Wind energy

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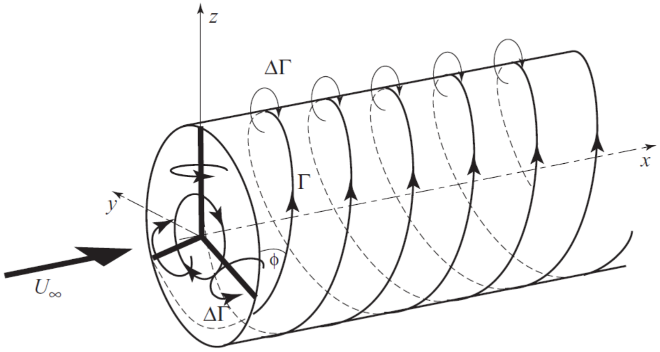
Ecole Polytechnique, Palaiseau



ECOCLIM2018
June 13th, 2018

Outline

Main objectives :

- explain how wind turbines work
  - Identify key parameters
- provide some orders of magnitude
  - *briefly* introduce some notions on the wind itself

1. Introduction and preliminary notions in aerodynamics
2. Drag machines
3. Qualitative understanding of turbines
4. The Betz limit
5. Three-bladed turbines : a bit of history
6. Variations of the wind near the surface
7. Wind resource assessment, and wind forecasts
8. Recent trends, perspectives, innovations

1. Introduction

What force does a fluid exert
on an object ?

Expectation for the force exerted on the object by the flow ?

Dimensional analysis

- relevant variables :
  - Incoming wind, $\boldsymbol{U}$ *(m/s)*
  - Size of the object, say cross-section, $\boldsymbol{A}$ *(m²)*
  - Density of the air, $\boldsymbol{\rho}$ *(kg/m^3)*

- Force exerted on the object by the fluid F_D *(kg m/s²)*

$$\Rightarrow F_D \propto \boxed{}$$

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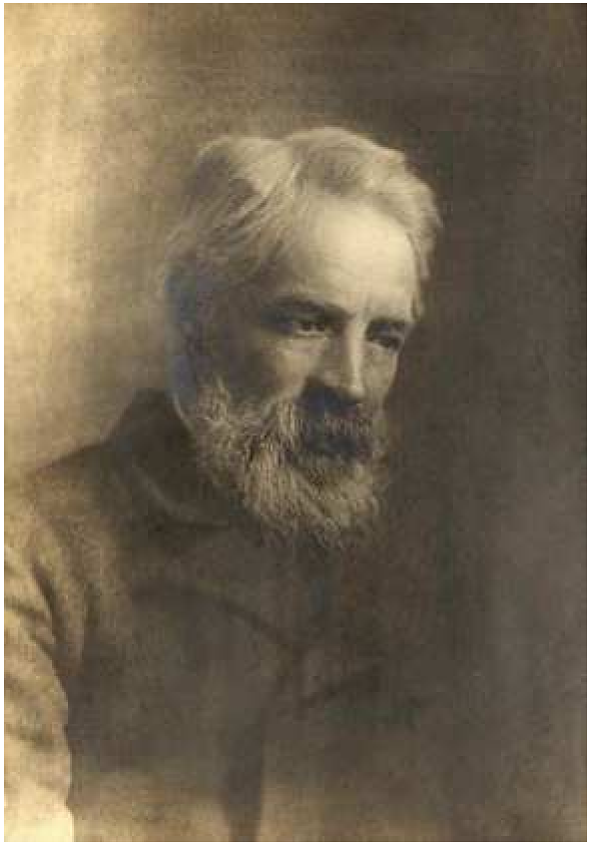
- Force exerted on the object by the fluid F_D *(kg m/s²)*

$$\Rightarrow F_D \propto \boxed{C_D \, \frac{1}{2} \rho \, A \, U^2}$$

2. Drag machines



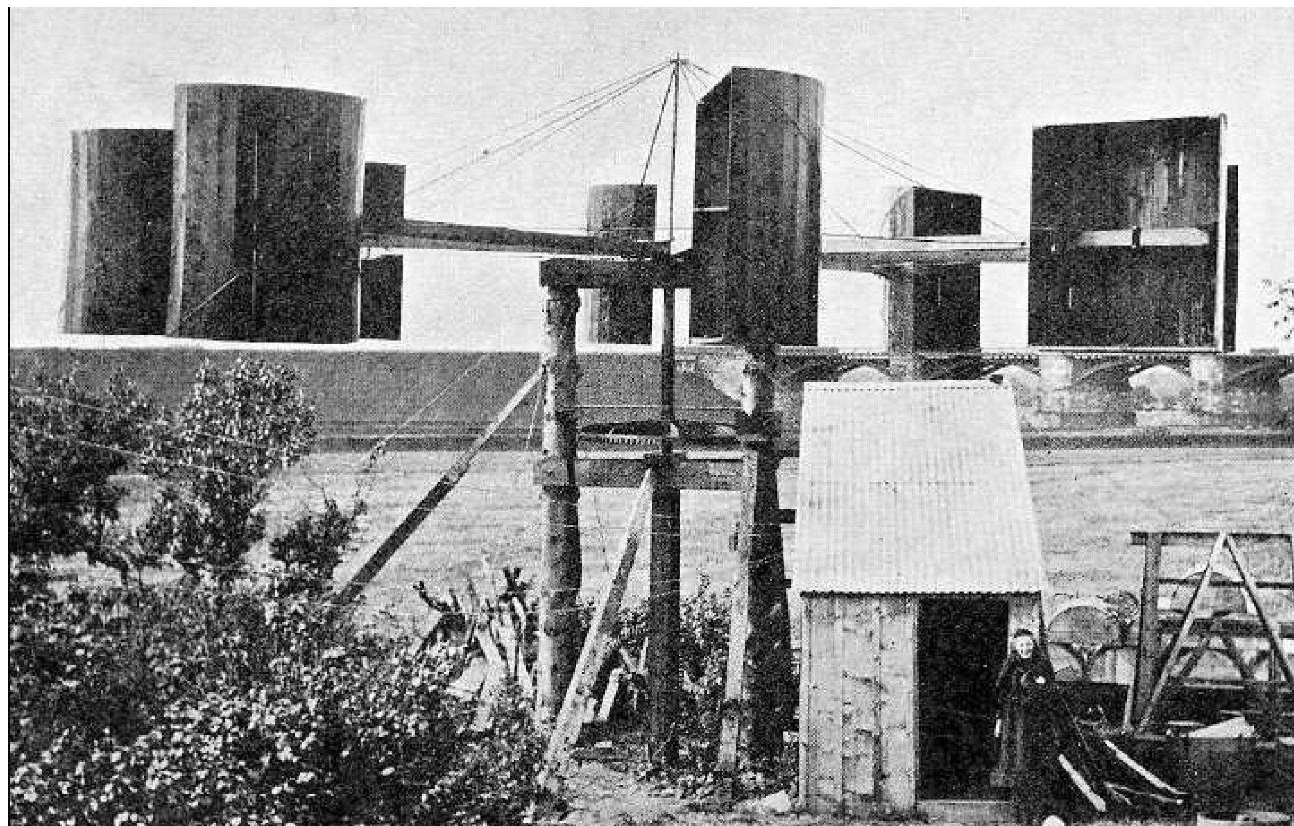
James **Blyth**, 1839-1906

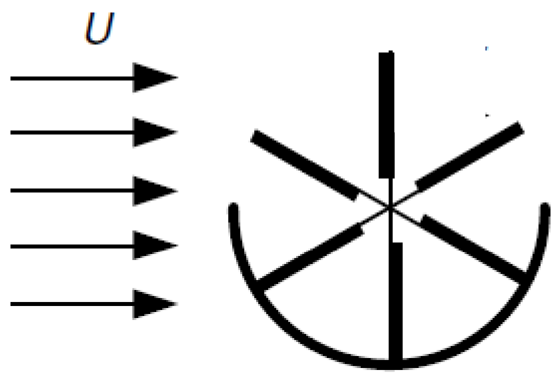
University of Strathclyde, Glasgow

July 1887 : cloth-sailed wind turbine in the garden of his holiday cottage in Marykirk, Kincardineshire

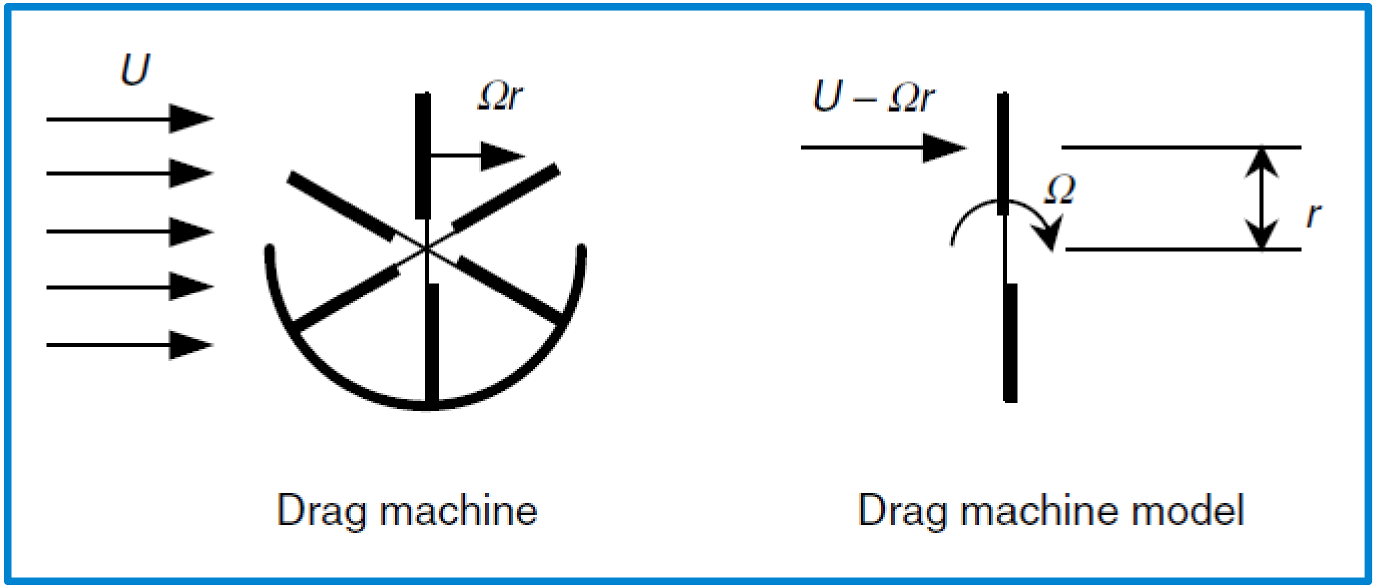
Vertical axis, drag machine

1891 windmill at his cottage in Kincardineshire





Drag machine



(Drag) force on one blade : $F_D = C_D\left[\frac{1}{2}\rho(U-\Omega r)^2 A\right]$

Resulting power : $P = C_D\left[\frac{1}{2}\rho A(U-\Omega r)^2\right]\Omega r = (\rho A U^3)\left[\frac{1}{2}C_D\lambda(1-\lambda)^2\right]$

Let’s introduce **2 key dimensionless parameters** :

Tip speed ratio :

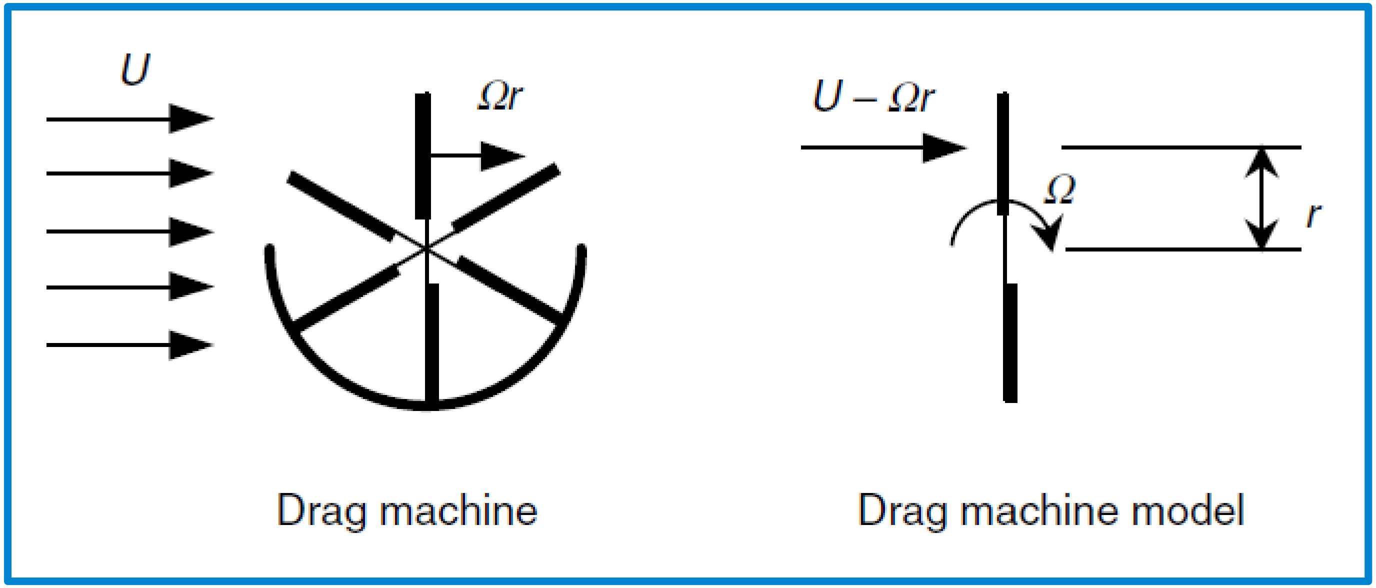
$$\lambda = \frac{\Omega\, R}{U}$$

Ratio of blade velocity at the tip over incoming wind

Power coefficient :

$$C_P = \frac{P_{turbine}}{\frac{1}{2}\rho\pi R^2 U^3}$$

Ratio of extracted power over total wind power



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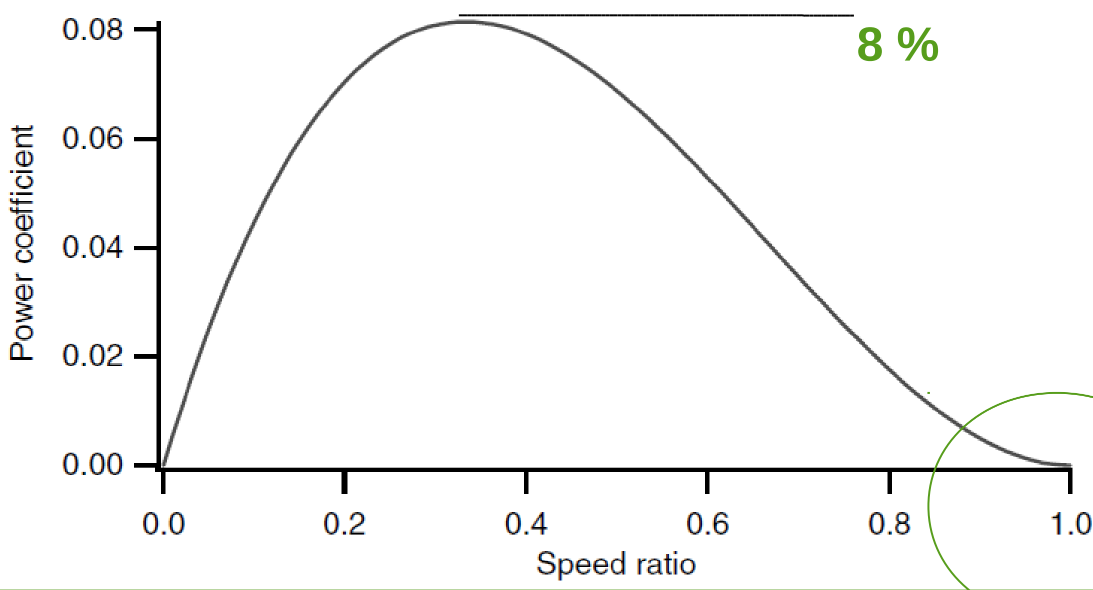
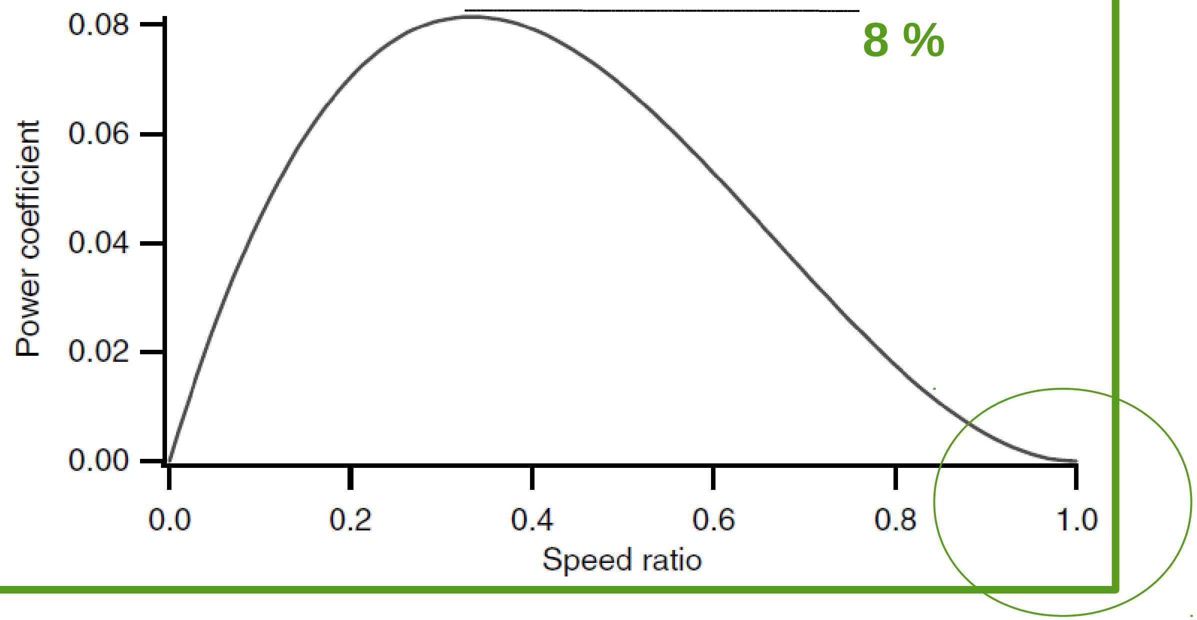


2. Drag machines

$$C_P = \left[\frac{1}{2} C_D \lambda (1-\lambda)^2\right]$$



Crude estimate of maximum power coefficient : less than 10 %

Why so **poor** ?

