# Advances in Wind Turbine Aerodynamics

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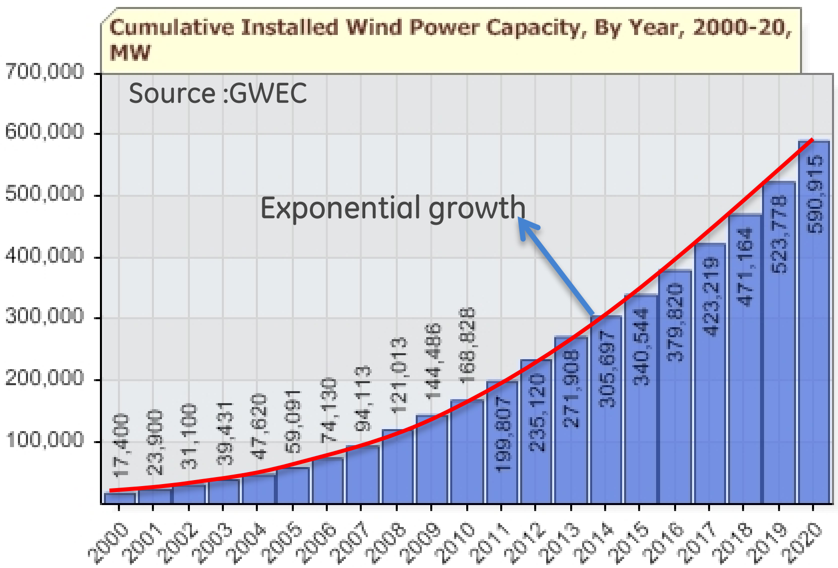
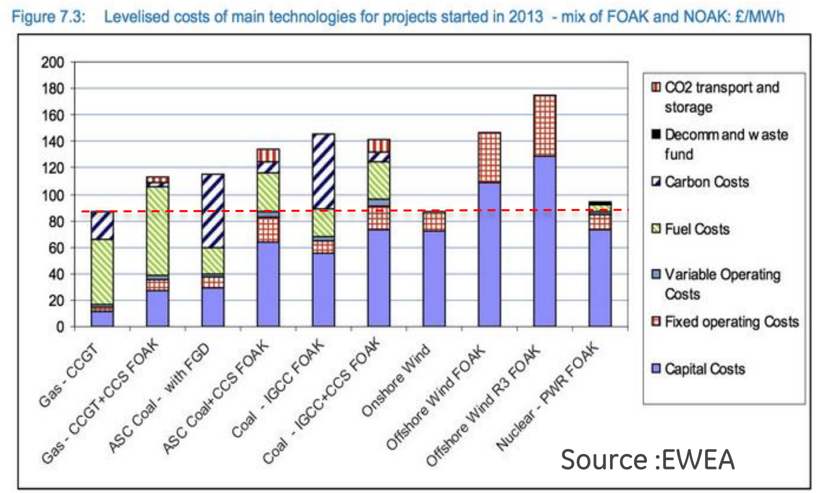
Imagination at work.

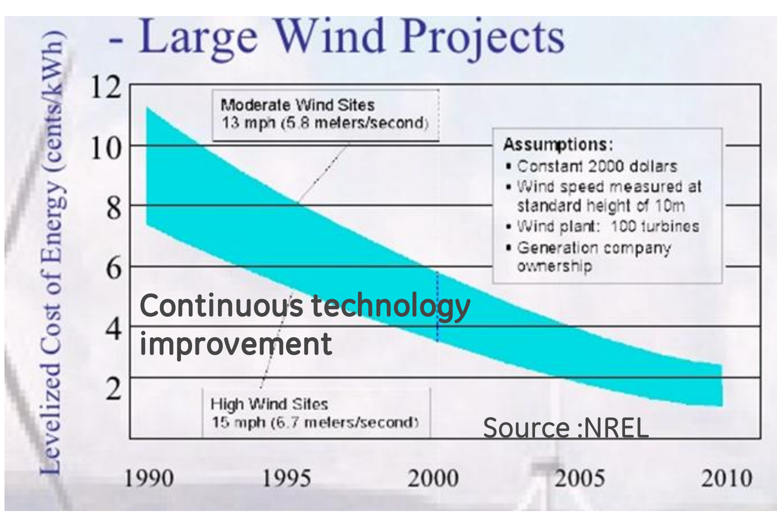
# Outline

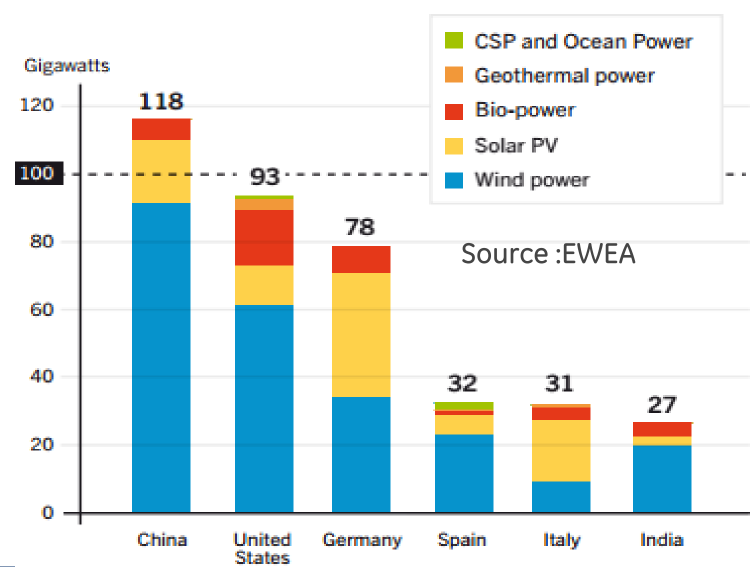
- Introduction
- Wind turbine design process
- Wind turbine aerodynamics
- Airfoil and blade design
- Wind park as a product
- What next?
- Conclusion

# Introduction



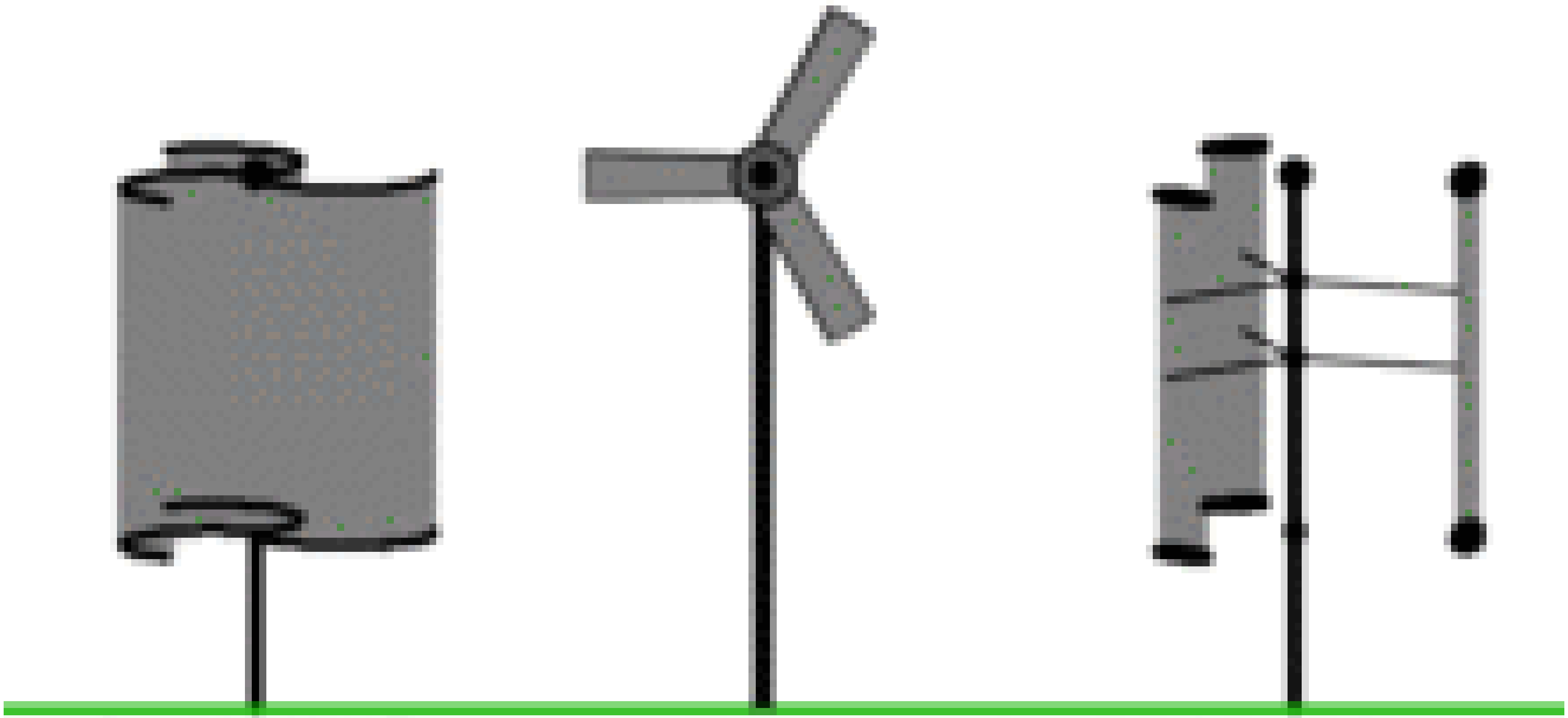

**Wind cost of energy is poised to overtake fossil fuel**

# Steps Wind farm development

Source : AWEA

- Understand Your Wind Resource
- Determine Proximity to Existing Transmission Lines
- Secure Access to Land
- Establish Access To Capital
- Identify Reliable Power Purchaser or Market
- Address Siting and Project Feasibility Considerations
- Understand Wind Energy's Economics
- Obtain Zoning and Permitting Expertise
- Establish Dialogue With Turbine Manufacturers and Project Developers
- Secure Agreement to Meet O&M Needs

