Up-scaling

by

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The Challenge

To achieve

...large wind energy penetration into the power systems (in accordance with Europe 20-20-20 targets)

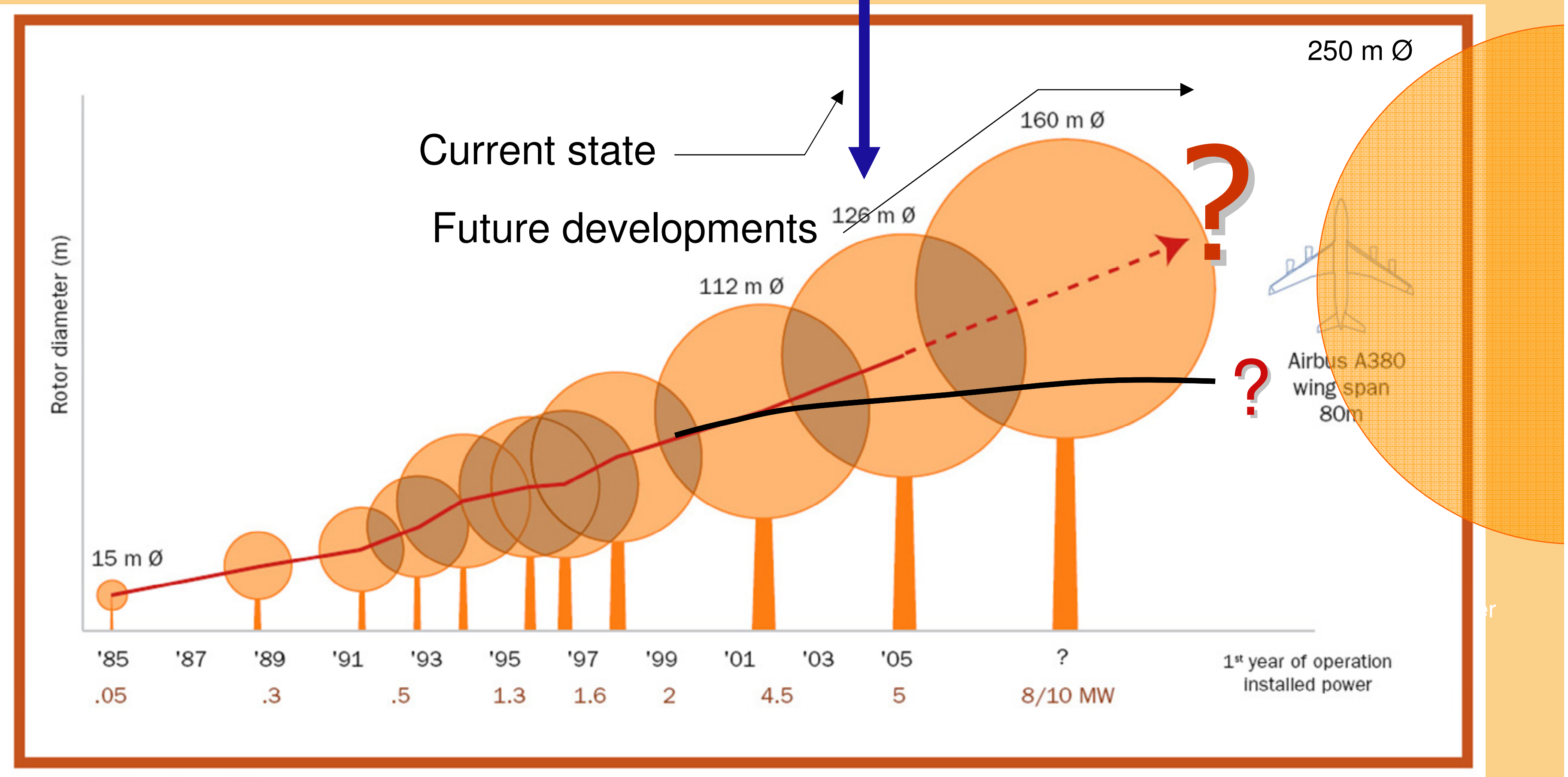
...in a cost efficient way

...with a highly reliable technology

Larger Wind Turbines might be an answer

(at the 10-20 MW range for Offshore installations)

How Large?


250 m Ø
Current state
Future developments
160 m Ø
126 m Ø
112 m Ø
15 m Ø
Rotor diameter (m)
?
?
Airbus A380
wing span
80m
'85 '87 '89 '91 '93 '95 '97 '99 '01 '03 '05 ?
.05 .3 .5 1.3 1.6 2 4.5 5 8/10 MW
1st year of operation
installed power

20MW wind turbines: The questions

- Is manufacturing feasible ?
- Is the concept economically viable ?
- Is the technology needed available ?

Feasibly, Cost-competitiveness, Maturity

1st question: Technical feasibility

- … we were able to build and transport this some decades ago …

Examples from presentation by B. Hendriks (EWEC 2008)

Technical feasibility

- … we were able to design and manufacture this some years ago …

Examples from presentation by B. Hendriks (EWEC 2008)

Technical feasibility

- … we were able to design and manufacture this some years ago …

Examples from presentation by B. Hendriks (EWEC 2008)

Feasibility of 20MW wind turbines

The answers from available technical expertise and UPWIND project experience:

- Manufacturing *is* possible
- Transportation and installation *are* possible

BUT…

- …this does not mean that a 20MW version of a current state-of-the-art 5MW W/T will offer any cost/performance advantages

2^{nd} question: Is a 20MW wind turbine economically viable ?

