Overview: Wind Energy Technology Fundamentals, the 20% Scenario, and Innovation Opportunities

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Purdue University
April 8, 2010
Sandia National Laboratories
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• Safety, security and reliability of our nation’s nuclear weapons stockpile

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>7000 in New Mexico

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Livermore, California
Kauai, Hawaii
Yucca Mountain, Nevada
WIPP, New Mexico
Pantex, Texas
Tonopah, Nevada
Outline

• Wind Turbine design evolution
• Typical modern turbine
• How it works:
  ✓ Limitations
  ✓ Opportunities
• 20% wind scenario
• Efforts to enhance the technology
Evolution of U.S. Commercial Wind Technology

**The 1980's**
- Altamont Pass, CA Kenetech 56-100kW 17m Rotor
- Altamont Pass, CA Kenetech 33-300kW 33m Rotor

**The 1990's**
- Buffalo Ridge, MN Zond Z-750kW 46m Rotor
- 500kW
- 300kW

**2000 & Beyond**
- Arklow, Scotland GE 3.6MW 104m Rotor
- 5 MW
- 2.5 MW
- 1.5 MW

- Hagerman, ID GE 1.5 MW 77m Rotor
- Medicine Bow, WY Clipper 2.5MW 93m Rotor
- 3.6 MW
- Land Based

- Offshore

Rotor Diameter in meters

Wind Power – large and small

Small Wind (1-100 kW)

Utility-Scale Wind (1-5 MW)

American Wind Energy Association
www.awea.org
Small Wind Turbines Are Different

• Utility-Scale Wind Power
  1,000-3,000 kW wind turbines
  – Installed on wind farms, 10–700 MW
  – Interconnected to transmission
  – Professional maintenance crews
  – Class 4-6 (quality) wind resource

• Small Wind Power
  up to 100 kW wind turbines
  – Installed at individual homes, farms, businesses, schools, etc.
  – Interconnected to distribution, on the “customer side” of the meter
  – Few moving parts, high reliability, low maintenance
  – Class 2-4 (marginal) wind resource

Energy Overview - 8

Courtesy Jim Green, NREL
Example Small Wind Systems

Bergey Windpower

BWC XL.1
1 kW, 8.2 ft Dia.
Battery-Charging

Southwest Windpower

Skystream 3.7
1.8 kW
12 ft Dia.
Grid-Connect

Northern Power Systems

Endurance Wind Power Inc.

Endurance S-250
4.25 kW, 18 ft Dia.
Grid-Connect

NorthWind 100/21
100 kW, 69 ft dia.
Grid-Connect

Courtesy Jim Green, NREL
The Change from Small Machines to Large Multi-Mega-Watt Machines

- **Above**: Tehachapi, CA – 65kW, 900kW, and 3MW machines
- **Left**: Palm Springs, CA – field of 65kW with four larger machines in foreground (~750kW)
GE 1.5 MW machines in Fort Sumner, NM and Bonus (Siemens) 2.0 MW machines in Copenhagen Harbor
Logistics become difficult as size increases

45-meter Blade Fatigue Test at NREL/NWTC

50-meter Blade Transport

Courtesy of LM Glassfiber
Typical Modern Turbine
Current Wind Turbine Systems

Conventional Drive Train
- Hub
- Gear Box
- Generator
- Tower
- Blade

Direct Drive System
- Pitch System
- Yaw System

1. Main Carrier
2. Yaw Motors
3. Ring Generator
4. Blade Adaptor
5. Rotor Hub
6. Rotor Blade
Typical Wind Farm Components

- Turbine
- Foundations
- Electrical collection
- Power conditioning
- Substation
- SCADA
- Roads
- Maintenance facilities
Bottom Up Wind Capital Costs (current on-shore)

64% Turbine
25% Balance of Plant
7% Developer
4% Transportation

Notes: 100MW Wind Power Plant; Flat terrain w/ easy access and good geotechnical conditions; Nominal technology MMW Wind Turbine price; 10% BOP contingency inclusive
Reported Capacity Factors - Trends

