Wind Energy: Today, Tomorrow

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PNW AIAA Event
University of Washington
16 October 2013

Acknowledgements

- Kevin Jackson, Dynamic Design Engineering, Inc.
- Mike Zuteck, MDZ Consulting
- Wind Energy Technology Department, Sandia National Laboratories, Albuquerque
- TPI Composites, Inc.
- Knight & Carver Wind Group
- Jonathan Baker, Frontier Wind
- Myra Blaylock, Sandia National Laboratories
- David Chao, Vestas Windpower
- Aubryn Cooperman, TU Delft
- Scott Johnson, Siemens Windpower
- Scott Larwood, University of the Pacific
- Edward Mayda, Siemens Windpower
- Kevin Standish, Siemens Windpower
- UC Davis
  - Henry Shiu
  - Raymond Chow
  - Rob Kamisky
  - Phillip de Mello
- California Energy Commission
- Department of Energy
- Sacramento Municipal Utility District
- California ISO

Outline

- How does it function?
- Wind energy today
  - Industry
  - Technology
- Selected research areas
  - Passive load control
  - Active aerodynamic control
  - Windplant wake losses
  - Offshore
- Concluding remarks

Wind Resource

$$P = \tfrac{1}{2}\rho A V^3$$

Wind Power Air Density Capture Area Wind Speed

Power in the wind depends on:

- Air density
- Area over which wind is captured (area normal to the wind)
- Wind speed cubed

Wind Turbine Power

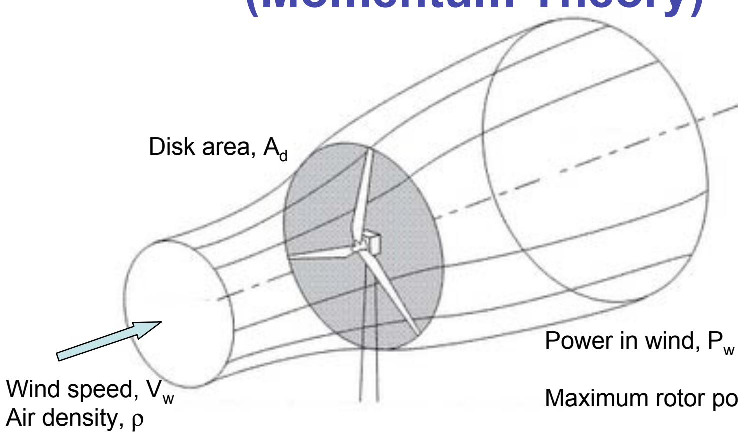
- The amount of power generated by a turbine depends on the power in the wind and the efficiency of the turbine:

$$\begin{pmatrix}\text{Power}\\ \text{Turbine}\end{pmatrix} = \begin{pmatrix}\text{Efficiency}\\ \text{Factor}\end{pmatrix} \times \begin{pmatrix}\text{Power}\\ \text{Wind}\end{pmatrix}$$

- Power in wind $P = \frac{1}{2}\rho A V^3$

- Efficiency or Power Coefficient, C_p:
  - Rotor (Conversion of wind power to mechanical power)
  - Gearbox (Change in rpm)
  - Generator & Inverter (Conversion of mechanical power to electrical power)

Basic Rotor Performance (Momentum Theory)



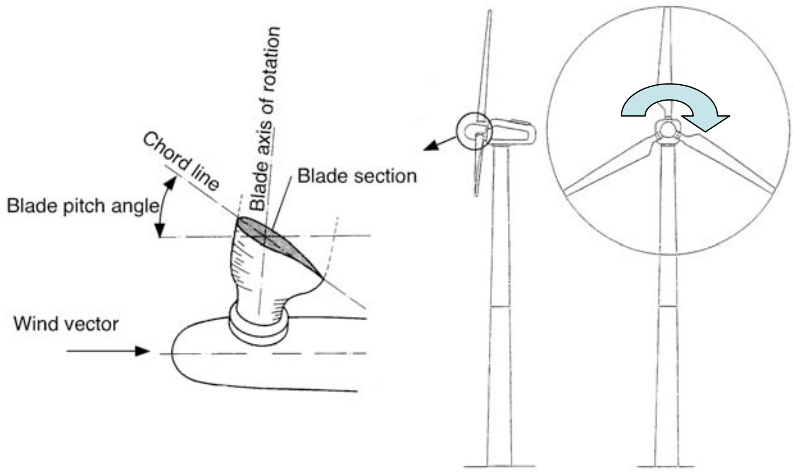
Power in wind, $P_w = {}^1/_2\ \rho\ V_w^3\ A_d$

Maximum rotor power, $P = {}^{16}/_{27}\ P_w$

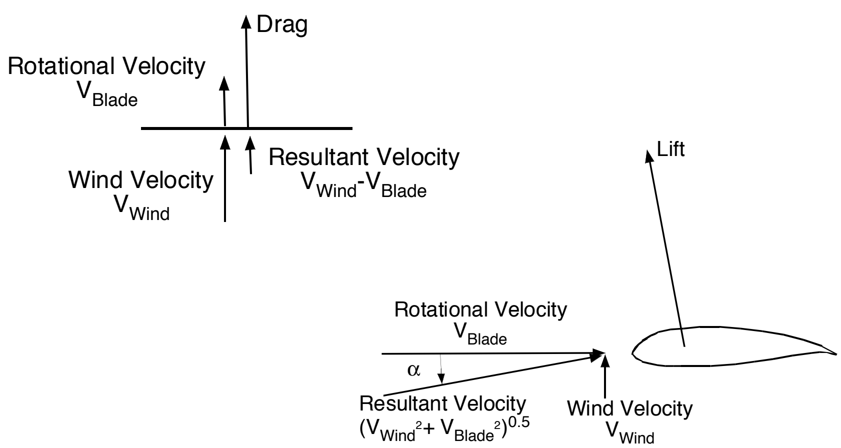
Rotor efficiency, $C_p = P / P_w$

Betz limit, max $C_p = {}^{16}/_{27} = 59.3\%$

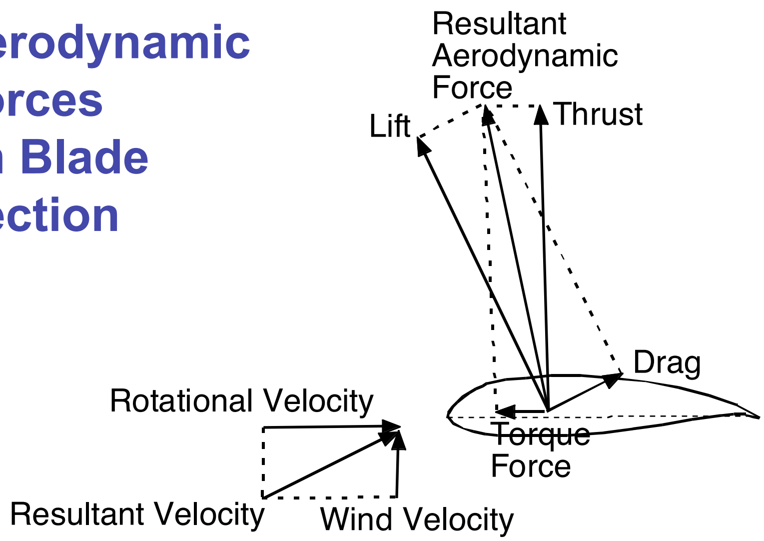
Upwind, Variable Pitch, Horizontal Axis Wind Turbine



