GCEP Energy Tutorial Wind 101

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Imagination at work.

Agenda

- Introduction & fundamentals
- Wind resource
- Aerodynamics & performance
- Design loads & controls
- Scaling
- Farm Considerations
- Technology Differentiators
- Economics
- Technology Development Areas

Power from Wind Turbines

Power in Wind

$$P_{wind} = \frac{1}{2}\rho v^3 Area$$

Extractable Power from Wind turbine

$$P_{wind} = \frac{1}{2} C_p \rho v^3 Area$$

v = wind speed
Importance of site identification (local wind resource) & understanding of wind shear

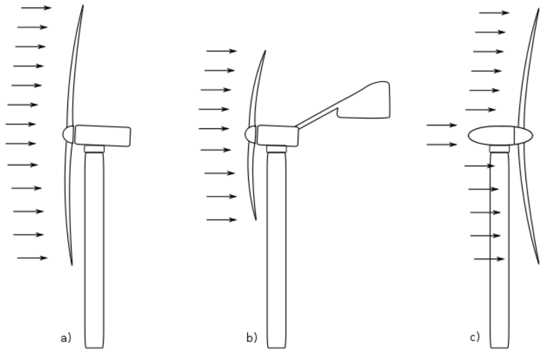
Area = rotor swept area
Power increases with rotor^2

C_p = power coefficient
a measure of aerodynamic efficiency of extracting energy from the wind

Configurations

Horizontal-Axis (HAWT)

Upwind vs. Downwind



Source: http://en.wikipedia.org/wiki/File:Wind.turbine.yaw.system.configurations.svg
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Number of Blades

Source:
http://en.wikipedia.org/wiki/File:Water_Pumping_Windmill.jpg
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Vertical-Axis (VAWT)

Lift Based (Darrieus) vs. Drag-Based (Savonius)

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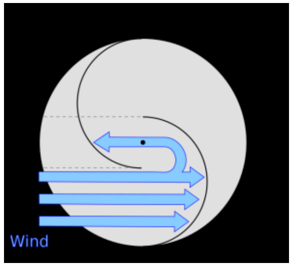

Source: http://en.wikipedia.org/wiki/File:Savonius-rotor_en.svg
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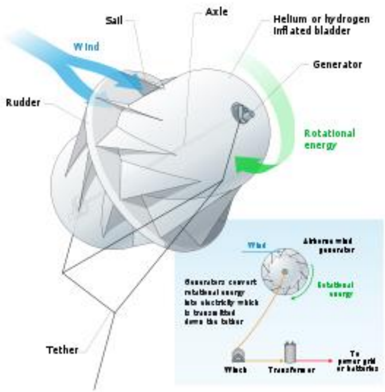
Airborne Wind Turbine



Source: http://en.wikipedia.org/wiki/File:Airborne_wind_generator-en.svg
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Utility-Scale Turbine Types

Convergence of industry

- Horizontal axis
- Upwind
- 3 blades
- Variable rotor speed
- Active (independent) pitch

Main differentiators

- Direct drive vs. gearbox
- Generator design
- Full vs. Partial Power Conversion
- Controls

Basic Wind Turbine Terminology

Term	Typical Value*	Definition
Rated Power	1.6MW	Max nominal power output
Diameter	100m	Rotor diameter
Capacity Factor	48%	$\frac{\text{Annual Energy Production (kWh)}}{\text{Rated Power (kW)} \times 24 \times 365}$
Avg wind speed	7.5m/s	Annual average wind speed at hub height
Turbulence Intensity	16%	σ_u / U_{avg} @ U_{avg} = 15 m/s
IEC class	II	U_{avg} = 8.5 m/s @ hub height 50-yr, 10-min extreme wind = 42.5 m/s 50-yr, 3-sec extreme gust = 59.5 m/s Turbulence = 18% (IEC = International Electrotechnical Commission)
Design life	20 years	Calculated Life according IEC 61400 and DP's

*values can vary significantly with turbine & site

Utility Scale Wind Uniqueness

Massive Structural ***Size***

<u>Rotor</u>
40 to 70 tons
77 to 120m diameter

<u>Nacelle</u>
57 to 82 tons

<u>Tower</u>
132 to 1200 tons
60m to 139m hub height

Substantial Heights

Hoover Tower (87m)

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Statue of Liberty (91m)

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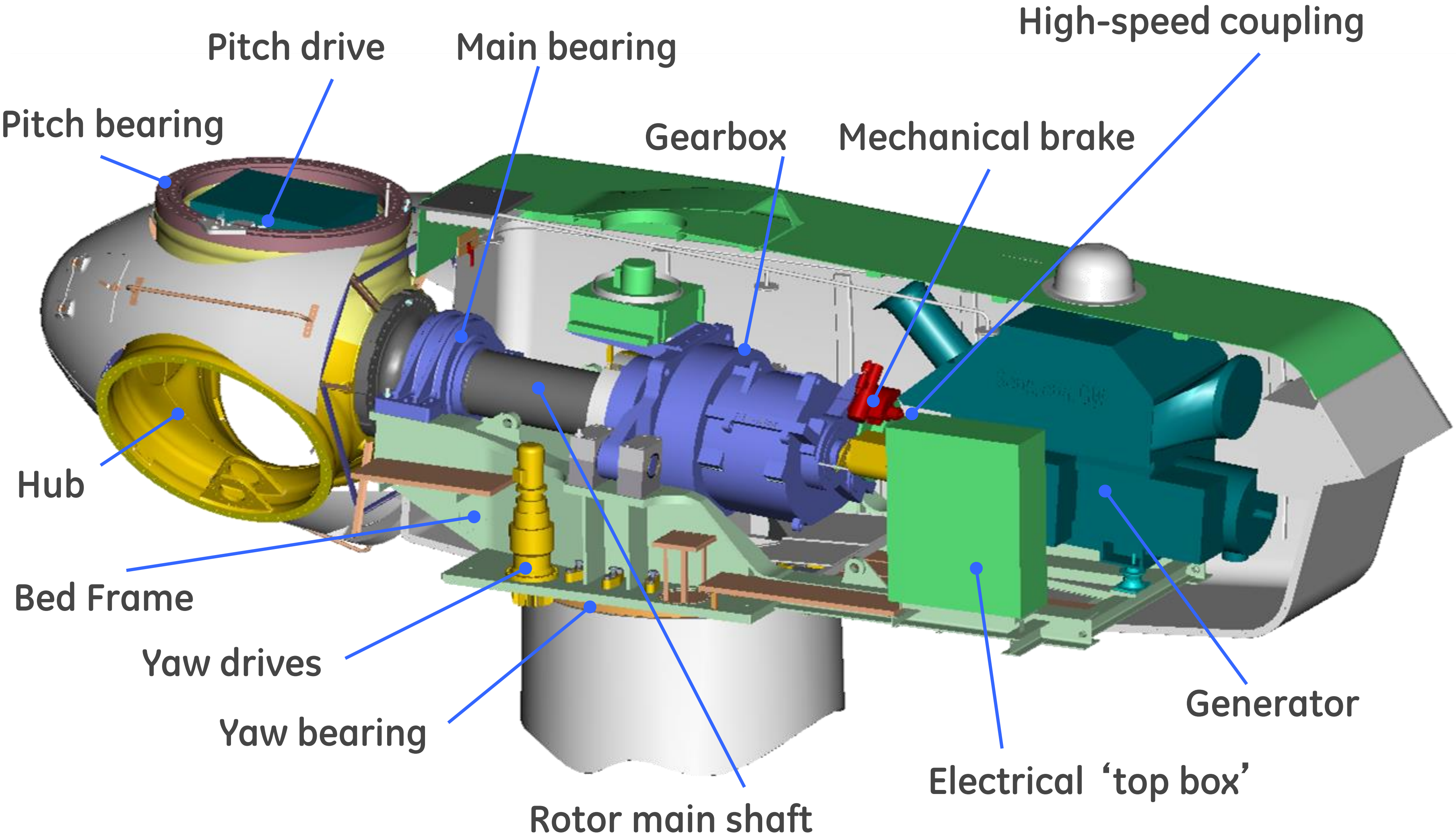
… but Values Low Cost Design … ***Simplicity***