What we need to optimize is *power*
Rotation limited because **blade velocity has to be weaker than the wind** (drag)

1. Introduction

For a stationary, incompressible, inviscid flow, Bernoulli's theorem indicates that along a streamline :

$$\frac{1}{2}U^2 + \frac{P}{\rho} + g\,z = Cst$$

Flow around a symmetric airfoil, zero angle of attack :

Very little signature of the boundary layer

→ flow similar to inviscid theory

→ weak drag, no *lift*

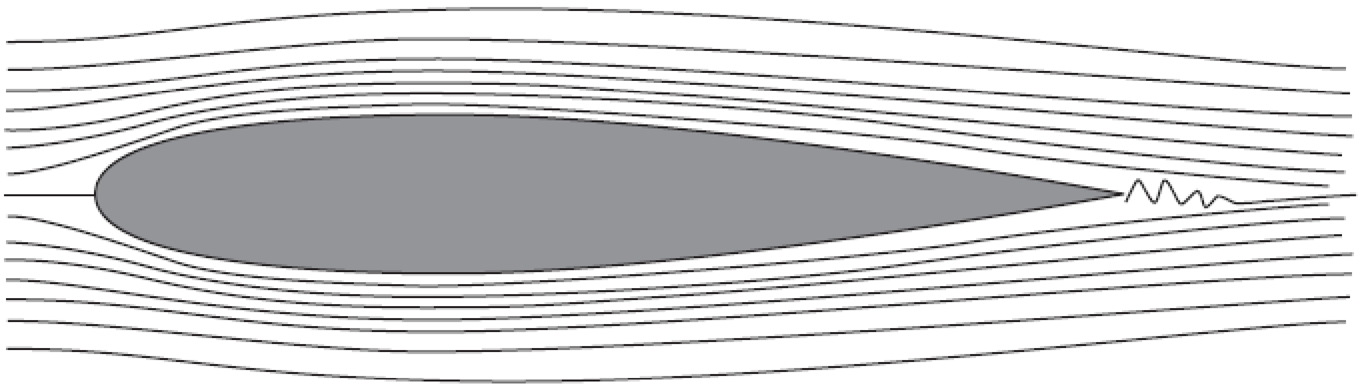
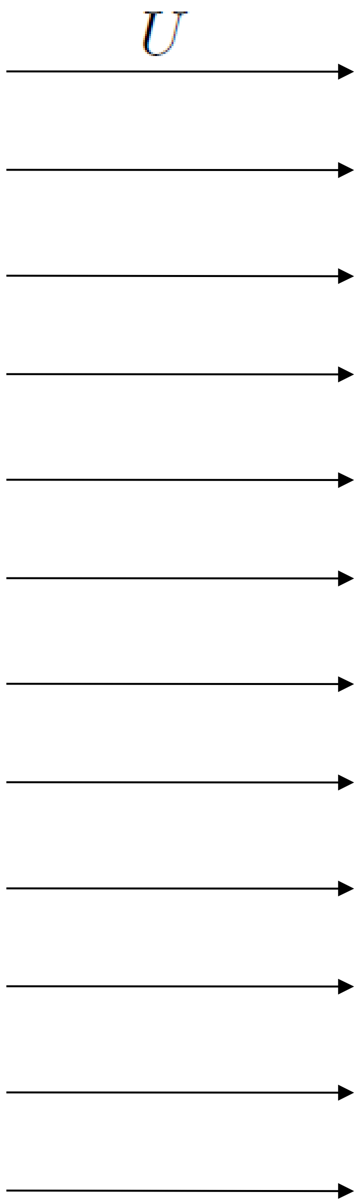


Figure A3.11 Flow past a streamlined body

1. Introduction



Incoming flow

Forces exerted by a uniform flow on a 2D object :

Lift : force perpendicular to the incoming flow
Drag : force parallel to the incoming flow

Lift and drag coefficients

Lift coefficient for an object like a sphere :

$$C_L = \frac{Lift}{\frac{1}{2}\rho U_{rel}^2 A}$$

Lift coefficient for a wing or a blade :

$$C_l = \frac{Lift/unit\ span}{\frac{1}{2}\rho U_{rel}^2 c}$$

Drag coefficient for a wing or a blade :

$$C_d = \frac{Drag/unit\ span}{\frac{1}{2}\rho U_{rel}^2 c}$$

Flow around a symmetric airfoil, zero angle of attack :

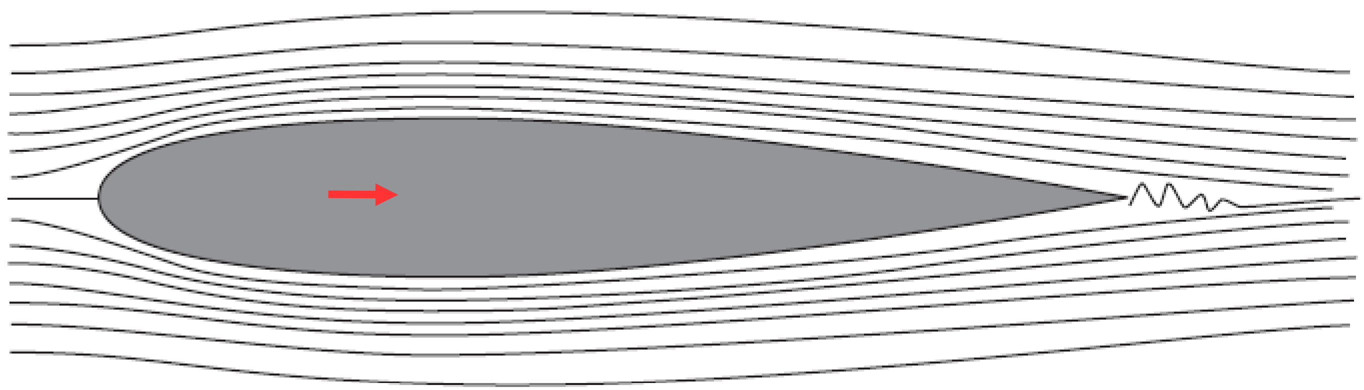
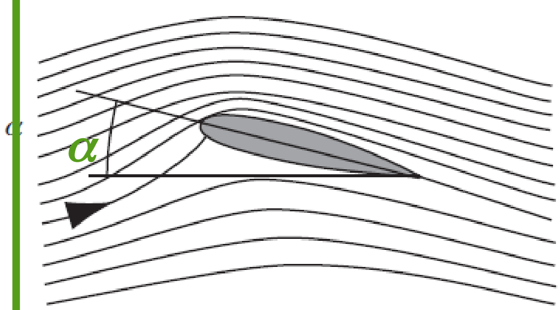


Figure A3.11 Flow past a streamlined body

A little drag

No Lift

Flow around a symmetric airfoil, small angle of attack :



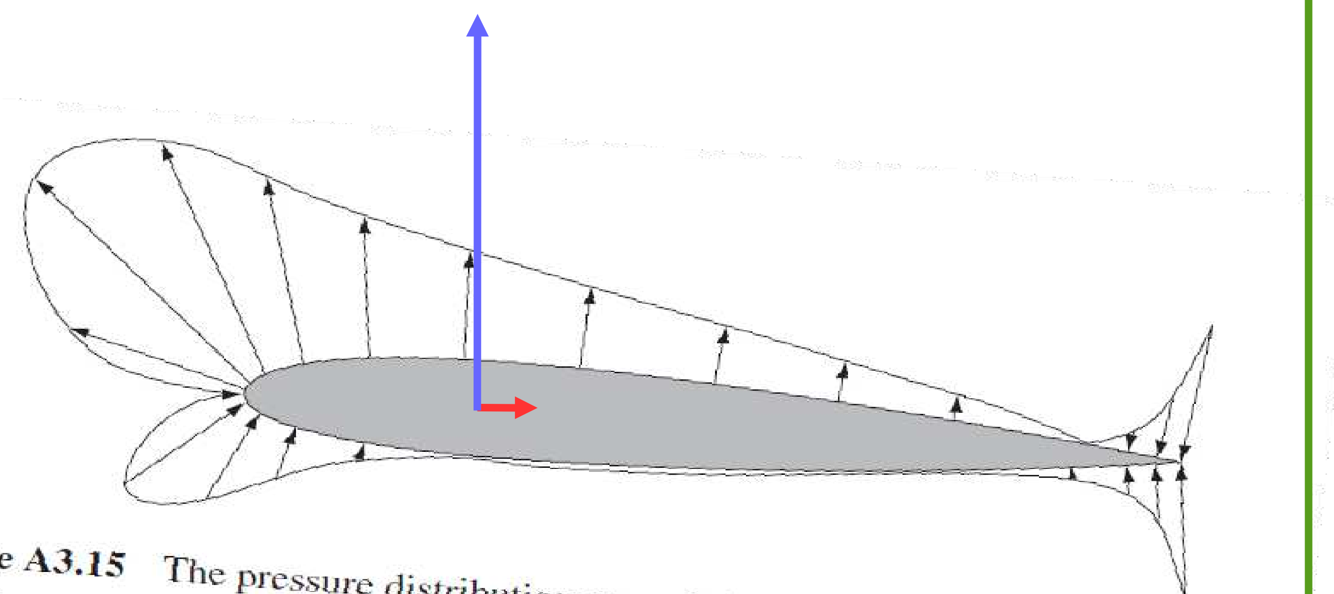


Figure A3.15 The pressure distribution around the NACA0012 aerofoil at $\alpha = 5°$

Resulting **lift** for small angles of attack α

Flow around a symmetric airfoil, larger angle of attack :

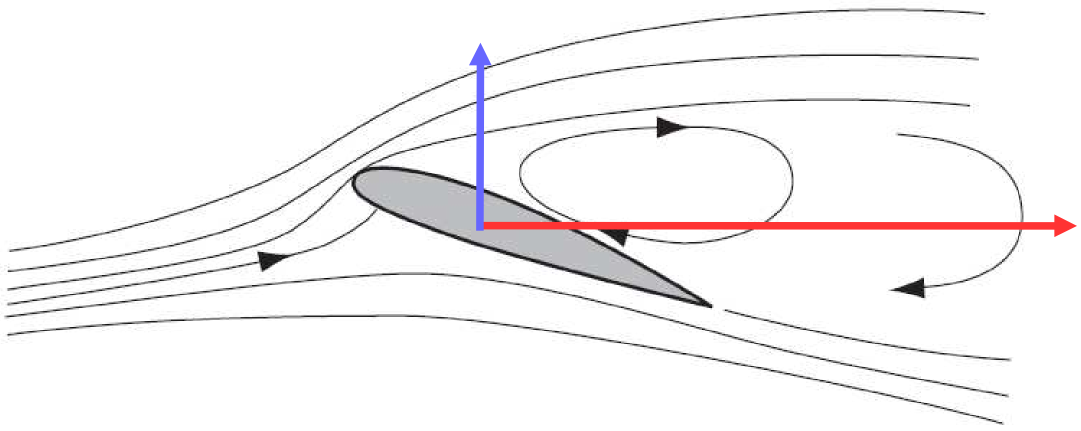


Figure A3.17 Stalled flow around an aerofoil

Stall :
Boundary layer detaches,
Lift decreases, drag increases

Lift and drag coefficients : an example

NB : for one airfoil, for a given Reynolds number

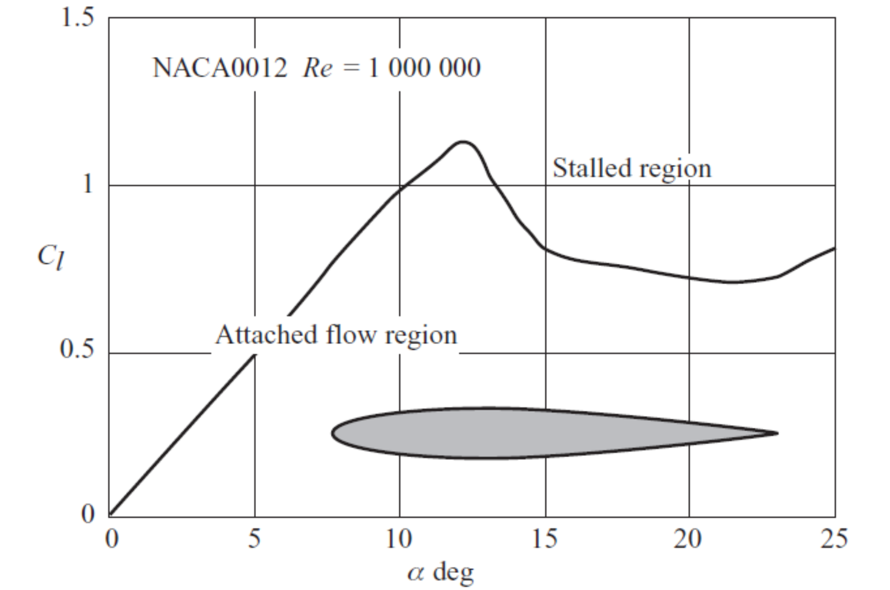


Figure A3.18 $C_l - \alpha$ curve for a symmetrical aerofoil

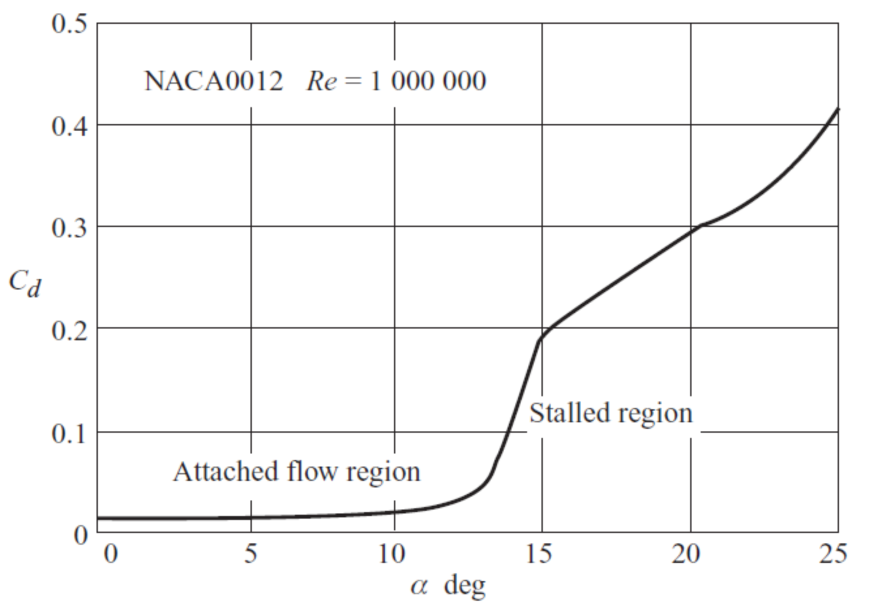


Figure A3.19 Variation of C_d with α for the NACA0012 aerofoil

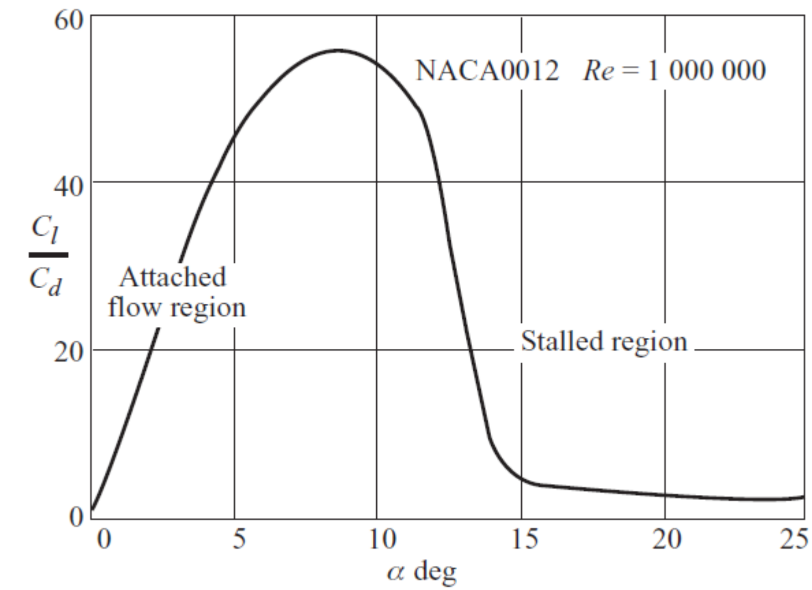


Figure A3.20 Lift/drag ratio variation for the NACA0012 aerofoil

NB : for small enough angles of attack (<~12°), the ratio can be of ~50 !!