Drag versus Lift



Aerodynamic Forces on Blade Section



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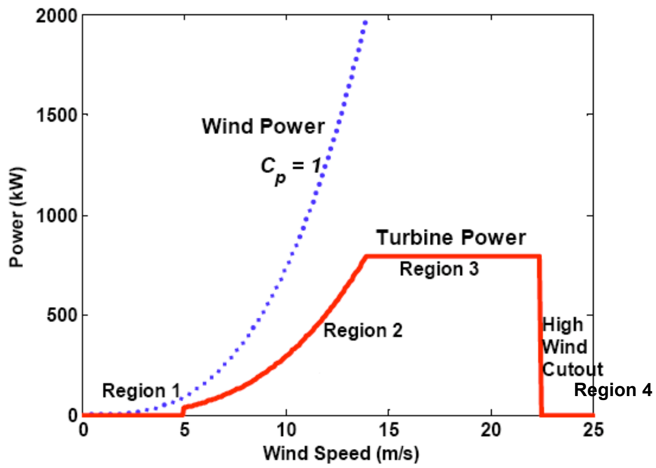
HAWT Power Characteristics

Source: Johnson et al (2005)



- Region 1
  Turbine is stopped or starting up
- Region 2
  Efficiency maximized by maintaining optimum rotor RPM (for variable speed turbine)
- Region 3
  Power limited through blade pitch
- Region 4
  Turbine is stopped due to high winds (loads)

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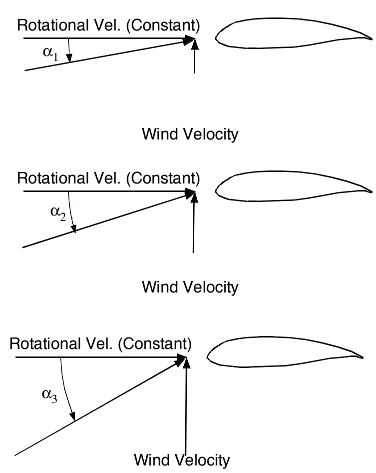
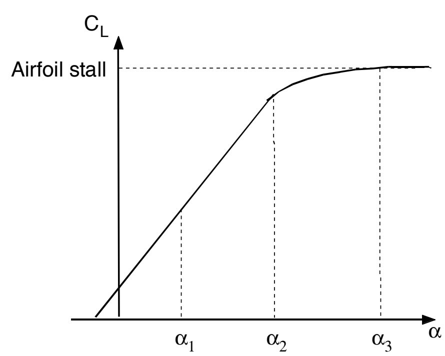
Wind Turbine Power Control

- Fixed pitch stall controlled
- Variable pitch - pitch to stall
- Variable pitch - pitch to feather

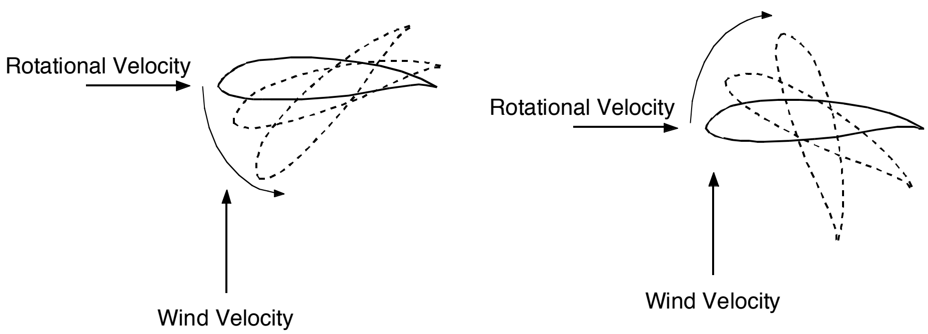
Fixed Pitch Blade





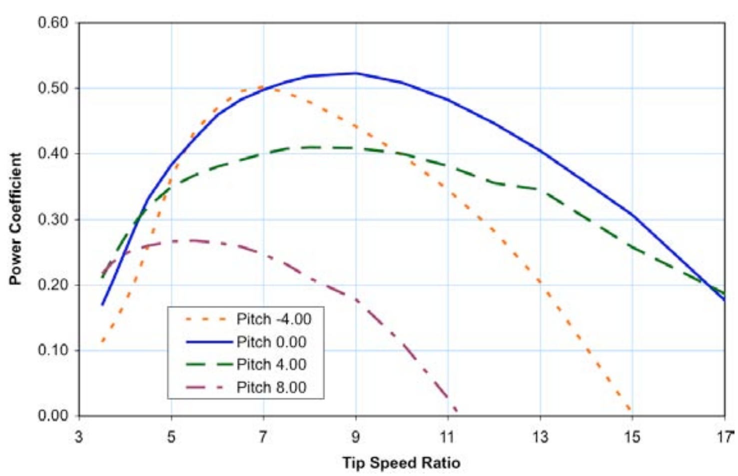
- Fixed pitch, constant speed rotor relies on airfoil stall to limit lift and, hence, torque and power output of rotor

Variable Pitch Blades



HAWT C_p-TSR Curve

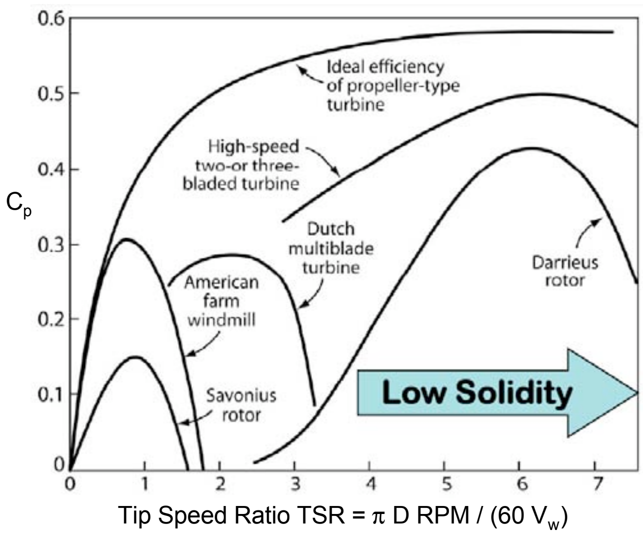
Jackson (2005)



- Peak C_p at TSR = 9
- This C_p is maintained in Region II of power curve by controlling rotor RPM
- In Region III power is controlled by changing blade pitch.