Conventional Layout



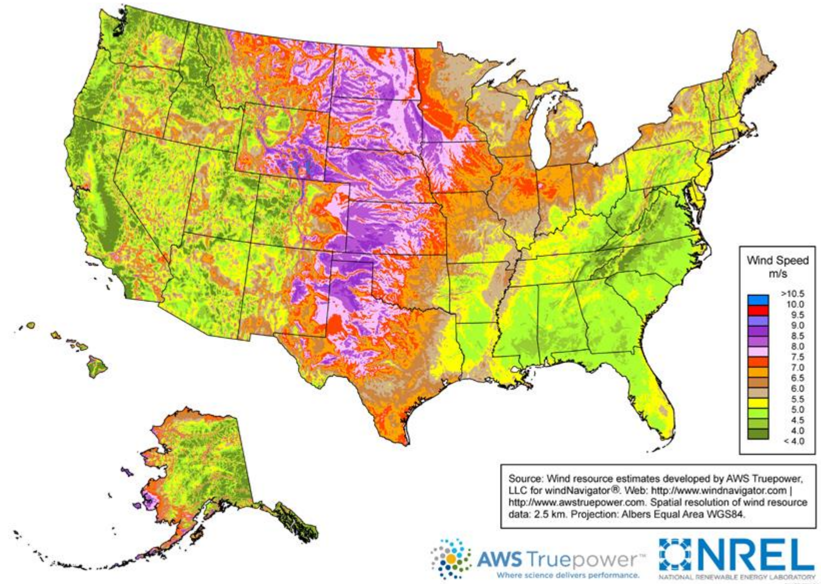
Wind Resource

The Wind Resource is the #1 Driver of Wind Economics

The most productive wind sites:

- have high average wind speeds
- are generally somewhat remote from population centers
- integration with utility grid is generally challenging

Average Wind Speed Map



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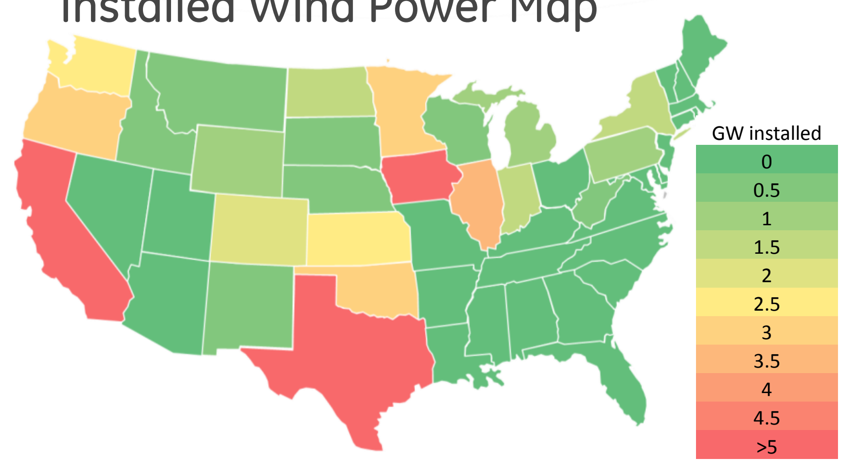
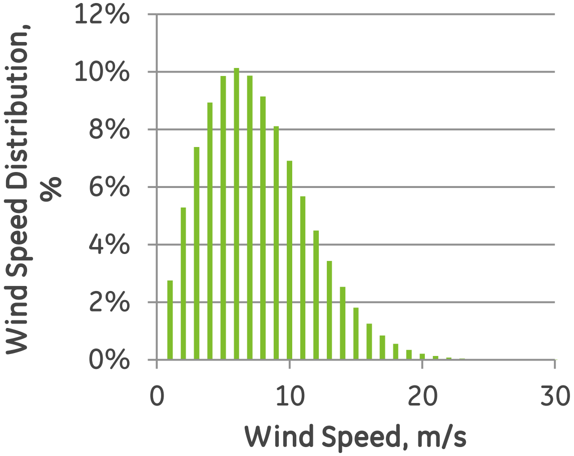
Installed Wind Power Map

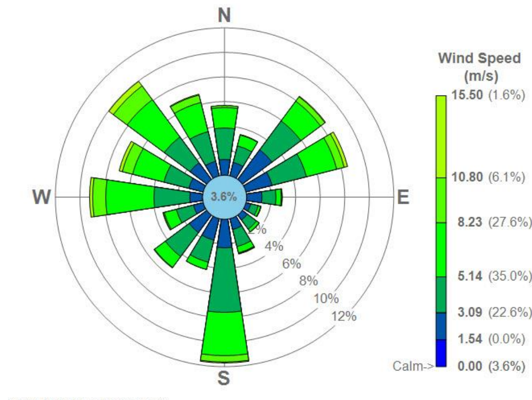


Wind Characteristics

Wind Speed Distribution



Wind direction distribution



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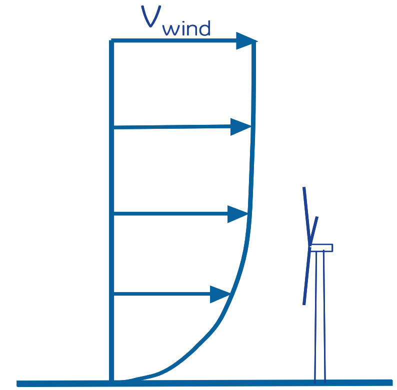
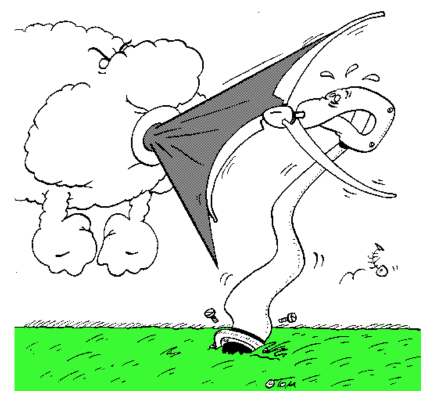
Wind shear



Extreme winds

1-yr & 50-yr extreme gusts



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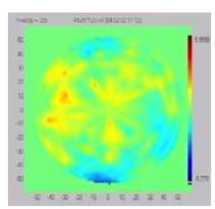
Turbulence intensity

$TI = \sigma / \mu$

σ : std. dev.