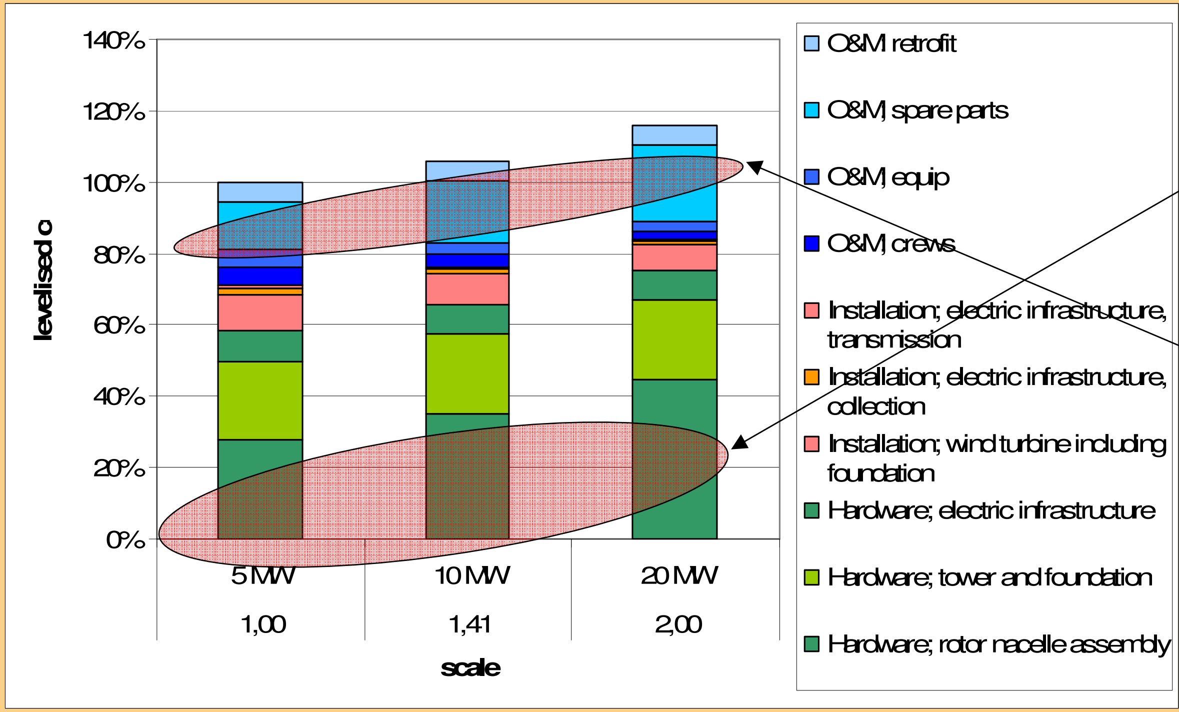
In the energy industry, economies of scale generally lead to larger designs for cost-effectiveness

BUT…

…it is not obvious that this applies after a certain size

Economical viability of 20MW W/Ts

Up scaling – levelised cost



- Levelised cost *increases* with scale
- Reasons:
  - Rotor and nacelle costs scale ~s^3 (?)
  - Spare parts costs follow
- Economy of scale in other costs **is negated by the increase in rotor nacelle cost**

SIMILARITY RULES FOR COMPONENTS UP-SCALING

1.1. External Geometry

Assuming geometric similarity for the external geometry of the rotor blades, i.e. the blade planform characteristics scale-up proportionally to the blade radius, the twist distribution and the airfoil types remain the same, we end-up with the following size dependency table.

Symbol	***Defining Formula***	***Description***	***Size-Dep.***
R		*Blade Radius*	*R*
r		*Local Radius*	*R*
L	$L = R - r_0$	*Blade length*	*R*
x	$x = r / R$	*Non-dimensional spanwise distance:* $[x_h, 1]$ *h=hub*	*I*
$c(r)$		*Chord distribution*	*R*
$t(r)$		*Max-Thickness distribution of airfoils*	*R*
$c^*(x)$	$c^*(x) = c(r) / R$	*Non-dimensional chord distribution*	*I*
$t^*(x)$	$t^*(x) = t(r) / c(r)$	*Non-dimensional Max-Thickness distribution*	*I*
$twist(x)$		*Twist distribution*	*I*
$airf(x)$		*Airfoil type*	*I*

R: denotes linear dependency on blade radius.
I: denotes size independency.

1.1. Operational Conditions

To achieve aerodynamic rotor similarity we assume that the blade tip-speed and the collective pitch are size-independent, depending only on the actual wind-speed through the turbine control. It is notable, though, that the local Reynolds number *Re* increases proportionally to the turbine size. Aerodynamic airfoil similarity requires geometrically similar blades and equal Reynolds number, Mach number and reduced frequency (turbulence, 1P, tower passage) of the effective wind speed.

Symbol	Defining Formula	Description	Size-Dep.
ρ_a		*Air density*	*I*
U		*Wind Speed*	*I*
ω		*Rotational Speed*	*1/R*
ωR	$\omega R = function(U)$	*Tip-speed*	*I*
p	$p = function(U)$	*Collective Pitch*	*I*
$V(x)$	$V(x) = function(U, x)$	*Effective Wind Speed*	*I*
$\mathrm{Re}(x)$	$\mathrm{Re}(x) = V(x) * c(x) / \nu$	*Reynolds Number (ν = air kinematic viscosity)*	*R*
$M(x)$	$M(x) = V(x) / a$	*Mach number (a = speed of sound)*	*I*
$k(x)$	$k(x) = f * c(x) / 2V(x)$	*Reduced frequency (f = frequency)*	*I (for 1P)*

1.1. Loads and stresses

Symbol	Defining Formula	Description	Size-Dep.
$d\Phi(x,U)$	$\bar{\rho}_m(x)A(x)\omega^2 r dr = \omega^2 R^4 . \bar{\rho}_m(x)A^*(x)xdx$	Centrifugal force diff.	$\omega^2 R^4 \sim R^2$
$\Phi(x_0,U)$	$= \omega^2 R^4 . \int_{x_0}^{1} \bar{\rho}_m(x)A^*(x)xdx$	Centrifugal force at blade root	$\omega^2 R^4 \sim R^2$
$\sigma_{xx,\Phi}(x_0,U)$			$(\omega R)^2 \sim I$
$dm(x)$			R^3
$B(x_0)$			R^3
$M_B(x_0)$			R^4
$\sigma_{xx,B}(x_0)$		stress at blade root (tension or compression)	R
$\sigma_{xx,M_B}(x_0)$	$= M_B(x_0)/W_z(x_0)$	Weight bending stress at blade root	R
$\sigma_{xx,A}(x_0,U)$	$= \pm M_y(x_0,U)/W_y(x_0) \pm M_z(x_0,U)/W_z(x_0)$	Aero bending axial stress	I
$\tau_A(x_0,U)$	$= M_x(x_0,U)/W_t(x)$	Aero-Torsion shear stress	I

Where g stands for the acceleration of gravity.

Centrifugal stresses are size independent

Aerodynamic stresses are size independent

Weight stresses are proportional to *R*, rendering longer blades sensitive to:
- **buckling (all kinds, local buckling included),**
- **weight triggered low-cycle fatigue failure**

1.1. Natural Frequencies

In our analysis we shall rely on a single-beam model with uniform sectional properties along its span. Let L be the length of the beam. The angular natural frequencies ω_n of the different modes are proportional to $(K_m / M_m)^{½}$, where M_m stands for the generalized mass and K_m for the generalized stiffness. i is the radius of gyration scaling-up with R.

