Wind Energy Systems

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U.S electricity flow, 2005

Unit is in quadrillion BTU
Energy can be used for a wide variety of purposes:

- Electricity generation
- Transportation
- Heating

Electricity net generation by source

Electricity from wind was 0.3% of total (2003)

In 1989, wind generated 2.1 billion kWh
In 2003, wind generated 11.2 billion kWh
In 2005, wind generated 14.6 billion kWh

Total electricity generation in 2003 and 2005 is around 3800 billion kWh
Death Attributed to Coal Burning Power Plants

Texas Energy Picture

- Oil production peaked in 1972
- Texas became a net energy importer in 1993
- 5th largest energy user in the world
- Texas accounts for 12% of U.S. energy consumption, why?
  - 60% of US petrochemical production
  - 25% of US refining capacity
  - 19 million automobiles
  - 22 million population
Texas Energy Picture

- Annual growth in electrical use averaged +3.5% over last 10 years
- 437 electric generating plants
- Electric generating capacity
  - Natural gas 49%
  - Coal 39%
  - Nuclear 10%
  - Renewable* 2%

US Wind Energy Outlook

- Total electricity generation in 2002: 3,800 billion kWh = 3,800 TWh.
- Total electricity potentially generated by wind: 11,000 billion kWh = 11,000 TWh annually.

| THE TOP TWENTY STATES for wind energy potential, as measured by annual energy potential in the billions of kWhs, factoring in environmental and land use exclusions for wind class of 3 and higher. |
|---|---|---|
| 1 North Dakota | 1,210 | 11 Colorado | 481 |
| 2 Texas | 1,190 | 12 New Mexico | 435 |
| 3 Kansas | 1,070 | 13 Idaho | 73 |
| 4 South Dakota | 1,030 | 14 Michigan | 55 |
| 5 Montana | 1,020 | 15 New York | 82 |
| 6 Nebraska | 866 | 16 Illinois | 61 |
| 7 Wyoming | 747 | 17 California | 59 |
| 8 Oklahoma | 725 | 18 Wisconsin | 58 |
| 9 Minnesota | 597 | 19 Maine | 56 |
| 10 Iowa | 551 | 20 Missouri | 52 |


- Total installed wind energy capacity: 10,039 MW (10 GW).

Renewable Portfolio Standards
Where is the wind?

Region holds > 90% of U.S. Wind Resource

Wind turbine advances

<table>
<thead>
<tr>
<th>Wind Turbine Characteristics</th>
<th>1981</th>
<th>2000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated Capacity (kW)</td>
<td>25</td>
<td>1,650</td>
</tr>
<tr>
<td>Rotor Diameter (m)</td>
<td>10</td>
<td>71</td>
</tr>
<tr>
<td>Total Cost ($)</td>
<td>$65k</td>
<td>$1.3m</td>
</tr>
<tr>
<td>Cost per kW ($)</td>
<td>2,600</td>
<td>790</td>
</tr>
<tr>
<td>Output, MWh/year</td>
<td>45</td>
<td>5,600</td>
</tr>
</tbody>
</table>
Early Wind Turbines

Dr. Charles Brush
17m / 12 kW
1886 – 1908

Jacobs Wind Electric
Battery Charger
c. 1931

First Turbine > 1 MW
53m – 1.25MW
Putnam, VT 1941

First “Grid Tied” turbine
30m – 100kW
Russia 1931

Photos from
“Wind Turbine Technology”
by David A. Speara

Vertical Axis Wind Turbine: Darrieus

Sandia Labs: 17m, experimental

FlowWind 170kW, Altamont Pass, CA
Early (but also new) Wind Farms: Tehachapi, CA

- Early 1980’s – 10 kW
- Late 1990’s > 1.0 MW
- Total 4,600 turbines
- Capacity – 610 MW

Modern Wind Turbines

- Upwind Design
- 3 Fiberglass Blades
- “Cut-in” speed: approx. 5 m/s
- “Rated speed” (max. power output): 11-15 m/s
- “Cut-out”, except for short bursts, > 25 m/s
- Constant RPM, Stall or Pitch regulated
- Tip speeds 130-190 mph
- Technologies:
  - Fixed speed (Danish wind turbine): induction gen
  - Variable speed turbines
    - induction
    - doubly-fed
- Power control
  - Aerodynamic stall
  - Active stall
  - Pitch regulated
Modern Wind Turbines

Turbine Output vs Swept Area for misc. Vendors

Data from Vendor Websites

Rotor Diameter: 60 meters
Hub Height: 65 meters
1.3 MW @ 15 m/s

GE WindEnergy 3.6 MW Prototype Turbine in Spain

Boeing 747-200
GE Wind Turbines

Main Data:
- Tower options: 100 - 140m (328 to 459 ft)
- Rotor diameter: 104 m (341 ft)
- Generator capacity: 3600 kW
- Control: Pitch
- Rotor speed: 8.5 – 15.5 Rpm
- Swept area: 7854 m²

Other Technologies

Enercon 30 m & 112 m (4.5MW):
• Direct Drive, no RPM step up transmission
• High Pole Count “Ring Generator”

The Wind Turbine Company:
• 2 Blade, Downwind (self yaw)
• Blade tilting reduces “root” stress
• Guyed Tower, aim to lower cost.