Efficiency of Various Rotor Designs

Butterfield (2008)



- $C_p = P_{rotor} / (1/2\ \rho\ V_w^3\ A_d)$
- Solidity = Blade Area / A_d
- TSR = Tip Speed / V_w
- High power efficiency for rotors with low solidity and high TSR
- Darrieus (VAWT) is less efficient than HAWT

kidwind.org

Persian grain mill
9th century

Gedser Mill
1956, Denmark
Forerunner to modern wind turbines

telos.net/wind

Dutch Mill
16th century
Water pumping, Grinding materials/grain

C.P. van Dam

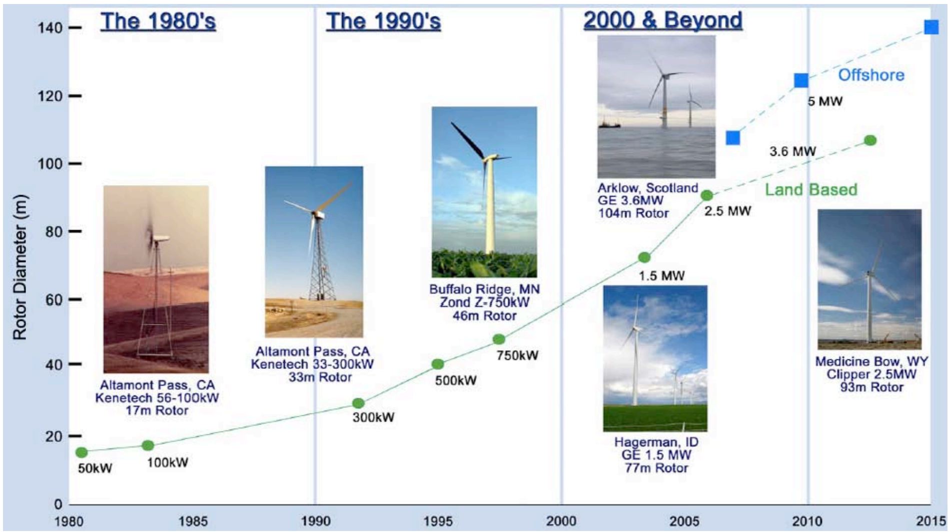
W. Gretz, DOE/NREL

American Multi-blade
19th century
Water pumping - irrigation

Charles F. Brush Special Collection, Case Western Reserve University

Brush Mill
1888
First wind turbine
12 kW
17 m rotor diameter

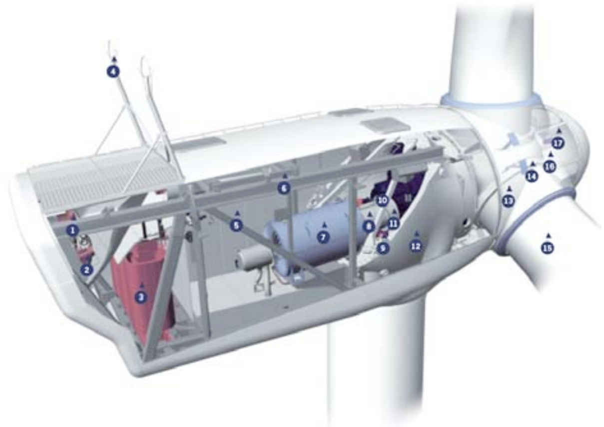
Evolution of U.S. Utility-Scale Wind Turbine Technology



NREL

Modern Wind Turbines

- 1.0-3.0 MW
- Wind speeds: 3-25 m/s
  - Rated power at 11-12 m/s
- Rotor
  - Lift driven
  - 3 blades
  - Upwind
  - Full blade pitch
  - 70–120 m diameter
  - 5-20 RPM
  - Fiberglass, some carbon fiber
- Active yaw
- Steel tubular tower
- Installed in plants/farms of 100-200 MW
- ~40% capacity factor
  - 1.5 MW wind turbine would generate about 5,250,000 kWh per year
  - Average household in California uses about 6,000 kWh per year



1. Oil cooler
2. Generator cooler
3. Transformer
4. Ultrasonic wind sensors
5. VMP-Top controller with converter
6. Service crane
7. Variable speed generator
8. Composite disc coupling
9. Yaw gears
10. Gearbox
11. Parking brake
12. Machine foundation
13. Blade bearing
14. Blade hub
15. Blade
16. Pitch cylinder
17. Hub controller

Vestas V90-3.0 MW

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Technical Specifications - Vestas V90

- Rotor
  - Diameter 90 m
  - Swept area 6,362 m^2
  - Nominal rpm 16.1 $\rightarrow$ Tip speed= $\pi \cdot D \cdot rpm/60 = 75.9$ m/s
  - Operational range 8.6 - 18.4 rpm
  - Number of blades 3
  - Power regulation Pitch/OptiSpeed (Note, OptiSpeed not available in USA and Canada)
  - Brake Independent blade pitch (Three separate hydraulic pitch systems)
- Tower
  - Hub height 80 m, 105 m

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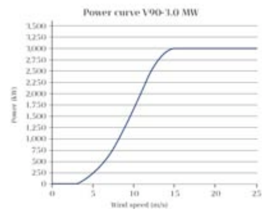
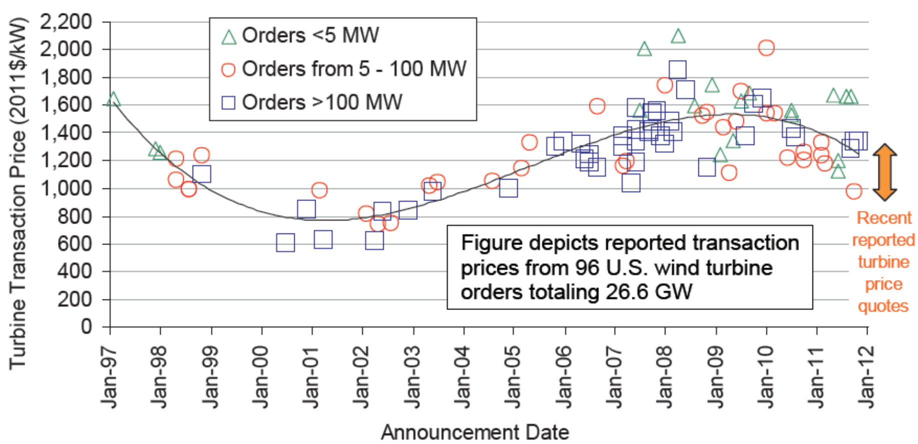
Technical Specifications - Vestas V90



- Operational data
  - Cut-in wind speed — 4 m/s
  - Nominal wind speed — 15 m/s
  - Cut-out wind speed — 25 m/s
- Generator
  - Type — Asynchronous with OptiSpeed
  - Rated output — 3,000 kW
  - Operational data — 50 Hz, 1000 V
- Gearbox
  - Type — Two planetary and one helical stage
- Weight
  - Nacelle — 70 t
  - Rotor — 41 t
  - Tower
    - 80 m, IEC IA — 160 t
    - 105 m, IEC IIA — 285 t