→ **better use lift than drag**

→ **best to try and achieve large relative windspeeds**

3. Qualitative understanding of turbines

1. use **lift**, not drag

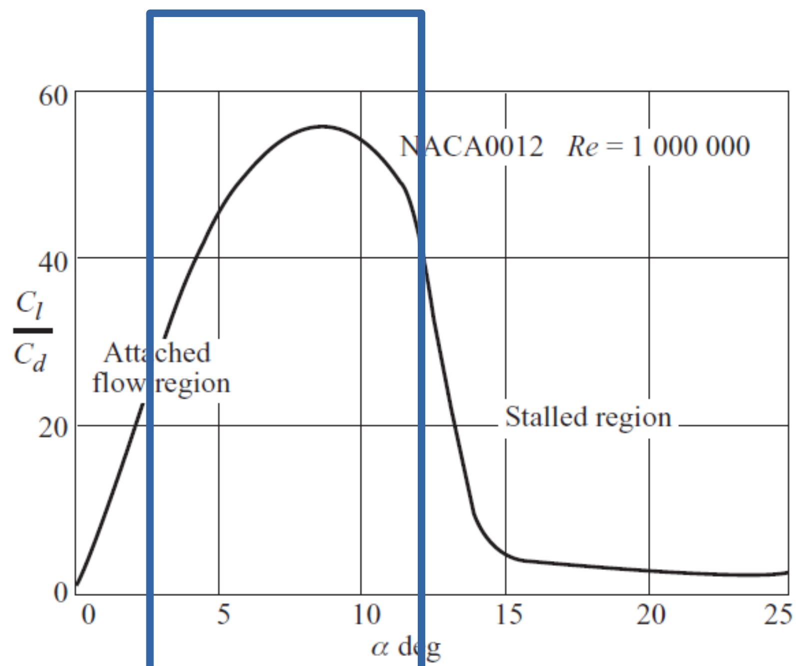


Figure A3.20 Lift/drag ratio variation for the NACA0012 aerofoil

2. fast rotation : lift varies as the **square of the relative flow**

$$C_l = \frac{Lift/unit\ span}{\frac{1}{2}\rho U^2 c}$$

3. Qualitative understanding of turbines

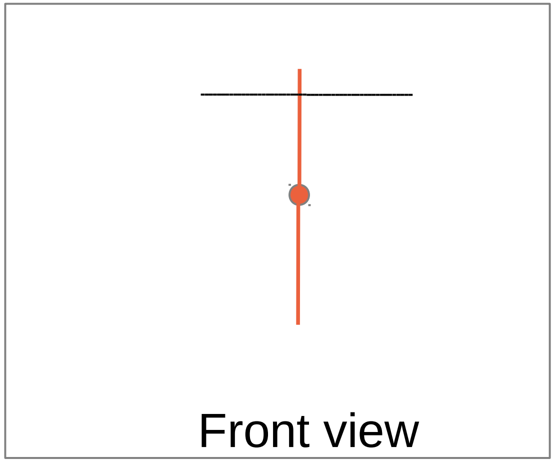
3. fast rotation implies few blades

Too many blades → blades affected by the wake of the previous blade

Too few → some air unaffected by the rotor

?? For a fast rotating rotor, does the lift still contribute to enhancing the rotation ??

3. Qualitative understanding of turbines



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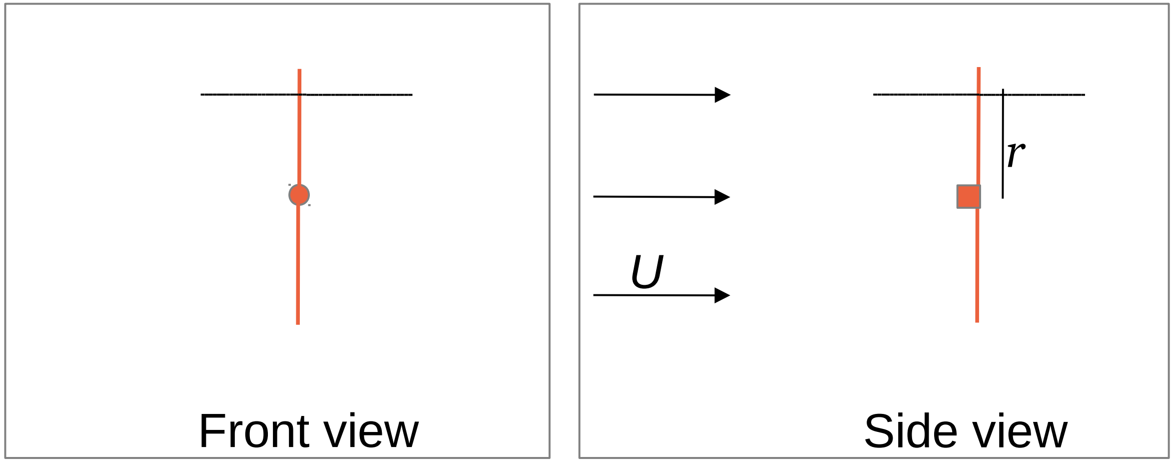

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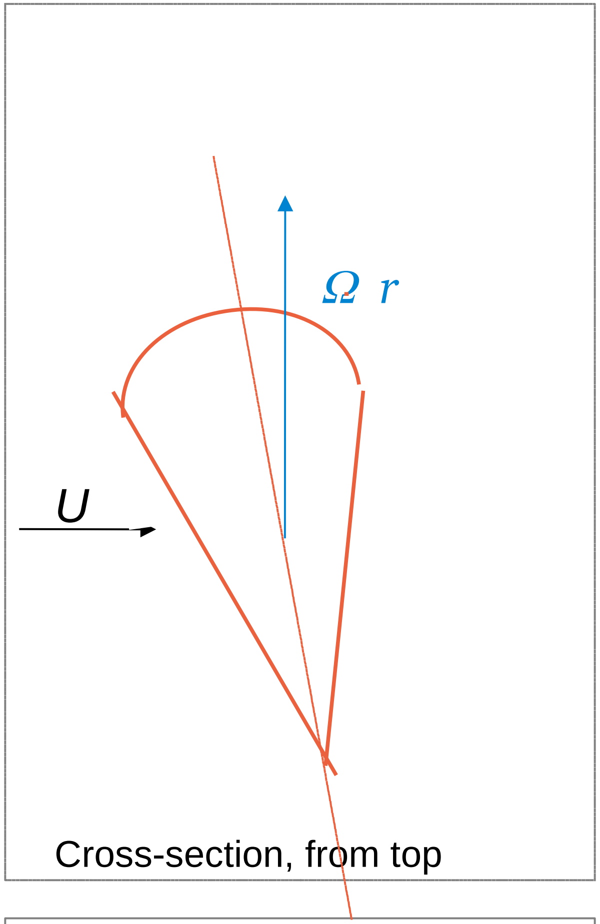
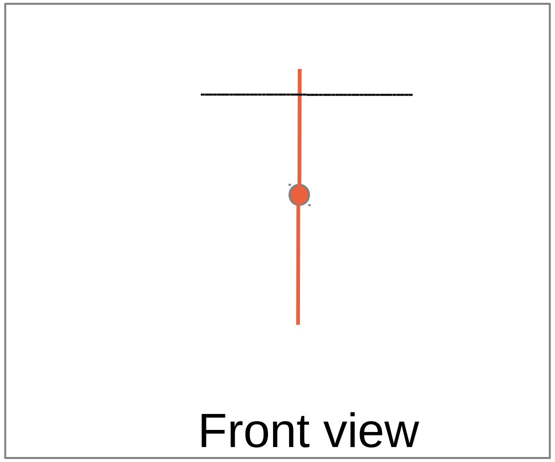
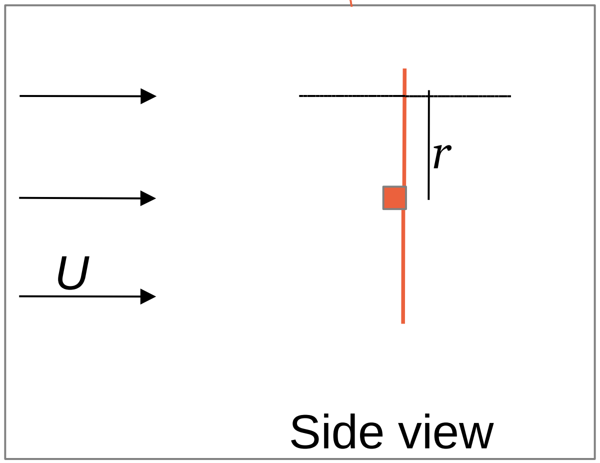
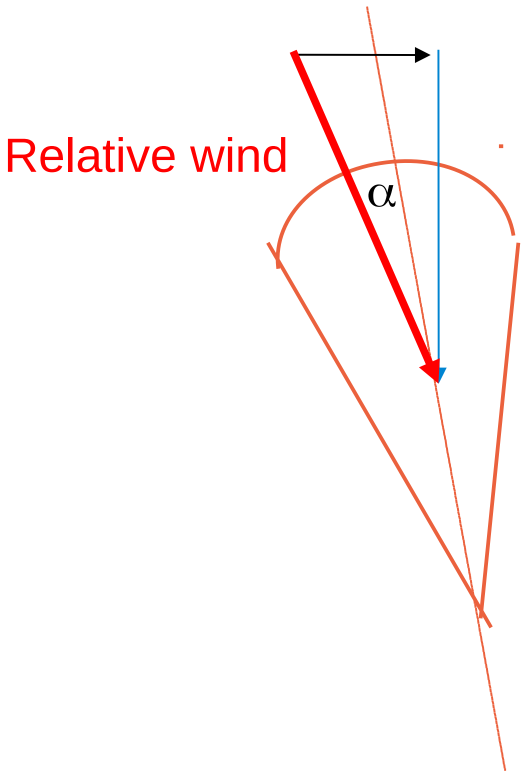


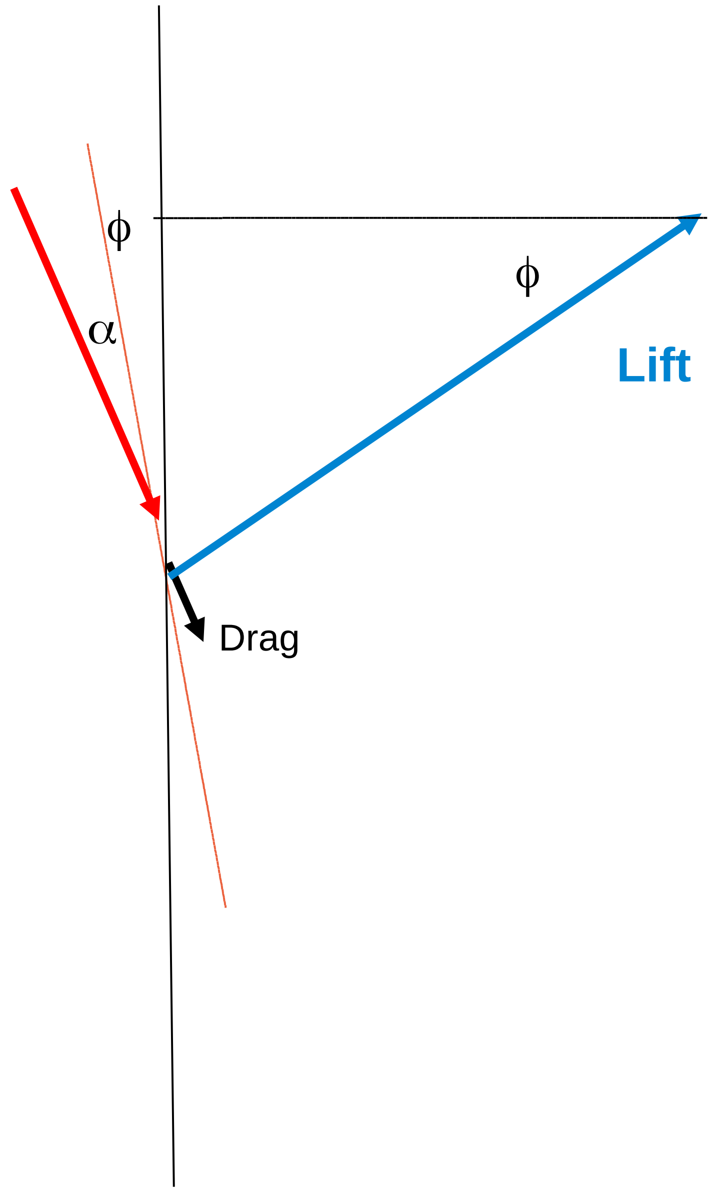




3. Qualitative understanding of turbines



α : angle of attack



α : angle of attack

Relative Wind increases as ΩR

-> lift increases as $\Omega^2 R^2$

-> useful component of lift :

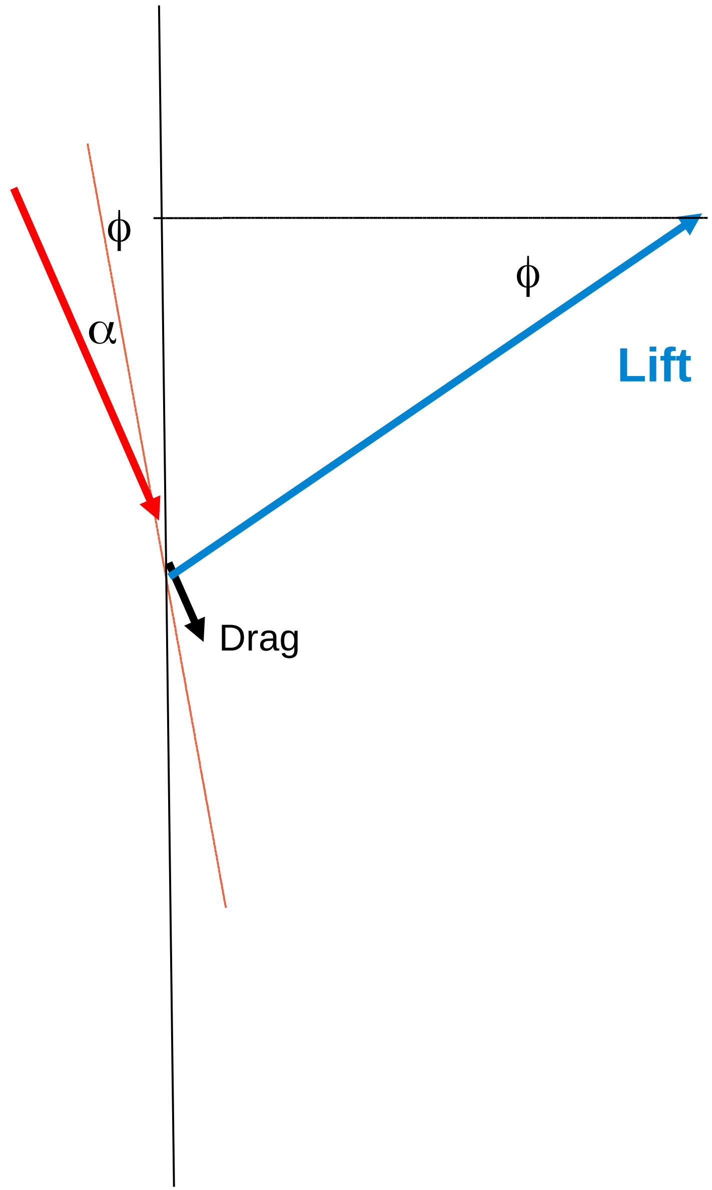
$$L \sin\varphi \propto C_l \frac{1}{2} U_{rel}^2 \rho \frac{U}{\Omega R}$$

$$\propto C_l \frac{1}{2} \rho U \, \Omega R$$

-> faster rotation is favorable

(as long as the **Mach number** remains small, and as long as **drag** effects remain negligible)

