What the Characteristics of Wind and Solar Electric Power Production Mean for Their Future

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March 1, 2012
First, some background
Why de-carbonize electric power?

Electric Power CO2 emissions as a percentage of total US CO2 Emissions

Source: U.S. EIA 2011
Why de-carbonize electric power?

Electric Power CO2 emissions in metric tons per MWh

Source: U.S. EIA 2011
US Electrical Net Generation 1950 - 2010

Source: U.S. EIA 2011
45% Demand Growth by 2030?

US Electrical Net Generation

(or more, with plug-in hybrid electric vehicles)

Source: U.S. EIA 2011
30% low-CO$_2$ in 2010

Source: U.S. EIA 2011
What percent of US electricity is now generated by renewables?

10.3 %
US Renewables Net Generation 2010
10.3% of total electric net generation

- Hydro 6.2%
- Wind 2.3%
- Wood 0.9%
- Waste 0.5%
- Geothermal 0.4%
- Solar 0.03%

Source: U.S. EIA 2011
Operating Wind Farms February 22, 2012

Wind farms > 5 MW
Land use can be benign
Or, Not so Benign
Occasionally, the failures are dramatic

Vermont is one of the few US states that requires owners to put aside money for decommissioning old wind farms.

Source: http://www.youtube.com/watch?v=QL-cRuYAxg0
Where the wind is

United States - Annual Average Wind Speed at 80 m

Data are good!
ERCOT 2011 Hourly Wind Output

33.7% Capacity Factor

Source: ERCOT
ERCOT Load and Wind in 2011 Averaged by Hour of the Day

Source: ERCOT data processed by J. Apt
ERCOT Load and Wind in 2011 Averaged by Hour of the Day

Onshore Texas Wind and Load have a correlation of -0.8

Source: ERCOT data processed by J. Apt
Monthly electricity demand and wind generation capacity factors in the Mid-Atlantic Highlands. 
Source: National Research Council
Wind sometimes fails for many days

BPA Balancing Authority Total Wind Generation

Sum of ~1000 turbines

MW

Date in January 2009
15 Days of 10-Second Time Resolution Data

Time (days since 12:00 March 11, 2007)
What is the character of the fluctuations?

What frequencies are present, and at what amplitudes?
Fourier Transform to get the Power Spectrum

Frequency (cycles per second)

- 2.6 Days
- 30 Seconds
2.6 Days

30 Seconds

Frequency $-\frac{5}{3}$

Sensor Noise Floor

Turbine inertia (low-pass filter)

Log (Frequency)

Log (kW)
Frequency $^{-5/3}$

- Turbulent eddies in fluids were predicted in 1941 by Kolmogorov on theoretical grounds to have just such a spectrum.
- First confirmed in 1962 by Grant, Stewart and Moilliet in a tidal channel near Vancouver, over a factor of 100 in frequency.
- Not white noise! Very important implications.
We can learn some important things from the power spectrum.
Smoothing by Adding Wind Farms

Power Spectral Density

Frequency (Hz)

24 Hours

1 Wind Plant
Smoothing by Adding Wind Farms

24 Hours

- 1 Wind Plant
- 4 Wind Plants

Power Spectral Density

Frequency (Hz)
Smoothing by Adding Wind Farms

Two implications from this

1. When we talk about smoothing, the time scale is very important: 12 hours has much less smoothing than 1 hour.

2. The point of diminishing returns from connecting wind plants together is quickly reached.
Smoothing by adding wind farms in ERCOT ... has diminishing returns

Larger areas

- BPA
- CAISO
- MISO
- ERCOT
2009 PSDs for all 4 regions

- Kaimal spectrum
- Sum of all four
- ERCOT
- MISO
- BPA
- CAISO

Power Spectral Density (GW^2/Hz)

Frequency (Hz)

24 h
Does interconnecting regions provide additional smoothing?
Correlation coefficients
2009 and (2008)

<table>
<thead>
<tr>
<th></th>
<th>BPA</th>
<th>CAISO</th>
<th>ERCOT</th>
<th>MISO</th>
</tr>
</thead>
<tbody>
<tr>
<td>BPA</td>
<td>1</td>
<td>0.32</td>
<td>0.04 (0.16)</td>
<td>−0.06 (−0.07)</td>
</tr>
<tr>
<td>CAISO</td>
<td></td>
<td>1</td>
<td>0.02</td>
<td>−0.23</td>
</tr>
<tr>
<td>ERCOT</td>
<td></td>
<td></td>
<td>1</td>
<td>0.24 (0.25)</td>
</tr>
<tr>
<td>MISO</td>
<td></td>
<td></td>
<td></td>
<td>1</td>
</tr>
</tbody>
</table>
Interconnection **does** reduce hour-to-hour step changes.
Estimating the Cost of Wind Power Variability