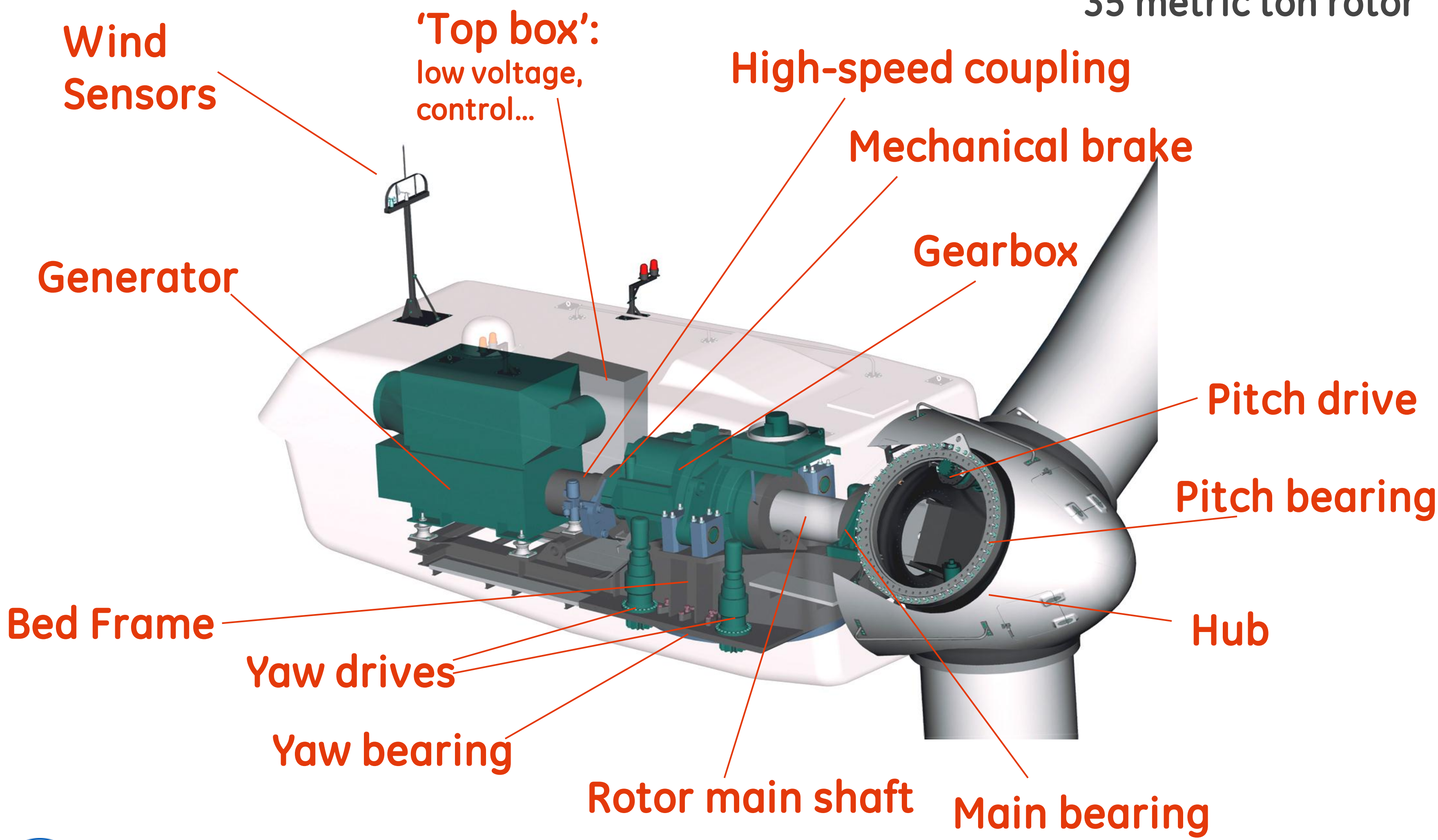
# Wind Turbine Design Concepts



Savonius VAWT    Danish HAWT    Darrieus VAWT

# Components

1.5 wind turbine
52 metric ton nacelle
35 metric ton rotor



# Number of rotors

| | One | Two | Three |
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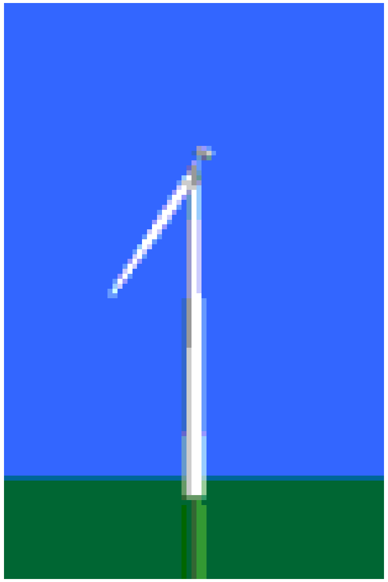
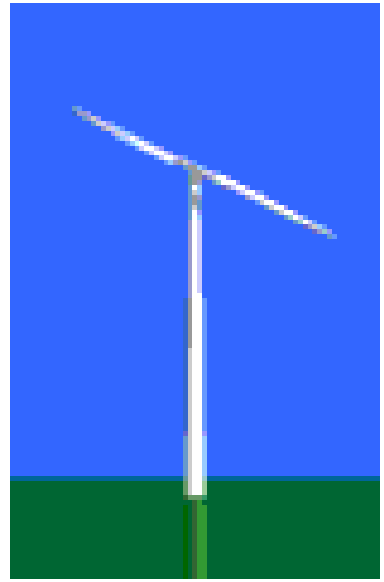
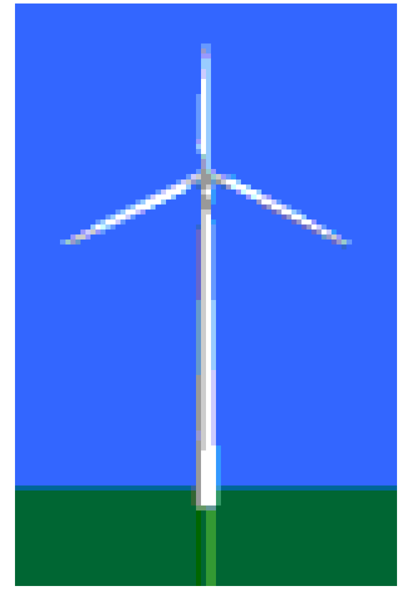
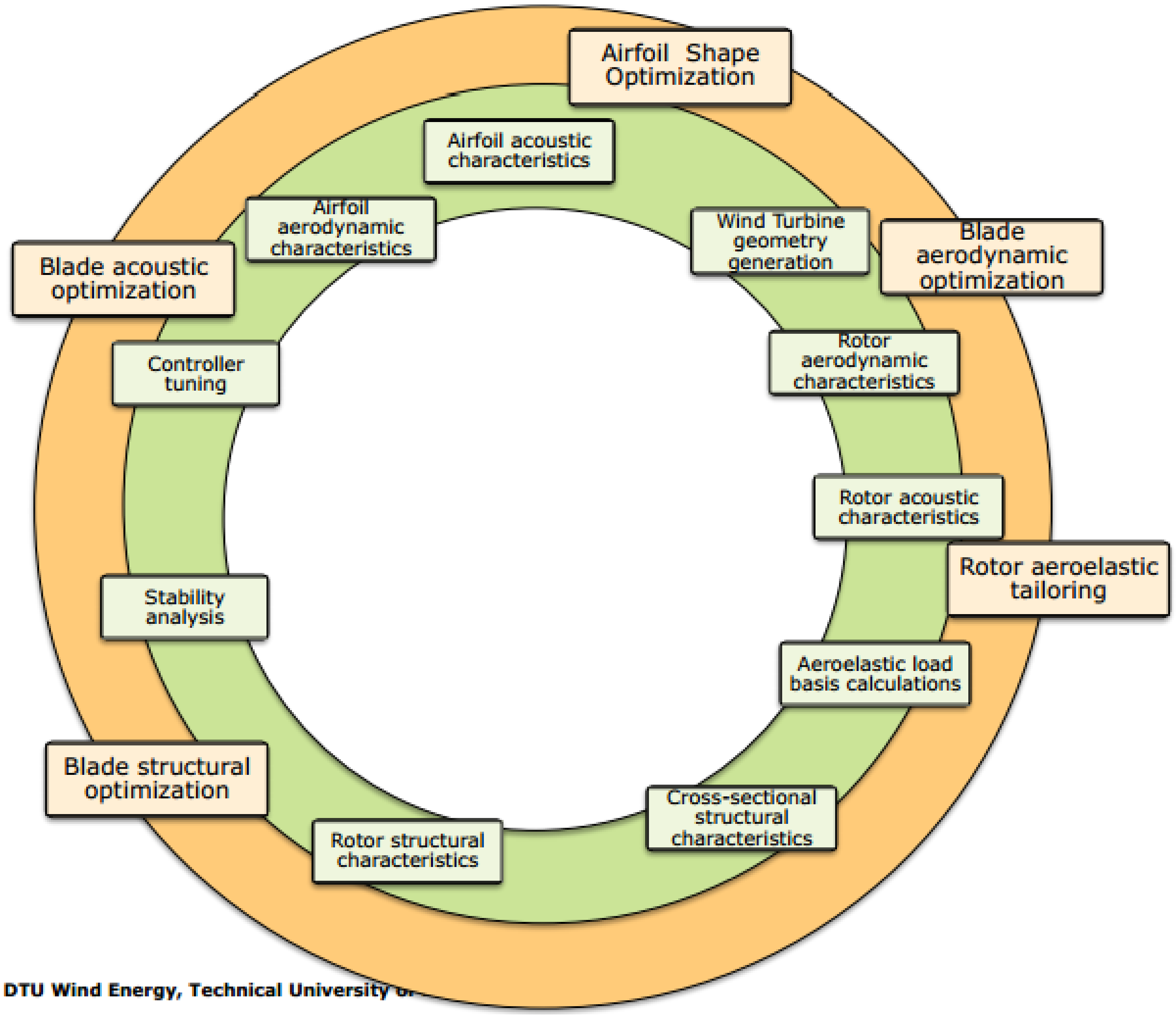
| |  |  |  |
| |  |  | |
| Gearbox | ✓ | | ✗ |
| Efficiency | ✗ | | ✓ |
| Loads | ✗ | | ✓ |