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<table>
<thead>
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<td>20</td>
<td>25</td>
<td>25</td>
<td>25</td>
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<tr>
<td># MW</td>
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<td>875</td>
<td>1,741</td>
<td>1,911</td>
<td>2,455</td>
</tr>
</tbody>
</table>

Source: Berkeley Lab database

CF = Average Output/ Rated Power
```
Rising prices are caused by:
- Weak Dollar
- Growing commodity prices
  - steel
  - copper
  - concrete
- Limited availability of machines (seller’s market)
20% Wind Energy by 2030

- The Scenario
- Costs
- Benefits
- Summary
The 20% Technical Report

- Explores one scenario for reaching 20% wind energy by 2030 and contrasts it to a scenario in which no new U.S. wind power capacity is installed
- Is not a prediction, but an analysis based on one scenario
- Does not assume specific policy support for wind
- Is the work of more than 100 individuals involved from 2006 - 2008 (government, industry, utilities, NGOs)
- Analyzes wind’s potential contributions to energy security, economic prosperity and environmental sustainability
20% Wind by 2030 Scenario Requires 300 GW

Cumulative Installed Capacity (GW)

- Offshore
- Land-based

20% by 2030 Scenario

Actual
Resource Potential Exceeds Total Electricity Demand

2010 Costs w/o PTC, w/o Transmission or Integration costs
Energy Overview

Onshore
- Class 7
- Class 6
- Class 5
- Class 4
- Class 3

Offshore
- Class 7
- Class 6
- Class 5
- Class 4
- Class 3

Cost of Wind and Transmission: Economically Available

10% of existing transmission capacity available to wind

Levelized Cost of Energy, $/MWh

Needed for 20%

Quantity Available, GW
46 States Will Have Wind Development by 2030 under the 20% Wind Scenario

The black open square in the center of a state represents the land area needed for a single wind farm to produce the projected installed capacity in that state. The brown square represents the actual land area that would be dedicated to the wind turbines (2% of the black open square).
Need for New Transmission: Existing and New in 2030
Economic Costs of 20% Wind Scenario

Incremental investment cost of 20% Wind Scenario

- **2% investment difference between 20% Wind and No New Wind**

- $60 Billion additional Transmission cost

- $43 Billion net additional cost
Most area available for farming or grazing
CO₂ Emissions from the Electricity Sector

- No New Wind Scenario CO₂ emissions
- 20% Wind Scenario CO₂ emissions
- USCAP path to 80% below today’s levels by 2050

CO₂ Emissions in the Electric Sector (million metric tons)

2006 2010 2014 2018 2022 2026 2030
Significant Water Use Savings

Cumulatively, the 20% Wind Scenario would avoid the consumption of 4 trillion gallons of water through 2030.

The 20% Wind Scenario cuts electric sector water consumption by 17% in 2030.
<table>
<thead>
<tr>
<th>Summary: Costs &amp; Benefits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Incremental direct cost to society</td>
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<tr>
<td></td>
</tr>
<tr>
<td>Reduction in emissions of greenhouse gasses and avoided carbon regulation costs</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Reduction in water consumption</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Jobs supported and other economic benefits</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Reduction in nationwide natural gas use and likely savings for all gas consumers</td>
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<tr>
<td></td>
</tr>
</tbody>
</table>

Sources: DOE, 2008 and Hand et al., 2008