	M_m	K_m	$\omega_n \approx \sqrt{K_m / M_m}$	$\overline{\omega_n} = \omega_n / \omega \approx$
Tension	$\bar{\rho} L \sim R^3$	$EA / L \sim R$	$\frac{1}{L}\sqrt{EA / \bar{\rho}} \sim R^{-1}$	$R^{-1}/R^{-1} \sim I$
Bending	$\bar{\rho} L \sim R^3$	$EI / L^3 \sim R$	$\frac{1}{L^2}\sqrt{EI / \bar{\rho}} \sim R^{-1}$	$R^{-1}/R^{-1} \sim I$
Torsion	$\bar{\rho} L i^2 \sim R^5$	$GJ / L \sim R^3$	$\frac{1}{L}\sqrt{GJ / (\bar{\rho}\, i^2)} \sim R^{-1}$	$R^{-1}/R^{-1} \sim I$

- **Blade natural frequencies are inversely proportional to *R***
- **Non-dimensional natural frequencies (normalized by the blade rotational frequency) are size independent**

1.1. Elastic deformations

Symbol	Defining Formula	Description	Size-Dep.
$w^*(x,U) = w(x,U)/R$	$\frac{d^2 w^*(x,U)}{dx^2} \approx R.\frac{M_y(x,U)}{EI_{yy}(x)}$	*Normalized out-plane deflection*	*I for* M_y *Aero* *R for* M_y *Weight*
$v^*(x,U) = v(x,U)/R$	$\frac{d^2 v^*(x,U)}{dx^2} \approx R.\frac{M_z(x,U)}{EI_{zz}(x)}$	*Normalized in-plane deflection*	*I for* M_z *Aero* *R for* M_z *Weight*
$\varphi(x,U)$	$\varphi(x,U) = \frac{M_x(x,U)}{GJ(x)/L}$	*Torsional deflection*	*I for* M_x *Aero*

- **The normalized deflections are size independent when produced by aerodynamic loads**

- **The weight loads, on the contrary, produce deflections proportional to *R***

This has a direct effect on the in-plane maximum blade deflection and an indirect in the out of plane deflection related to the blade-tower clearance

1.1. Aeroelastic stability – single blade

We shall base this analysis on a simplified typical-section model applied at x_0 with three degrees of freedom (n = flap, lag, torsion). Further to the earlier defined variables we add the following which are essential for stability considerations.

Symbol	Defining Formula	Description	Size-Dep.
$k(x_0,U)$	$k(x_0,U) = \omega c(x_0)/V(x_0,U)$	Reduced frequency	$(\omega R)/V \sim I$
$R_f(x_0)$	$R_f(x_0) = \rho_a c(x_0)^2/\overline{\rho}(x_0)$	Density factor	I

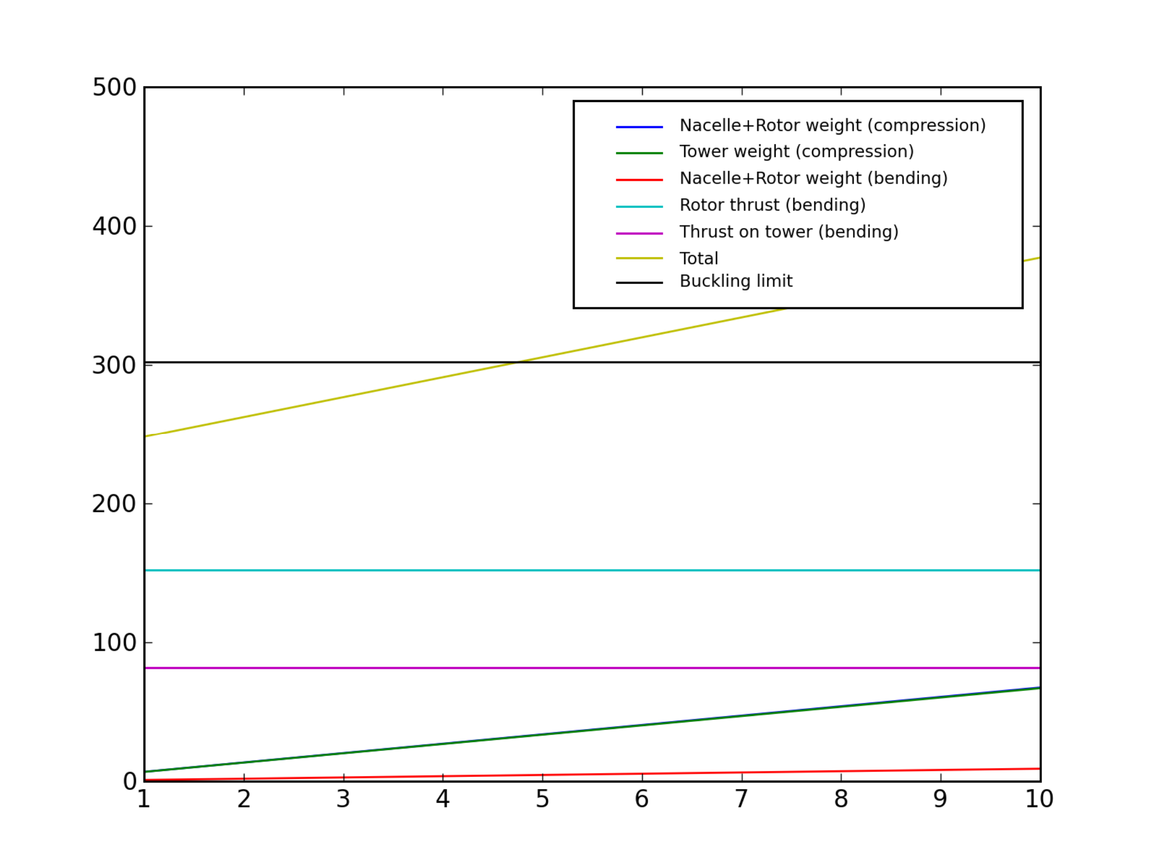
Let $\mathbf{X} = \{v^*, w^*, \varphi\}^T$ be the vector of normalized (with the local chord and, essentially with R) displacements due to the aeroelastic action. Then, the stability equations for the typical section, ignoring structural damping, can be written in the following vectorial form:

$$\mathbf{F}\,(\mathbf{X}'',\mathbf{X}';\, k, R_f, \overline{\omega}_n,\ c_n,\ \overline{r}_n) = 0$$

Where (') denotes reduced-time derivation, $\overline{\omega}_n$ are the normalized blade frequencies (first flap, lag and torsional), c_n are the aerodynamic coefficients once again assumed as Reynolds independent and $\overline{r}_n$ represent normalized geometrical properties of the section.