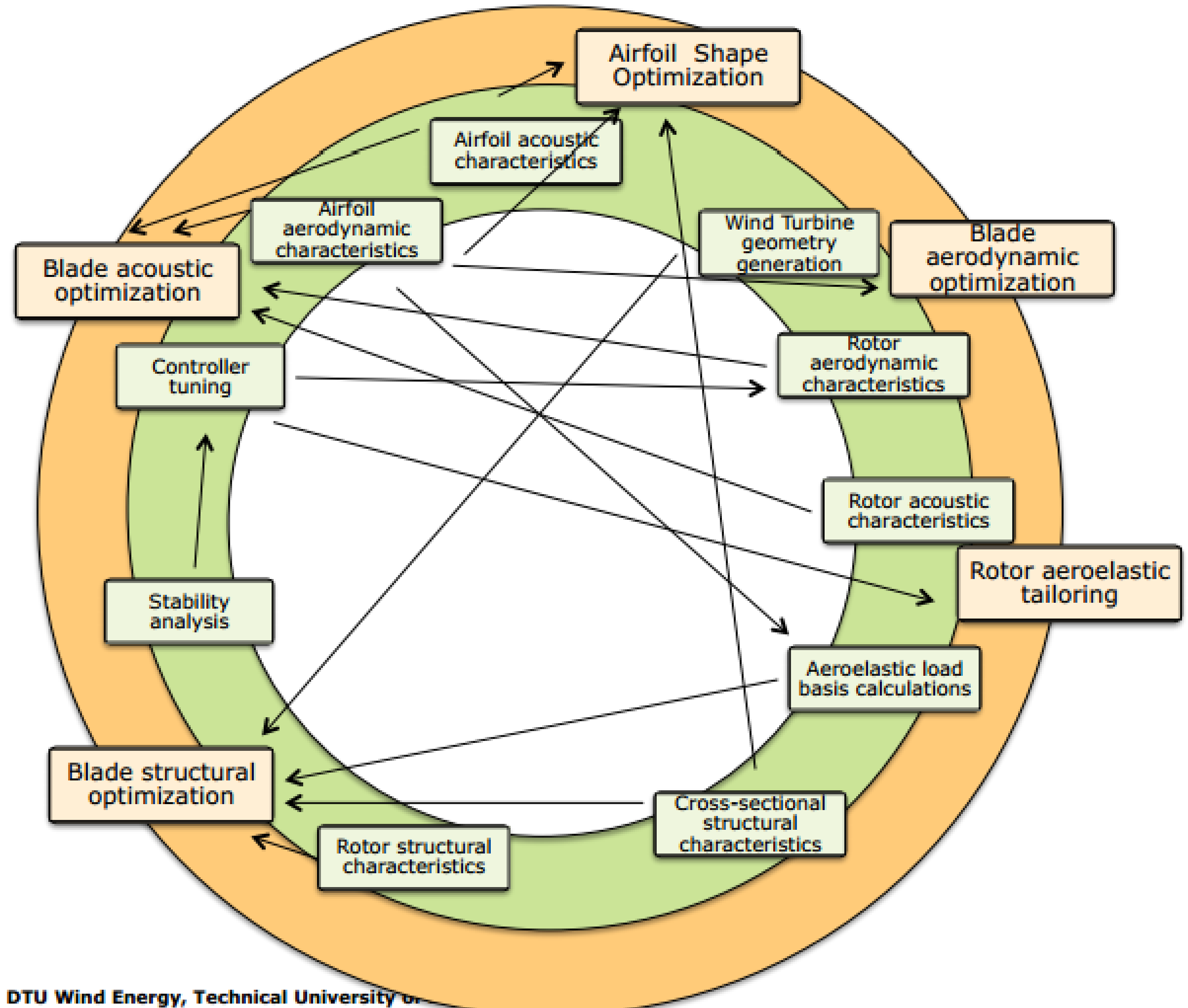
# Wind turbine design

Source: DTU

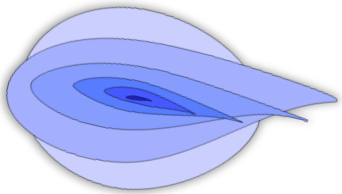


# Wind turbine design

Source: DTU



# Wind turbine Aerodynamics



Airfoil

Blade

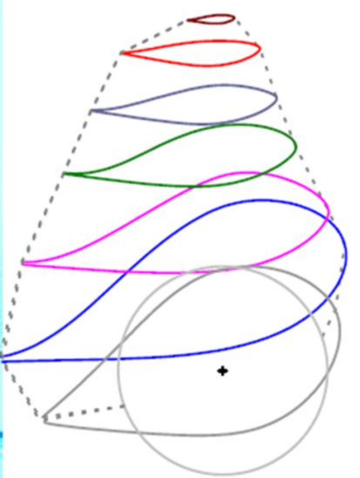
Wind turbine

Wind Farm

# Airfoil design

Source: TUDelft

## Blade geometry



**Structural:**

Outboard: t/= .15-18

Mid span: t/= .25

Inboard: t/> .30

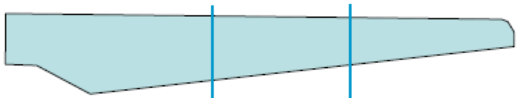
Transition piece

**Airfoil:**

- High max. L/D
- Insensitive to roughness
- Similar design angle
- High max. lift (Rot. Effects)

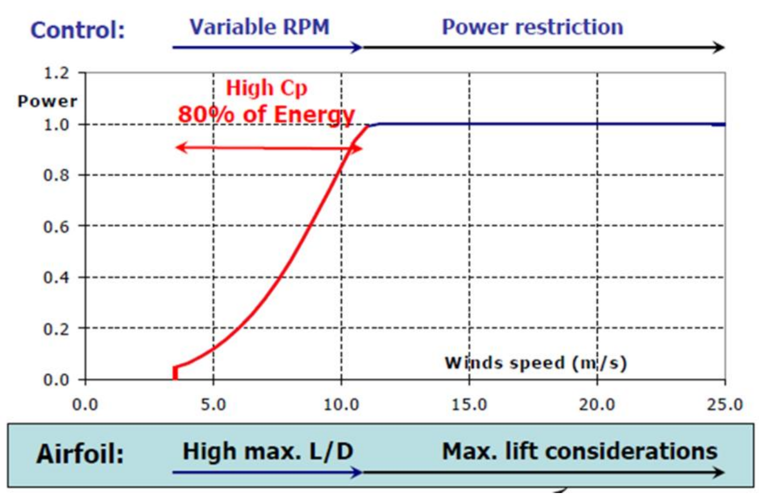
No Aerodynamic demands

## Design goals



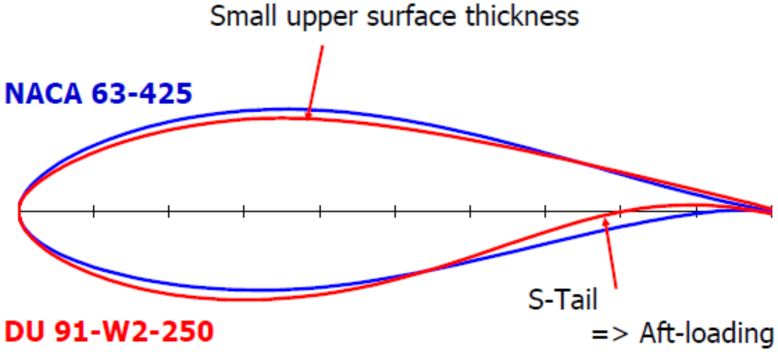
| Thickness-to-chord ratio | > .28 | .28 - .21 | .21 > |
|---|---|---|---|
| High maximum lift-to-drag ratio | ● | ●● | ●●● |
| Low max. and benign post stall | | | ●● |
| Insensitivity to roughness | ● | ●● | ●●● |
| Low noise | | ● | ●●● |
| Geometric compatibility | ●● | ●● | ●● |
| Structural demands | ●●● | ●● | ● |

