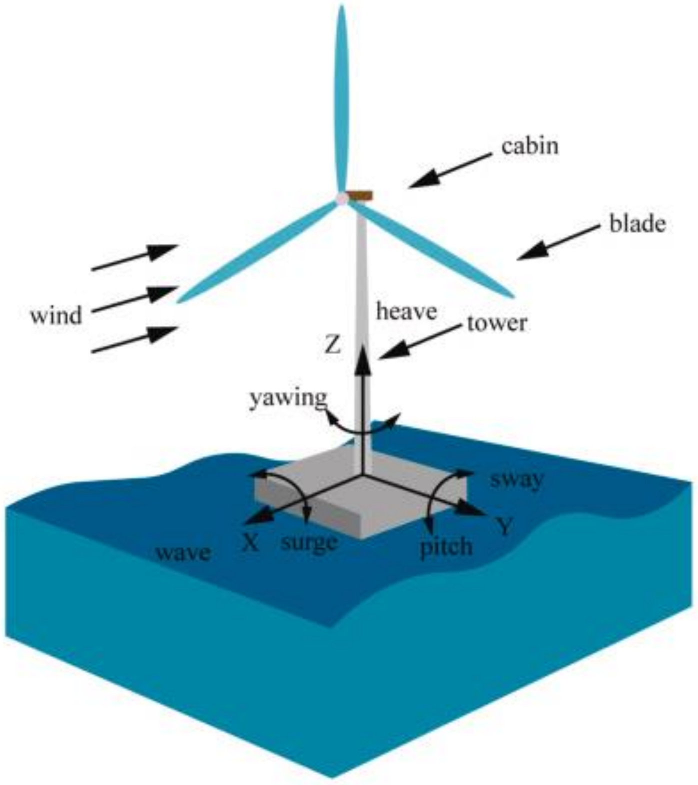
Offshore wind turbines – floating concepts



Offshore wind turbines – floating concepts

- Forces due to waves depend on how the structure is connected to the seafloor
- In buoyancy or ballast stabilised concepts in which the barge/ballast are close to the surface, wave loads can cause large overturning moments as the wave forces act near the water surface
- If the mooring lines form an angle with the vertical line, the horizontal stiffness of the system increases
- Load effects and fatigue analysis should be determined by considering all (statistically relevant) sea states that might be experienced by the structure over its lifetime

Dynamics of floating wind turbines – floating concepts



6-DoF floating platform dynamics, under the assumption of *small displacements* (linearised dynamics):

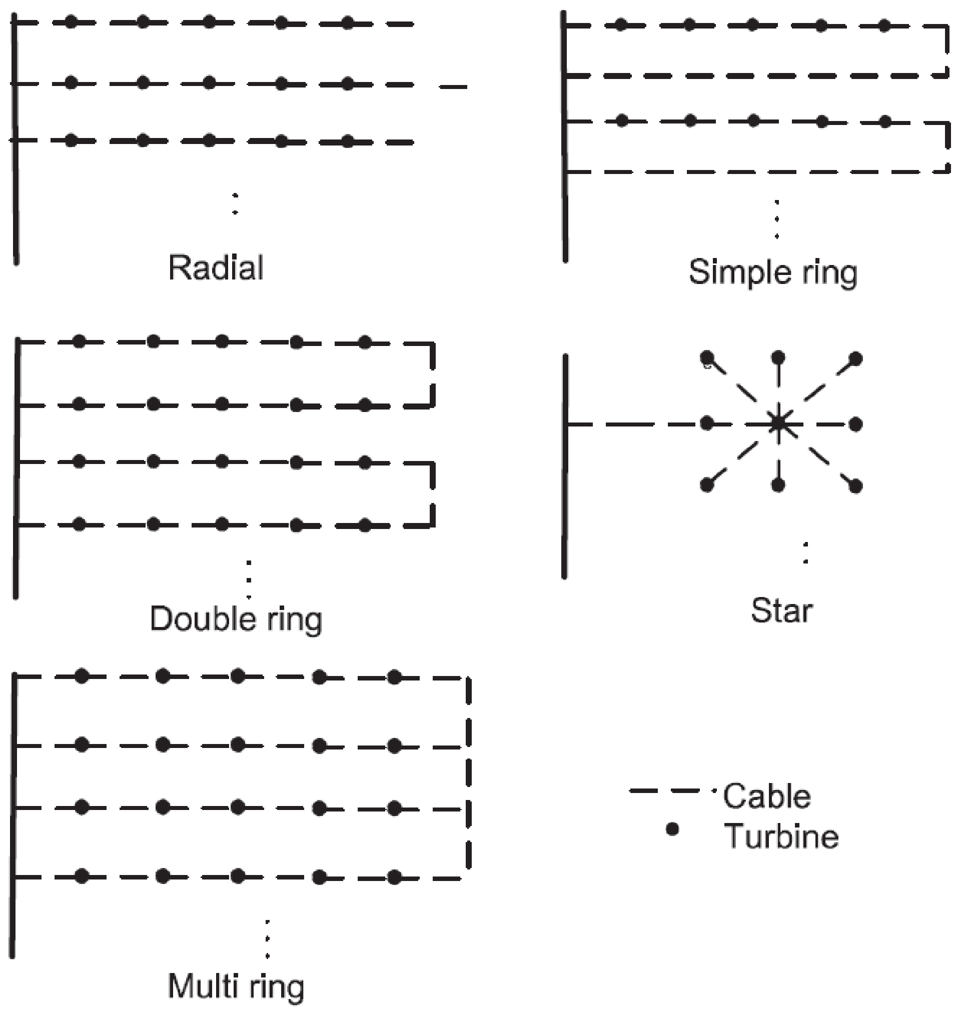
$$(\boldsymbol{M} + \boldsymbol{M_{ad}})\ddot{\boldsymbol{\xi}} + \boldsymbol{C}\dot{\boldsymbol{\xi}} + \boldsymbol{K}\boldsymbol{\xi} = \boldsymbol{F_A} + \boldsymbol{F_M} + \boldsymbol{F_w}$$