μ : average



IEC Class A: 18% at 15 m/s

IEC Class B: 16% at 15 m/s

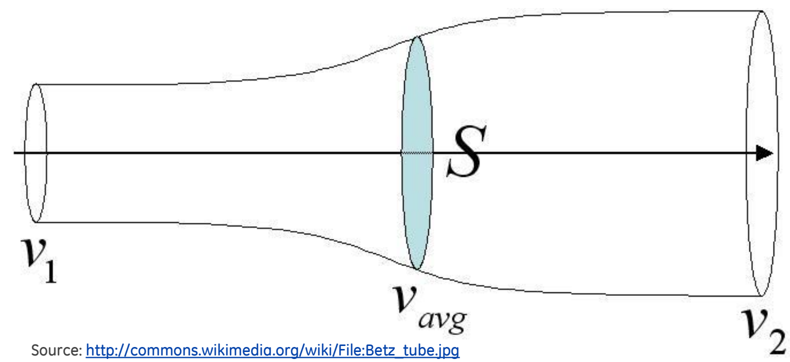
Voice of Physics – Actuator Disk Theory

Model

- Rotor is a permeable disc
- Velocity reduction is equally distributed before/after the rotor and $V_2 = (1-2a)\cdot V_1$
  a: Axial Induction factor for slow down
- Power: Change in momentum caused by pressure difference across disk

$$P = \dot{m}\cdot\Delta p_d = \tfrac{1}{2}\rho V_1^3 A_d \left\{4a(1-a)^2\right\}$$

→ **for V_2=0: only load, no power**



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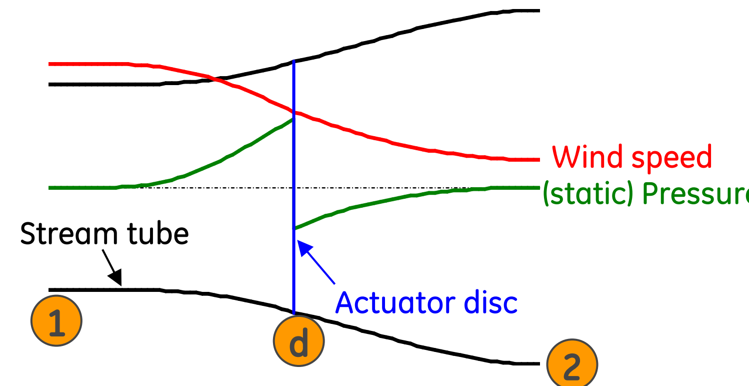
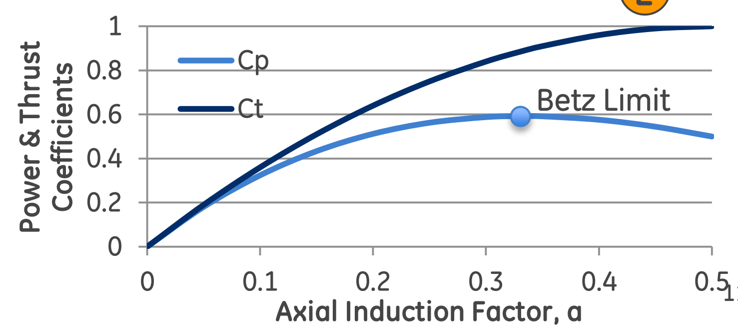


Main Results

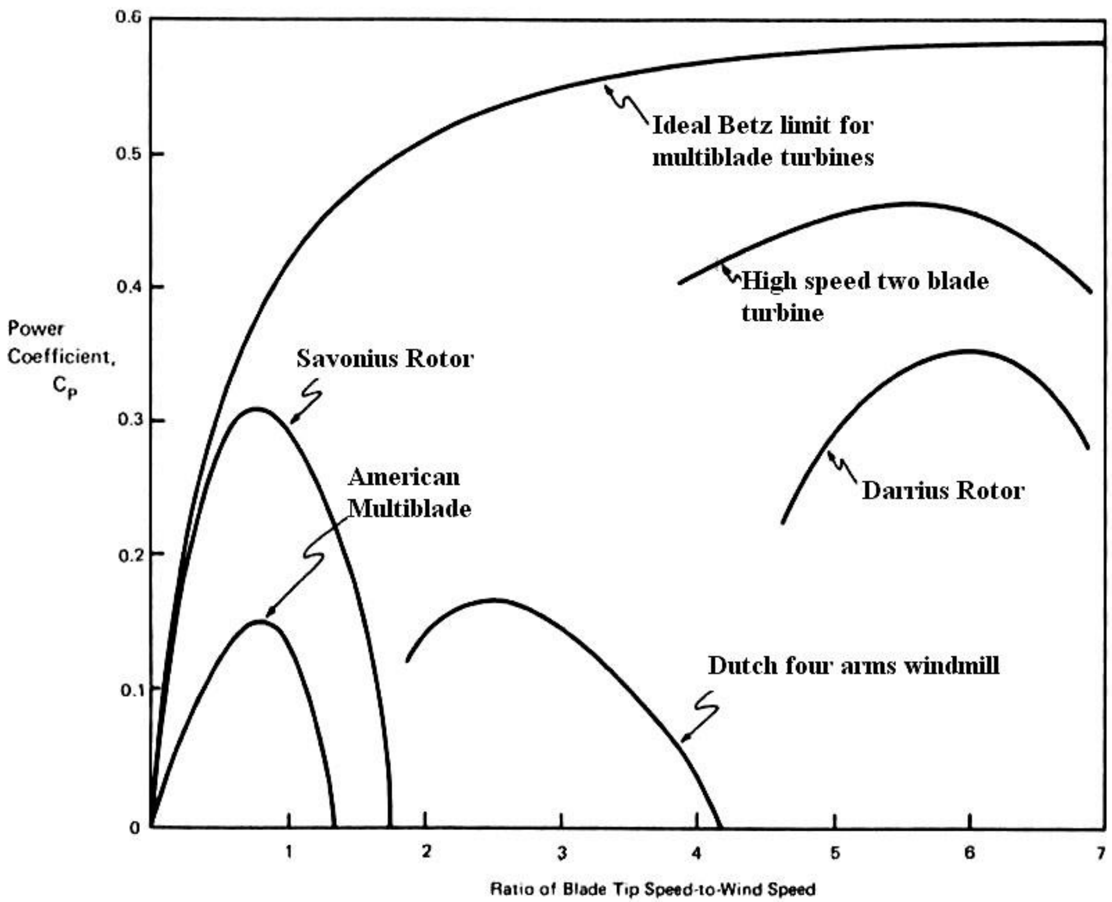
→ Power coefficient: $C_p = \dfrac{P_{ower}}{\frac{1}{2}\rho V_1^3 A_d} = 4a(1-a)^2$

→ Thrust coefficient: $C_t = \dfrac{T_{hrust}}{\frac{1}{2}\rho V_1^2 A_d} = 4a(1-a)$

→ Maximum extractable Power is 59.3%



Optimizing Cp's through Configuration



Source: http://www.intechopen.com/books/fundamental-and-advanced-topics-in-wind-power/wind-turbines-theory-the-betz-equation-and-optimal-rotor-tip-speed-ratio
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Horizontal-axis wind turbines

- More blades increase Cp … but increase cost

Vertical-axis lift (Darrieus)