Note: All dollar values are in NPV
Technology Fundamentals
Measuring and Modeling Dynamic Stall and Unsteady Aerodynamics

Visualizing the flow through the rotor

NASA Ames 80' by 120' Wind Tunnel Test

Smoke Test

Field Test
Wind Power Basics

\[
\text{WindPower} = \frac{1}{2} \rho A C_P V^3
\]

\[C_{P \text{ max}} \approx 0.3\] (Drag)

\[C_{P \text{ max}} \approx 0.59\] (Lift)

The Betz Limit

Wind Power output is proportional to wind speed cubed.

Courtesy Jim Green, NREL
Energy Overview

Turbine Power: What is available and what is useable?

Regions of the Power Curve

Region I – not enough power to overcome friction
Region II – Operate at maximum efficiency at all times
Region III – Fixed power operation

“Rated Power” governs the size and cost of the entire turbine infrastructure
<table>
<thead>
<tr>
<th>Wind Power Class</th>
<th>Resource Potential</th>
<th>Wind Power Density at 50 m W/m²</th>
<th>Wind Speed at 50 m m/s</th>
<th>Wind Speed at 50 m mph</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fair</td>
<td>300 - 400</td>
<td>6.4 - 7.0</td>
<td>14.3 - 16.7</td>
<td>47.6 - 53.8</td>
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<tr>
<td>Good</td>
<td>400 - 500</td>
<td>7.0 - 7.5</td>
<td>15.7 - 16.6</td>
<td>56.0 - 60.7</td>
</tr>
<tr>
<td>Excellent</td>
<td>500 - 600</td>
<td>7.5 - 8.0</td>
<td>16.8 - 17.9</td>
<td>60.4 - 67.0</td>
</tr>
<tr>
<td>Outstanding</td>
<td>600 - 800</td>
<td>8.0 - 8.8</td>
<td>17.9 - 19.7</td>
<td>67.0 - 75.0</td>
</tr>
<tr>
<td>Superb</td>
<td>800 - 1600</td>
<td>8.8 - 11.1</td>
<td>19.7 - 24.8</td>
<td>75.0 - 90.3</td>
</tr>
</tbody>
</table>

Wind speeds are based on a Weibull k value of 2.0.

Best National Map ~ 2002

U.S. Wind Resource Maps (50 meter elevation)

Copyright © 2008 3TIER, Inc. All Rights Reserved. For permission to reproduce or distribute: info@3tiergroup.com

5km Wind Map at 80m

Copyright © 2008 3TIER, Inc.
The wind resource is much better as you go higher above ground.
Performance Enhancement Options

Power Curve

Resource

Energy

Larger Rotor

Rotor costs increase with diameter cubed, Rotor power grows with the diameter squared

Taller Tower

Tower costs increase with height to the fourth power (constrained base diameter)

Greater Output

The cost benefits are constrained by the squared-cubed law

We can only win this battle if we build rotors that are smarter and components that are lighter to beat the squared-cubed law.
Wind Turbine Rotor Design Challenge

Numerous existing manufacturers of large composite structures in Military and Aerospace Technology/Expertise does not generally transfer

<table>
<thead>
<tr>
<th>High-end military</th>
<th>Commercial Aerospace</th>
<th>Wind Turbine Blade</th>
</tr>
</thead>
<tbody>
<tr>
<td>~ $1000/lb</td>
<td>~ $100/lb</td>
<td>~ $6/lb</td>
</tr>
<tr>
<td>$10^6$ cycles</td>
<td>$10^6$ cycles</td>
<td>$10^8$ cycles</td>
</tr>
</tbody>
</table>
Technology Challenges from the 20% Report

**Challenges:**
- Cost of Energy (Capital Cost / Energy Production)
- Reliability and Maintenance Cost
- Public acceptance and Investor Confidence

**Potential Impact from Rotor Enhancements:**
- Greater energy capture on a given tower/drivetrain
- Lower tower-top mass for given rotor size
- Lower Cost of Energy (COE)
- Increased deployment of wind power
Technology Advancements Under Sandia’s Blade Program

- **Prototype Sub-scale Blades Manufactured (9 meters)**
  - **CX-100**
    - Carbon spar cap
    - Glass skin and shear web
  - **TX-100**
    - Carbon triax in skin for passive bend-twist coupling
  - **BSDS (Blade System Design Study)**
    - Flatback airfoils
    - Carbon spar cap
    - Constant spar cap thickness