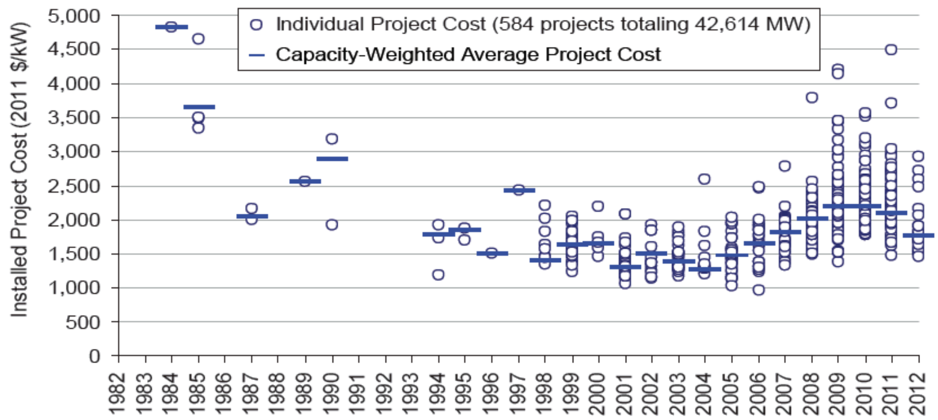
Wind Turbine Cost Trends

U.S. DOE, Wiser & Bolinger (2012)



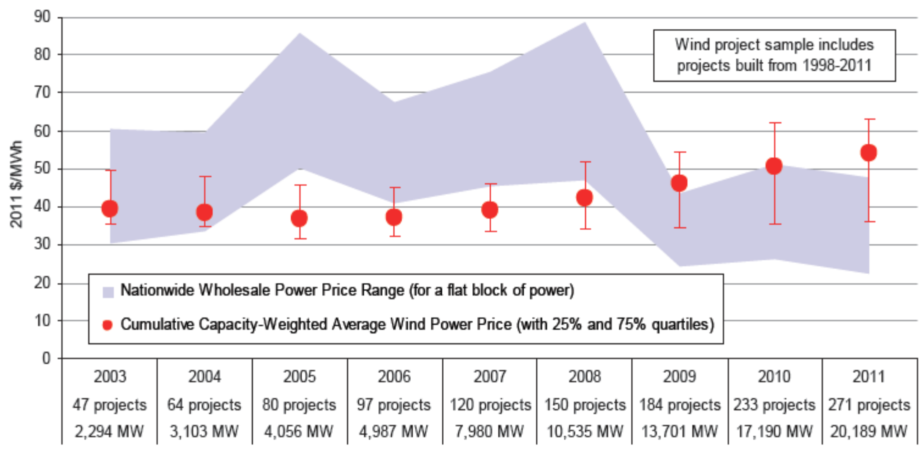
Wind Project Cost Trends

U.S. DOE, Wiser & Bolinger (2012)



Wind and Wholesale Energy Prices

U.S. DOE, Wiser & Bolinger (2012)

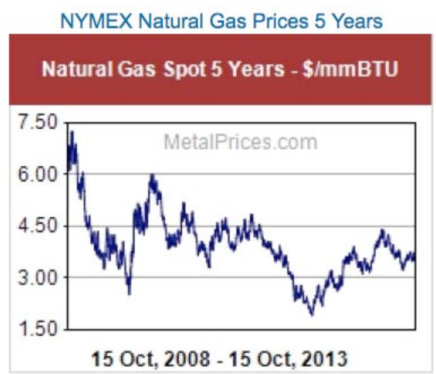


- Sharp drop in wholesale energy prices challenges the competitiveness of wind
- Regional price differences can be significant

Simple Cost of Energy Comparison

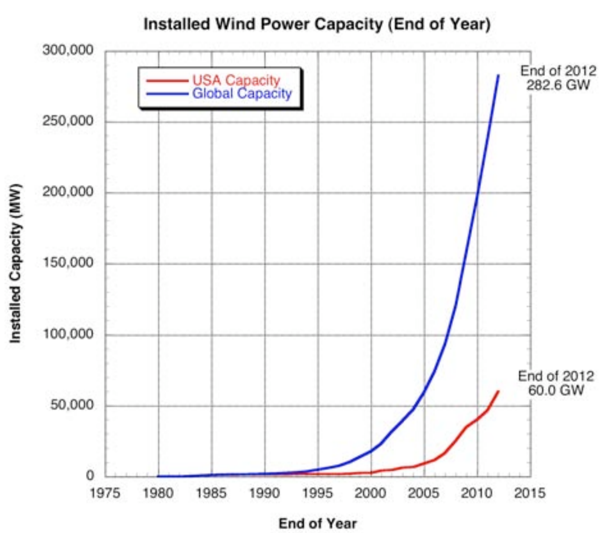
- Wind turbine
  - 1 MW, $1.5 million, 20 years, Capacity Factor = 0.35
  - COE = $24.46/MWh (based on capital cost only)
- Natural gas fired combined-cycle gasturbine CCGT
  - Natural gas = $3.80/MBtu (or MMBtu) *
  - Heat rate = 7000 Btu/kWh = 7.0 MBtu/MWh
  - COE = $26.60/MWh (based on fuel cost only)

* Nymex spot market price

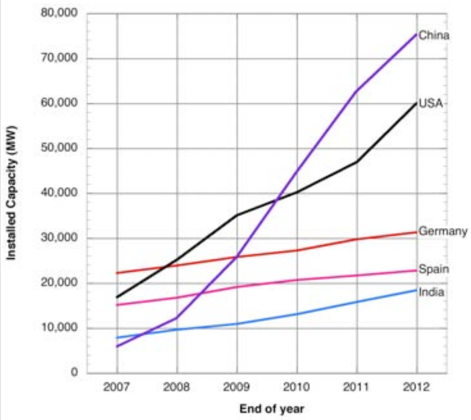


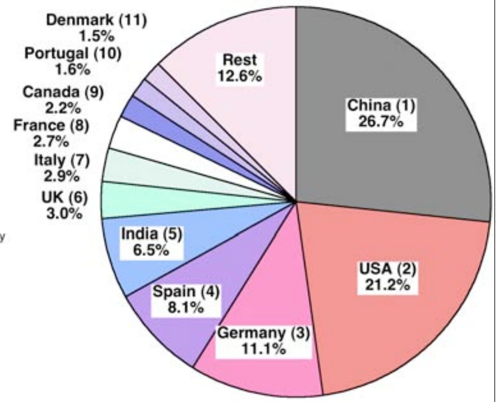
Historical Trend in Installed Wind Power Capacity

- 1980s: U.S. was the leader in installed wind power capacity
- 1990s: other countries quickly outpaced the U.S.
- 2000s: US installations rapidly increased, driven by competitive pricing and favorable policies
- 2012: Record new capacity
- 2013: Significant concern and uncertainty over Production Tax Credit (PTC) status, record low natural gas prices, competition from PV