## Operation

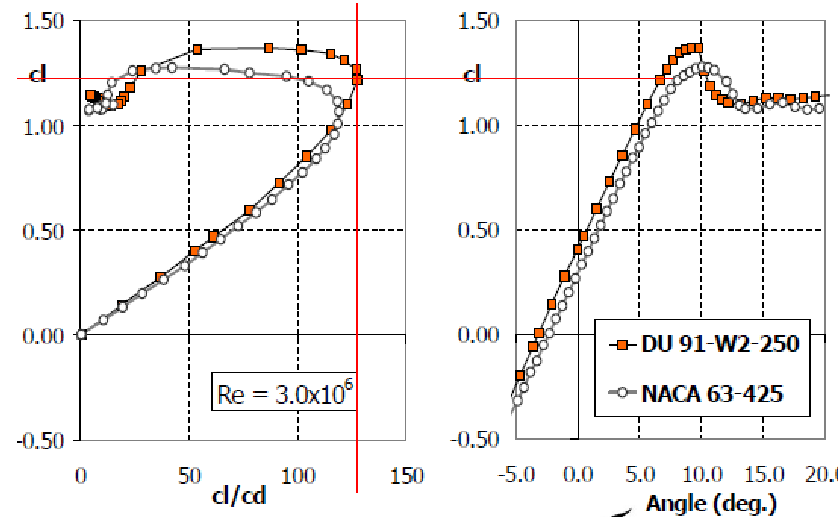


# Airfoil design

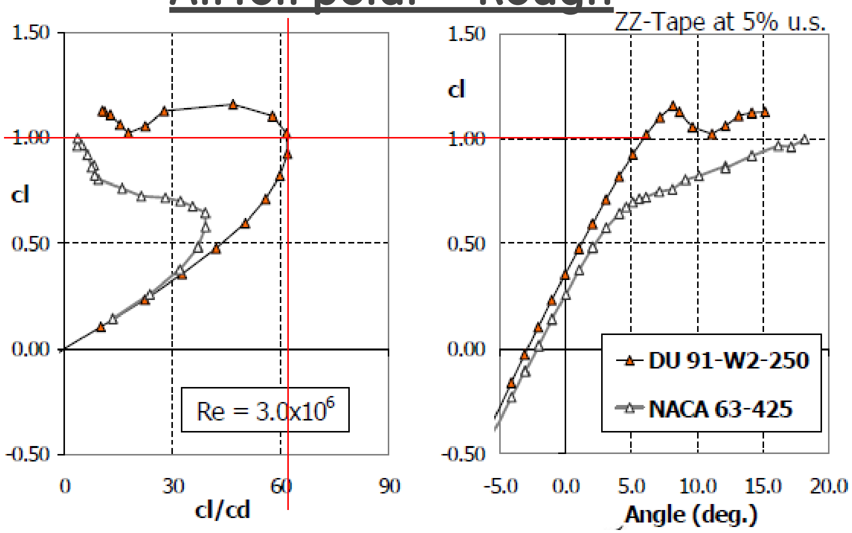
## Wind turbine airfoil



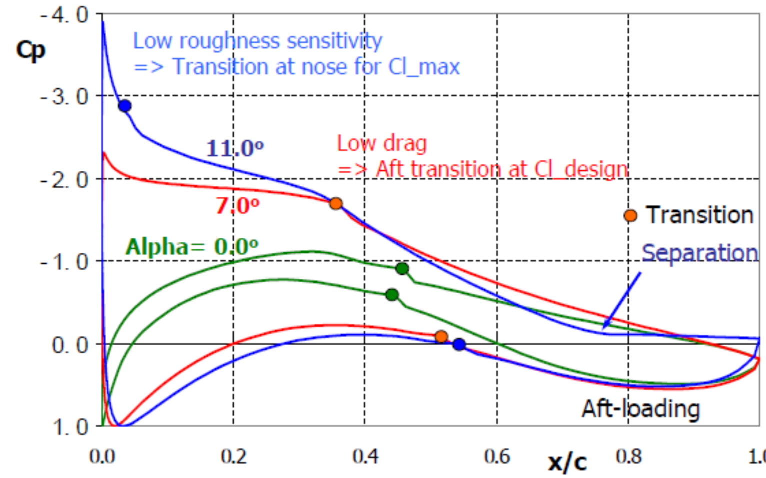

## Airfoil polar - Clean




## Airfoil polar - Rough

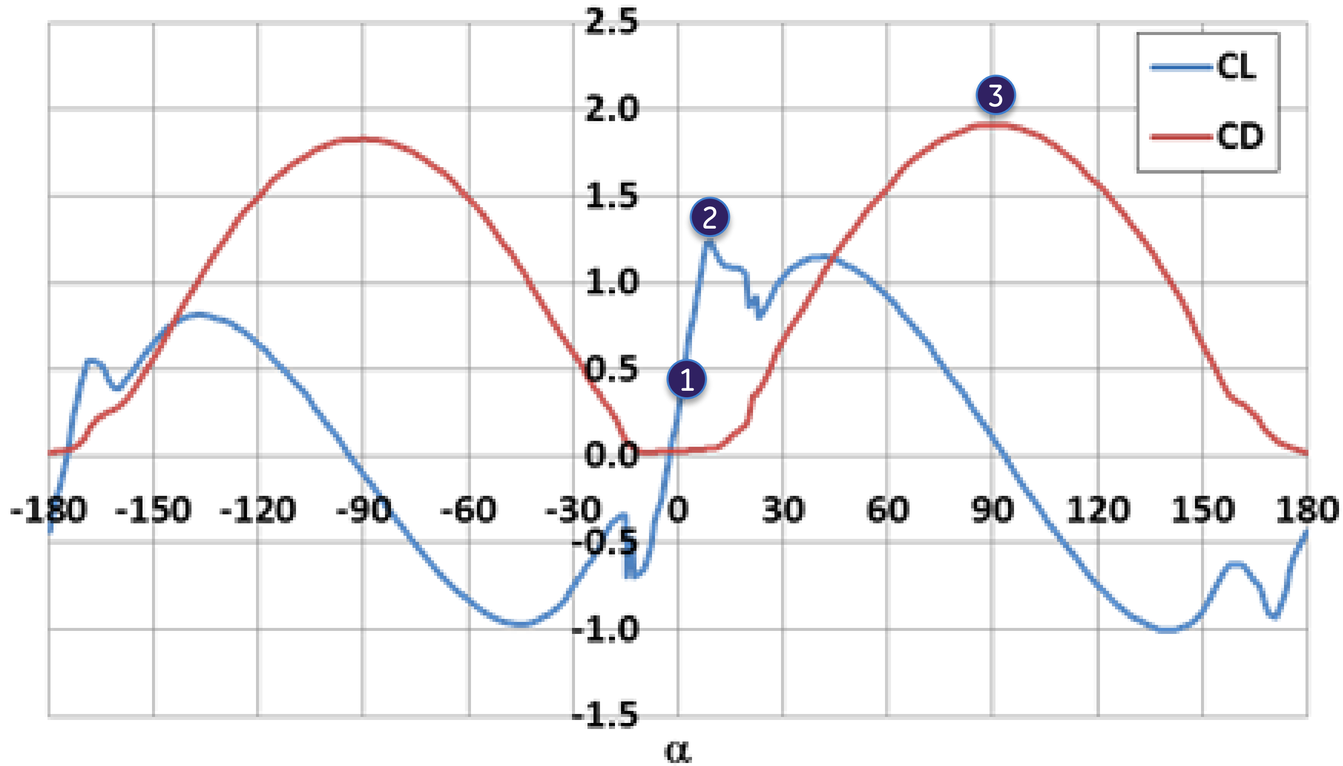



## Pressure distribution




Source: TUDelft

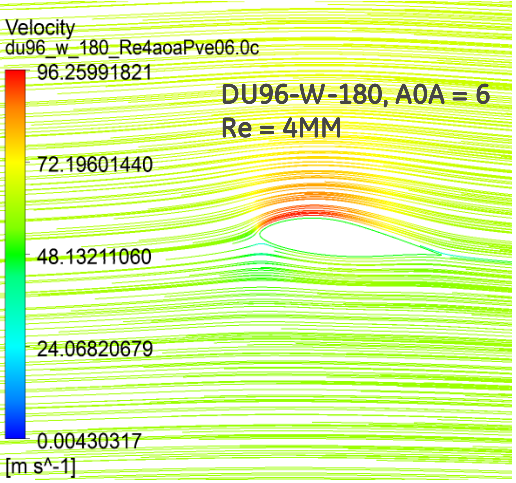
# Airfoil design key parameters




1. Design point (Max lift to drag ratio)
2. Stall point (Max CL)
3. Extreme load point (Max CD)

# Design point

- Max L/D - highest efficiency
- Transition location is critical
- Boundary layer is attached



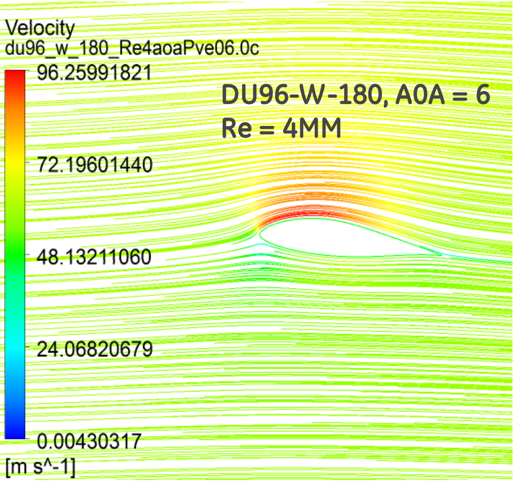

XFOIL

- Panel method - Mark Drela, MIT
- Inviscid - linear-vorticity stream function
- Viscous - Integral BL formulation
- Transition - e^n criteria

| | AOA | CL | CL/CD | X-Tran Suction | X-Tran Pressure |
|---|---|---|---|---|---|
| **Expt** | 5.90 | 1.08 | 150.26 | 38 | 70 |
| **XFOIL** | 6.00 | 1.10 | 153.25 | 40 | 71 |

# Design point

- Max L/D - highest efficiency
- Transition location is critical
- Boundary layer is attached



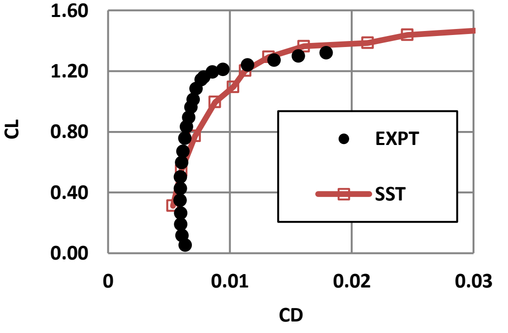

## XFOIL

- Panel method - Mark Drela, MIT
- Inviscid - linear-vorticity stream function
- Viscous - Integral BL formulation
- Transition - e^n criteria

## CFD (K$\omega$ SST)

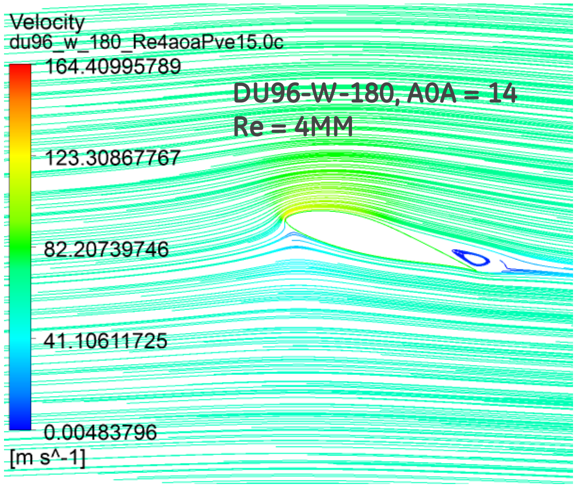
- RANS – 2 eq turbulence model
- K$\omega$ SST (zonal model, limiter on eddy viscosity)
- $\gamma$-Re$_\theta$ transition model

| | AOA | CL | CL/CD | X-Tran Suction | X-Tran Pressure |
|---|---|---|---|---|---|
| **Expt** | 5.90 | 1.08 | 150.26 | 38 | 70 |
| **XFOIL** | 6.00 | 1.10 | 153.25 | 40 | 71 |
| CFD | 6.00 | 1.09 | 115.00 | 39 | 71 |

