The Evolution and Future of Wind Energy

Colorado Renewable Energy Society

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Early U.S. Prototype Utility-Scale Wind Turbines

The Smith-Putnam Wind Turbine
1941-45 1250 kW
Source: SERI/CP-635-1273

Source: DOE Wind Program
Evolution of U.S. Commercial Wind Technology

**The 1980's**
- Altamont Pass, CA Kenetech 56-100kW 17m Rotor
- Induction Generator
- 1st Variable Speed Turbine

**The 1990's**
- Altamont Pass, CA Kenetech 33-300kW 46m Rotor
- Buffalo Ridge, MN Zond Z-750kW 67m Rotor
- Power Converter Technology Matured

**2000 & Beyond**
- Arklow, Scotland GE 3.6MW 104m Rotor
- Hagerman, ID GE 1.5 MW 77m Rotor
- First Grid Friendly Converters
Installed Cost becomes Competitive

Decade of Rapid Technology Evolution

- California & federal capital subsidy + high electricity prices/SO4 contracts, with strong DOE R&D support
- PTC driven California with technology R&D by DOE
- Breakout of CA to National with DOE support and PTC

Note: 2012 data represent preliminary cost estimates for a sample of 20 projects totaling 2.6 GW that have either already been or will be built in 2012, and for which substantive cost estimates were available.

Source: Berkeley Lab (some data points suppressed to protect confidentiality)
Wind Power Purchase Agreement (PPA) Prices Today
(PPA - price that wind plant operators sell energy)

Note: Size of "bubble" is proportional to project nameplate capacity

Source: Berkeley Lab

Figure 45. Levelized wind PPA prices by PPA execution date and region
Wind is the Cheapest Unsubsidized LCOE

LAZARD’S LEVELIZED COST OF ENERGY ANALYSIS—VERSION 9.0

Unsubsidized Levelized Cost of Energy Comparison

Certain Alternative Energy generation technologies are cost-competitive with conventional generation technologies under some scenarios; such observation does not take into account potential social and environmental externalities (e.g., social costs of distributed generation, environmental consequences of certain conventional generation technologies, etc.) or reliability-related considerations (e.g., transmission and back-up generation costs associated with certain Alternative Energy technologies).

![Graph showing Levelized Cost of Energy Comparison](image)

Source: Lazared estimates.

Note: Here and throughout this presentation, unless otherwise indicated, analyses assume 60% debt at 8% interest rate and 40% equity at 12% cost for both conventional and Alternative Energy generation technologies. Assumes diesel price of ~$2.50 per gallon, Northern Appalachian bituminous coal price of ~$2.00 per MMBtu and a natural gas price of ~$3.50 per MMBtu for all applicable technologies other than Natural Gas Reciprocating Engine, which assumes ~$5.50 per MMBtu. Analysis does not reflect potential impact of evolving regulations/rules promulgated pursuant to the EPA’s Clean Power Plan. See following page for footnotes. Denotes distributed generation technology.
Figure 5. Location of wind power development in the United States.
World Wide Annual Wind Energy (as % of national annual energy consumption)

Source: Berkeley Lab estimates based on data from Navigant, EIA, and elsewhere

Figure 4. Approximate wind energy penetration in the countries with the greatest installed wind power capacity
In 2008 the question was is it possible to deploy 20% Wind Energy by 2030

www.eere.energy.gov/windandhydro
US Goal = 20% or 300 GW by 2030

Cumulative Installed Capacity (GW)

- **Offshore**
- **Land-based**

China’s Goal

US DOE Goal

US Actual

China’s Actual

2000 2006 2012 2018 2024 2030
Now in 2015 the question is how to get to 80% Renewables by 2050?

Department of Energy and industry collaborated on answer

http://www.energy.gov/ee/re/wind/maps/wind-vision
The Outcome of the RE Futures Study
[nrel.gov/analysis/re_futures/]

- A mix of generation will be required
- A higher percentage of the generation mix will be “variable” (i.e. power varies as the wind or solar varies)
- More variable generation requires utilities to predict both power available AND power required (“load”)
But More Renewables Requires Less Coal

- Load growth is expected to level off in the future
- Coal generation must reduced to make head room for renewable generation
- Less coal is essential for any greenhouse warming solution
RE generation from technologies that are commercially available today, in combination with a more flexible electric system, is more than adequate to supply 80% of total U.S. electricity generation in 2050 while meeting electricity demand on an hourly basis in every region of the country.
What about Grid Stability?
Technology advancements supporting integration

- DONG Energy (Largest EU Wind Operator):
- International transmission agreements (DK, DE, SE, NO)
- Up/down ramp control
- Grid standards critical
- Dispatch agility
- Forecasting
- NextEra: (largest in US)
- Curtailment Control
- Voltage Control
- Frequency Response
- Voltage Droop
- VAR regulation
- Load Control

![SCADA Control Functions For Improved Grid Operations](image)
Forecasting Wind is key to agile dispatching

Forecast Accuracy:
- Day ahead forecast uncertainty within 15% of actual generation.
- 2-hour forecast more accurate than 5% of actual.
Technology: It’s All About the Cost of Energy