- Limited applicability due to lower Cp

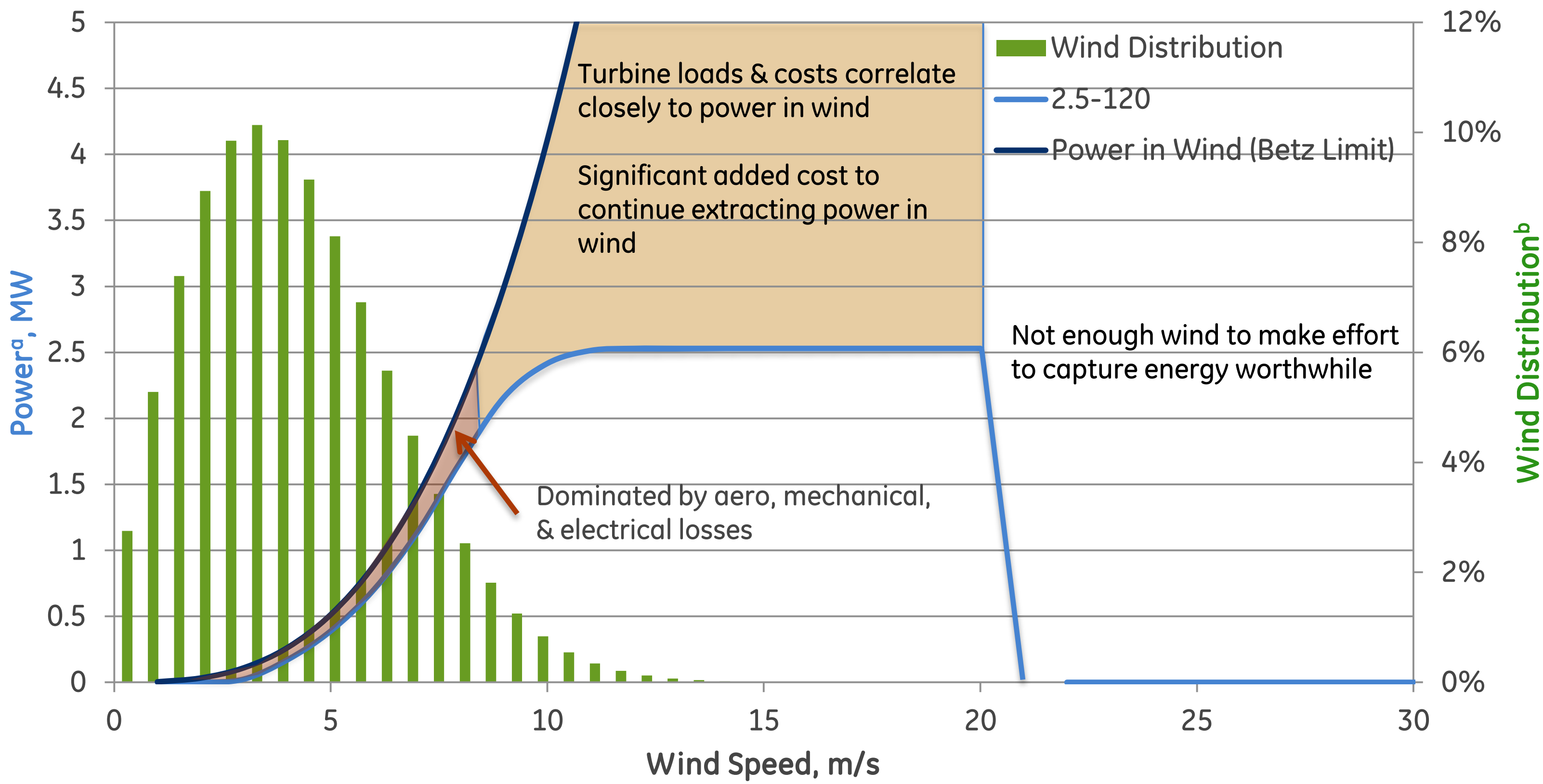
Horizontal-axis windmills

- Designed for torque not electricity … results in low tip speed operation

Vertical-axis drag (Savonius)

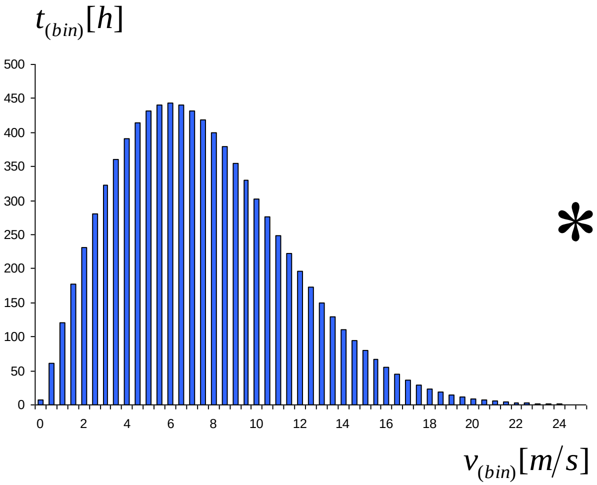
- Used as primary technology for anemometers

Power Curve



a) Power is for a 120m rotor diameter turbine
b) Wind distribution calculated from Weibull distribution, 7.5 m/s average wind speed, k=2

Annual Energy Production (AEP)



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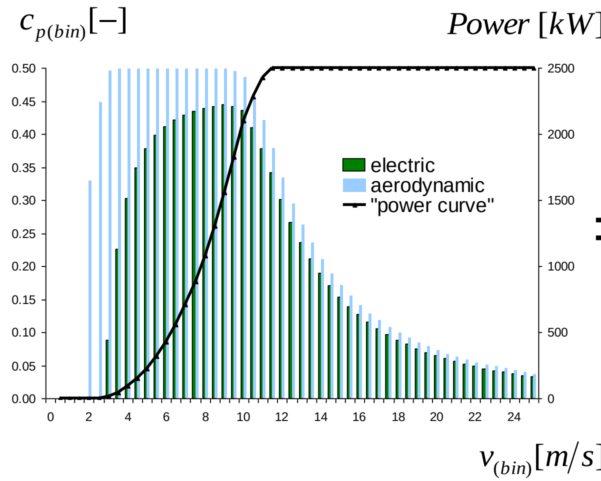