α : angle of attack



4. The Betz limit (momentum theory) ; angular mom. theory

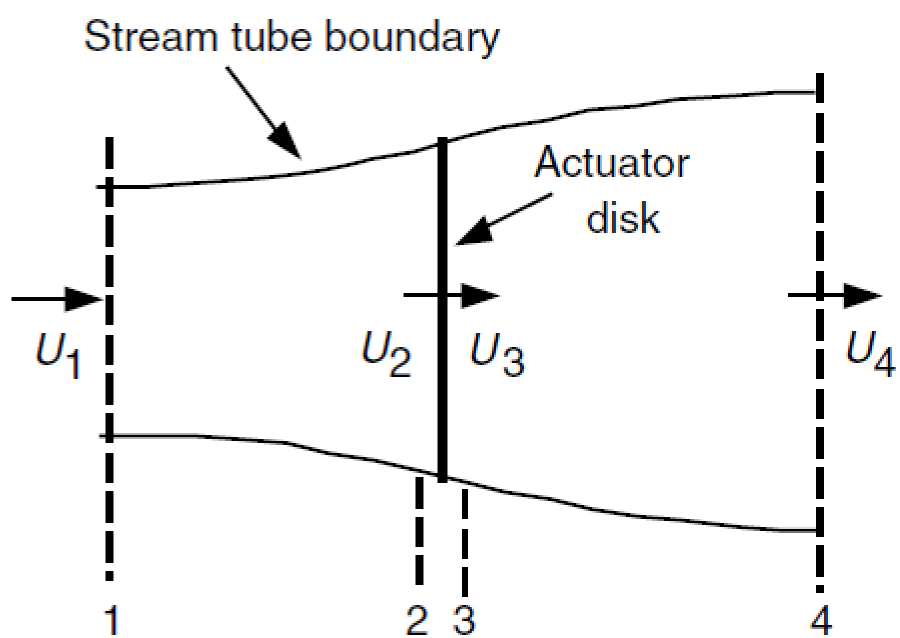
Aim : estimate the **maximum energy that a *device* can extract**,
Irrespective of how the device would work

4.1 Betz limit, or Lanchester-Betz limit

Albert Betz, 1885-1968, German aerodynamicist
Frederic Lanchester, 1868-1946, British aeronautical pioneer)

Incoming flow is uniform (*U, or U1*), incompressible*, irrotational
Actuator disk :
- uniform ('*infinite number of blades*')
- non-rotating wake
- far upstream and far downstream pressures are equal to ambient pressure

*** low Mach number**

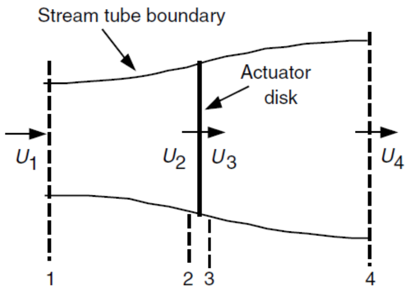


Steady, incompressible flow :

Conservation of Bernoulli function along streamlines upstream (1→2) and downstream (3→ 4):

$$p_1 + \tfrac{1}{2}\rho U_1^2 = p_2 + \tfrac{1}{2}\rho U_2^2 \qquad p_3 + \tfrac{1}{2}\rho U_3^2 = p_4 + \tfrac{1}{2}\rho U_4^2$$

Far field pressures are the same (p1=p4), and conservation of mass at the disk yileds U2=U3



Flow rate constant along the stream tube

$$(\rho A U)_1 = (\rho A U)_4 = \dot{m}$$

Axial momentum budget on the volume control indicated above :

$$T = U_1(\rho A U)_1 - U_4(\rho A U)_4$$

where *T* is the force exerted by the wind on the turbine (« *Thrust* »)

Relation between thrust and pressure drop at the device :

$$T = A_2(p_2 - p_3)$$

Non-dimensional parameter to quantify the decrease of wind speed :
Axial induction factor *a :*

$$a = \frac{U_1 - U_2}{U_1}$$

Obtaining the velocities at different location in the streamtube :

a. using Bernoulli, find an expression for the pressure drop at the disk

$$(p_2 - p_3) = \frac{1}{2}\rho\,(U_1^2 - U_4^2)$$

b. equate the two expressions for the thrust and find *U2*

On one hand we have $\quad T = A_2\,(p_2 - p_3) = A_2\,\frac{1}{2}\rho\,(U_1^2 - U_4^2)\,,$
and on the other we have $\quad T = \dot{m}\,(U_1 - U_4)\,,$
so that, choosing to write $\dot{m} = \rho\,A_2\,U_2$, we find:

$$\boxed{U_2 = \frac{U_1 + U_4}{2}\,.}$$

c. express *U2* and *U4* in terms of *U* (or *U1*) and *a*

Using the axial induction factor a:

$$\boxed{U_2 = (1-a)\,U_1\,, \quad \text{and} \quad U_4 = (1-2a)\,U_1\,.}$$

What are we really interested in ?

Power 'taken' from the wind : $P = \frac{1}{2}\rho A_2(U_1^2 - U_4^2)U_2 = \frac{1}{2}\rho A_2 U_2(U_1 + U_4)(U_1 - U_4)$

Substituting for U2 and U4 : $P = \boxed{\frac{1}{2}\rho A U^3} 4a(1-a)^2$

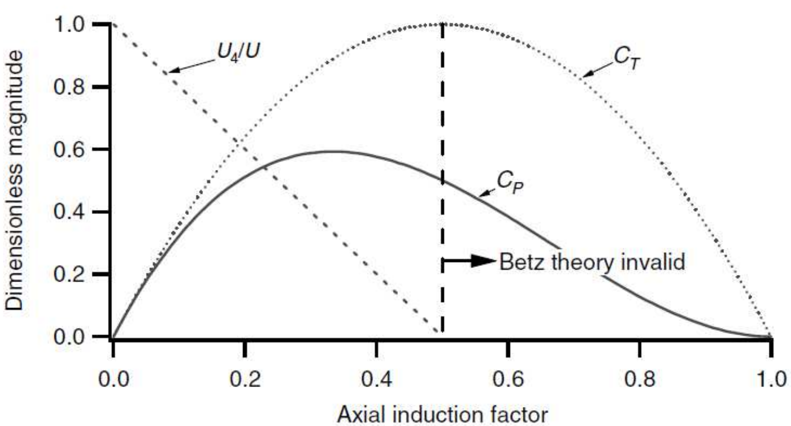
Flux of kinetic energy

To characterize the performance of a device, we introduce the **power coefficient** :

$$C_P = \frac{P}{\frac{1}{2}\rho U^3 A} = \frac{\text{Rotor power}}{\text{Power in the wind}}$$

We obtain the power coefficient as a function of *a* : $C_P = 4a(1-a)^2$

which is maximum for *a=1/3*, yielding :



$$C_{P,\max} = 16/27 = 0.5926$$

Betz limit :
the best we can *hope* to extract is ~60 % of the kinetic energy

4.2 Angular momentum theory

Disk is still assumed uniform (*'infinite number of blades'*), but we now take into account that energy is extracted by making the device **rotate**.

By **reaction**, there is **rotation in the wake**.

Hence, this further **reduces the fraction of energy** that we can extract.

Axial induction factor, *a*, now varies with radius : *a(r)*

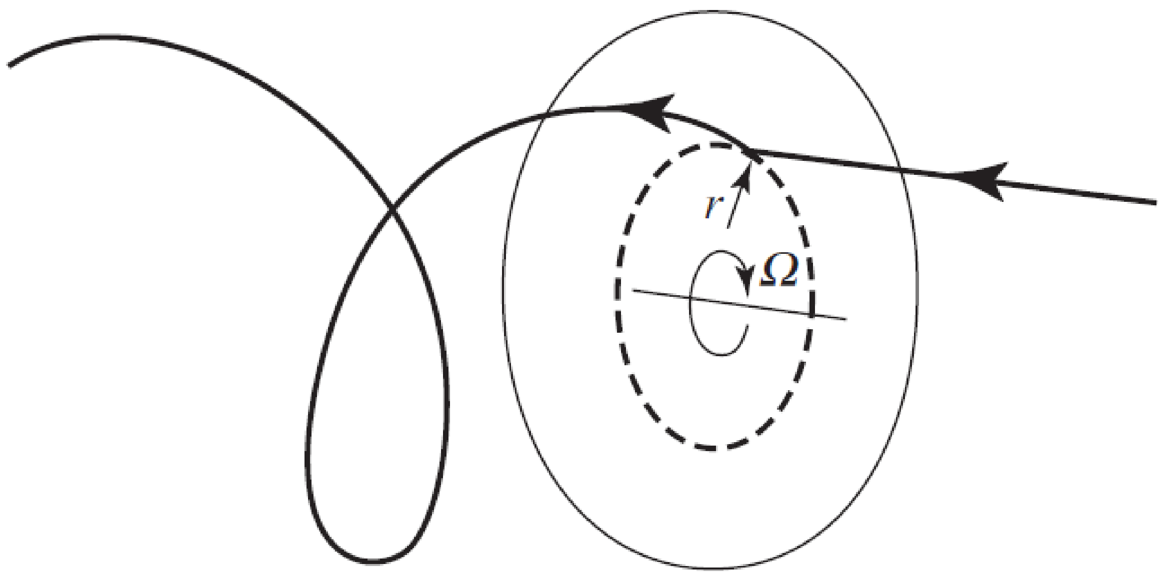


Figure 3.4 The trajectory of an air particle passing through the rotor disc

In a nutshell :

Momentum theory (Betz limit)

Conservation of Bernoulli function

Flow rate constant

Axial momentum budget

Input : U, A

Output : $C_p(a)$

Angular momentum theory

Conservation of Bernoulli function

Flow rate constant

Axial momentum budget

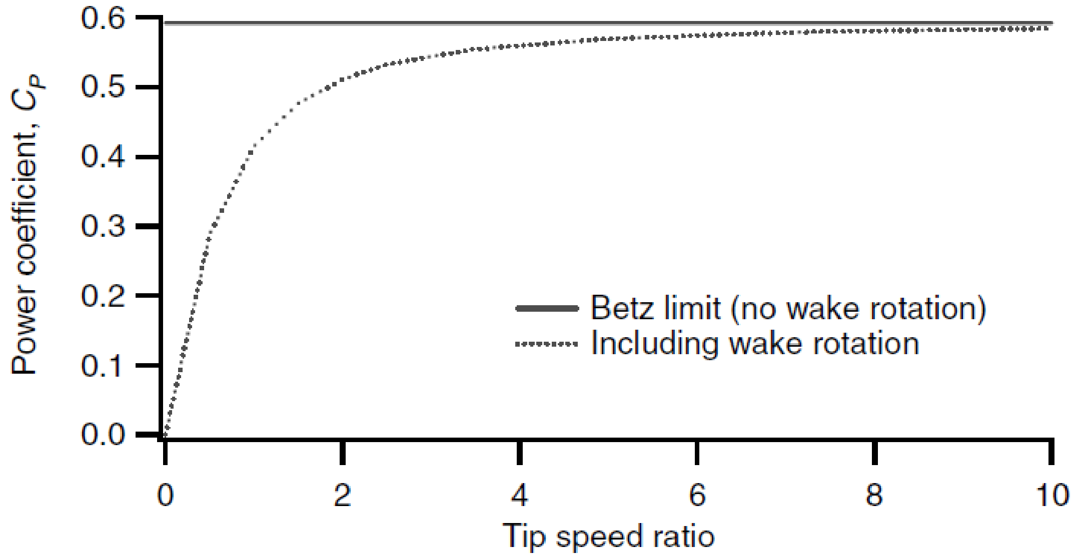
Angular momentum budget

Input : U, A, λ

Output : $C_p(a, a', \lambda)$

a' : angular induction coefficient

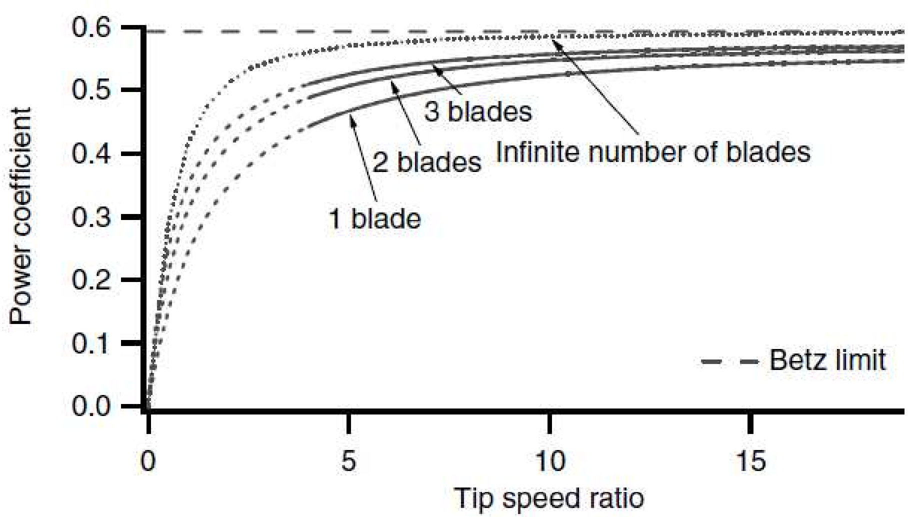
An essential plot, & variations on it :



→ **best to use large λ**

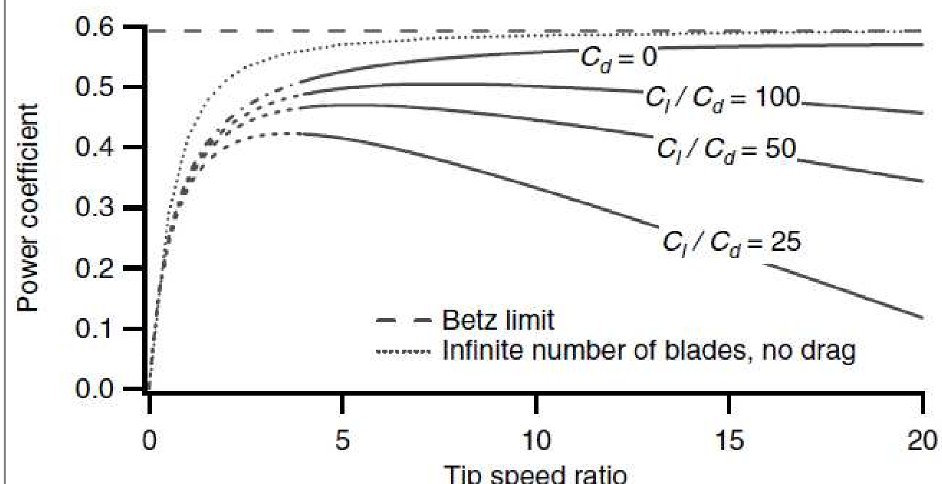
but not too large
(+ Mach number...)

Finite number of blades



In favor of a larger number of blades

Non-zero drag



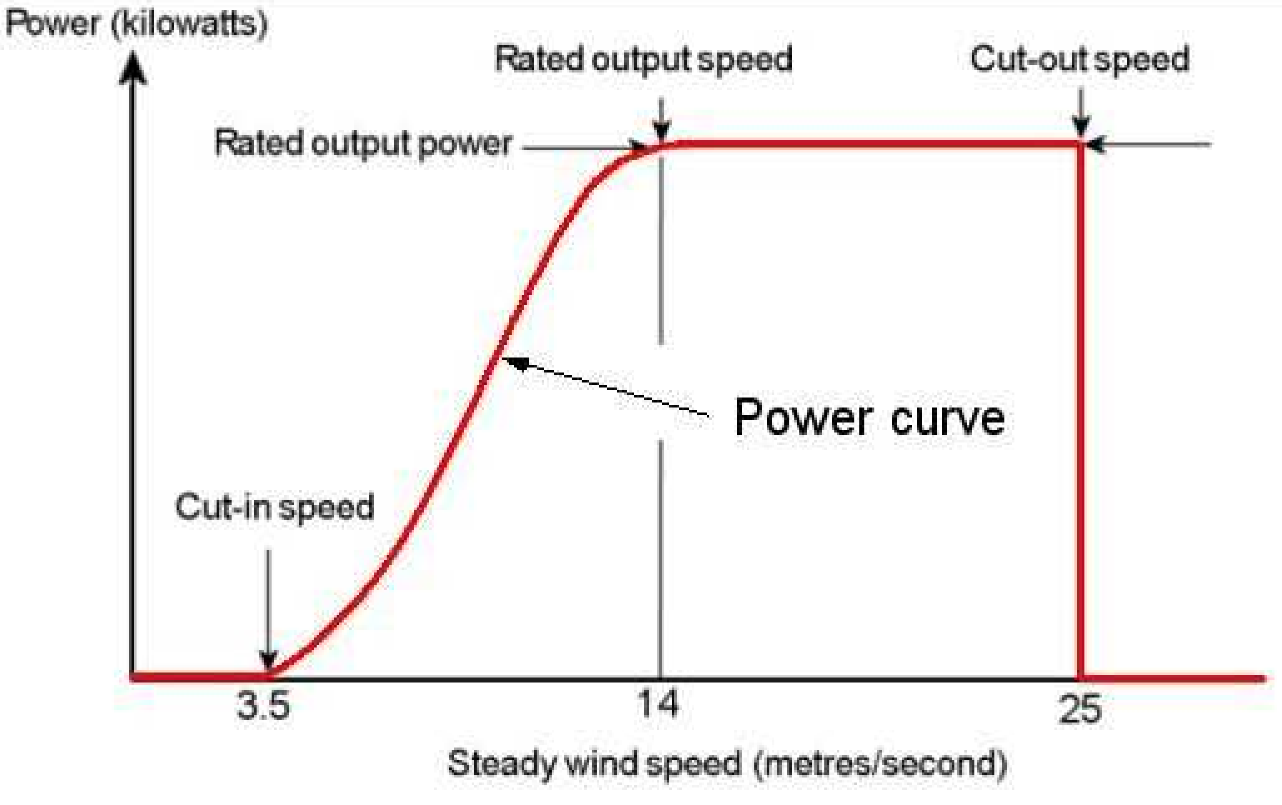
In favor of λ not too large

(Mach << 1 → also in favor of λ not too large)

Characteristics of a wind turbine :

Power curves : for a given wind, power produced

example :



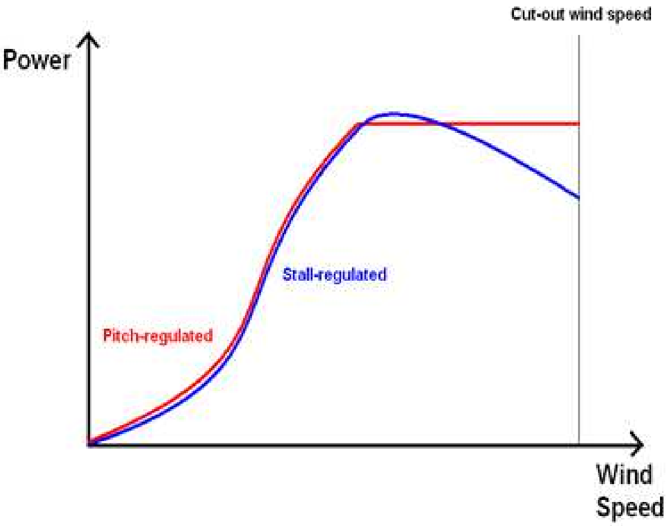
Typical wind turbine power output with steady wind speed.