Under the above assumptions, and size independent *k* and *Rf,* the stability bounds of the above aeroelastic system will also be size independent

Similarity Rules applied to Tower Design



- Weight scales according to ~s^3
- Material strength limit exceeded for large s

Up scaling beyond similarity

- "Basic" scale factor *(s)*, and additional scaling for diameter and thickness defined by g_D and g_t

$$m_{nacelle}(s) = m_{nacelle}(1) \cdot s^3,$$

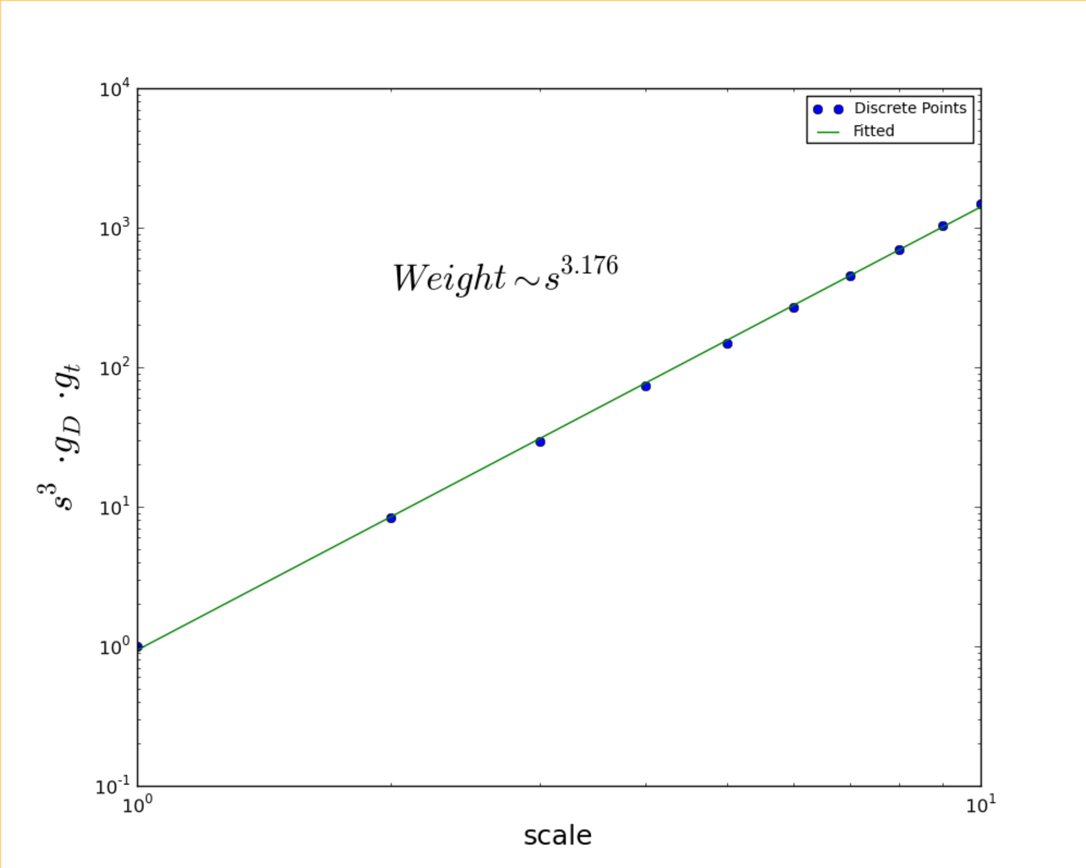
$$m_{rotor}(s) = m_{rotor}(1) \cdot s^3,$$

$$H(s) = H(1) \cdot s,$$

$$D(s) = D(1) \cdot s \cdot g_D(s),$$

$$t(s) = t(1) \cdot s \cdot g_t(s)$$

Optimum Up scaling



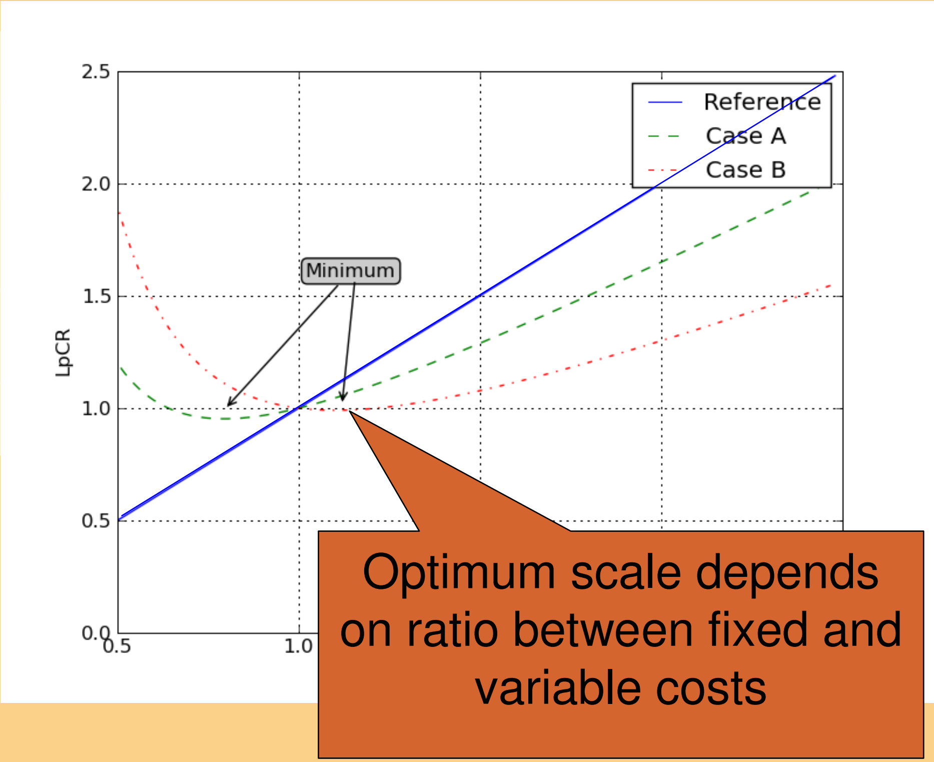
- Weight variation with scale
- Based on volume

- Weight scales following s^{3+}

$$s^3 \cdot g_D \cdot g_t$$

Economical viability of 20MW W/Ts

Why does cost seem to favor small size?