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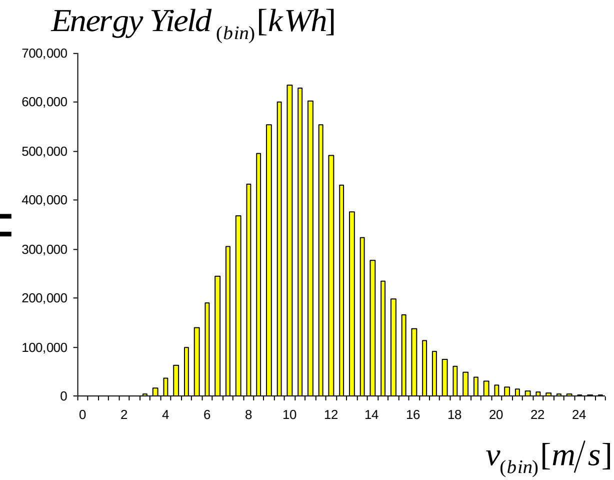
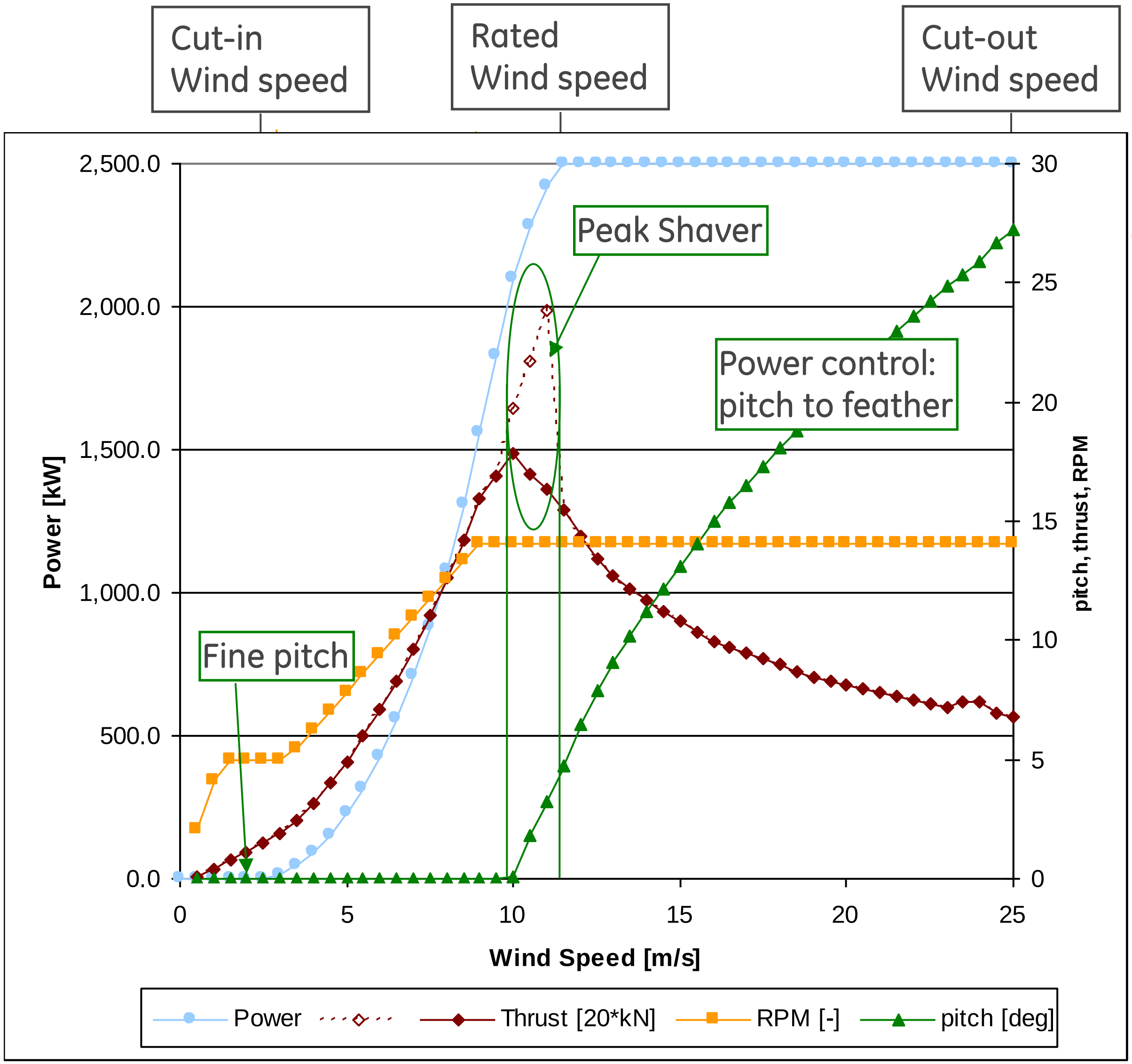


$$\sum_{Weibull} t_{(bin)} \cdot v_{(bin)}^3 \cdot \frac{1}{2} \cdot \rho \cdot c_{p\ elec.(bin)} \cdot \pi \cdot R^2 = AEP_{actual}$$

AEP is the product of:

- Wind distribution – v^3
- Rotor size (swept area) – R^2
- Efficiency (aerodynamic, mechanical, electrical)

Power Curve – Regions



- Power curve region:
  1. below cut-in
  2. cut-in to rated (partial power)
  3. rated to cut-out
- Variable speed: RPM ~ wind speed
- Constant speed: RPM constant
- Pitch actuation:
  - > Fine pitch
  - > Peak shaver
  - > Power control

⇒ (Thrust) Load reduction

Loads Analysis

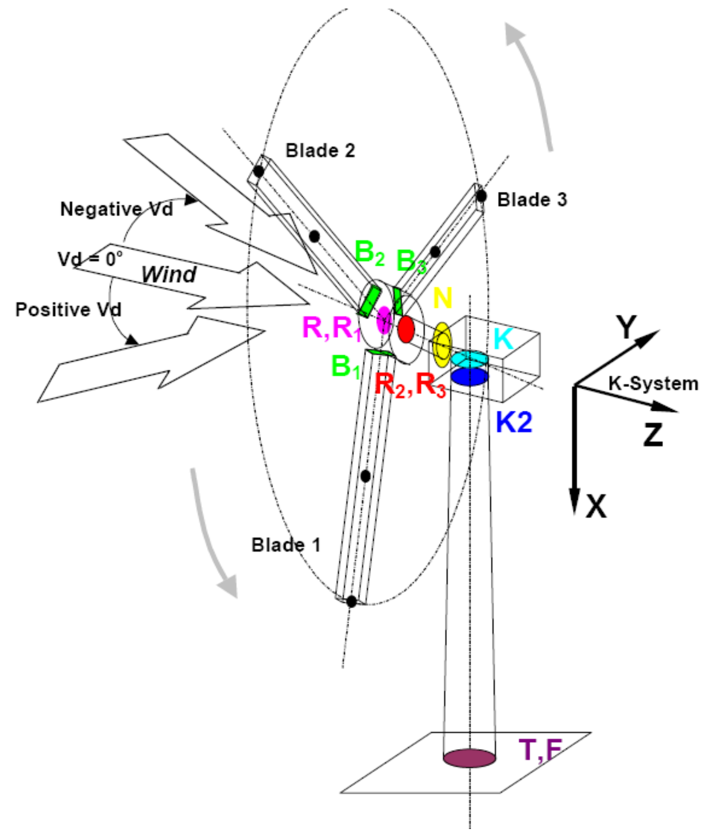
Simulation Driven … incorporate wind turbulence, control strategy, aero & structural properties

Structural Design … used to design components

Certification … meet specific design load cases (DLC's)

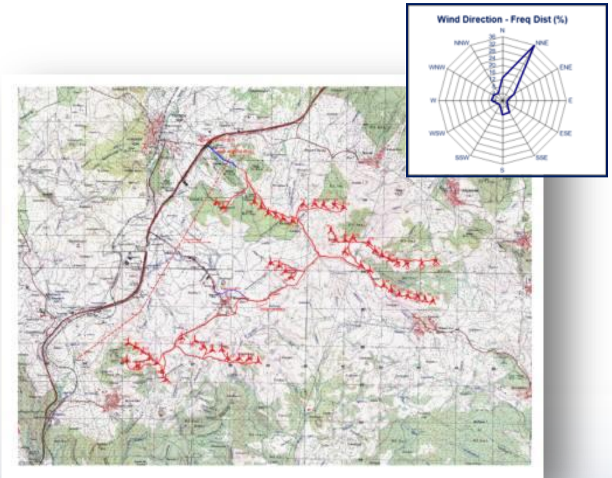
- **IEC 61400 ed. 2 / ed.3** (-1 onshore; -2 small; -3 offshore)
- **DIBt** (partly identical with IEC, but HH-dep.-windspeeds, add. DLCs)
- **NVN 11400** (similar to IEC)