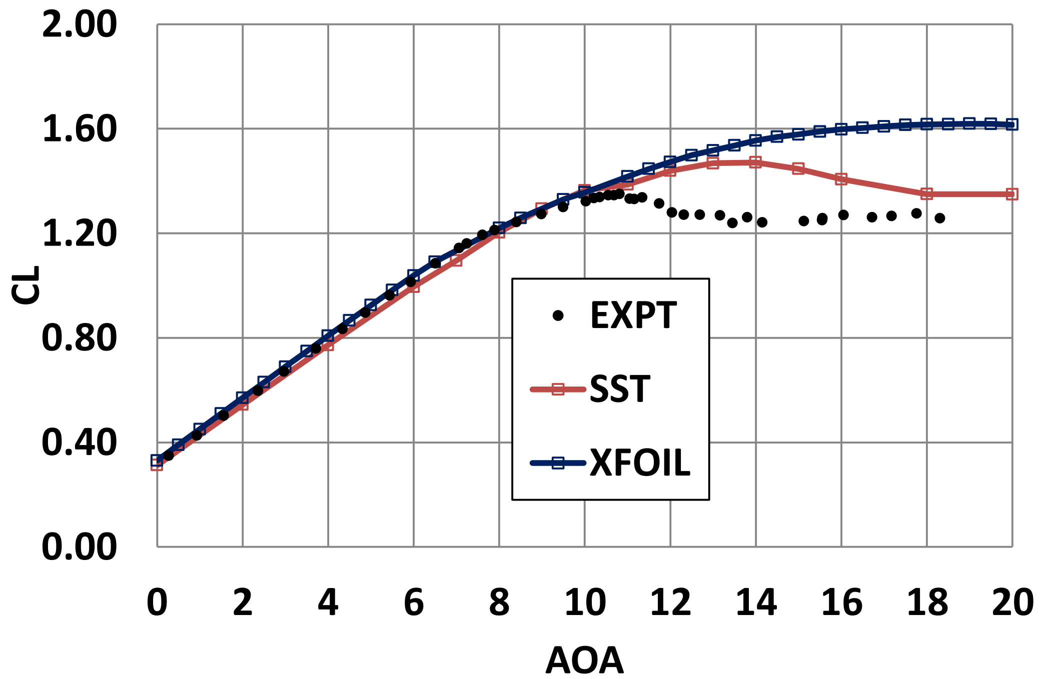


# Stall point

- Max CL  - high loads
- Boundary layer is partially separated

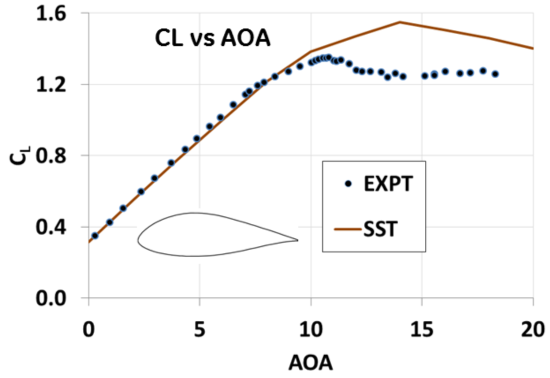


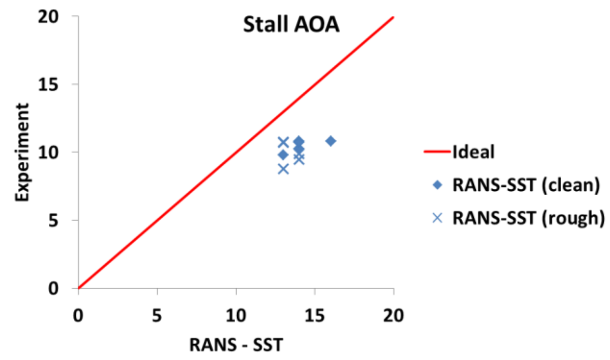

Comparison with XFOIL & CFD

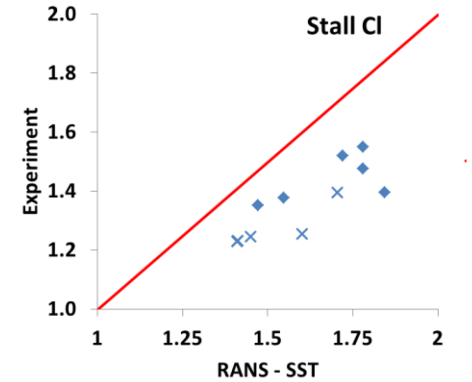


# Delayed stall prediction

- Best practice **K-ωSST** predicts a delayed flow separation and stall



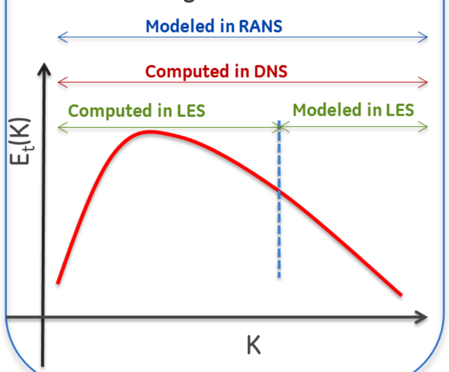




- Limitation of RANS models

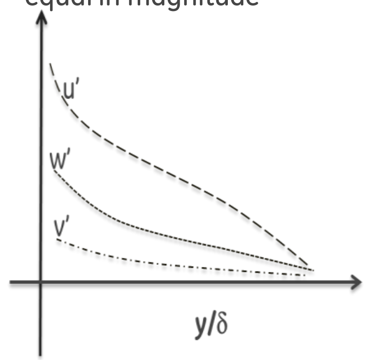
## Spectral Gap

- Overlap of turbulent length scales with energy containing scales



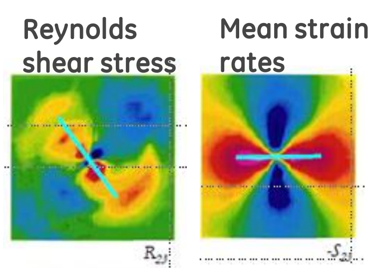

## Anisotropy

- Turbulent velocity components assumed to be equal in magnitude




## Stress – Strain lag

- Stress and strain are directly proportional
- Wind tip vortex flow by Jim chow

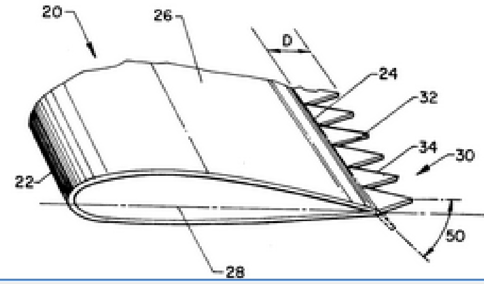


# Next gen airfoils

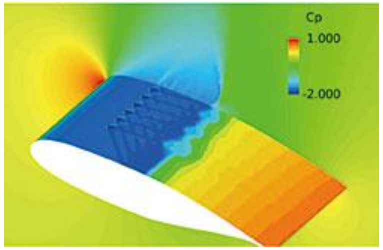
## Add-Ons

- Serrations (noise)
- Vortex generators (flow separation)

- 2 dB



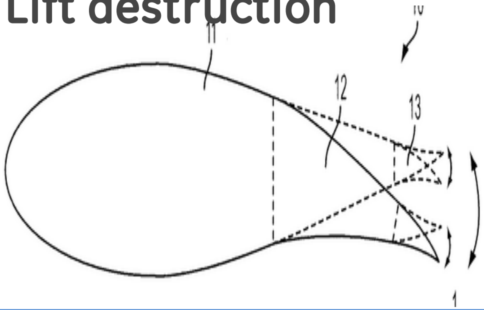

+0.5% Cp



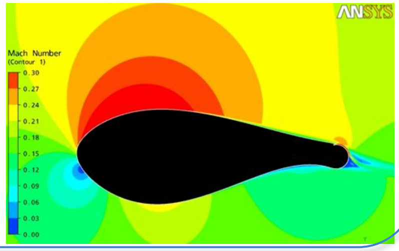

## Flow control

- Flexible trailing edge
- Circulation control

Lift destruction



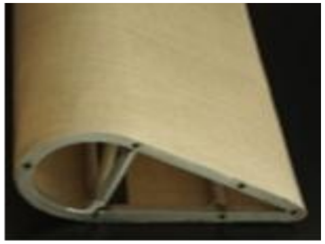

Lift Augmentation




## New architecture

- Flexible airfoils
- Sail wing

Low cost



Low loads

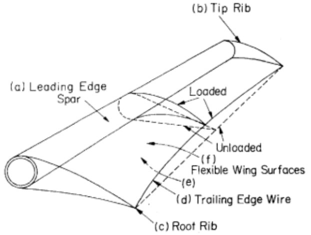
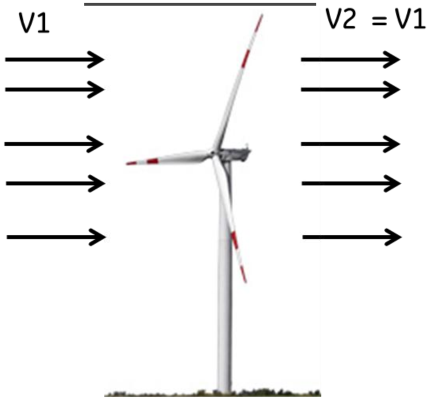



Fig. 1 Concept of sailwing with curved leading edge and thickness.