1. The Basic Equation: (Levelized cost of energy or “LCOE”)

   \[
   \text{Levelized Cost of Energy (“LCOE”)} = \frac{\text{Turbine Cost including BOS and Installation} + \text{Cost of Capital} + \text{Operations & Maintenance Costs}}{\text{Annual Energy Produced (kWh)}}
   \]

2. Economic Harvesting Of More Challenging and Low Wind Sites

   - Bigger rotors (low speed) = **High TORQUE**
   - Greater reliability = **REDUCE O&M**
   - Easier to repair = **REDUCE O&M**
   - More Efficient = **INCREASE AEP**
Large Blades must be Low Cost and Reliable

New Large Blade Test Facility:
- Boston, MA with Massachusetts Technology Collaborative
- Static and Fatigue tests of blades up to 90 m
- NREL staff to operate facility

Large Blade Structural Testing
- NREL has developed and patented advanced blade testing
- NREL supports R&D blade testing for DOE and industry
- Supporting development of new blade test facilities worldwide
TPI Builds Wind Turbine Blades

- BIG Wind Turbine Blades!
- And the trend is BIGGER.
  - The goal, as always, is lower Levelized Cost of Energy (LCOE)
  - \( \text{LCOE} = \frac{\text{Costs}}{\text{AEP}} \) and Annual Energy Produced (AEP) scales with rotor size.
  - Blade Swept Area: \( \pi \times R^2 \) where \( R = \text{Blade Length} \)
- As a manufacturer we see blades designs continuously being extended for a fixed asset
Technology Trends: Wind Turbine Blades

• Materials with higher specific performance for spar caps
  – H-Strand ("high" modulus) glass
  – Carbon fiber

• Pultruded Plates for Spar Caps
  – Reduced Cycle time
  – Lower cost
  – Higher axial performance vis-à-vis infusion of NCF’s

• Thermoplastic matrix materials

• Segmented blades for field level assembly
  – Reduce cost of transportation/logistics
  – Enable continued blade growth for land-based operations

• Embedded Systems & Active Control Elements
• Passive aero-elastic tailoring for load reduction
• Direct to mold tool manufacturing
  – 3D Printing: Big Area Additive Manufacturing
Tall Towers and Onsite Manufacturing

- Taller towers = greater energy production
- Transportation constraints
- Onsite manufacturing relieves transportation constraints but present quality mfg. challenges
Drivetrain Reliability is Key to LCOE.
Major Improvements from DOE Industry Research Collaborative

Goals:
• improve reliability,
• find design process gaps,
• educate

Approach:
• Analysis/dyno tests/field tests
• Gearbox failure data base
• Industry & National Lab participation
  ✓ operators,
  ✓ maintenance,
  ✓ OEMs,
  ✓ designers,
  ✓ consultants,
  ✓ suppliers
Next Generation: Direct Drive Generators

- Simplicity = reliability
- Slow rotor speed requires larger generator diameter & high torque
- One large generator rotor vs many smaller gears and bearings
- If weight and size can be controlled Direct Drives will be the winner

The BWP Generator

Traditional Generator
Offshore Wind: Why?

Land-based sites are not close to coastal load centers

Load centers are close to offshore wind sites

28 Coastal States Use 78% of Electricity

Population Density of the Conterminous United States

US Population Concentration

U.S. Wind Resource

Offshore Wind Resource Estimates

Wind Power Classification

<table>
<thead>
<tr>
<th>Wind Power Class</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>
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<td>5.6 - 6.4</td>
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<td>7.5 - 8.0</td>
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<td>8.8 - 11.1</td>
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Wind speeds are based on a Weibull k value of 2.0

Graphic Credit: Bruce Bailey  AWS Truewind
<table>
<thead>
<tr>
<th>Land-based</th>
<th>Shallow Water</th>
<th>Transitional Depth</th>
<th>Deepwater Floating</th>
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<tbody>
<tr>
<td>Offshore Wind Technology</td>
<td>Development</td>
<td>No exclusions assumed for resource estimates</td>
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</table>

- Shallow Water: 0m - 30m, 430 - 450 GW
- Transitional Depth: 30m - 60m, 541 - 601 GW
- Deepwater Floating: 60m - 900m, 1533 - 1543 GW
Offshore: Opportunities & Challenges

Horn’s Rev

- Picture used by permission of Uni-Fly A/S.

- Power performance and reliability influenced reduced in arrays.
- Understanding inflow / array interaction is key.
- Atmospheric Stability and Wind Shear profiling
- Computational models, control paradigms and hardware development will be required.
Avian (Bird) Research

- Extensive research on avian impact.
- Insignificant impact on mortality
- Significant positive benefit on habitat preservation
- Managed by careful site assessment, selection & mitigation

Nysted Windfarm - Denmark

Tracks of water foul avoiding offshore wind turbines

Bird mortality causes

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<tr>
<th>Mortality Cause</th>
<th>U.S.</th>
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<tr>
<td>Birds killed per year</td>
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ESTIMATED NUMBER OF BIRDS KILLED PER YEAR
Thank You

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