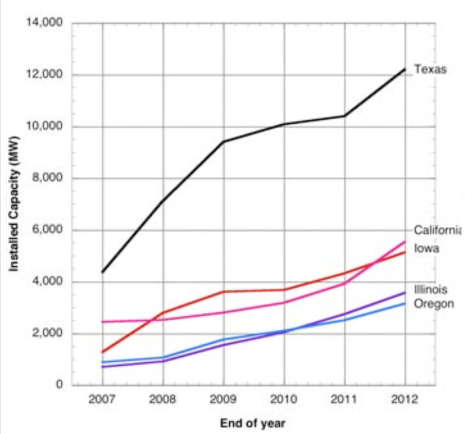
Global Installed Wind Power Capacity

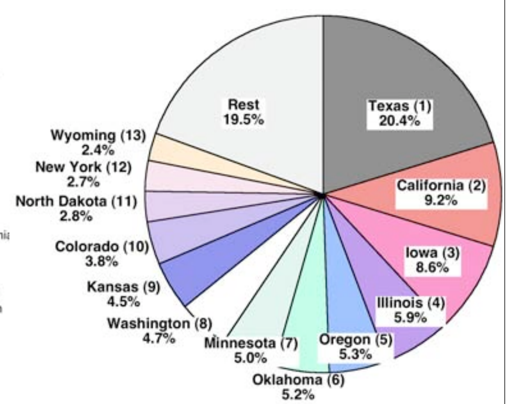




World Installed Capacity (283 GW) Start 2013

USA Installed Wind Power Capacity





USA Installed Capacity (60.0 GW) Start 2013

Wind Power Research & Innovation

Blades and rotors
- Airfoil design
- Inboard separation
- Soiling
- Passive load control
- Active aerodynamic control
- Segmented blades
- Blade manufacturing automation

Resource assessment
- Wake effects
- Complex terrain
- Offshore
- Wind in urban environments

Grid integration
- Short term forecasting
- Distributed generation
- Energy storage

Operations
- Anemometer calibration
- Structural health monitoring
- Condition monitoring

Alternative configurations
- Multi-rotor arrays
- VAWTs
- Ducted/shrouded rotors

Drivetrain
- Direct drive generators
- Gearbox reliability
- Bearing reliability

Alternative tower designs

Offshore

Wind Power Innovation Economics

- Primary metric: Levelized Cost of Energy
  - Over the turbine lifetime:

$$\text{LCOE} = \frac{\text{Initial capital cost} + \text{Total O\&M cost}}{\text{Total energy production}}$$

  - Units: ¢/kWh
  - Not:
    - Initial capital cost ($ or $/kW)
    - Capacity factor
    - Power coefficient
    - “Efficiency”

Rotor Scaling

- Larger rotor captures more energy
  - 5%-15% longer blades ➡ 10%-32% increased capacity factor

$$P \propto \tfrac{1}{2}\rho A V^3$$

$$P \propto r^2$$

$$\text{Loads (moments)} \propto r^3$$

$$\text{Blade volume} \propto r^3$$

$$\text{Blade cost} \propto r^3$$

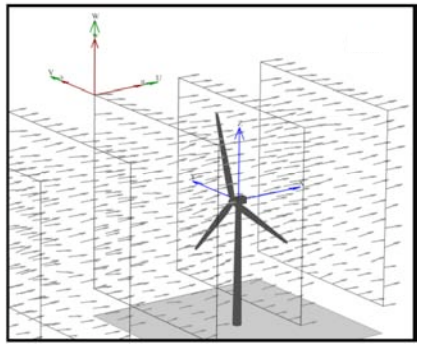
"Square-Cube Law"

- Can we mitigate loads while increasing energy capture?

Aerodynamic Control: Flaps, Ailerons, Spoilers

Operating in a Difficult Atmospheric Regime

- Wind turbines do not operate in a benign, uniform flow field
- Atmospheric boundary layer
- Turbulence
- Vertical, horizontal, and directional shear
- Gusts
- Low level jets
- Complex terrain interactions



NREL, Turbsim

Economics: Wind Power versus Aviation

	APPLES Wind Turbine	ORANGES Boeing 777
CapEx per pound ($/lb)	5	800
Operating life (hrs)	150,000	60,000
CapEx per hour of operation ($/hr)	18	5,300

“Wind power is aerospace technology on a sailboat budget.”

— G. Kanaby, MFG Wind

Blade Load Control Techniques

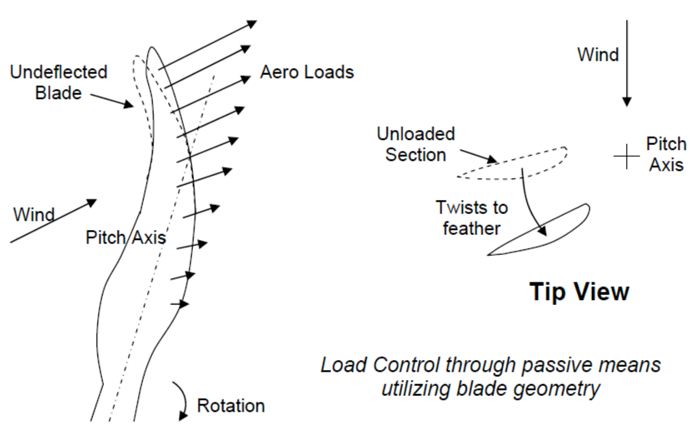
- Techniques to control blade loads and rotor performance:
  - Blade size (variable blade length)
  - Incidence angle (variable pitch, variable twist)
  - Airspeed (variable speed)
  - Section aerodynamic characteristics

$$L = \int_{r=0}^{R} \left[C_L \tfrac{1}{2} \rho \left\{ V_{wind}^2 + (2\pi n r)^2 \right\} c \right] dr$$

$$C_{L_{min}} \le C_L = C_{L_\alpha} (\alpha + \beta - \alpha_o) \le C_{L_{max}}$$

1. **Passive load control**
2. Active load control

Sweep Twist Passive Load Control



Load Control through passive means utilizing blade geometry

Sweep Twist Adaptive Rotor (STAR)


Source: van Dam

- 2004 DOE award to Blade Division of Knight & Carver to design, build, and demonstrate a rotor based on the sweep-twist concept
- Rotor designed for testing on a Zond Z48 turbine with 750 kW rating
- Goal to increase annual energy capture of baseline turbine by 5%-10% without exceeding baseline rotor loads
- To achieve this rotor radius was increased from 24 m to 27 m
- Rotor test commenced in April 2008
- Program results published in SAND2009-8037