Terminology :
Cut-in speed : for weaker winds, no energy production
Cut-out speed : for stronger winds, turbine **stopped**
Rated output : power produced for wind speeds between the rated wind speed and the cut-out wind speed
constant power obtained over a range of winds thanks to pitch control

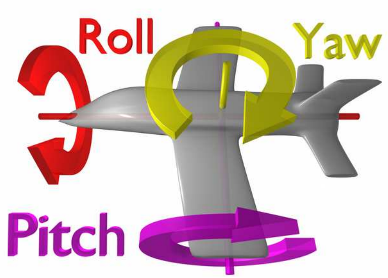
Some important notions on wind turbines :

Pitch-controlled turbines : active adjustment of the pitch angle of each blade (rotation around its axis) to maintain torque below a certain threshold

Stall-controlled turbines : blades aerodynamically designed so that the flow detaches for stronger winds, hence limiting the lift

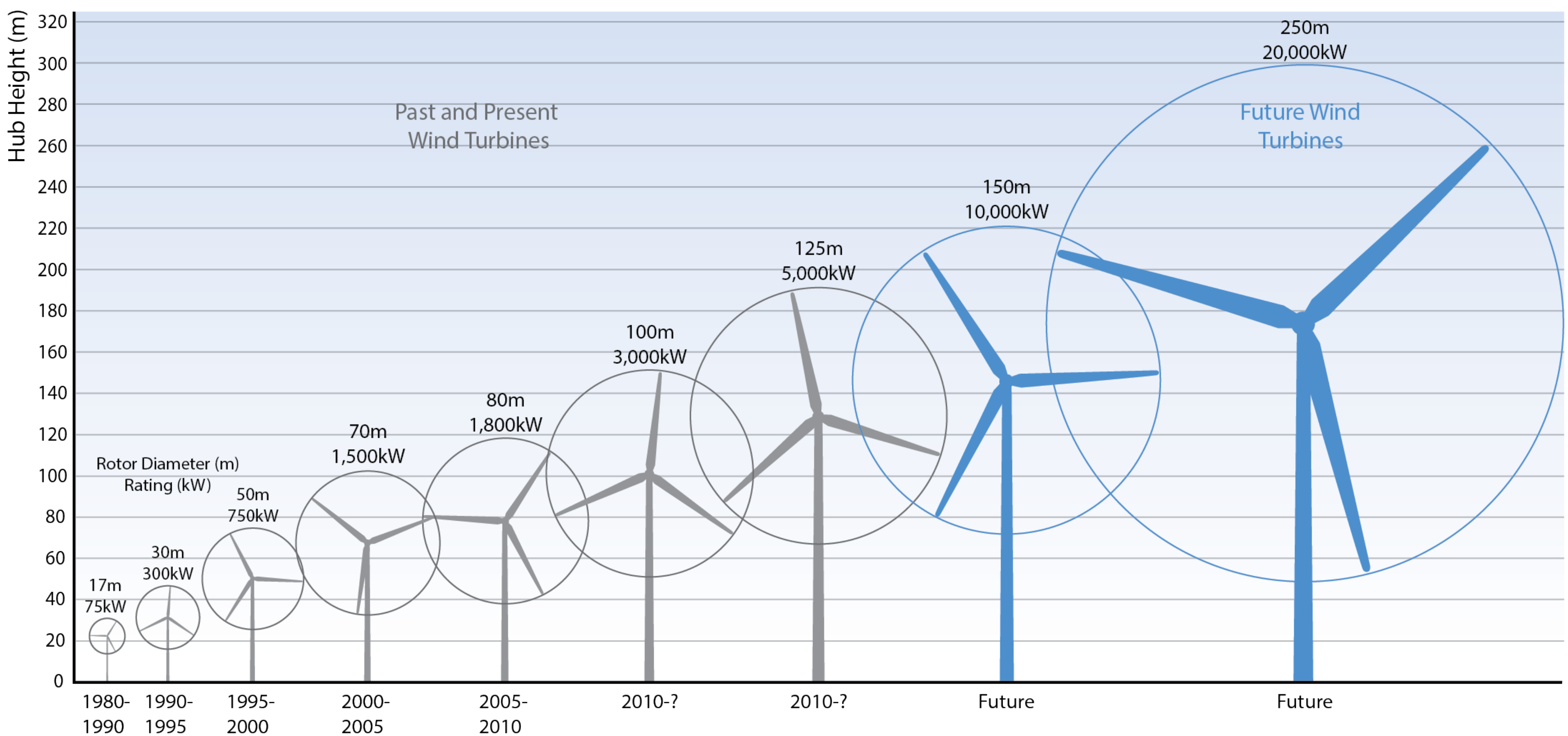


Yaw control : aims at orienting the turbine so that it always faces the wind



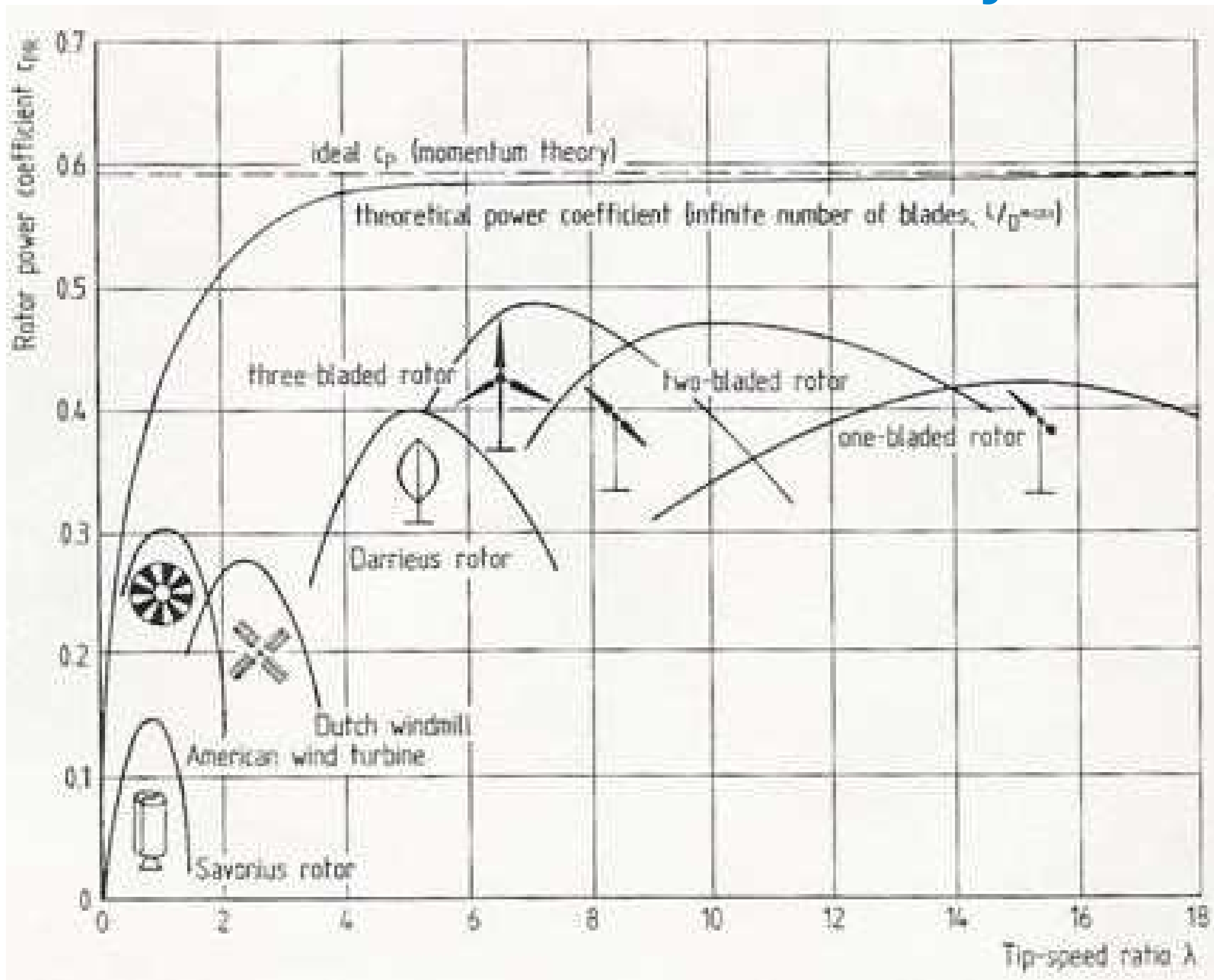
Wakes : flow is slowed down and more turbulent ; to be carefully considered in planning of wind farms

Order of magnitude for wind turbines power



6. Three-bladed or two-bladed : a bit of history

Darrieus rotor



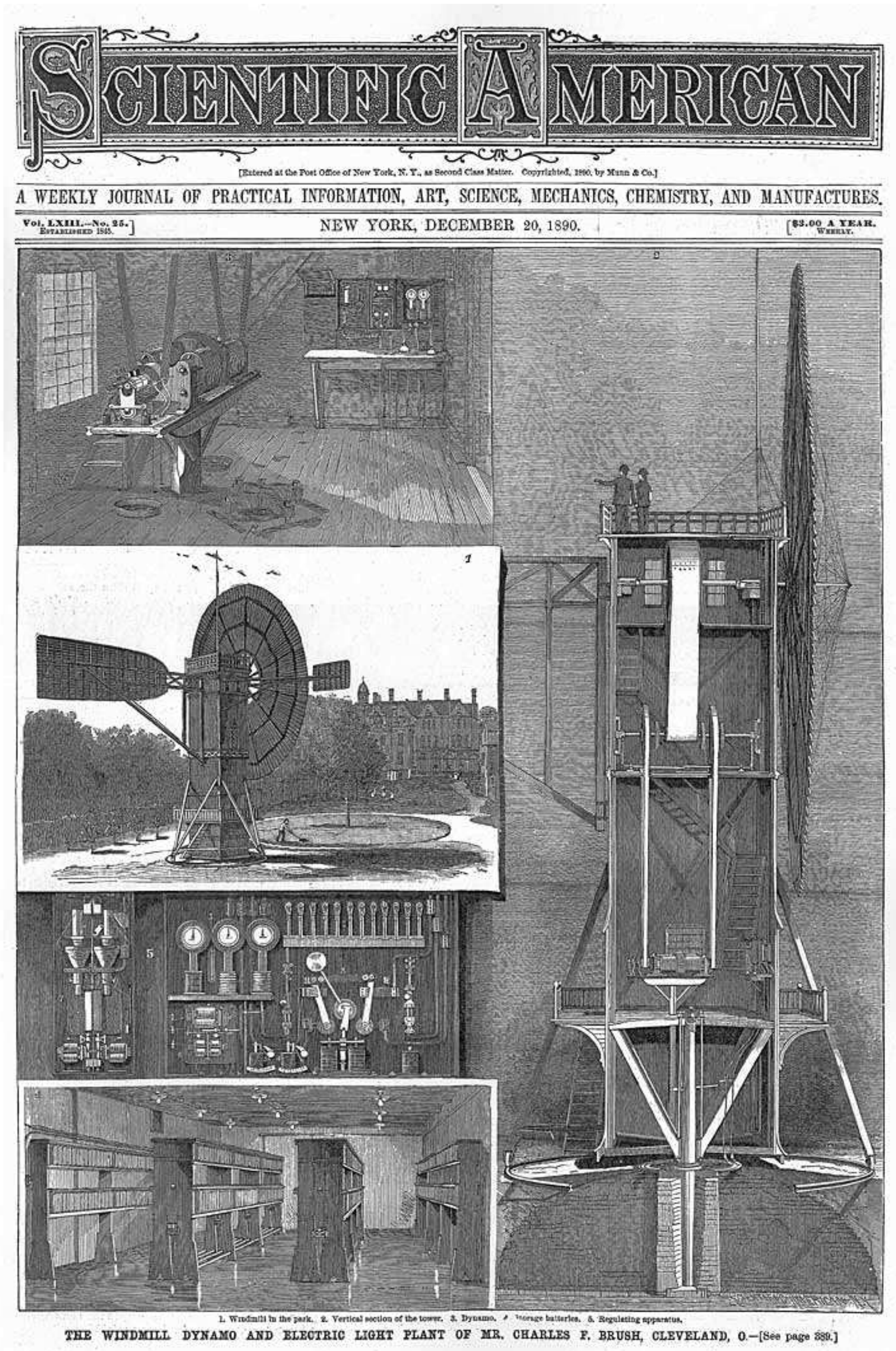
One-bladed

Three-bladed :
Very slightly higher Cp
Lower λ → more gearbox

Limited range of λ (6-9)

Two-bladed :
Similar Cp
Larger λ
Less weight
Larger range of λ (7-15)

Aerodynamicist's choice ?



SCIENTIFIC AMERICAN

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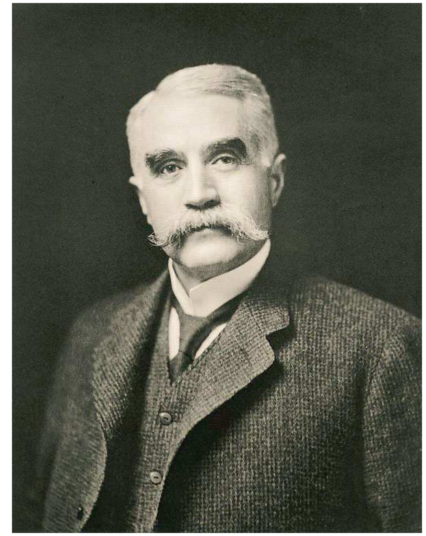
Vol. LXIII.—No. 25.] Established 1845. NEW YORK, DECEMBER 20, 1890. [$3.00 A YEAR. Weekly.

1. Windmill in the park. 2. Vertical section of the tower. 3. Dynamo. 4. Storage batteries. 5. Regulating apparatus.

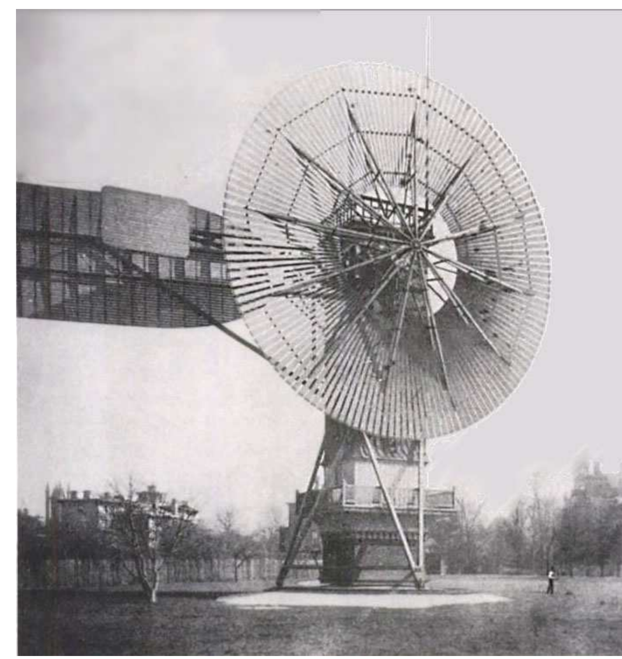
THE WINDMILL DYNAMO AND ELECTRIC LIGHT PLANT OF MR. CHARLES F. BRUSH, CLEVELAND, O.—[See page 389.]