**TX-100 skin w/ off-axis carbon fiber**

- **Graph**
  - X-axis: Span (m)
  - Y-axis: Weight (lbs)
  - Data points:
    - ~1990
    - 2002
    - 2004
    - 2004
    - 2005
  - Materials:
    - SER18
    - ERS
    - CX
    - TX
    - BSDS
Previous Load Control Concepts

*Past work has investigated blade load control*

- Individual blade pitch (rather than collective)
  - Pitches entire blade (slow response)
  - Responds to some “average” blade load
  - Current “state-of-the-art” in industry research

- Passive bend/twist or sweep/twist blade load control (load causes blade to twist and reduce load)
  - Response fixed at time of design
  - Unable to tailor to specific site/wind conditions

STAR Sweep-Twist Coupled Blade

**PASSIVE BEND-TWIST COUPLED BLADE**

*Courtesy: NREL*
Knight & Carver Swept (STAR) Blade
Investigate use of distributed active aerodynamic load control devices to reduce locally fluctuating blade loads

• Improved load control capability
  – Respond to loads at locations along blade
  – Respond to site-specific conditions

• Utilize full system dynamic simulations
  – Analyze system response
  – Develop control system

• Develop prototype control devices
  – Microtabs, microflaps, morphing trailing edges
  – Fast response, low loads
  – Study impact on flow field (UC Davis)
    • Analytical (2-D and 3-D CFD)/experimental
Load Control Decreases Blade Motion & Fatigue
Grow the Rotor (GTR) Concept

Comparable Blade Flap Fatigue Damage – 1.5MW
Typical Offshore Wind Turbine

Credit: GE Energy

Horns Rev

The Horns Rev Turbine

Principal Components and Dimensions of an Offshore Wind Turbine

Graphic courtesy of Horns Rev wind project, Denmark (http://www.hornsrev.dk). Copyright Etables A/S.
Why Offshore Wind?

Land-based sites are not close to population centers

Cities are close to offshore wind sites

28 coastal states use 78% of the electricity in US

US Population Concentration

28 coastal states use 78% of the electricity in US

U.S. Offshore Wind Resource

Offshore Wind Resource Estimates

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<tbody>
<tr>
<td>2</td>
<td>200 - 300</td>
<td>5.6 - 6.4</td>
<td>12.5 - 14.3</td>
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<td>3</td>
<td>300 - 400</td>
<td>6.4 - 7.0</td>
<td>14.3 - 15.7</td>
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<td>4</td>
<td>400 - 500</td>
<td>7.0 - 7.5</td>
<td>15.7 - 16.8</td>
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<td>5</td>
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*Wind speeds are based on a Weibull k value of 2.0

Graphic Credit: Bruce Bailey  AWS Truewind

Individuals per Square Mile

- greater than 1,000
- less than 1
Offshore Wind Turbine Development for Deep Water

- **Onshore Wind Turbine**
- **Monopile Foundation**
  - depth: 0 – 30 m
- **Tripod Fixed Bottom**
  - depth: 20 – 80 m
- **Floating Structure**
  - depth: 40 – 900 m
### Floating Wind Turbines

**Technical data**

- **WTG:** 2,3 MW
- **Turbine weight:** 138 tonnes
- **Turbine height:** 65 m
- **Rotor diameter:** 82.4 m
- **Draft hull:** 100 m
- **Displacement:** 5300 m³
- **Diameter at water line:** 6 m
- **Diam. submerged body:** 8.3 m
- **Water depths:** 120-700 metres
- **Mooring:** 3 lines

Statoil/Hydro (Norway) tested a floating system in 2009.
Grid Integration and Transmission
Wind Grid Integration and Transmission Challenges

• Inability to dispatch
  – Weather determines output

• Variability
  – Makes it more difficult to balance load

• Uncertainty
  – Can be forecasted to a large extent

• Different electrical characteristics
  – Lower inertia, voltage tolerance, reactive controls
  – Still compatible with the grid