with $\boldsymbol{\xi} = \left[x, y, z, \theta_x, \theta_y, \theta_z\right]^T$

$\boldsymbol{M}$ platform inertia matrix
$\boldsymbol{M_{ad}}$ is an added mass matrix, which accounts for inertial effects due to the moving water surrounding the platform (rigorously speaking, this contribution is not constant, as it depends on frequency)
$\boldsymbol{C}$ is a damping matrix accounting for the energy dissipated by the radiated waves generated by the platform motion
$\boldsymbol{K}$ is a stiffness matrix that accounts for the hydrostatic restoring loads (Archimede's loads)
$\boldsymbol{F_A}$ are the (generalised) aerodynamic loads (thrust force, wind torque)
$\boldsymbol{F_M}$ are (generalised) loads due to the mooring lines
$\boldsymbol{F_w}$ are (generalised) wave loads due to the incident waves

Details @ the blackboard

Electrical layouts for offshore farms



The power from a farm of offshore turbines is gathered by a collector, so that it can be transmitted to shore. Present generators work in AC. Several standard configurations have been proposed and used in the design of collector systems.

- Radial. A set of turbines are connected to the same feeder in series. This solution requires few conductors, but it has scarce reliability, as any fault will prevent upstream turbines from delivering power
- Simple ring. Redundancy is implemented via a parallel cable from the last turbine in a row back to the collection hub. This cable should be able to carry the total power generated by the string. It is the most expensive and most reliable of standard assortments.
- Double ring. The double-sided ring tries to overcome the cost disadvantages of the single-sided ring by using the cable of the neighbor string as the redundant circuit. Any string would, if a fault occurs, need to deliver the full power of two strings.
- Star. Each turbine is connected to a central cable individually. The total cable length is higher, but the rated power of the individual cables are lower.
- Multi-ring. The multi-ring was conceived as a way of dividing the power generated in a faulted string among the rest of the rows so that the capacity does not need to be upgraded as in the double-sided ring.

LEVELISED COST OF ENERGY

LCOE – calculation procedure

year	Expenditure	Income	Depreciation factor
0	$I_0 + \cancel{M_0}$	$\text{LCOE} \cdot \cancel{E_0}$	1
1	$\cancel{I_1} + M_1$	$\text{LCOE} \cdot E_1$	$\frac{1}{1+r_1}$
…	…	…	…
N	$\cancel{I_N} + M_N$	$\text{LCOE} \cdot \cancel{E_N}$	$\frac{1}{(1+r_N)^N}$

Lifetime of the plant ← N

discount rate ↑ $(1+r_N)^N$

EXPEND. = INCOME

$$\sum_{k=0}^{N} \frac{I_k + M_k}{(1+r_k)^k} = \text{LCOE} \sum_{k=0}^{N} \frac{E_k}{(1+r_k)^k}$$

$$\boxed{\text{LCOE} = \frac{\sum_{k=0}^{N} \frac{I_k + M_k}{(1+r_k)^k}}{\sum_{k=0}^{N} \frac{E_k}{(1+r_k)^k}}}$$

I_k investment cost (at year k) - CAPEX

M_k maintenance/decommissioning cost (at year k) - OPEX

E_k energy produced (at year k)

LCOE – examples

NREL Transforming ENERGY

		Land-Based	Offshore		Distributed		
Parameter	Unit	Utility-Scale Land-Based	Utility-Scale (Fixed-Bottom)	Utility-Scale (Floating)	Single-Turbine (Residential)	Single-Turbine (Commercial)	Single-Turbine (Large)
Wind turbine rating	MW	3	8	8	20 (kW)	100 (kW)	1.5
Capital expenditures (CapEx)	$/kW	1,501	3,871	5,577	5,675	4,300	3,540
Fixed charge rate (FCR) [real]	%	5.88	5.82	5.82	5.88	5.42	5.42
Operational expenditures (OpEx)	$/kW/yr	40	111	118	35	35	35
Net annual energy production	MWh/MW/yr	3,775	4,295	3,336	2,580	2,846	3,326
Levelized Cost of Energy (LCOE)	$/MWh	34	78	133	143	94	68