Charles Brush, 1849-1929
American inventor, entrepreneur and philanthropist

1888 :
First automatically operated wind turbine.

12kW



Poul la Cour (1846-1908)

Danemark, Askov
Breakthrough : **less blades, faster rotation**

Progress in aerodynamics : airfoils, propellers...

Works of **Ludwig Prandtl** in Germany (Göttingen)

Works of **A Rateau** and **G Eiffel** in France (Eiffel laboratory in Auteuil)

1923 Louis Constantin

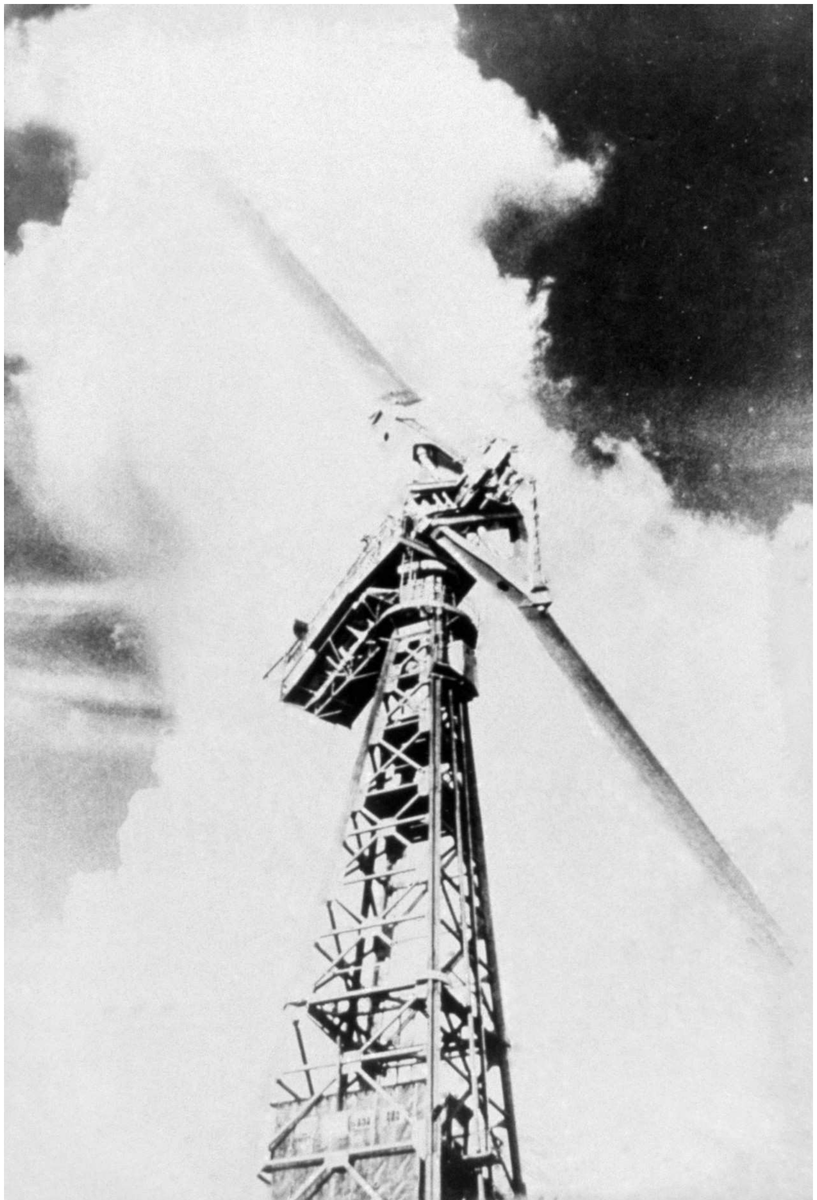
First 'modern horizonatl axis wind turbine' (HAWT)

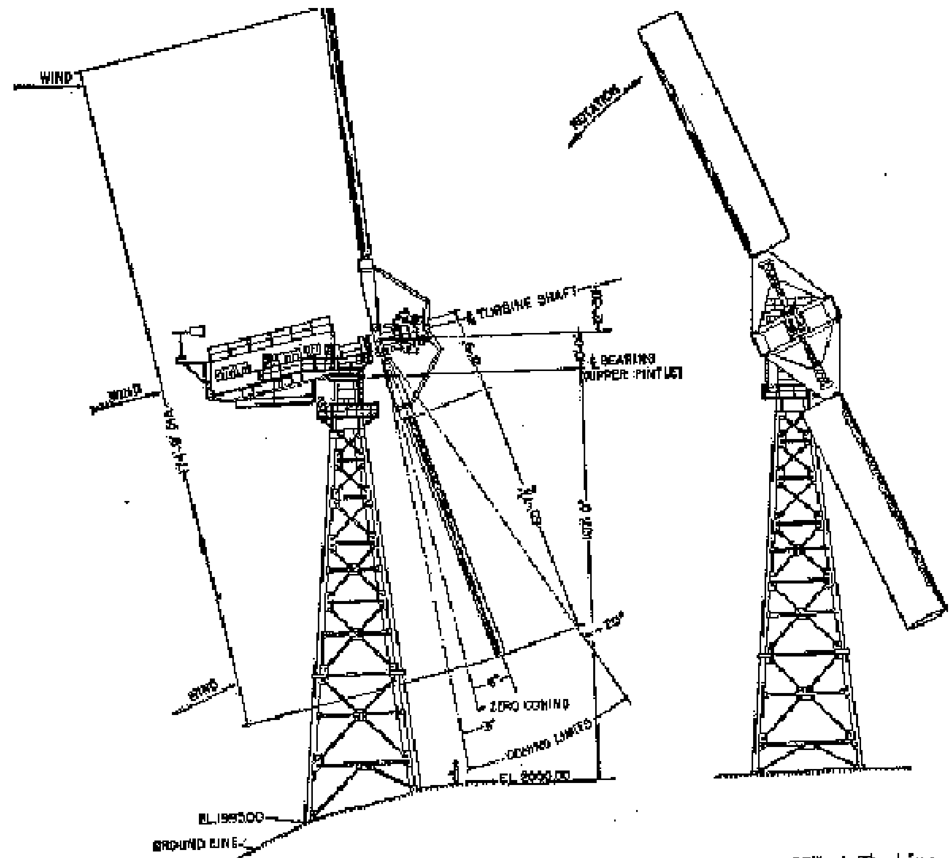
1929 : Article in 'La Nature' with fundamental principles for modern wind turbines :

- few blades
- fast rotation (importance of the tip speed ratio...)
- schematic of a wind farm and connections...

Attempt for a transition to larger power

Putnam Windmill
1941 First MW size turbine (1250 kW)
On Grandpa's Know, Vermont,USA
Downwind 2 blades





After WWII – Germany

Ulrich Hütter
Austrian, worked for Ventimotor (Weimar) until 1943
Further worked on wind turbines, their optimization and aesthetic qualities

1958 : 100kW prototype,
2-bladed, downwind, 34m diameter

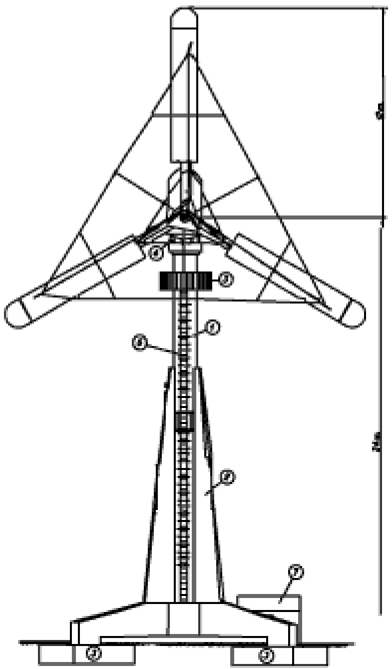
reminiscent of Darrieus' 2 bladed turbine, but
- more slender blades, made of glass fiber
- teeter rotor
- pitch regulation

In operation for 10 years close to Stuttgart

1980 : 300kW, 52m diameter machine

After WWII – Denmark

Very different development: population familiar with small turbines (Lykkegaard, 30kW)
During WWII, F.L. Smidth (a cement company) developed the Aeromotor
(60 and 70 kW, 2 or 3 wooden blades)



1959 : Johannes Juul* set up the Gedser turbine

Robust, upwind, 3 bladed, 200 kW, 24 m diameter
Motors for controling the orientation, 'tip-brake'
Asynchronous generator, output sent into the Danish electricity network

In operation until 1967!

* he had followed Poul la Cour's courses in 1904

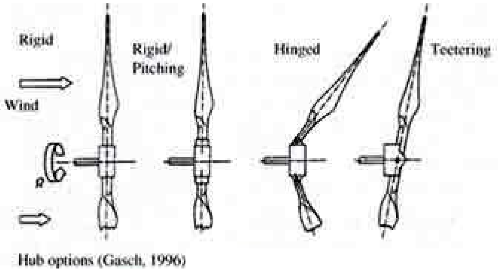
After 1973 : U.S.A.

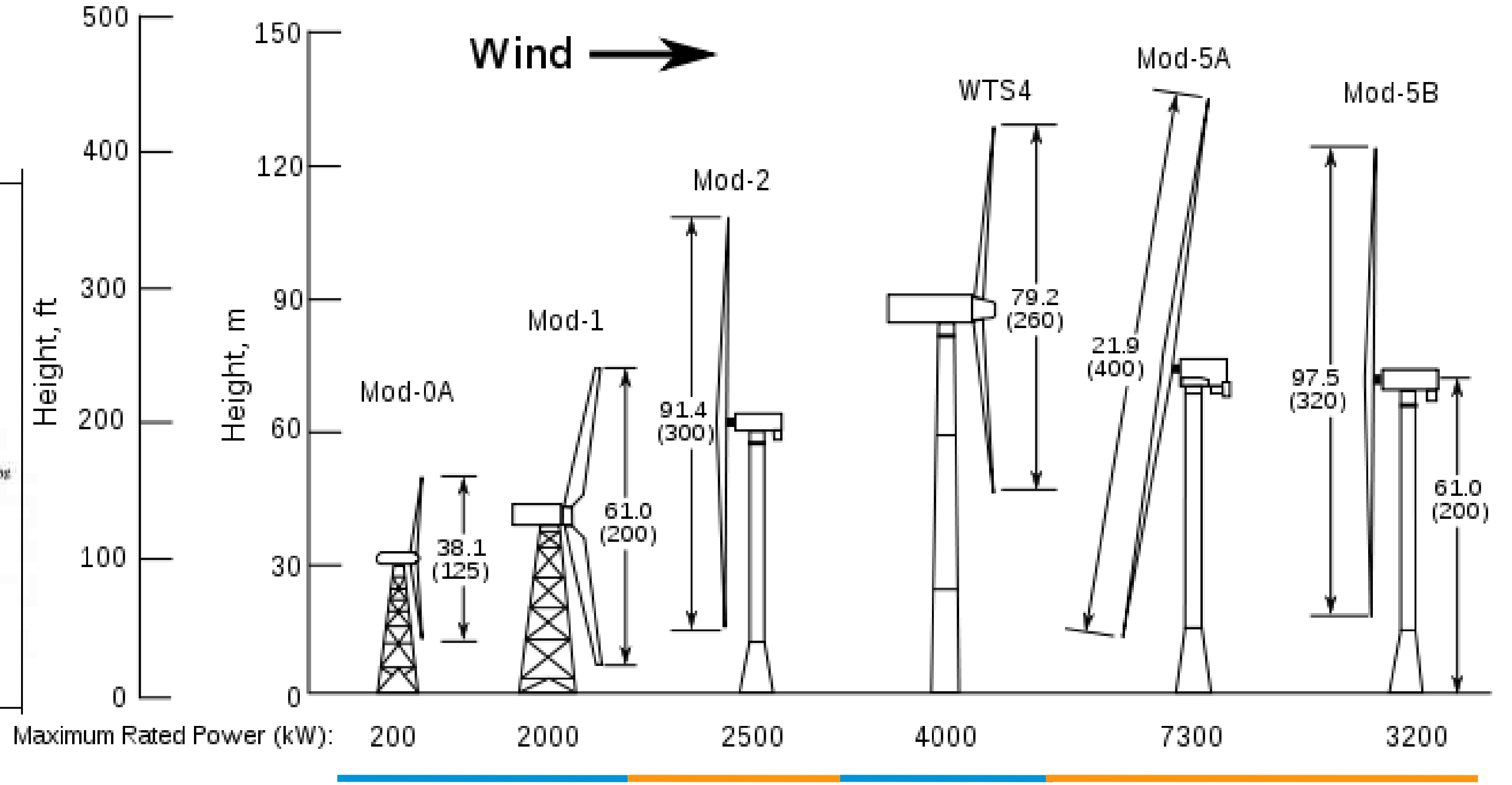
1974-1992: Research program set up by the Dept of Energy (DOE) (330M$)
Carried out by **NASA**, with industrial partners in aeronautics (Lockheed, Boeing, Hamilton) and electricity (General Electric, Westinghouse)

Aim of the programme was to develop utility scale wind turbines, leaping over then state-of-the art turbines

2 bladed, downwind then upwind rotors realized and tested
Numerous problems encountered (vibrations, fatigue due to tower shadow*)

* Yet Putnam, **Hütter,** Romani had thought about this issue and proposed solutions, e.g. teetering hub :





MOD 0

MOD 1

MOD 2

MOD 5B

After 1973 : Germany

1982 : 'Growian' – project managed by MBB and MAN, 55M$
3MW, 100m diameter, downwind
Unssuccessful... similar mistakes...

Research programs also in UK and Sweden...

2 bladed turbines remain attractive until end of the 90's:
- less weight
- less gearbox
- wider λ-range

Downwind is attractive because it is self-orienting

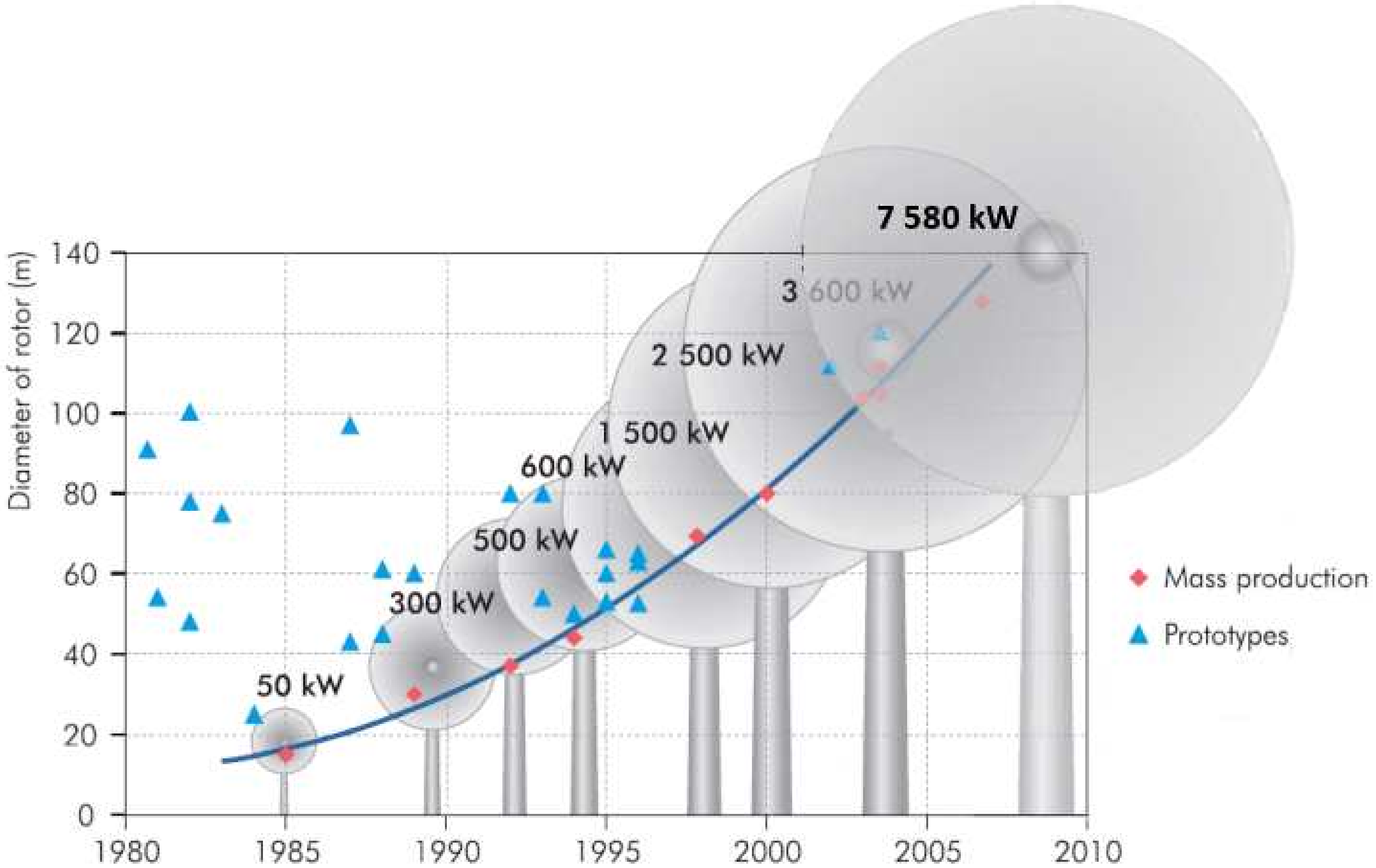
1980-1985 : Californian rush

1978 : *National Energy Act* + subsidies from Californian state
→ 50 % of price of wind farms subsidized