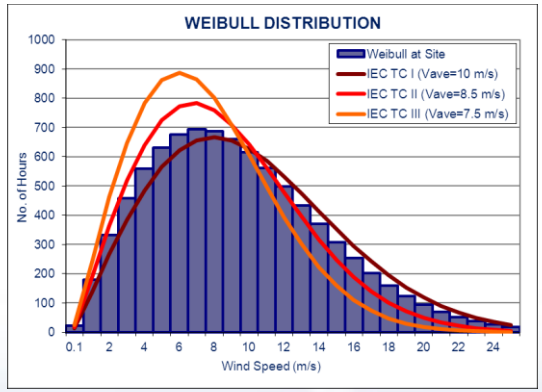
Bankability … required by customer & financing institutions

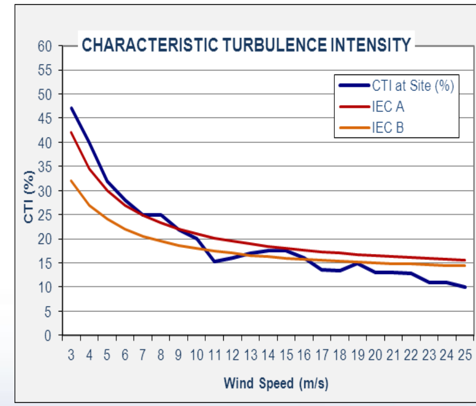


IEC 61400-1 Ed2		WIND TURBINE CLASS		
		I	II	III
V_{ave} [m/s]		10	8.5	7.5
V_{ref} [m/s]		50	42.5	37.5
TI_{15} [%]	a / b	18/16	18/16	18/16
Air density [kg/m³]		1.225		
Vertical shear [-]		0.2/ 0.11		
Flow angles [°]		< 8		

Site Specific Mechanical Loads Analysis





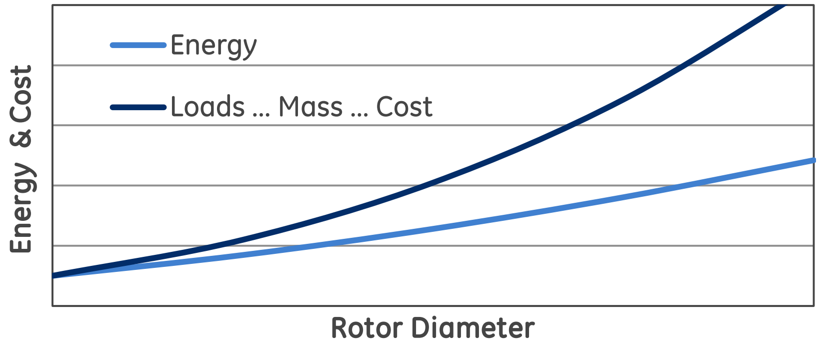


Determine turbine loads suitability at site specific locations

Square-Cube Law

Energy capture is proportional to RD^2

Loads → Mass → Cost are proportional to RD^3



… but this is a generalization & some economies of scale exist

Installation

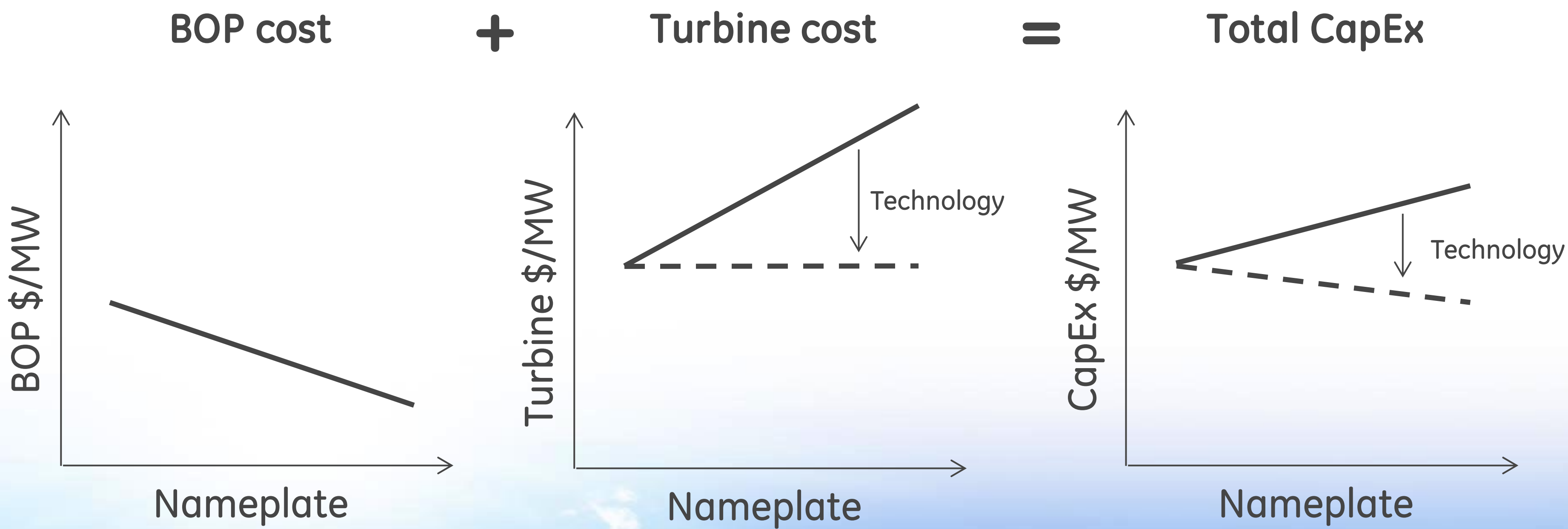
BOP

Tower

Power Electronics

… and some step changes like blade logistics

Turbine scale … costs and benefits

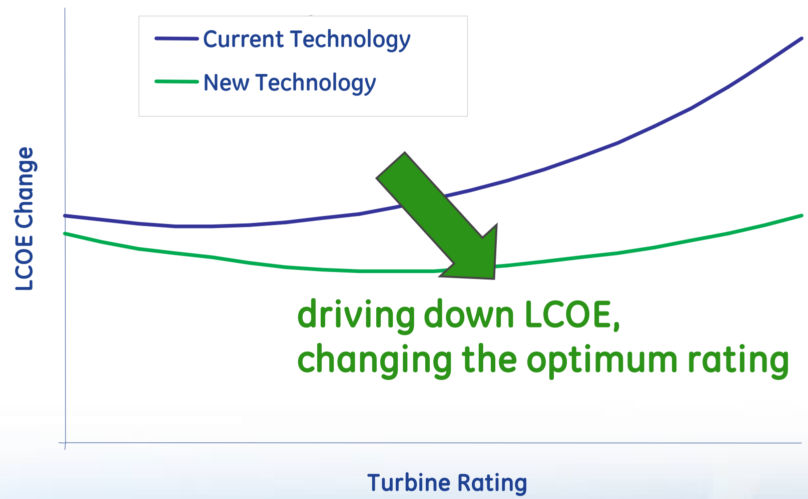


Technology advancements required to beat the cost curve

Wind System Engineering Objectives

Goal: Assess the system-level value of new technologies & next-generation product designs