Classical up scaling results

- Weight follows s^3
- Cost follows weight
- ...making a 20MW wind turbine non-attractive

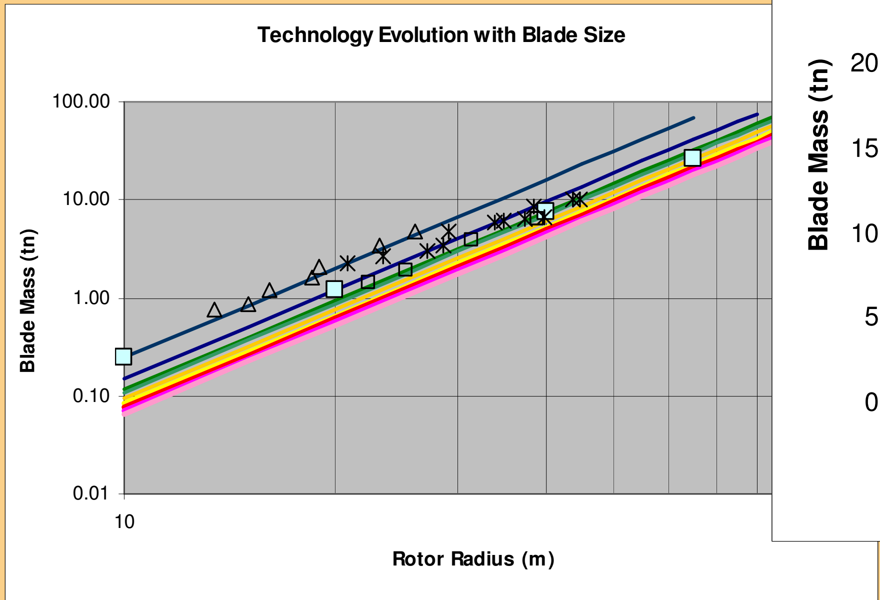
But… two factors can change this

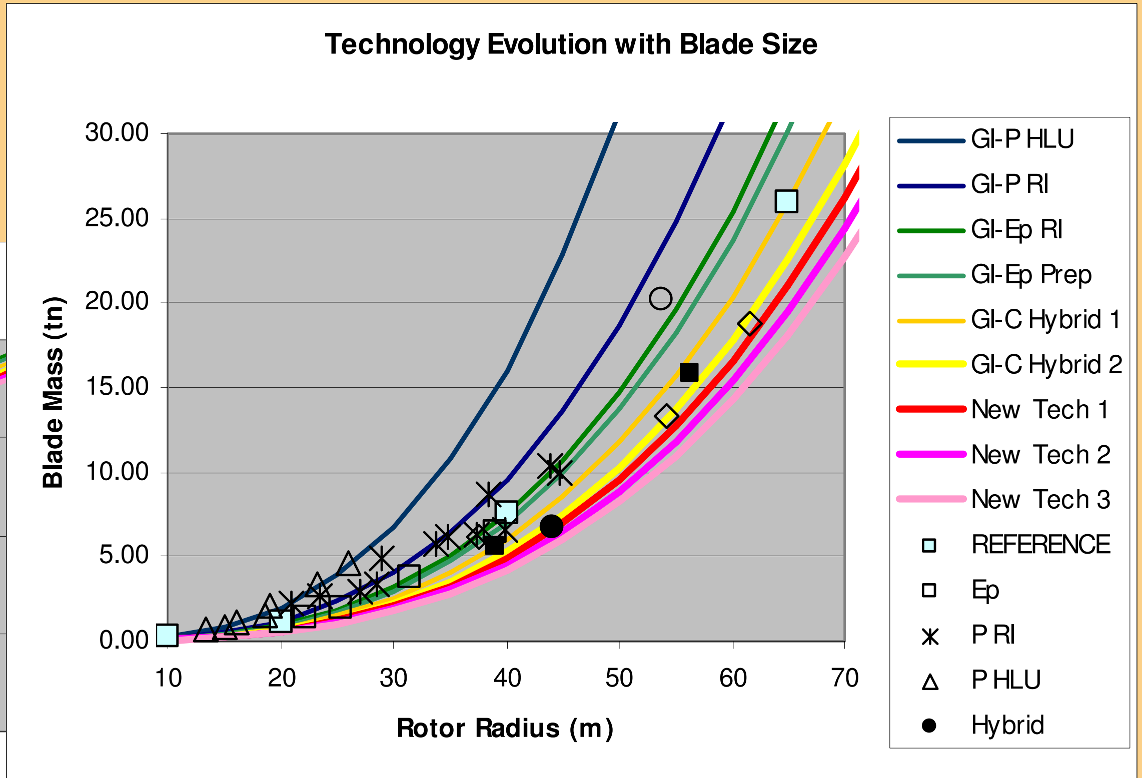
- Learning curve → cost reduction
- High initial-cost developments become attractive *only* at large scales