→ 1700 MW set up between 1980 and 1985,
17 000 machines of 20 to 350 kW

American machines, and ~ 7500 danish turbines
e.g. Vestas : 1983, stall regulated 55 kW turbine
1988, pitch-regulated, 200 kW turbine

Power for one turbine : order of magnitude



Source: International Energy Agency (IEA)

Remarks from the history of wind turbines

→ turbines for electricity have existed for **more than a century**

(re-)developed several times, **hindered by cheap oil**

→ maturity and economic viability have required

- Combination of **public and private** programs
- **Gradual buildup** from small to large turbines
- **Policies** to support the initial development

Trend : development of offshore wind energy

Stronger winds
Less wind shear
Less turbulence
More predictable
Limited environmental impact

Hostile environment
Complex conditions
Costs
Connection to grid
Limited to shallow water at present

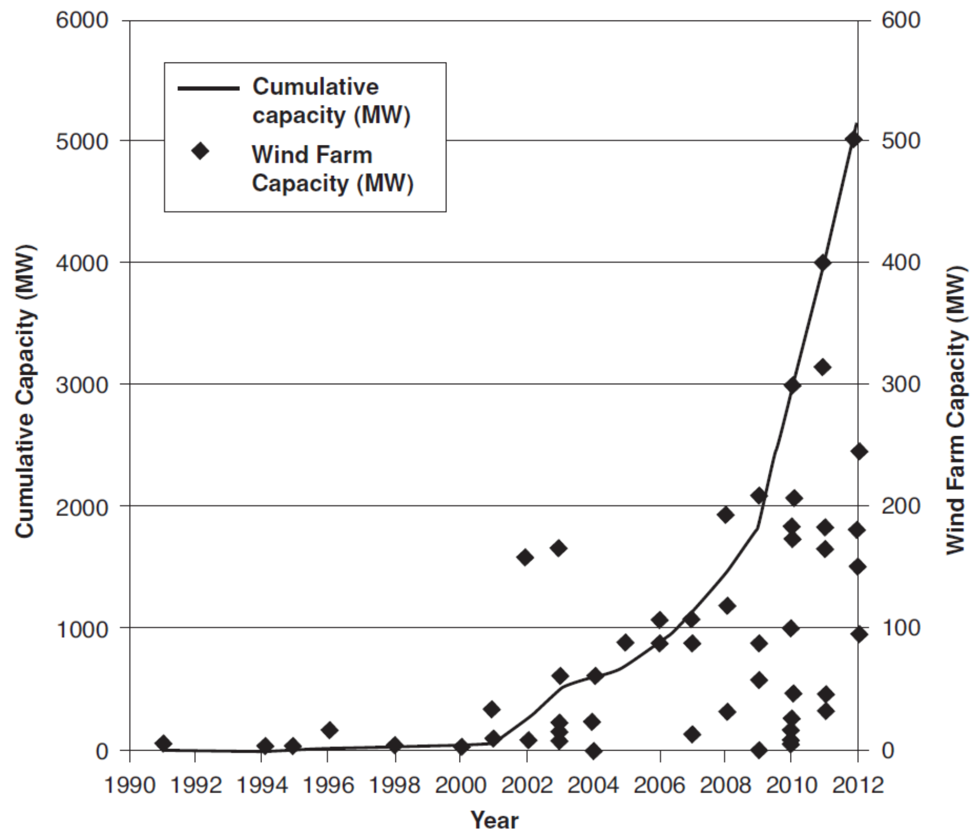


Figure 11.1 Offshore wind farm capacity worldwide (1991–2012)

(Costly) ship dedicated to the transport and installation of turbines

7. Some meteorological considerations

Statistical description of the wind :

Distribution such that cumulative distribution function (CDF) is 0 for U=0, and vanishes for large U :

$$F(U) = 1 - \exp\left[-\left(\frac{U}{c}\right)^k\right]$$

$$p(U) = \left(\frac{k}{c}\right)\left(\frac{U}{c}\right)^{k-1}\exp\left[-\left(\frac{U}{c}\right)^k\right]$$

Weibull distribution

Knowing *p(U)* for a site, the expected power for a given turbine is :

$$\overline{P}_w = \int_0^\infty P_w(U)\,p(U)\,\mathrm{d}U$$

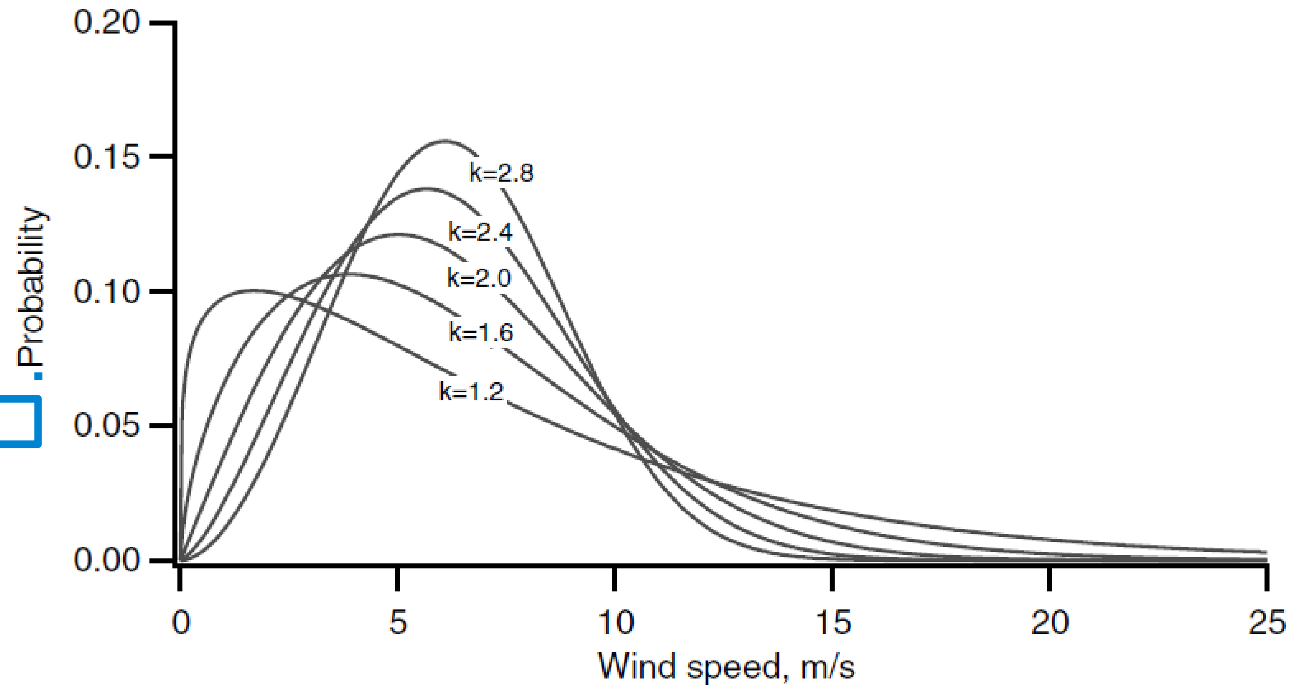
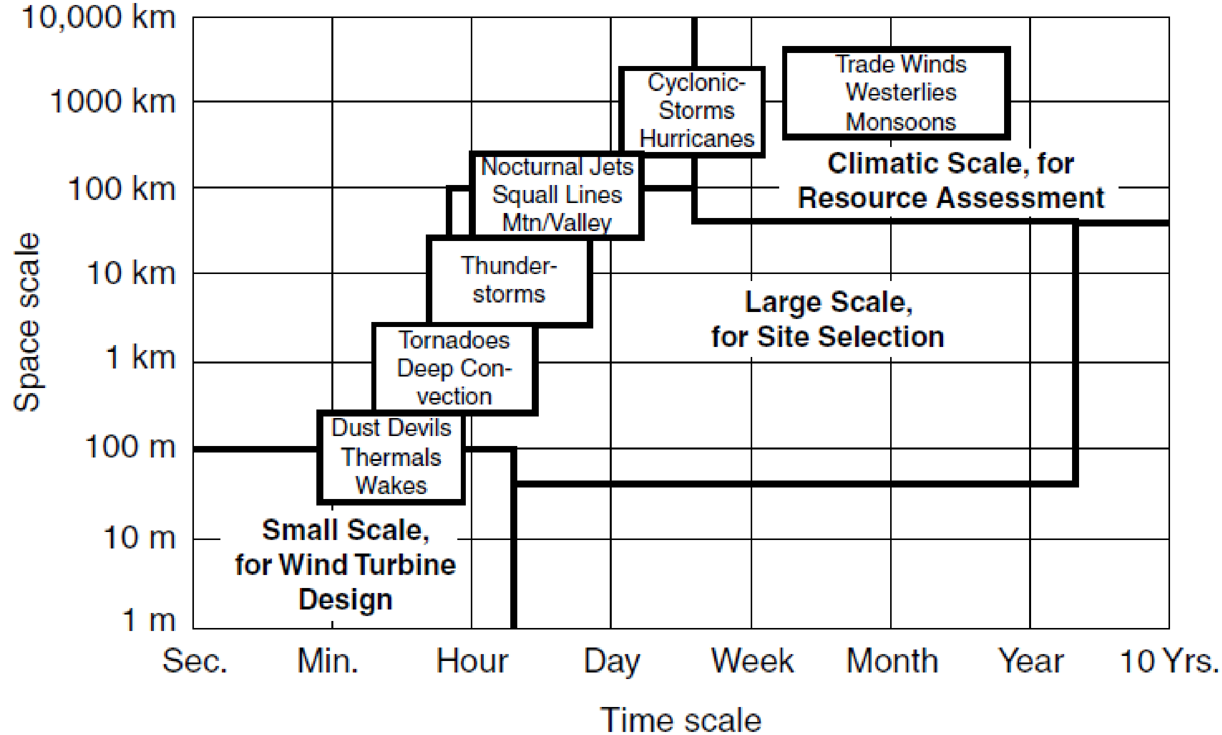


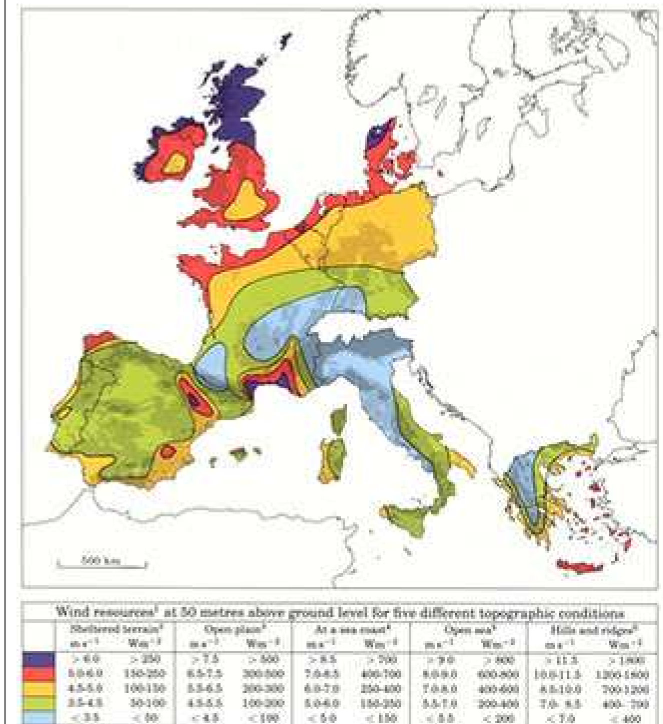
Figure 2.31 Example of Weibull probability density function for $\overline{U} = 6$ m/s

Dynamical understanding of the wind :
cf other courses on atmospheric circulation, environmental fluid dynamics...

Space and time scales of motion

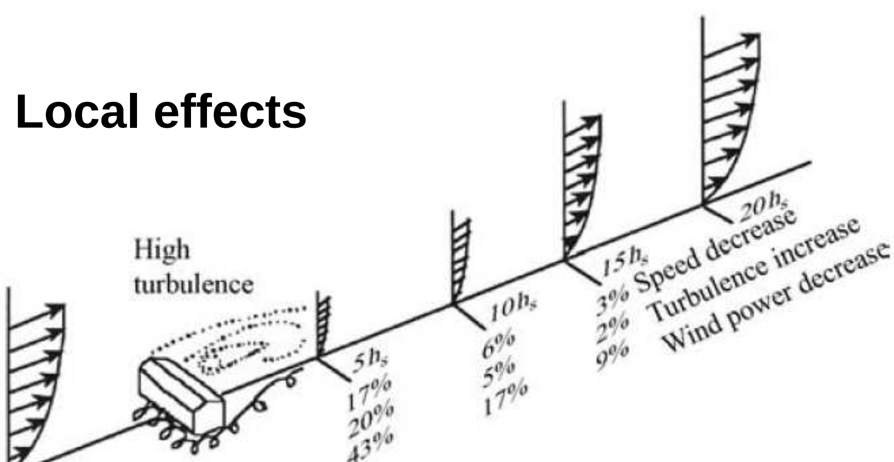


Wind Atlases



WASP, dk

Local effects



The logarithmic wind profile

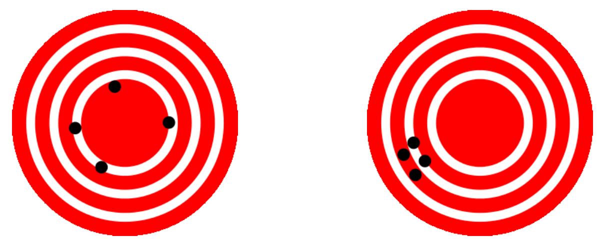
$$U(z) = \frac{U^*}{k} \ln\left(\frac{z}{z_0}\right)$$

Measuring the wind

Standard meteorological measurement : 10m wind
Desired observations for prospection for wind energy : 80 or 100m wind (+ shear)

Some vocabulary :

- ***accuracy*** : closeness to the true value (associated by systematic errors)
- ***precision*** : closeness within a set of measurements (associated with random errors)

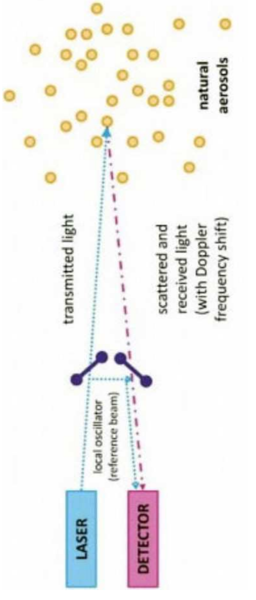


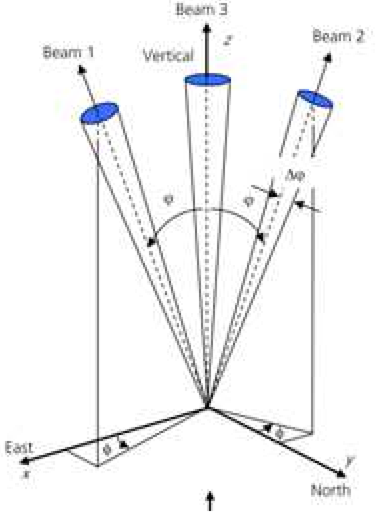
Instruments :

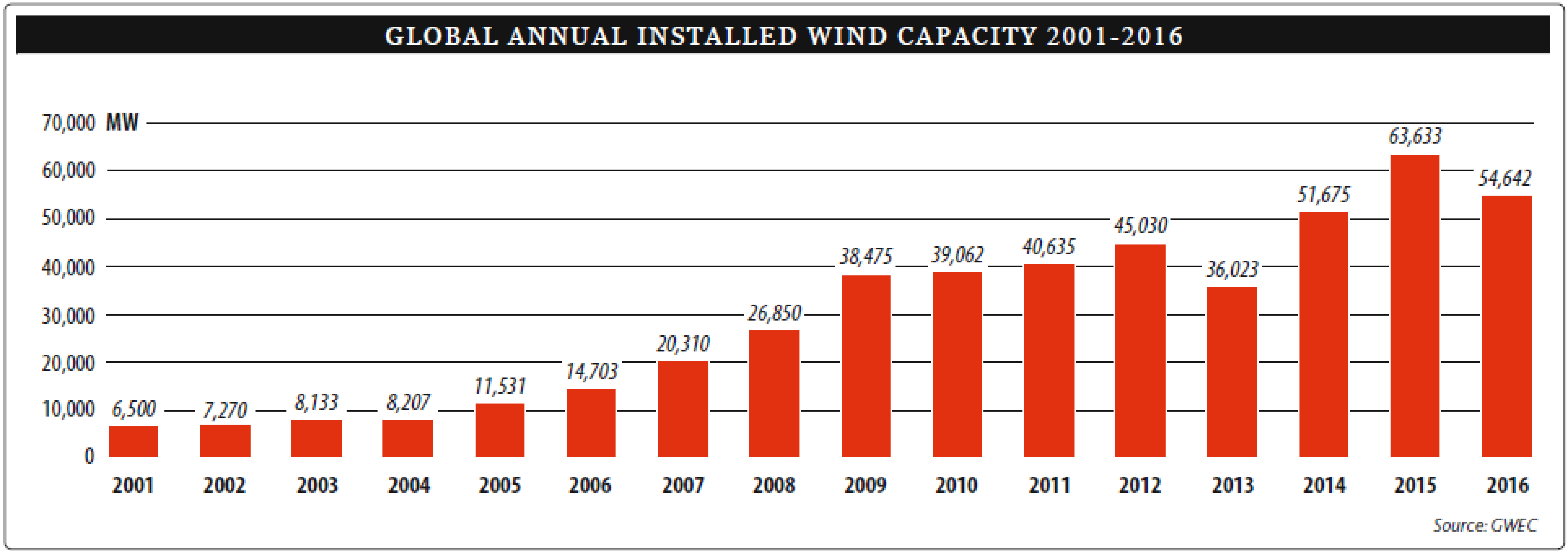
- in situ : anemometers
- remote sensing : lidars, sodars