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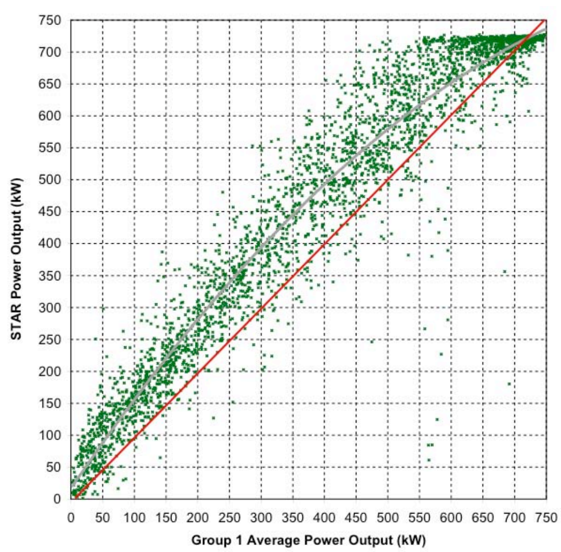
Power Comparison



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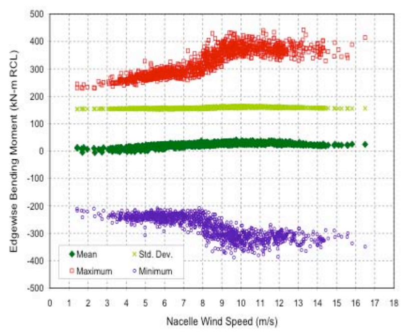
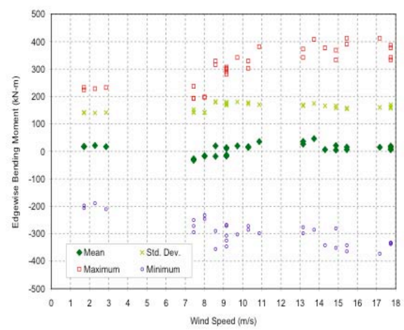
Edgewise Blade Root Moment Comparison

- STAR rotor loads compared to Z48 data collected at Lake Benton site.



STAR 54



Z48

Sweep Twist Adaptive Rotor

- Increased rotor energy capture through aeroelastically tailored blade design is feasible
- STAR-54 captured 12% more energy over baseline Z48 turbines without increasing blade loads.
  - Reports at http://www.sandia.gov/wind/TopicSelection.htm
- Prototype STAR-54 is continuing to operate without any issues more than 3 years after installation and it remains the highest grossing “Z48” in Tehachapi
- Problem remains that many of industry’s design codes do not properly model sweep twist feature.

Blade Load Control Techniques

- Techniques to control blade loads and rotor performance:
  - Blade size (variable blade length)
  - Incidence angle (variable pitch, variable twist)
  - Airspeed (variable speed)
  - Section aerodynamic characteristics

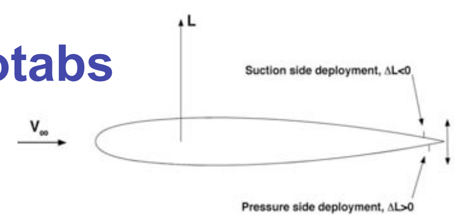
$$L = \int_{r=0}^{R} \left[C_L \tfrac{1}{2} \rho \left\{ V_{wind}^2 + (2\pi n r)^2 \right\} c \right] dr$$

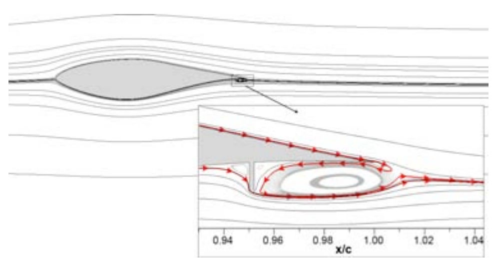
$$C_{L_{min}} \le C_L = C_{L_\alpha} (\alpha + \beta - \alpha_o) \le C_{L_{max}}$$

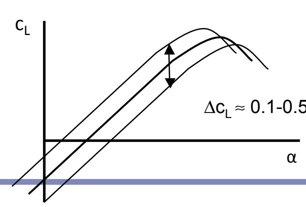
1. Passive load control
2. **Active load control**

Microtabs

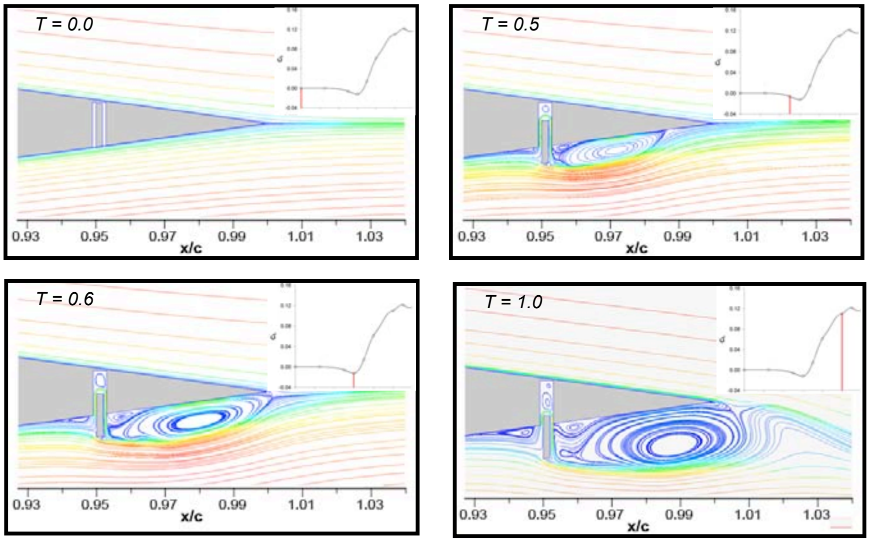
- Akin to Gurney flaps
- Tabs that deploy near-normal to flow direction
- Forward of the trailing edge
  - Upper or lower surface
- Hinge-less, low inertia device
  - Small actuation forces
  - Fast deployment/retraction
- h_{tab} ~ boundary layer thickness
- Trailing-edge flow condition is altered







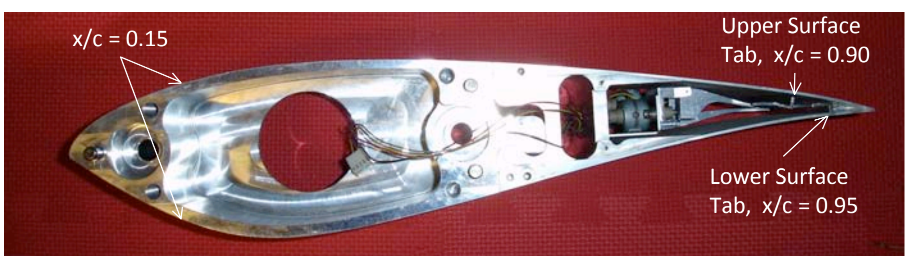
Microtab – Computational Modeling



Microtabs - Wind Tunnel Testing

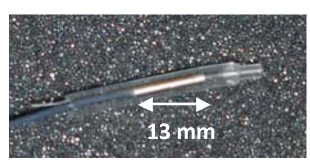
Model chord = 18 in. (0.45m) Tab height = 0.18 in. (1.0% chord)