Economical viability of 20MW W/Ts

Case study: Blades

Technology evolution
with size





Economical viability of 20MW W/Ts

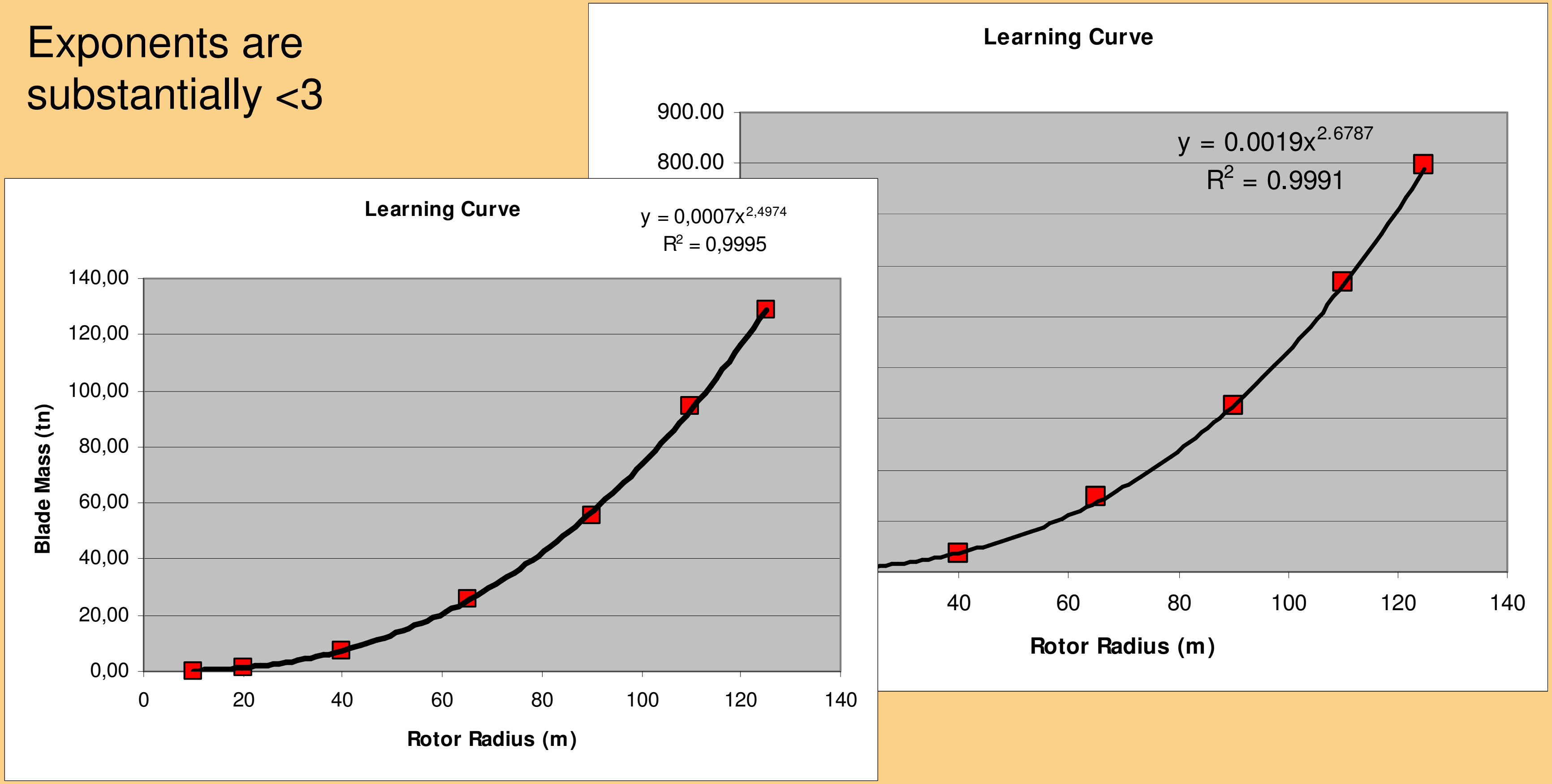
Case study: Blades

		PAST						FUTURE		
		GI-P HLU	GI-P RI	GI-Ep RI	GI-Ep Prep	GI-C Hybrid 1	GI-C Hybrid 2	New Tech 1	New Tech 2	New Tech 3
	Single Step r(t)/r(t-1)	1,00	0,59	0,79	0,93	0,86	0,87	0,93	0,93	0,93
	Cummulative r(t)	1,00	0,59	0,47	0,44	0,38	0,33	0,31	0,28	0,26
	Single Step a(t)/a(t-1)	1,00	1,08	1,08	1,10	1,10	1,00	1,03	1,03	1,03
	Cummulative a(t)/a(t0)	1,00	1,08	1,17	1,28	1,41	1,41	1,45	1,50	1,54
WT Power (MW)	Rotor Radius (m)	Mass (tn)	Mass (tn)	Mass (tn)	Mass (tn)	Mass (tn)	Mass (tn)	Mass (tn)	Mass (tn)	Mass (tn)
0,125	10	0,25	0,15	0,12	0,11	0,09	0,08	0,08	0,07	0,07
0,281	15	0,85	0,50	0,40	0,37	0,32	0,28	0,26	0,24	0,22
0,500	20	2,00	1,19	0,94	0,88	0,76	0,66	0,61	0,57	0,53
0,781	25	3,91	2,33	1,84	1,71	1,48	1,28	1,19	1,11	1,03
1,125	30	6,76	4,02	3,17	2,96	2,55	2,22	2,06	1,92	1,78
1,531	35	10,74	6,39	5,04	4,70	4,05	3,52	3,28	3,05	2,83
2,000	**40**	**16,02**	**9,53**	**7,52**	**7,01**	**6,04**	**5,26**	4,89	4,55	4,23
2,531	**45**	**22,82**	**13,57**	**10,71**	**9,99**	**8,60**	**7,49**	6,96	6,48	6,02
3,125	**50**	**31,30**	**18,62**	**14,70**	**13,70**	**11,80**	**10,27**	9,55	8,88	8,26
3,781	**55**	**41,66**	**24,78**	**19,56**	**18,23**	**15,71**	**13,67**	12,71	11,82	11,00
4,500	**60**	**54,08**	**32,17**	**25,40**	**23,67**	**20,39**	**17,75**	16,51	15,35	14,28
5,281	**65**	**68,76**	**40,90**	**32,29**	**30,09**	**25,93**	**22,57**	20,99	19,52	18,15
6,125	70		51,09	40,33	37,58	32,38	28,19	26,21	24,38	22,67
7,031	75		62,84	49,60	46,23	39,83	34,67	32,24	29,98	27,89
8,000	80		76,26	60,20	56,10	48,34	42,07	39,13	36,39	33,84
9,031	85			72,20	67,29	57,98	50,47	46,93	43,65	40,59
10,125	90				79,88	68,82	59,91	55,71	51,81	48,19
11,281	95				93,95	80,94	70,45	65,52	60,94	56,67
12,500	100					94,40	82,18	76,42	71,07	66,10
13,781	105					109,29	95,13	88,47	82,28	76,52
15,125	110					125,65	109,38	101,72	94,60	87,98
16,531	115						124,98	116,23	108,09	100,53
18,000	120						142,00	132,06	122,81	114,22
19,531	125						160,50	149,26	138,81	129,10
21,125	130						180,54	167,90	156,15	145,22