Cup anemometers

Sonic anemometer

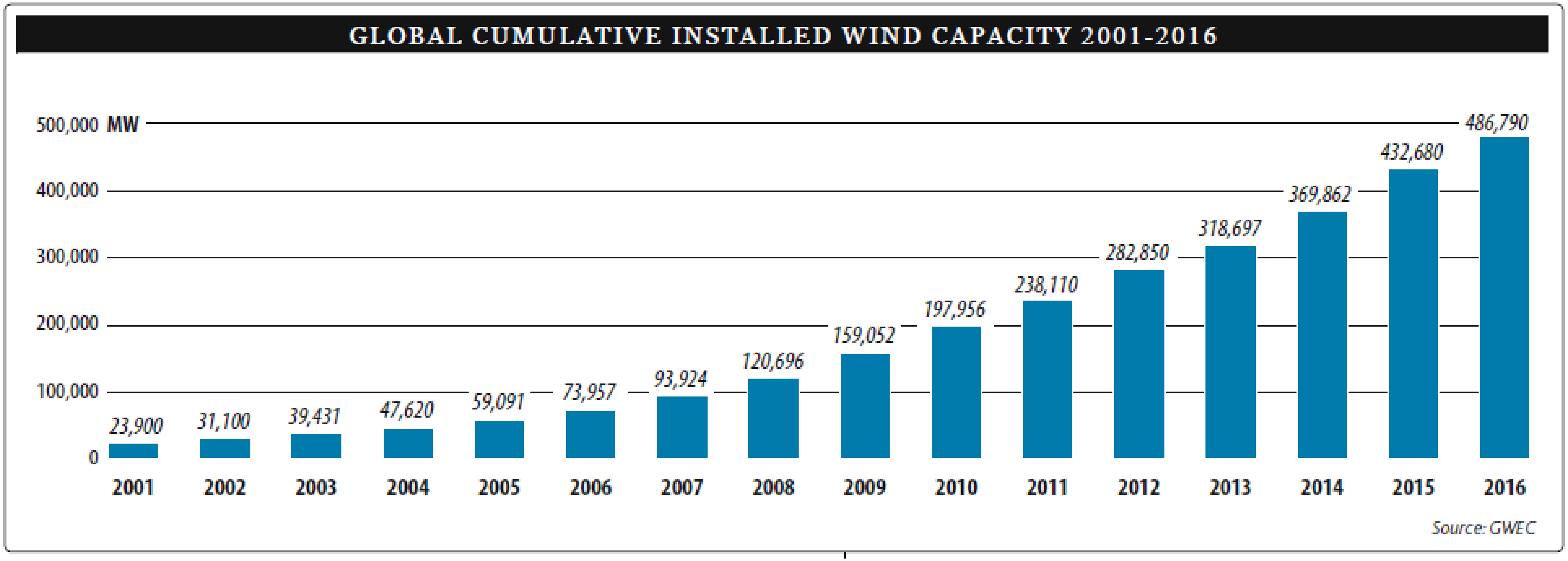






8. Wind energy today

Source : Global Wind Energy Council (GWEC) 2017 report

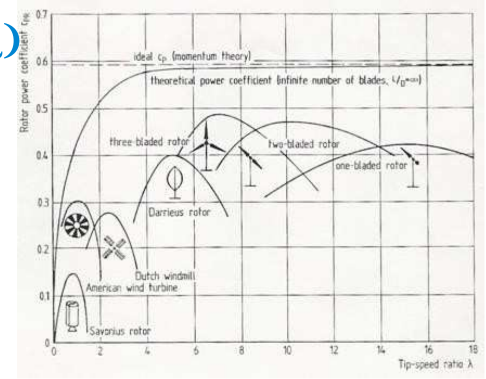


Summary

Aerodynamics of the flow around a turbine

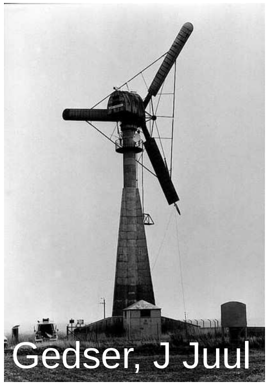
Optimize **power**
Large tip-speed ratio λ most favorable to energy extraction
Less blades (no interaction with wake of previous blade)

$C_p(\lambda)$



Over a century of development
Dominance of **three-bladed design** ('Danish model') :
Good aerodynamic performance, but also other reasons :
stability,
acceptability (visual and noise)

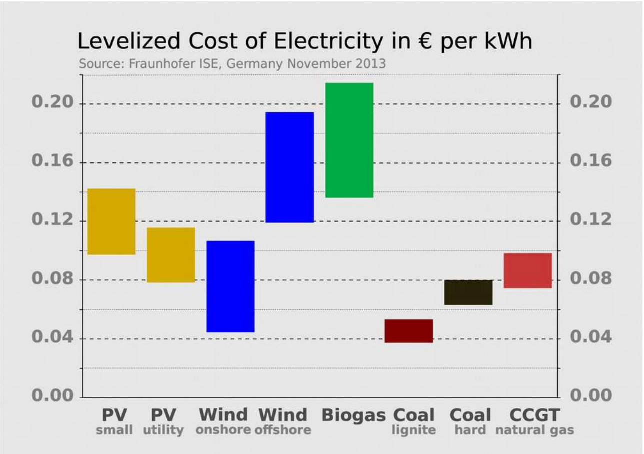
Trend towards **offshore** systems (in shallow water, e.g. North Sea)



Mature technology
Today's machines typically 100m :
Mast ~ 100m, diameter ~ 100m

A few MW per turbine
(e.g. 3 MW on land, 8 MW offshore)

'In 2013 wind generated
almost 3% of the worlds total electricity.'
[from Wikipedia page on World Energy Consumption, Historical Data Workbook, 2013]



Perspectives

Floating offshore platforms

Vertical Axis Wind Turbines

Advantages :

Generator at the bottom

→ lower center of mass

→ easier maintenance

No yaw mechanism

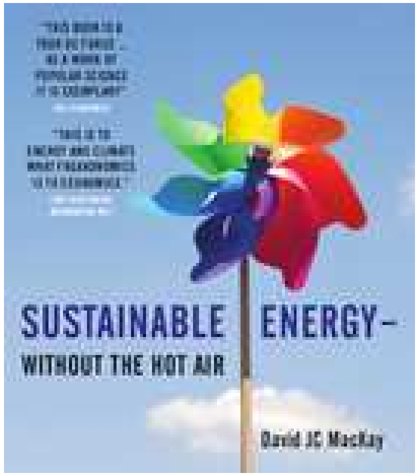
Disadvantage :

Lower power coefficient

Structure to support the blade

Wind Kites ?

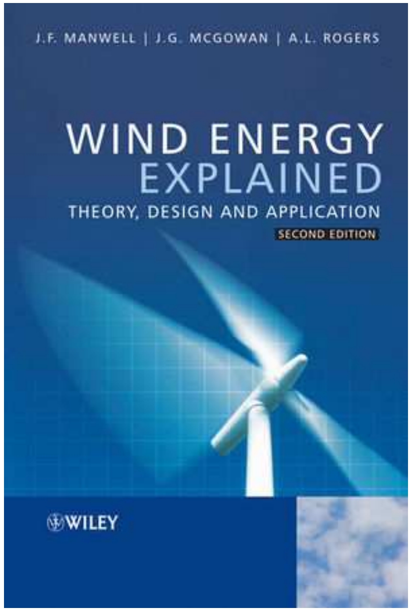
Further reading

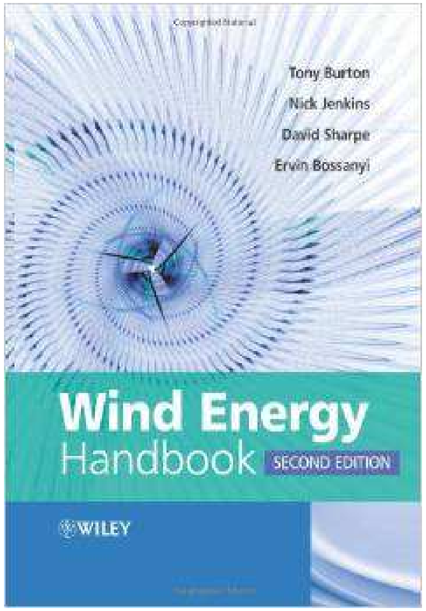


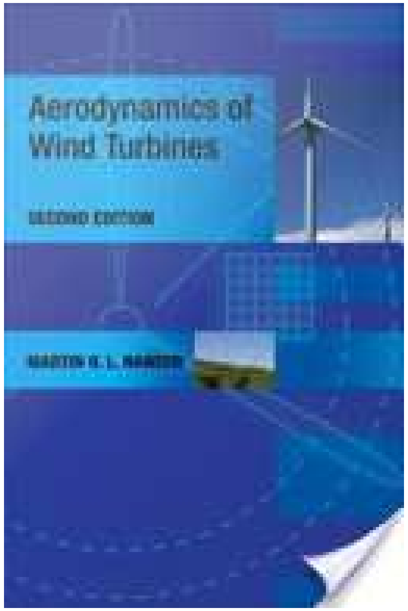
Wind Energy Explained, J.F. Manwell et al, Wiley
Wind Energy Handbook, T. Burton et al, Wiley
Aerodynamics of Wind Turbines, M.O.L. Hansen, Earthscan

Sustainable energy – without the hot air, David Mackay

L'énergie éolienne, Marc Rapin, Jean-Marc Noël, Dunod





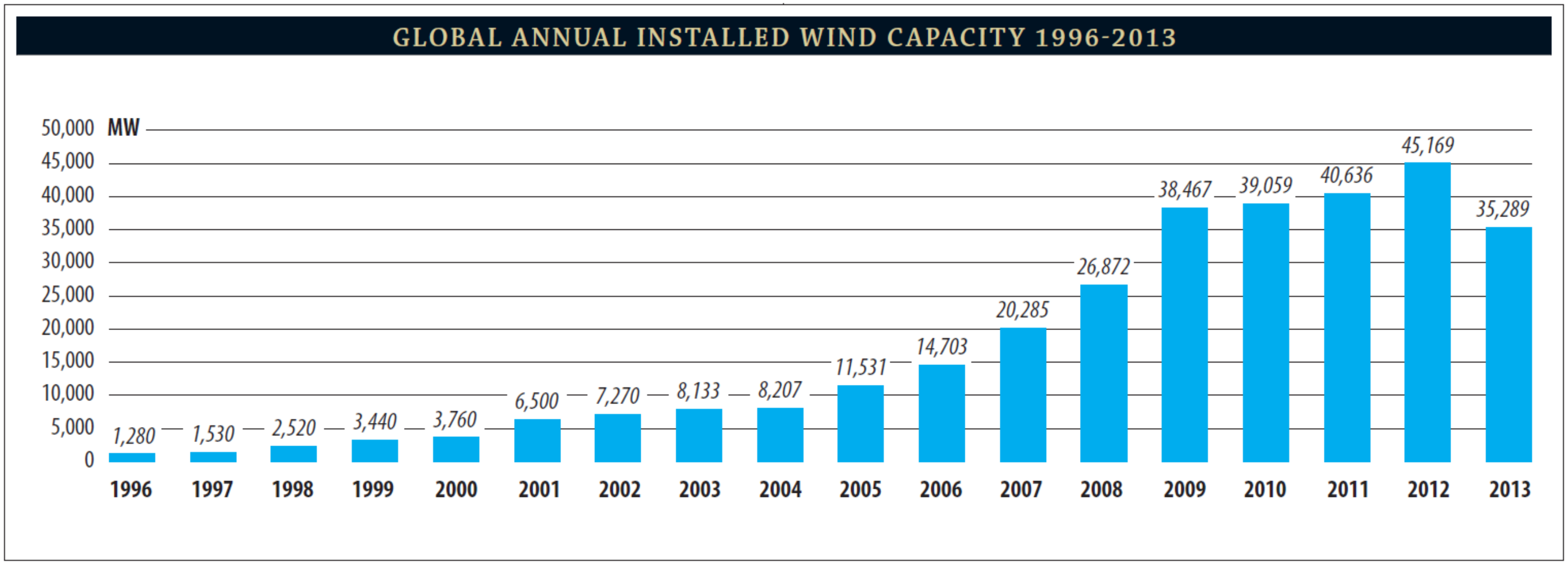


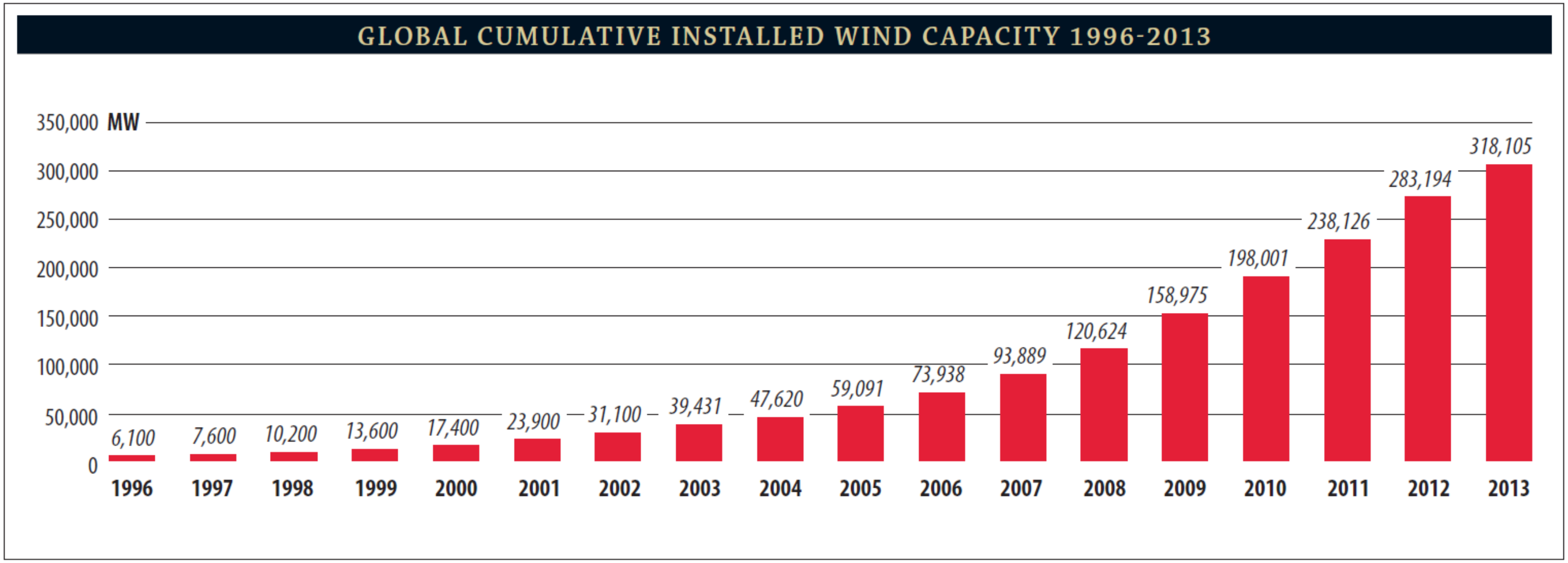
Reports from IEA, GWEC, EWEA :
- http://www.ieawind.org/
- http://www.gwec.net/
- http://www.ewea.org/

Database :
- http://www.thewindpower.net/

8. Wind energy today

New wind capacity installed each year, and global cumulative wind capacity





Source : Global Wind Energy Council (GWEC) 2014 report

Subjects that have not been treated :

- Wind resource :
  - Dynamic meteorology
  - Wind resource assessment
  - Wind variability
  - Essential challenge of wind energy :
    - Intermittency

  - Need for forecasts
  - Need for economic models
  - Need for adaptation of the grid