- Many system-level trades
  - rating & rotor diameter
  - hub height
  - control strategies (loads vs. AEP)
  - component technologies (cost vs. perf)
  - rotational speed (noise, DT size, loads)
- Need system-level approach to optimize
  - performance
  - capital cost
  - operation & maintenance
- Non-obvious interactions abound



Optimizing technology development & product moves around lifetime value to wind farm

Tower Height Optimization

Benefits of Tall Tower

- Higher mean wind speed
- Reduced wind shear
- Reduced turbulence

Modeling

Typical applied Power law in flat terrain:

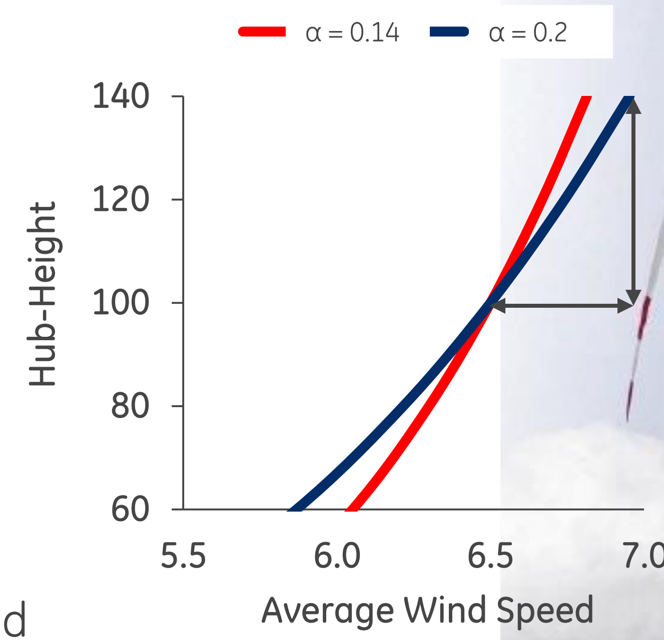
$$V_h = V_{ref} \, (h/h_{ref})^{\alpha}$$

- h is the height above ground
- α is the wind shear coefficient
- Typically $0.14 \leq \alpha \leq 0.20$ (Depends on terrain)

Negative shear

- Local increase in wind speed near ground
- Occurs on top of ridges and hills

Shear drives economics



Hub-Height	δAEP 0.14	δAEP 0.2
80	-9%	-13%
100	0%	0%
120	8%	12%
140	15%	22%

System Value Optimization

Customers focus areas

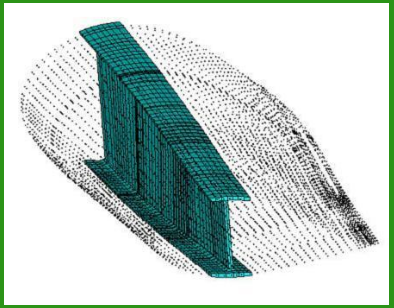
	Component Level	Turbine Level	Farm Level	Fleet Level
Key Metrics	Lifecycle Costs	Lifecycle Costs Rotor Diameter & Rating	LCOE, NPV, IRR	Fleet Operations Balancing Costs
Operation & Maintenance	Planned maintenance Failure rates	Overall turbine O&M cost	Servicing strategy Grid Integration	
Annual Energy Production	Component efficiency	Turbine power curve	Wind Resource Wake & cable losses (siting)	Forecasting
Capital Cost	Localized loads Materials	Full loads Operational limits	BOP Costs Logistics	

Technologists typical focus areas

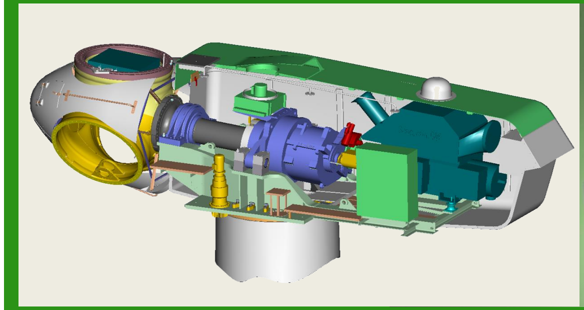
Complex multi-physics, multi-dimensional optimization at farm and fleet levels.

Technology Differentiators among Utility-Scale OEM's

Blade Materials … Carbon vs. Glass

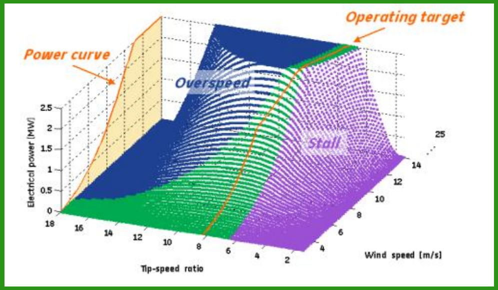


Drivetrain Architecture … DD vs. Geared



Power Conversion … Full Power vs. Partial Power

Controls

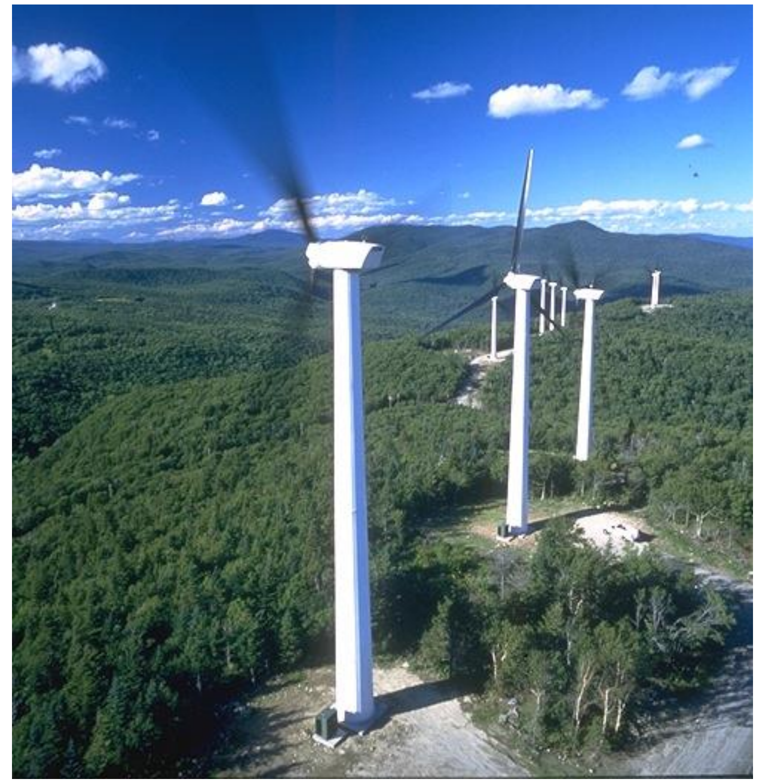


How are Wind Farms Laid Out ?