# Betz Limit

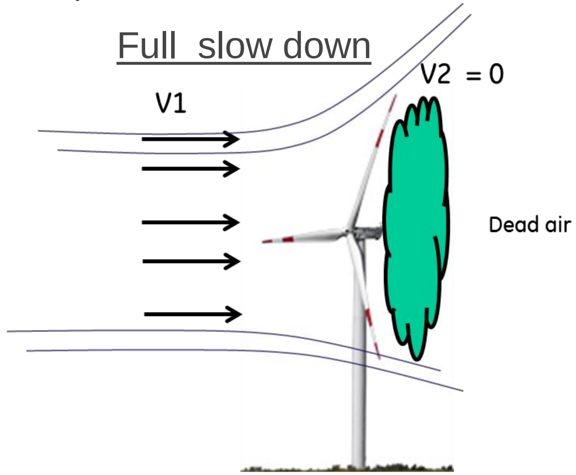
- Wind turbine extracts power by slowing down incoming wind
- Betz limit is the measure of optimal slow down

No slow down



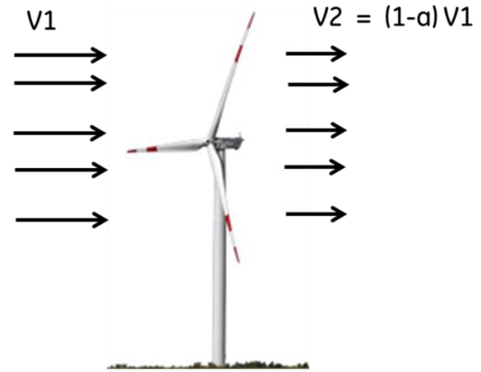

No slow down: no energy is extracted

Full slow down




Turbine becomes a big bluff body: no air passes through the blades

Optimal slow down




a = axial induction ant its value is 1/3 for maximized energy extraction

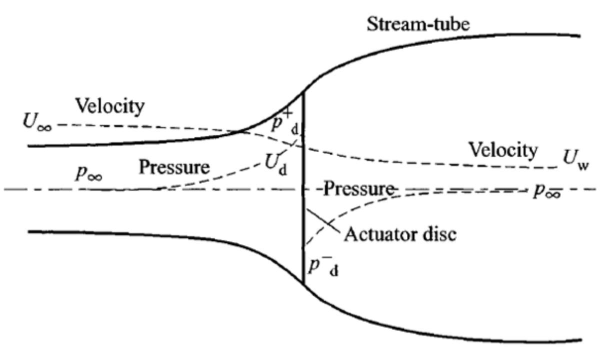


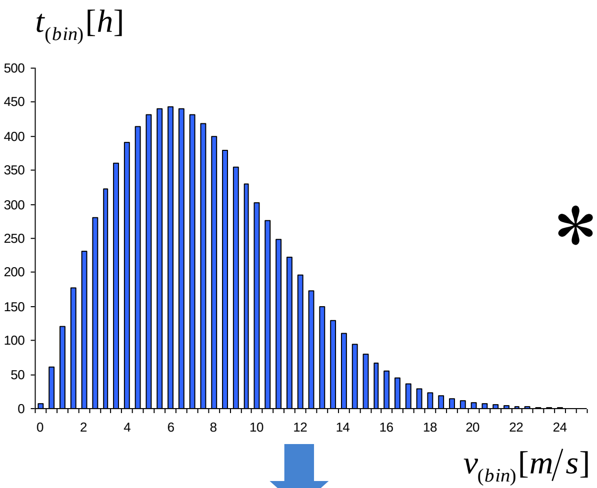

**Figure 3.2** An Energy Extracting Actuator Disc and Stream-tube

$$C_P = \frac{\text{Power}}{\frac{1}{2}\rho U_\infty^3 A_d}$$

$$C_P = 4a(1-a)^2$$

**Betz Limit - 59.3%**

# Annual Energy Yield (AEP)

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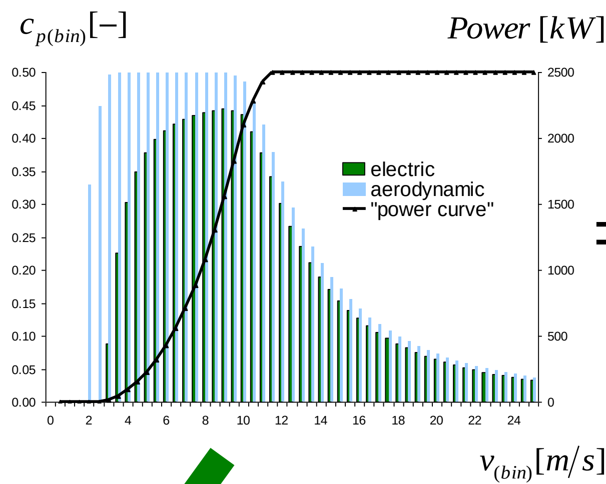
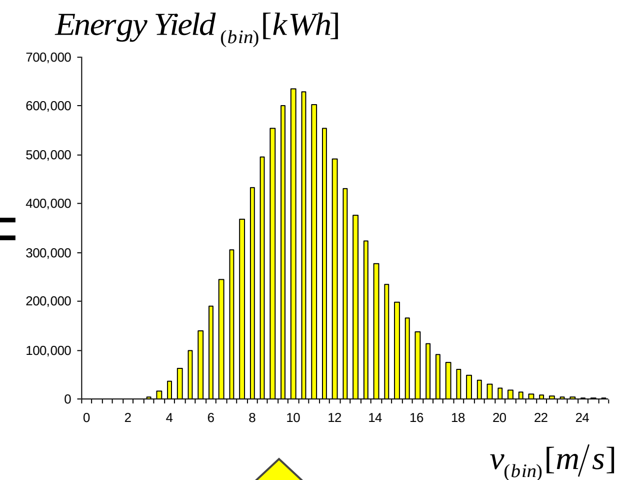


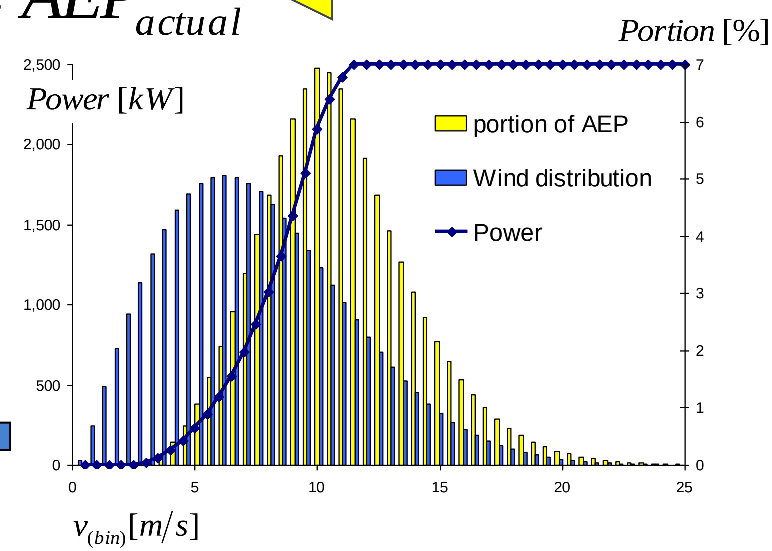

$=$




$$\sum_{Weibull} \overbrace{t_{(bin)} \cdot v_{(bin)}^{3}} \cdot \frac{1}{2} \cdot \rho \cdot c_{p\ elec.(bin)} \cdot \pi \cdot R^{2} = AEP_{actual}$$

AEP increase strategies:

- (higher) Wind distribution
- **Rotor growth (increase swept area)**
- **(turbine) efficiency increase**
- Biggest portion of AEP generated near knee of the power curve: 33% for 2 m/s wind speeds before rated



# Blade aero design

Conceptual design → ← Detailed design → Prototype test

$ — $$$ — $$$$$

**Inputs**
- Blade radius
- Power

↓

**Airfoil selection**
- Efficiency
- Stall
- Roughness

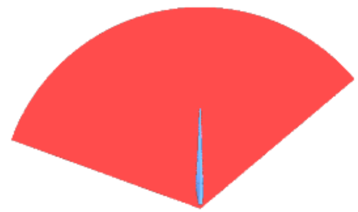
↕

**Blade design**
- Chord
- Twist
- Thickness

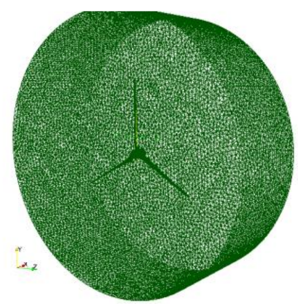
↓

**Geo smoothing**

**Design point**



**Off - design**




**Objectives**
- Maximize Cp
- Minimize noise

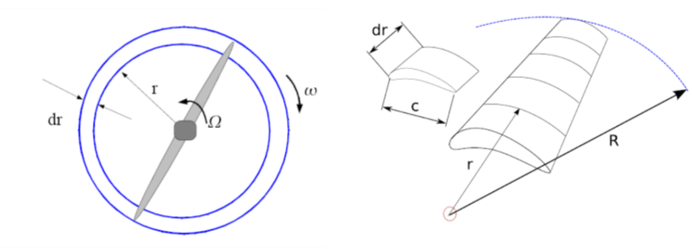
**Constraints**
- Max chord
- Thickness and twist rate

# Conceptual design - Blade

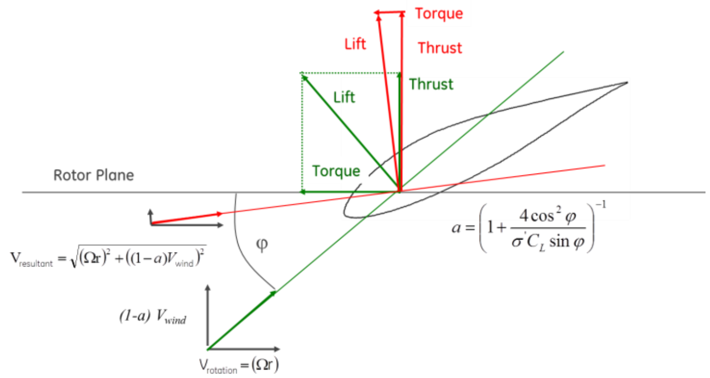
## Blade element momentum theory

- Blade element + momentum theory applied to a rotor disk
- Propeller ⟶ Helicopter ⟶ wind turbines
- Each annular ring is independent
- Does not account for wake expansion
- Applicable only to straight blades
- Fails at high blade loading and off design conditions
- Requires separate tip and root loss model