Tab locations = 90% chord (upper) 95% chord (lower)

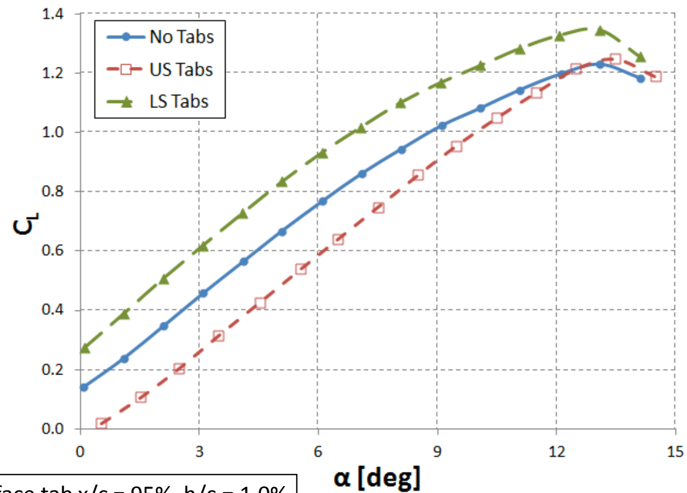


Endevco 8701C-1 pressure transducers:

- Location: 15% chord
- Diameter: 0.092 in. (2.3 mm)
- Range: 1 psig



Active Microtabs – Static Lift Test



Lower surface tab x/c = 95%, h/c = 1.0%
Upper surface tab x/c = 90%, h/c = 1.0%

Re = 1.0×10^6

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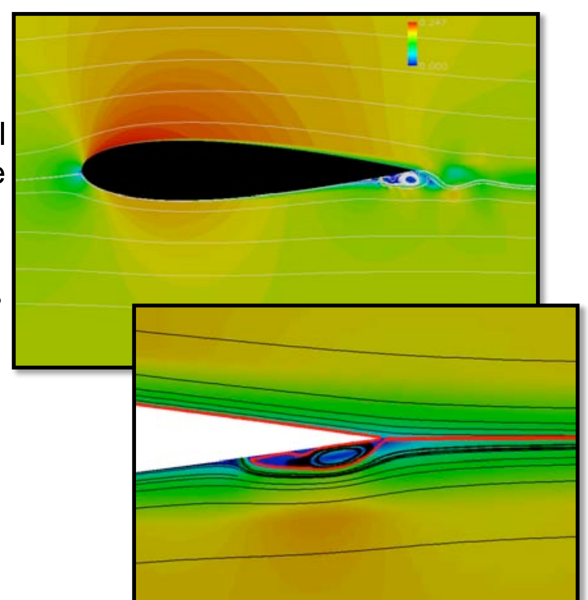
Microjets

- Conceptually similar to microtabs, but small pneumatic jets replace mechanical tabs
- Can potentially eliminate mechanisms at difficult to access locations
- Modulate by changing microjet mass flow rate/momentum
- Cost of blowing system is significant



NACA 0018, Re=6.6×10^5, M_∞=0.176, α=0°

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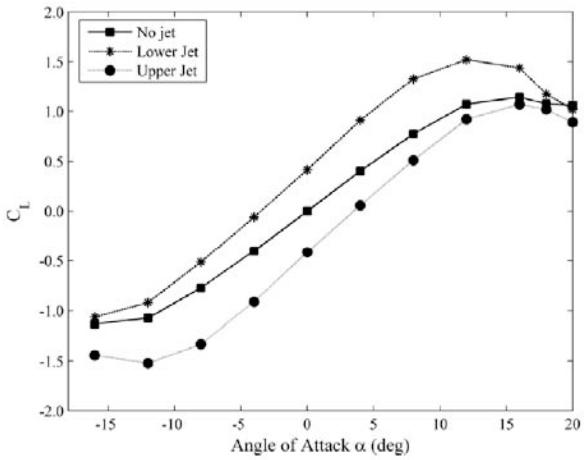
Microjet – Computational Analysis

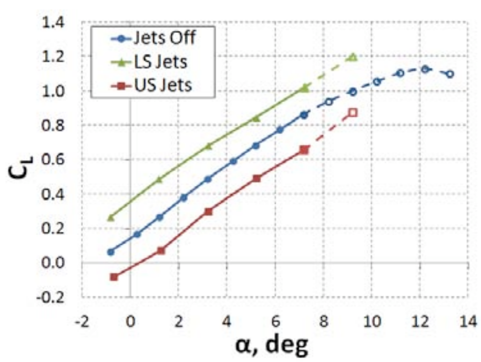
- U_{jet}/U_{∞}=1, h_{jet}/c = 0.006
  - Lower surface jet (x/c = 0.90)
  - Upper surface jet (x/c = 0.90)
- NACA 0018
- Re=6.6x10^5
- M_{∞}=0.176
- C_{μ}=0.012



ΔC_L = $f(\alpha)$ = boundary layer thickness effect

Microjets – Wind Tunnel Testing

- Same model as microtab tests, but electro-mechanical actuators/devices replaced by ducting and plenums
- Preliminary results show promising ΔC_L
- Requires automated valves for control system development



U_{jet}/U_{∞} = 0.7, Re = 1.0x10^6

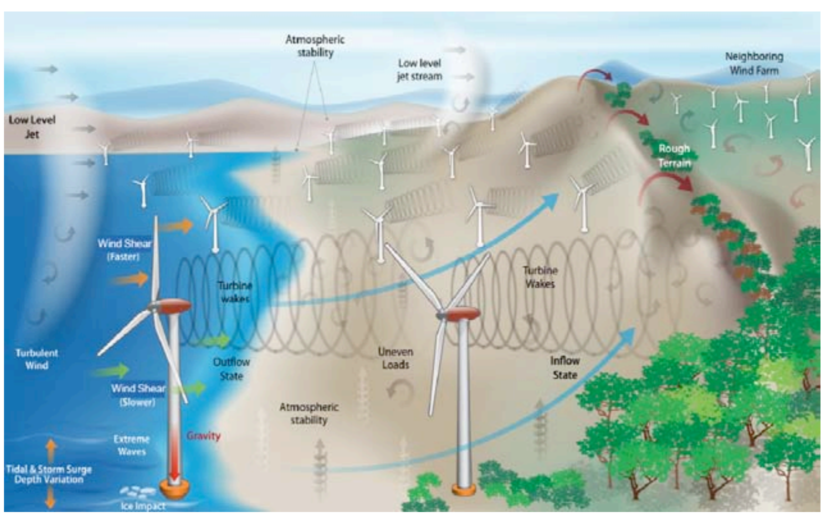
Windplant Loss Categories

Walls & Kline (2012)