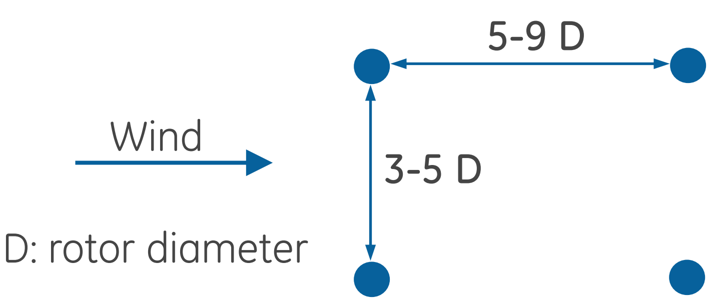
Examples:

Array

along a ridge



Spacing



Micro Siting Basics

Find the best wind

Select the best turbine model

Place turbines in energetic most locations on site

Minimize wake effects

Optimize BOP

Maximize AEP given constraints

Waked turbines

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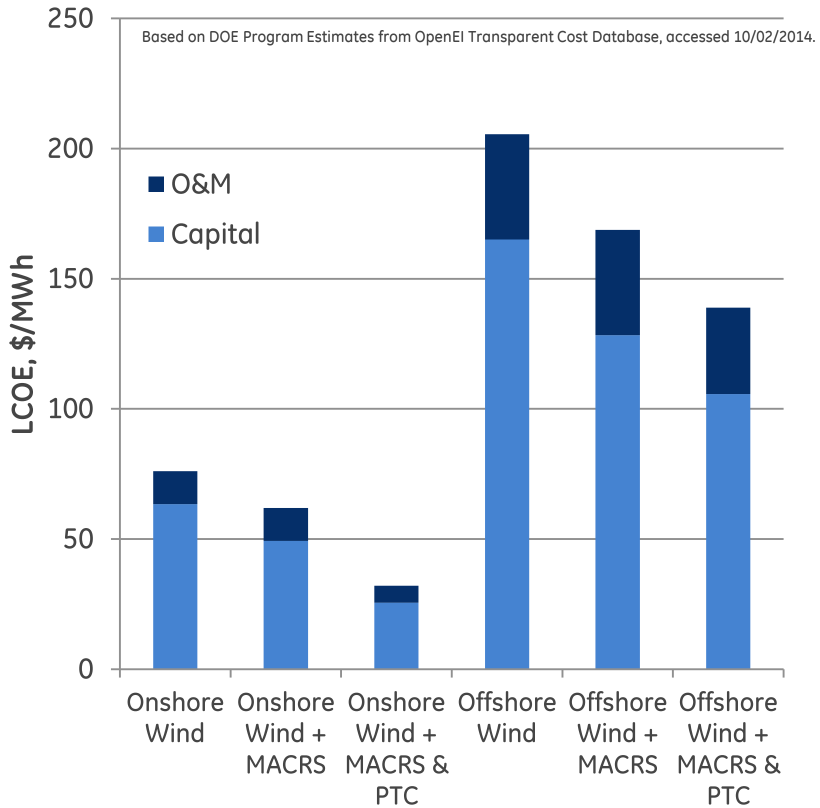
Economics – LCOE & Incentives

LCOE



Onshore wind competitive in many places

Incentives

Production Based

Production Tax Credit (PTC)

not taxed, 10 years, in addition to PPA

US 2.3 cents/kWh

Feed-In Tariffs

common in Europe, replaces PPA

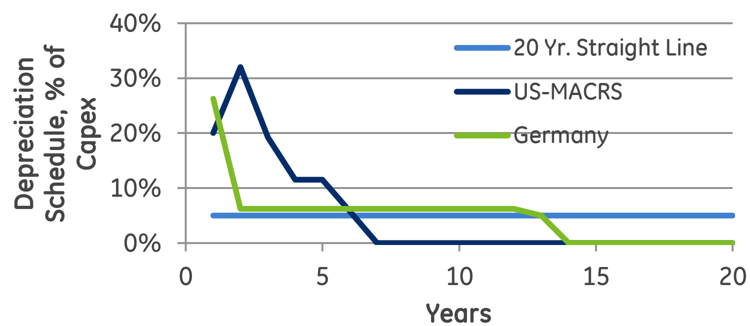
Germany has ~11.3 cents/kWh

Installed Cost Based

Investment Tax Credit (ITC)

like solar in US (30% of installed capex), no longer valid for utility-scale wind)

Accelerated Capital Depreciation



Economics – Markets Drive Product Platforms

North American Optimized Product

Constrained either by land available or electrical interconnect … Large Project Sizes (often >50 turbines)

Competes with variable cost of gas … low PPA values

Moderate wind resource … IEC Class II & III

2.3-107 1.7-100

1.85-82.5 1.85-87

Manage cost & performance for low PPA's

European Optimized Product

Constrained by land available … Small farm sizes (often <10 turbines)

Strong feed-in tariff rates … AEP valued

Poorer wind resource … IEC Class III & IV

3.2-103 2.75-120

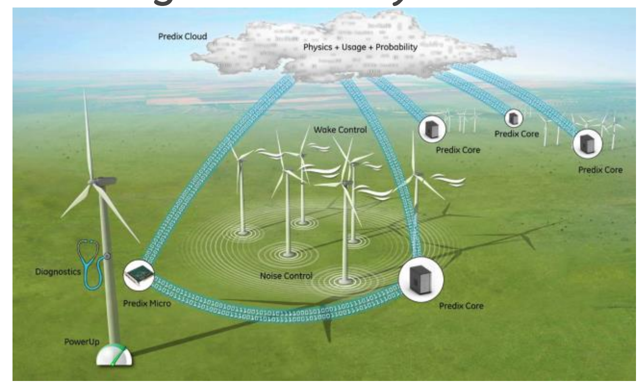
2.85-100 2.85-103

Increasing size can pay off with high feed-in tariffs

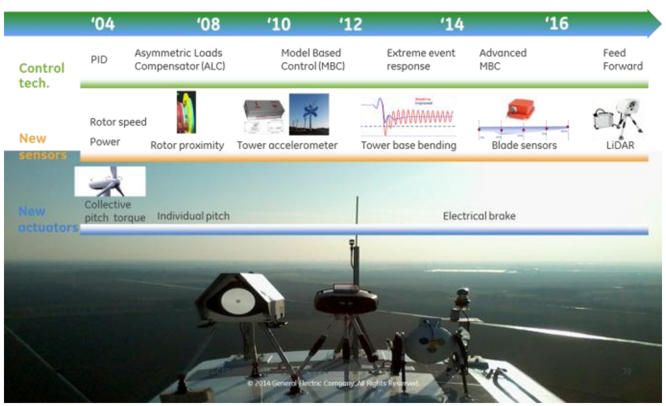
Current Research Trends

Cost Effective Scaling … Large Rotor & Tower Technologies

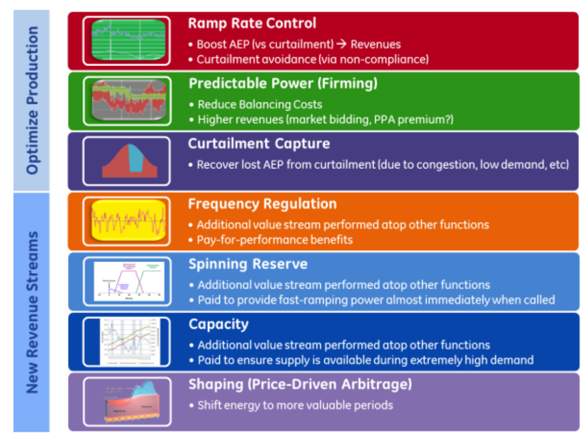
Farm Level Optimization … Farm Control & Big Data Analytics



Minimize Loads … Advanced Controls & Sensors



Grid Friendly … Storage Integration



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