### Actuator disk model




### Forces acting on a blade element



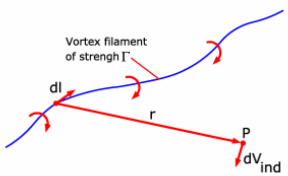

### 3 D Blades

**A powerful design tool**

# Conceptual design - Blade

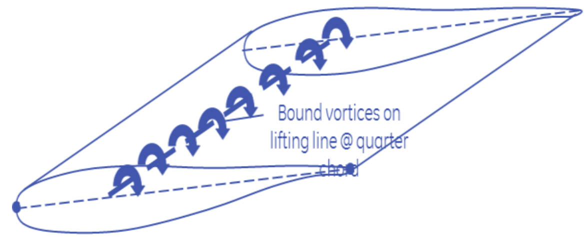
## Vortex lifting line model

- Blade modeled as a set of lifting lines
- Vorticity shed from the trailing edge is modeled as vortex filaments
- Induced velocities on blade and wake is computed using Biot-savart law

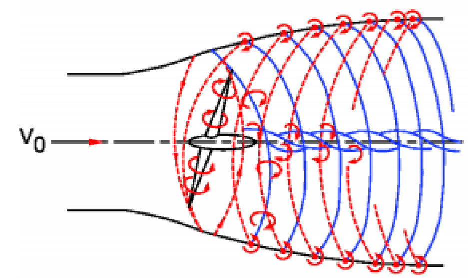


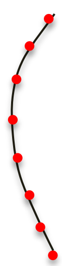

$$\mathbf{V}_{ind} = \frac{\Gamma}{4\pi}\frac{(r_1+r_2)(\mathbf{r}_1\times\mathbf{r}_2)}{r_1 r_2+\mathbf{r}_1\cdot\mathbf{r}_2}$$

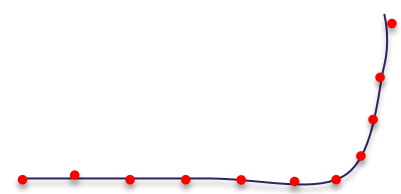
### Blade representation




### Wake representation

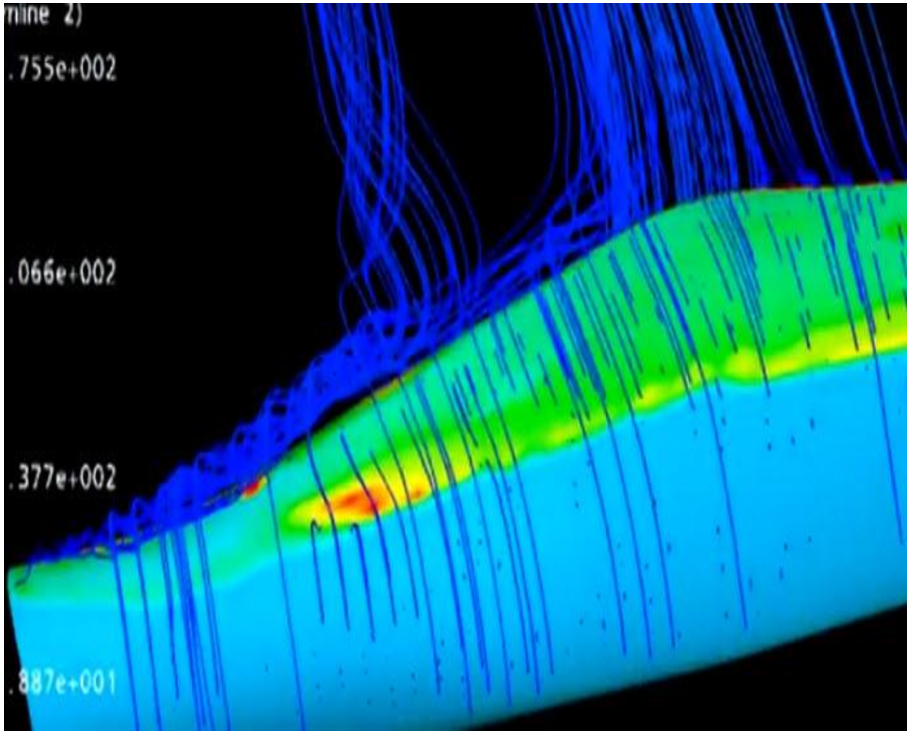




# Detailed design - CFD

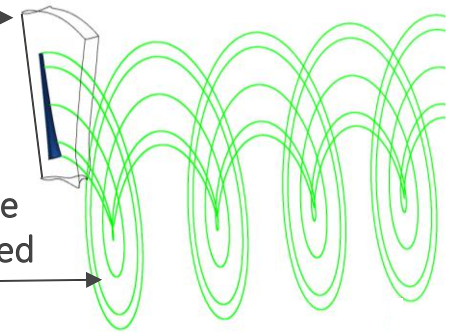
- A powerful tool to understand detailed flow structure
- RANS - Kω SST
- ~ 6 million cells for a single blade analysis
- Rotational effects
- Flow separation prediction ?
- Modelling transition – exorbitantly expensive
- Highly dissipative – smeared wake



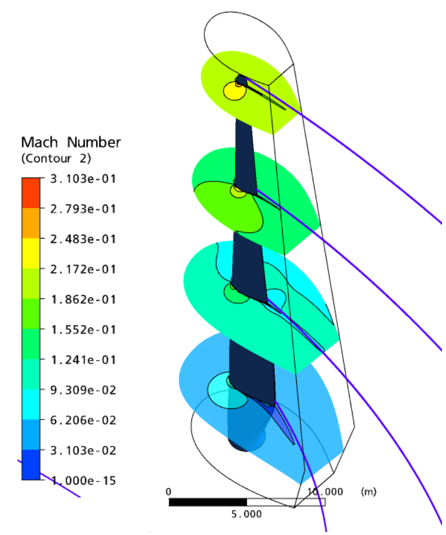
# Detailed design – Hybrid CFD

- Elegant combination of near wall Navier-Stokes and helicoidal vortex method
- Preservers wake structures
- Improved computational efficiency (1/8)
- Flow transition
- Unsteady, multi-blade analysis

Small Navier-Stokes domain



Modeled wake shape (function of computed circulation from NS domain)

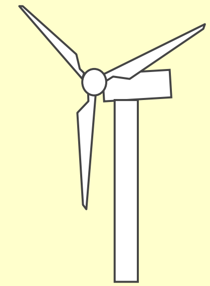


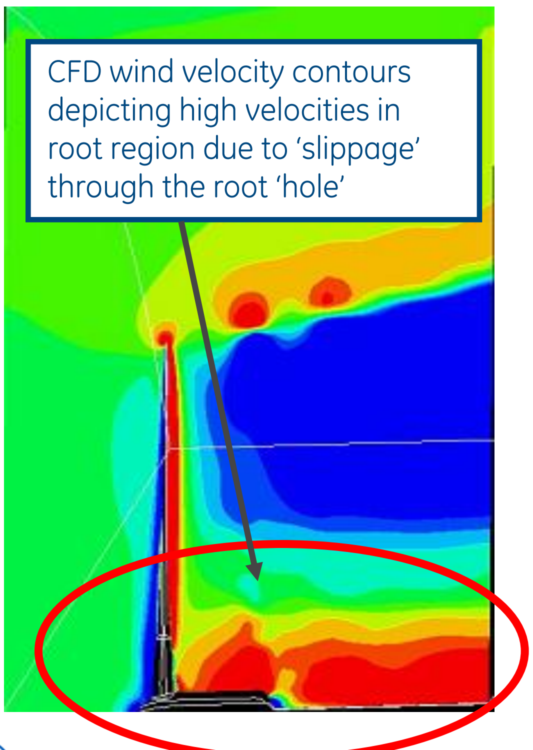

Source: UC Davis

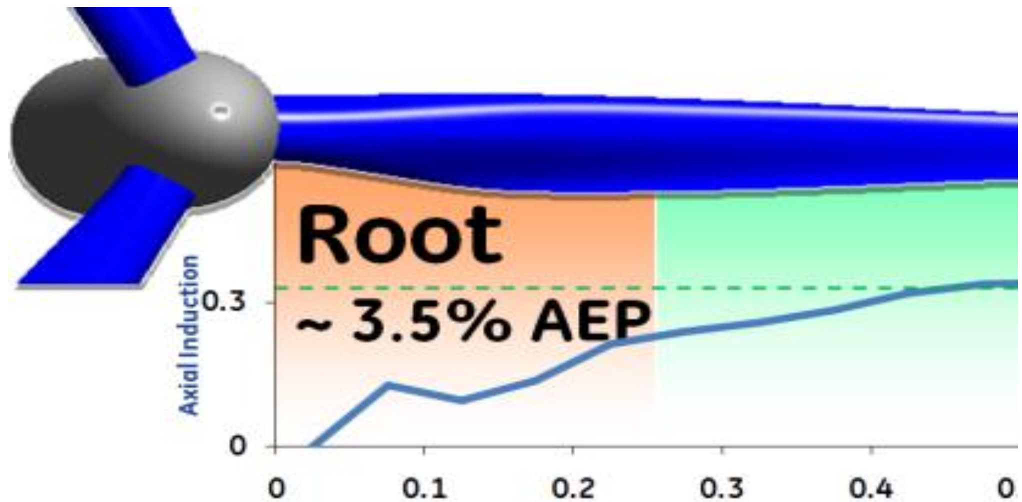
# Improving Blade Performance

## Aero Related Energy Losses for Wind Turbines

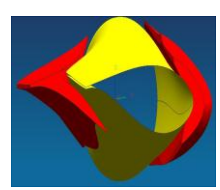
- Tip Loss : Entitlement ~1.5% AEP
- Main Blade Loss : Entitlement ~1.5% AEP
- Root Loss : Entitlement ~3.5% AEP *)
- Operation Loss : Entitlement ~2.0% AEP



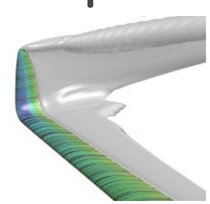


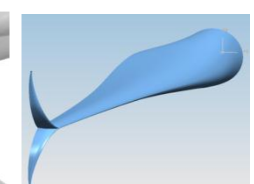




**Root enhancement**



**Tip enhancement**





# Industry trends

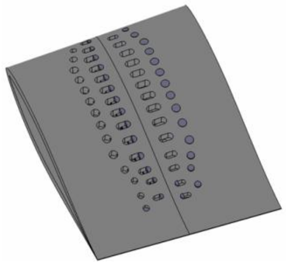
## Carbon

- Enhanced stiffness while managing weight
- ~32% mass reduction, 15% reduction in tip deflection
- Costly (10X time glass fibers)