Wind Turbine Technology Advancements

• **Low-Voltage Ride-Through**
  – Wind plants can contribute to system stability during a disturbance

• **Voltage Control Capability**
  – Capable of supplying reactive power at the point-of-interconnection

• **SCADA Integration**
  – Ability to provide frequency response

• **Wind Forecasting**
  – Reduces wind output uncertainty by using wind forecasts that incorporate meteorological data
  – Allows operators to anticipate wind generation levels and adjust other generators output
Balancing Area Size and Flexibility

• **BA functions**
  – Balance demand (load) & supply (generation)
  – Support interconnection frequency
  – Maintain desired level of interchange with other BAs

• **Larger BAs are generally more efficient**
  – More flexibility
  – BA consolidation being explored in some areas

Source: NERC
Geographic Diversity

- Substantially reduces short-term and long term variability
Cost of Wind Integration...

... can be broken down by time scale.
### Cost of Wind Integration is <0.5 cents/kWh

Source: UWIG

<table>
<thead>
<tr>
<th>Date</th>
<th>Study</th>
<th>Wind Capacity Penetration (%)</th>
<th>Regulation Cost ($/MWh)</th>
<th>Load Following Cost ($/MWh)</th>
<th>Unit Commitment Cost ($/MWh)</th>
<th>Gas Supply Cost ($/MWh)</th>
<th>Total Oper. Cost Impact ($/MWh)</th>
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<td>31**</td>
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<td>4.41**</td>
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<tr>
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<td>2.65</td>
<td>1.06</td>
<td>na</td>
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</tr>
</tbody>
</table>

* 3-year average; total is non-market cost

** highest integration cost of 3 years; 30.7% capacity penetration corresponding to 25% energy penetration; 24.7% capacity penetration at 20% energy penetration

*** found $4.37/MWh reduction in UC cost when wind forecasting is used in UC decision
Grid Issues: Summary

• Grid Integration of wind has technical and cost impacts
  – Reasonable 25% penetration level by energy
  – Dedicated “backup generation” or storage **not required**

• Things that can be done to reduce impacts
  – Geographical diversity
  – Better forecasting and implementation in operations
  – Larger balancing areas
  – More flexibility with generation (and load)
  – Perform detailed wind integration studies
WHAT DO PEOPLE REALLY CARE ABOUT?
Bird Collisions & Mortality

- Problem documented in Altamont Pass
  - One of nation’s largest concentrations of federally-protected raptors
  - Abundant prey base (migration path)
  - Heavy year-round raptor use
Acoustic Emission: Noise

- Jet airplane: 150 dB
- Industrial noise: 140 dB
- Inside car: 130 dB
- Home: 120 dB
- Bedroom: 110 dB
- Falling leaves: 100 dB
- Pneumatic drill: 90 dB
- Stereo music: 80 dB
- Office: 70 dB
- Wind turbine: 60 dB
- Whispering: 50 dB
- Falling leaves: 40 dB
- Home: 30 dB
- Bedroom: 20 dB
- Inside car: 10 dB
Benefits of Wind Power

- Economic Development
  - Jobs, lease payments, tax revenue

- Cost Stability

- Resource Diversity
  - Domestic, inexhaustible, reduced risk

- Environmental
  - no CO$_2$, SO$_2$, NO$_x$, mercury
  - no mining or drilling
  - no water use
World-Wide Growth in Energy Demand Will Require all Available Energy Technology Options Integrated into a System

- A complete portfolio of supply options: renewables, fossil, nuclear
- Highly efficient and environmentally benign technologies
- Fault-tolerant, self-healing infrastructures
- Enhance physical and cyber security and safety
Questions?

The view from 250 feet…

… is encouraging