- Wake losses
- Turbine availability
- Balance of Plant (BOP) availability
- Electrical
- Environmental
- Turbine performance
- Curtailment

Windplant Challenges

Zayas (2013)



Windplant Loss Categories

Walls & Kline (2012)

- Power losses can be as much as 20-30% in state of the art windplants:
  - Wake losses
  - Turbine availability
  - Balance of Plant (BOP) availability
  - Electrical
  - Environmental
  - Turbine performance
  - Curtailment

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Wake Losses

Walls & Kline (2012)

- Wind turbine wakes can persist over many rotor diameters (>10D)
- Wake losses depend on:
  - Plant size (number of turbines)
  - Turbine layout
  - Wind direction
  - Wind speed
  - Wind turbine operational conditions
  - Atmospheric conditions
- Models:
  - Park model
  - CFD
- Wake losses can range from approx 2% to >10%

Christian Steiness, Feb 2008

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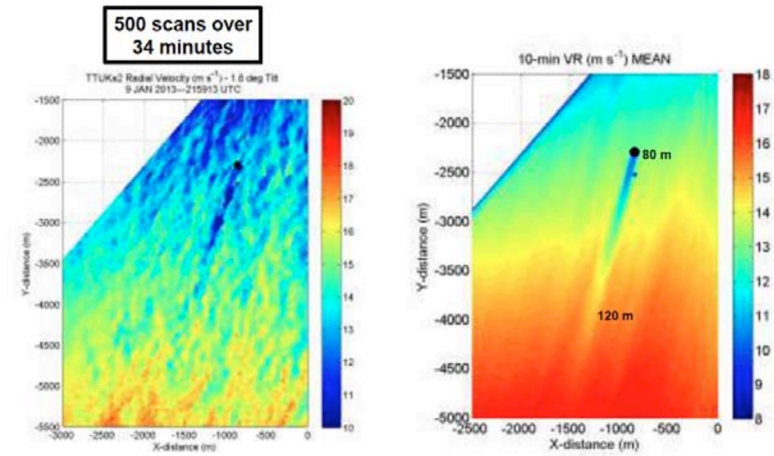
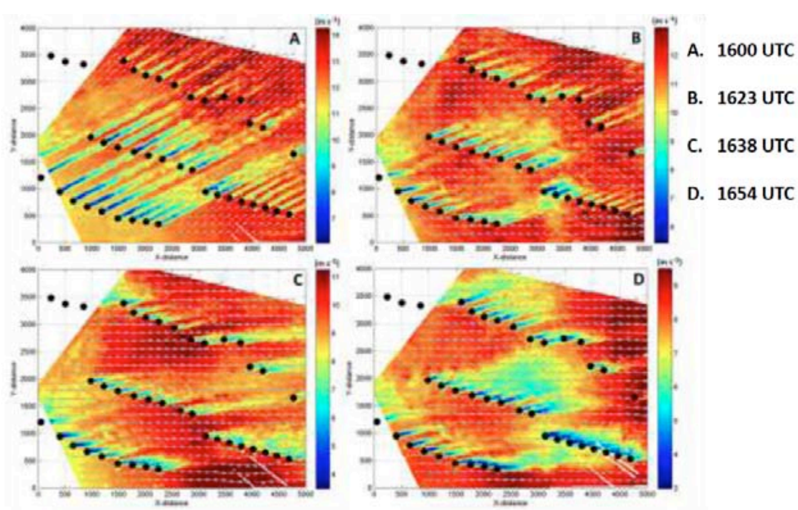
Doppler Radar Measurements of Windplant

Single turbine; Hirth, Schroeder, Guynes (2013)



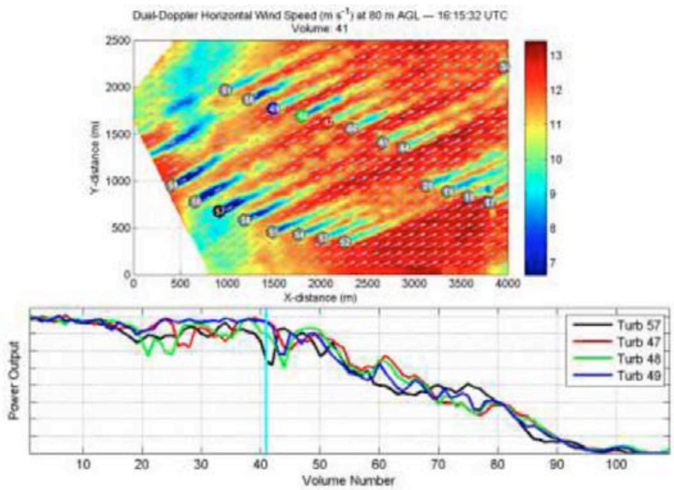
Doppler Radar Measurements of Windplant

Effect of atmospheric/wind conditions; Hirth, Schroeder, Guynes (2013)



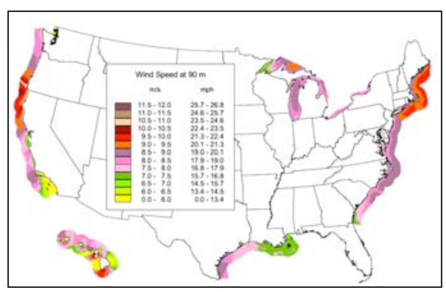
Doppler Radar Measurements of Windplant

Wake effect on turbine power performance; Hirth, Schroeder, Guynes (2013)



Offshore

- U.S. gross offshore wind resource: 4,000 GW
  - East Coast, West Coast, Gulf Coast, and Great Lakes
  - Large, aerodynamically clean resource
  - Near load centers
  - ~74% on > 30 m deep water
- No U.S. offshore plants
- Globally, little deep water experience

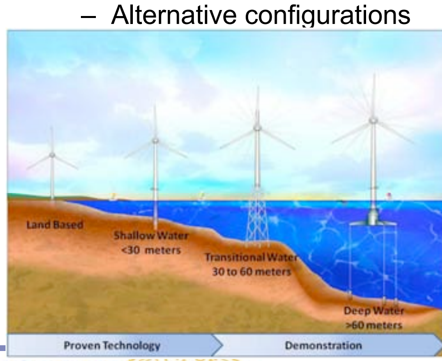


Schwartz et al., NREL

van Dam

Offshore: Opportunities & Challenges

- Vast resource
- Near load centers
- Low turbulence
- Potentially less visual/acoustic impact
  - Alternative configurations



- Higher capital and O&M costs
  - Draw upon design innovations to reduce cost of energy
- Moorings/floating platforms for deep water
- More complex structural dynamics: coupled wave-wind interaction
- Underwater transmission
- New regulatory processes
- New environmental considerations

Departing Thoughts

- Wind power is a mature and viable power generation technology
  - Global: 283 GW
  - U.S.: 60 GW
- There are still opportunities to do better:
  - Better turbines: advanced blades & rotor
  - Better operations: optimized windplants
  - Better grid integration: forecasting
  - Reaching better wind resources: offshore

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