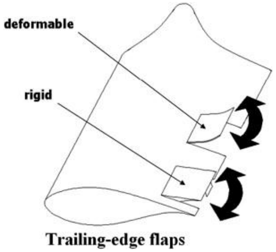
## Segmented blade

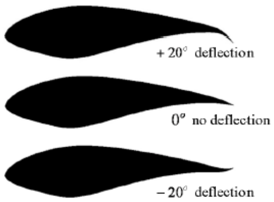
- Potential benefit in transportation & erection cost
- 9% increase in blade mass



## Active devices

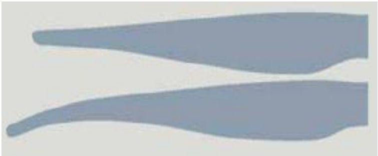
- Morphing trailing edge
- 2% rotor growth – loads neutral
- Controlled with compressed air or piezo electrics

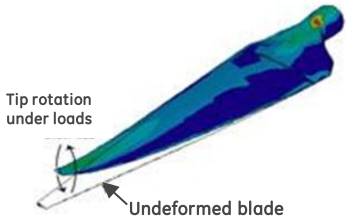


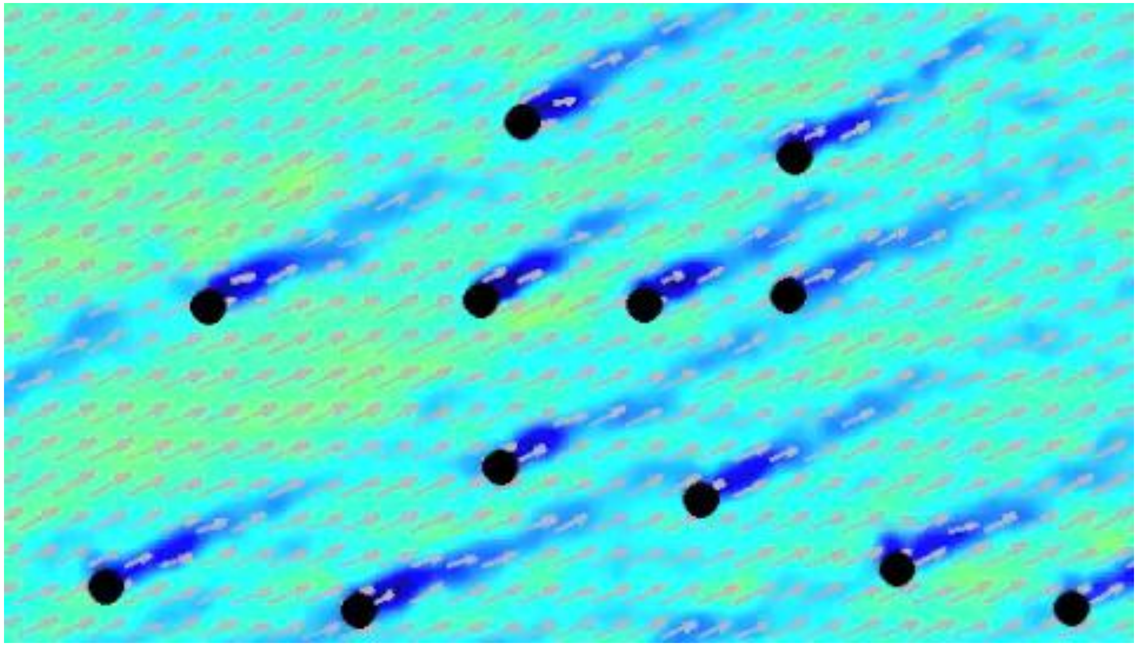

## Passive – Material tailoring

- Bend- Twist coupling
- 53m vs 49m Blade – less 500kg/5% more AEP
- Exploring natural fibers



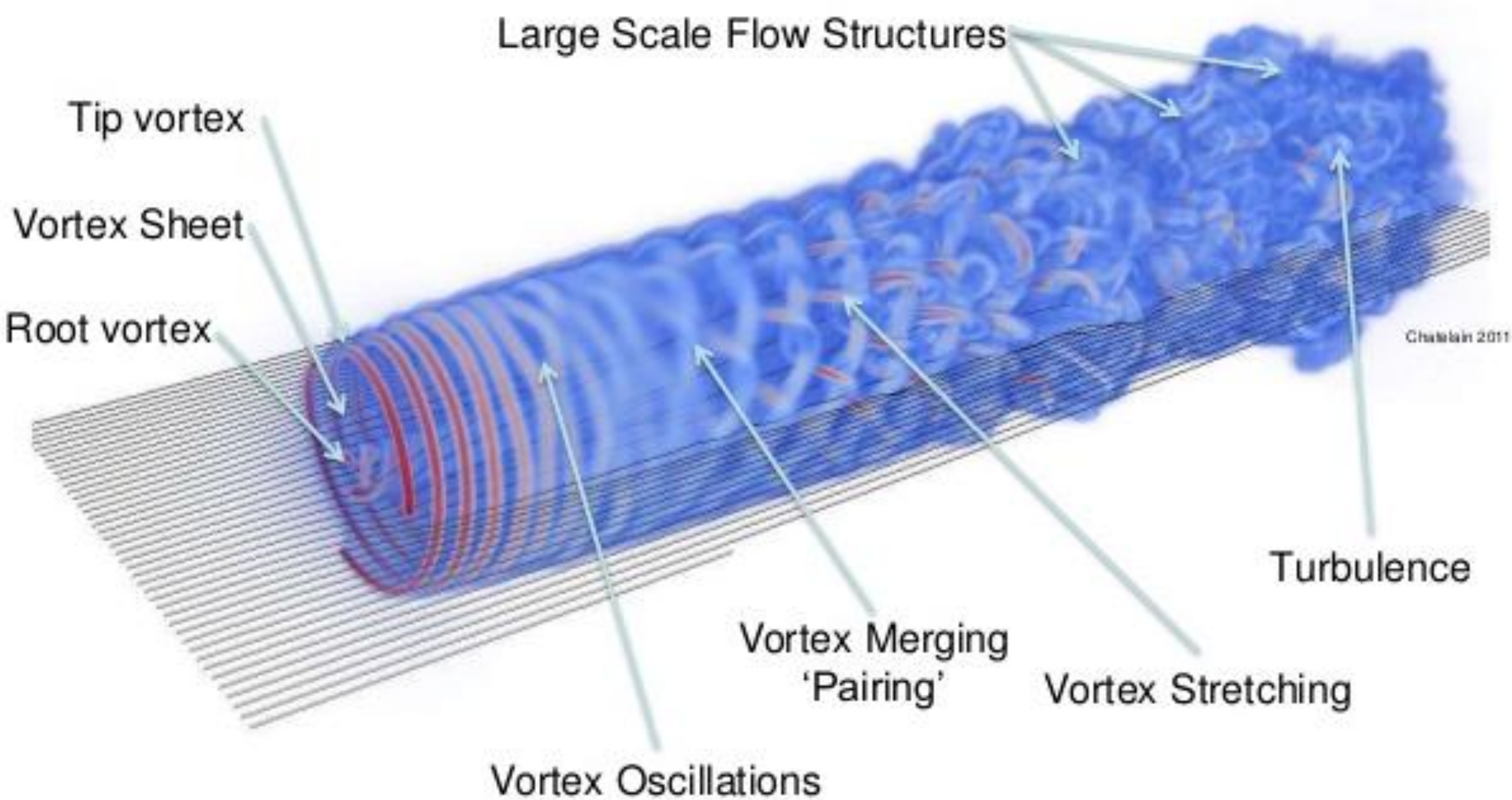


# Wind farm as a product



- Wakes behind the rotor cause losses
- Coordinated control reduce these losses
- Around 1-2% of farm AEP is gained

# Wake structure



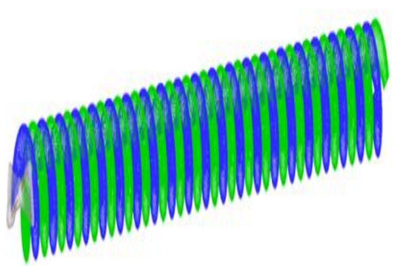

Source : SNL

# Wake modeling

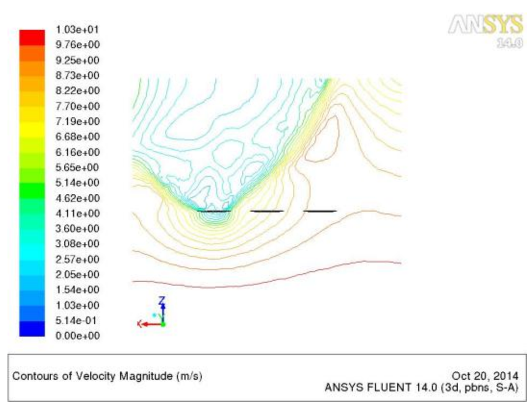
## objectives

- Predict the wake strength and behavior
  (stability, shear, veer & turbulence intensity)
- Determine sensitivity of wake development to rotor loading
- Micro siting
- Quantify effect of ambient flow conditions and terrain

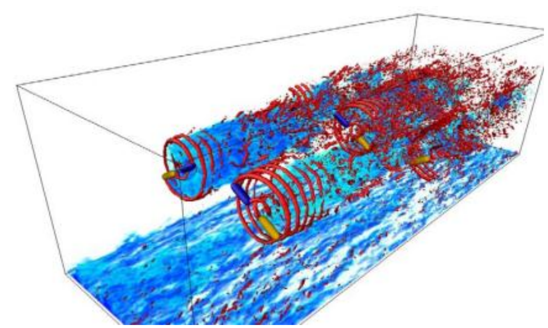
BEM + Free vortex



RANS + Actuator disk




LES + Actuator line



# Summary

- Wind turbine aerodynamics - maximize power output
- Airfoils – high L/D – Stall prediction
- Blade – Maximize Cp – computational efficiency
- Wake – understand, minimize & optimize
- Big data

# Thank you