Economical viability of 20MW W/Ts

Case study: Blades

Exponents are substantially <3

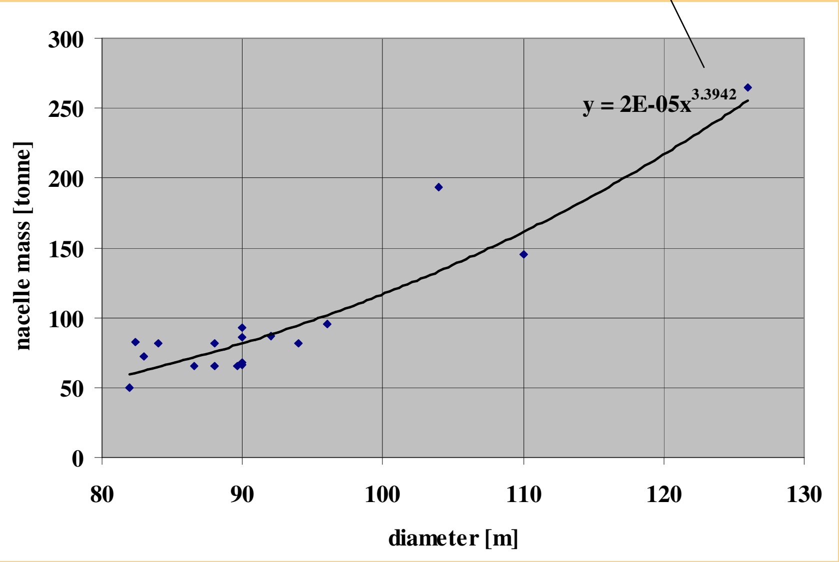


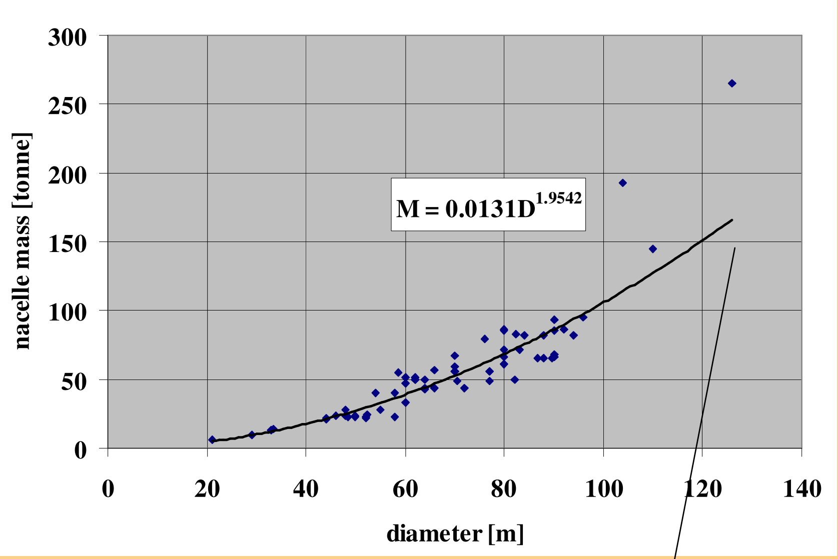
Economical viability of 20MW W/Ts

Case study: Nacelle

Nacelle mass evolution

Using recent data from large W/Ts (exponent =3+)





Using all historical data (exponent ~2)

3rd question: What are the technical advances required for economical viability?

Cost of energy *needs* to go down – Development paths

RAMS

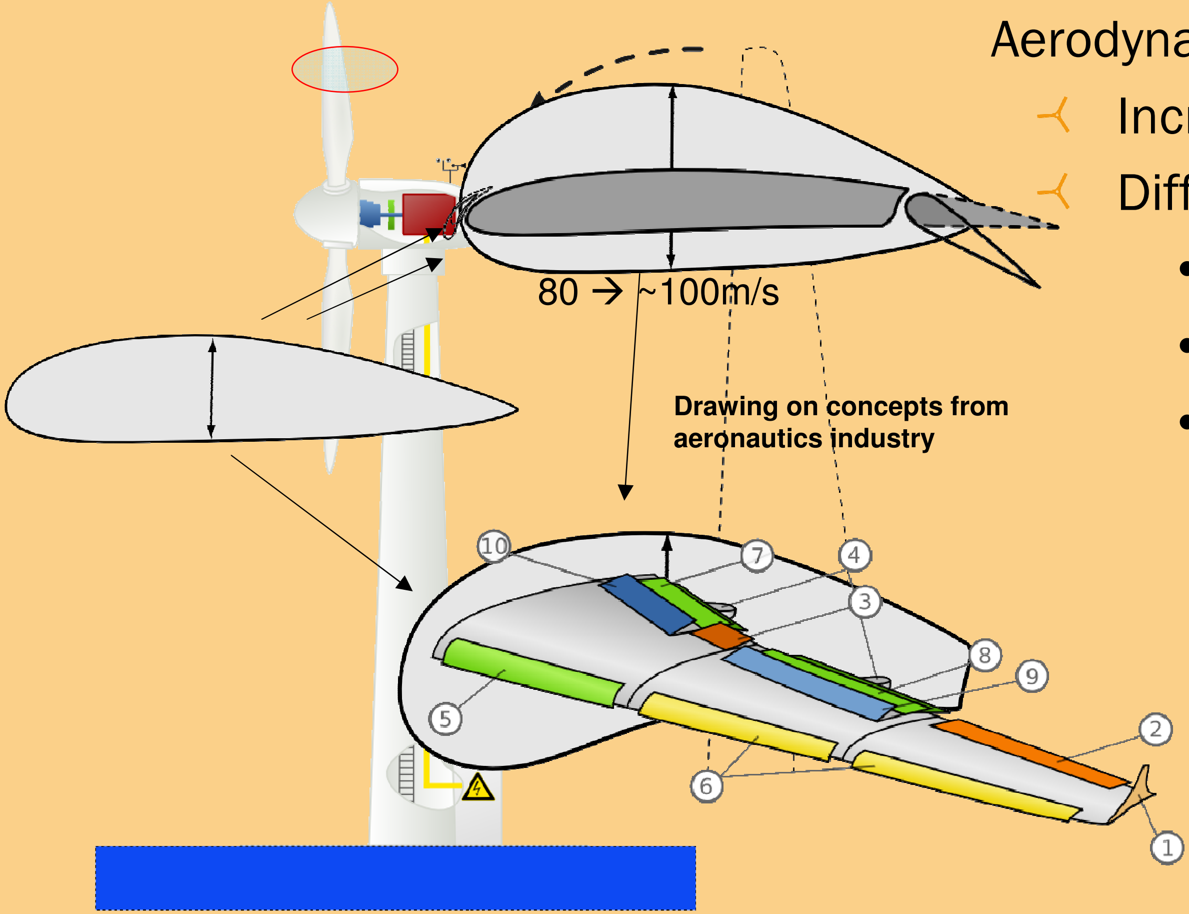
Increased availability

- Reliability-based design
- Condition monitoring

Reduced cost of energy

- Aerodynamic improvements
- New control systems for improved wind utilisation
- Weight reduction
- New manufacturing techniques
- Improved load calculations → rationalization of safety factors

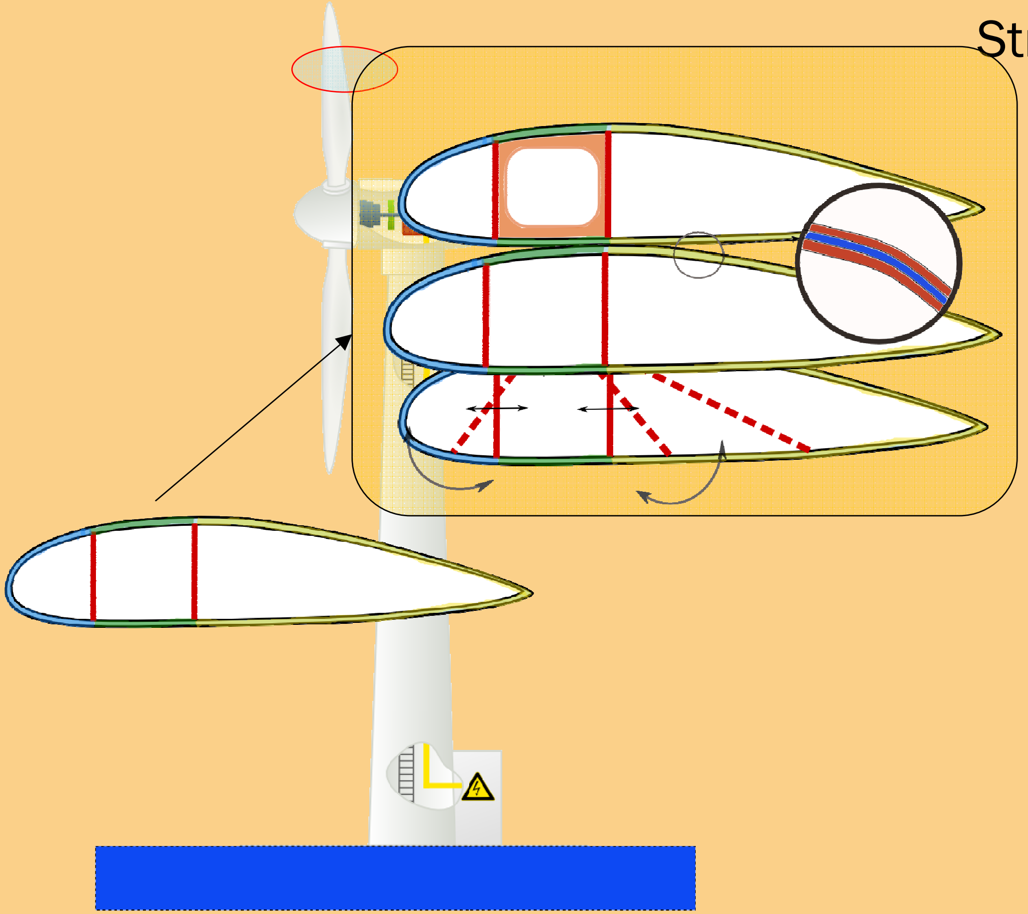
Improvements in Wind Turbine Design
Rotor