Clipper D-Gen:
• 8 generators
• Reduces gearbox load
• Reduces lost production
• Reduces repair cost

Photos from Vendor Websites or convention booths
Enercon 44: direct drive – sync machines

- Rated power = 900 kW
- Rotor diameter = 44 m
- Hub height = 55 m
- Technology = gearless
- Swept area = 1,521 sqm
- Gen = Synchronous
- Rpm = 12 – 34, variable

Other Technologies

- Clipper “Liberty” Turbine – 2.5 MW
  - 4 Permanent Magnet Generators
  - Power Electronic Inverters
  - Lower Installation & Maintenance Cost
1.3 MW Nacelle (Siemens-Bonus)

Rotor Attach Point

Nacelle with Canopy Open

Gear Box & Hydraulic Brake

1.3 MW Generator

Rotor Components (Siemens)

Hub, Blade attach & Spinner

Angled fins reduce noise, like airplanes

60 meter diameter
Turbine Siting in Arrays

- Turbine Array
- Substation Transformer & Switchgear
- Predominant Wind Direction
- Distribution Lines 13.8-35kV
- Power Grid

Typical Wind Projects

- **Sommerset, PA**
  - 10.4 MW (8 x 1.3 MW)
  - Nordex N-60

- **Stateline** Project (WA-OR)
  - 263.4 MW (400 x 0.66 MW)
  - Vestas V-47

- **King Mountain** (McCamey, TX)
  - 278 MW (214 x 1.3 MW)
  - Siemens (Bonus 62m) + 1 x 3 MW Vestas

- **“Desert Sky”** (Iraan, TX)
  - 160.5 MW (107 x 1.5 MW)
  - GE Turbines
Wind Turbines in Action!

GE 1.5 MW Desert Sky - Iraan, TX
Vestas V80, 2 MW probably Tx
Gamesa 0.85MW Mendota Hills, IL
Gamesa 0.85MW Mendota Hills, IL

Evolution of Commercial U.S. Wind Technology

THE EVOLUTION OF COMMERCIAL U.S. WIND TECHNOLOGY

1980’s
- Structurally stiff
- 3 blade - relaxed yaw design
- Constant speed - constant speed
- Gearless transmission
- Induction generator
- Side door or side tower

1990’s
- Structurally stiff
- 3 blade - relaxed yaw design
- Variable speed - variable speed
- Gearless transmission
- Electric generator
- Larger tower to reduce CCR

Future Innovation
- Drive to larger size
- Advanced blade materials
- sail power transformers
- Composite main shaft
- Durable power electronics
- Higher efficiency
- Larger wind farm
- Energy storage
- Dismantle and reduce larger wind farm
Cost of Energy on Land

1979: 40 cents/kWh

- Increased Turbine Size
- R&D Advances (testing based)
- Manufacturing Improvements

2004: 3.5 to 5.5 cents/kWh at 15 mph sites (30 ft height)

NSP 107 MW Lake Benton wind farm
4 cents/kWh (unsubsidized)

Offshore wind

- Developing offshore deep water resources
- Integrating wind into utility grid
- Opening federal lands to renewable energy production
- Using wind and hydropower to produce hydrogen and clean water.
System Operations with Wind Resources

- Challenge: How to integrate intermittent and unpredictable energy resources into power system operations.

- Variations in wind-plant output may increase the operating cost of the system as a whole
  - The power system must maintain an instantaneous balance between demand and generation.

- How to quantify the operating costs of wind power?

- Consider conventional power system operations:
  - Known variables: fuel availability, unit status, unit operating characteristics, day-ahead market price
  - Unknown variables: load demand → can be predicted with a great accuracy, using historical data, weather conditions, etc.

Major questions

- Do wind plants require backup with dispatchable generation? How to allocate the backup, i.e., reserve capacity? How to quantify the costs?

- How are the routine costs of operating the power system affected by the inclusion of wind power in the mix of generation?

- How do these cost impacts vary with wind power penetration into the entire mix of system generation?

- ETC