Aerodynamic design

- Increased tip speed
- Different blade shapes
  - Thicker sections
  - Blunt TE sections
  - Multi-element airfoils

Improvements in Wind Turbine Design
Rotor

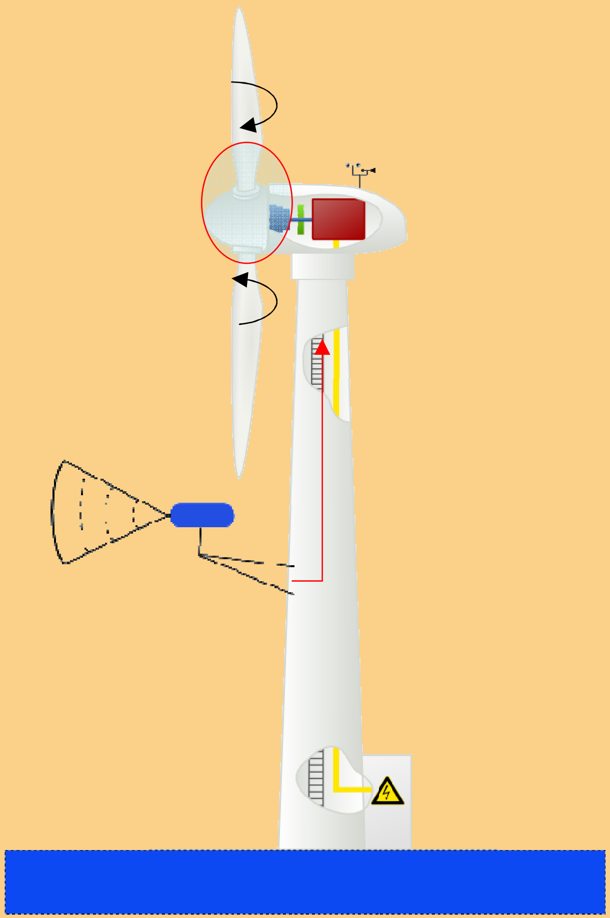


Structural design

- Optimized internal structure
  - Going beyond the standard spar concept
- Optimized material usage
  - Hybrid construction
  - Design for structural damping
  - New materials

Improvements in Wind Turbine Design

Controls



Control System

- Individual Pitch Control
- LIDAR Based control

Improvements in Wind Turbine Design

Drivetrain

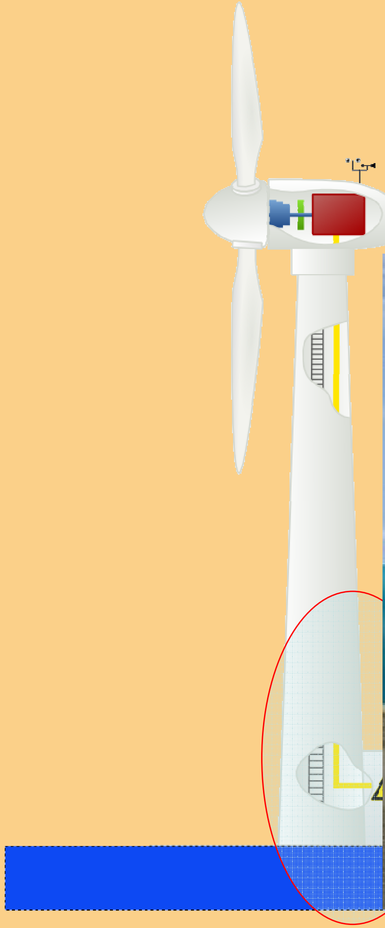
Changes in the drive-train

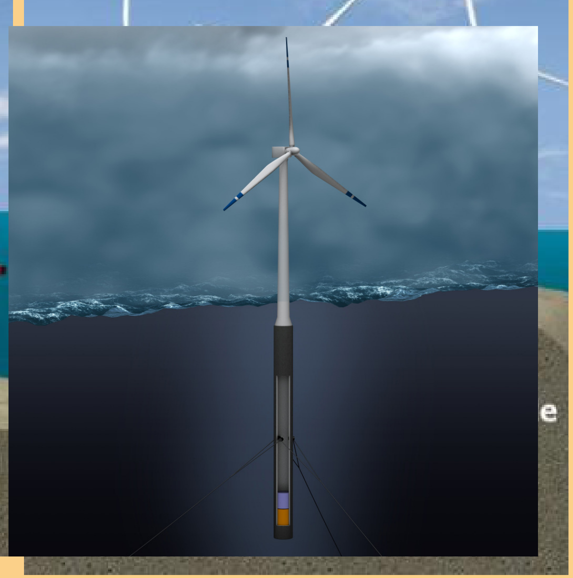
- Hybrid drive-trains (geared + Permanent Magnet)
- Superconducting direct-drive
- Permanent magnet direct-drive

Improvements in Wind Turbine Design
Support Structure

Off-shore support structures

- Alternative designs for deep off-shore (50m)
- Alternative floater designs for floating off-shore





Large Wind Turbines in the future

- The details of the future design may be uncertain
- However it is obvious that…
  - Up scaling existing designs will *not* be enough
  - Integrated design for large scale should be pursued
  - New ideas and technological breakthroughs will be necessary to make very large wind turbines economically attractive
- It is certain therefore that **substantial R&D and industrial effort is still needed** to conquer all technical barriers!