Time Scale

> 1 Hour

10 Minutes – 1 Hour

< 10 Minutes

Forecast Error

Load Following

Regulation

Variability Costs
Each hour decompose wind energy into the following components:

- **Up Energy**
- **Down Energy**

Wind Energy

*Graph showing the decomposition of wind energy into hourly energy, load following, and regulation components.*

q\text{Forecasted}

↓ Capacity

↑ Capacity

q_H

0 15 30 45 60 min
Hydroelectric Power has Droughts

US Hydroelectric Power Production

Billion kWh

Does wind power have droughts?
Wind Probably Does Too

Capacity Factor

The percent of nameplate energy (MWh) that is actually produced during a year.

ERCOT’s Wind Capacity Factor Varies Yearly

<table>
<thead>
<tr>
<th>Year</th>
<th>Capacity Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>2008</td>
<td>29.2%</td>
</tr>
<tr>
<td>2009</td>
<td>24.4%</td>
</tr>
<tr>
<td>2010</td>
<td>30.3%</td>
</tr>
<tr>
<td>2011</td>
<td>33.7%</td>
</tr>
</tbody>
</table>
Solar

• The Sun deposits on US land 4,000 times the US net electricity generation.
• At 7% efficiency, solar cells (not including packaging) would cover 0.5% of US land area, as compared to 27% cropland.
• Capacity factor: 19% in Arizona, 14% in Ohio, 11% for the PV on the DOE HQ in DC, 15% for USA produced solar as a whole in 2009.
Solar Photovoltaic

Unsubsidized cost is ~ 25 cents per kWh, 4 times the cost of electricity produced by a conventional coal-fired power plant. (32 in PA)

• Price of solar cells has not been decreasing much.

• Solar cells make up only 50-60% of the system price.
Even though it is much more expensive, solar must be better, right?

Work with Dr. Aimee Curtright of CMU (now at RAND)
Comparison of Wind with Solar PV
4.6 MW TEP Solar Array (Arizona)
Capacity Factor: 19%
Comparison of wind and solar PV

What about solar thermal?

New work with Colleen Horin Lueken and Gilbert Cohen

Source for images: Acconia-na.com
We have estimated variability costs, using CAISO prices

<table>
<thead>
<tr>
<th></th>
<th>One ERCOT wind farm</th>
<th>Solar thermal (NSO)</th>
<th>Solar PV (Springerville, AZ)</th>
<th>Solar PV (20 MW+ class)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average capacity factor</td>
<td>34%</td>
<td>23%</td>
<td>19%</td>
<td>25%</td>
</tr>
<tr>
<td>Cost of variability per MWh</td>
<td>$4.3</td>
<td>$5.2</td>
<td>$11.0</td>
<td>$7.9</td>
</tr>
<tr>
<td>Variability cost as a percent of total cost of power (@$42/MWh)</td>
<td>10.2%</td>
<td>11.9%</td>
<td>26.5%</td>
<td>18.9%</td>
</tr>
</tbody>
</table>

Source: CEIC Working Paper CEIC-11-04
Work with Warren Katzenstein

NO\textsubscript{x} and CO\textsubscript{2} Emissions from Gas Turbines Paired with Wind or Solar for Firm Power

GE LM6000
sealegacy.com

Siemens-Westinghouse 501FD
summitvineyardllc.com
Approach

Compensating Power

Variable Power

\[ \text{Variable Power} + 1 + 2 + n = \text{Firm Power} \]

Firm Power

Power

Time

Gas

Wind
Model with GE LM6000

Wind + CT Operating Parameters

- Ideal Fill Power
- Wind Power
- Actual Fill Power

Ramp Rates
Gas Turbine Data Obtained

- NO\textsubscript{x} emissions & heat rate
  - 1 minute resolution
  - 11 days (from 2 501FDs: 200 MW, DLN, SCR)
  - 145 days (from 3 LM6000s: 50 MW, steam NOx control)
  - Data:
    - Gas flow
    - Load (MW)
    - NO\textsubscript{x} ppm and pounds
    - NO\textsubscript{x} ppm corrected to 15% O\textsubscript{2}
    - O\textsubscript{2} %
    - Heat rate (mBtu/hour)
  - From operating gas turbines in a US power company
Siemens-Westinghouse 501FD Regression Analysis

NOx Emitted (lb/min) vs. Power (MW)

GE Document GER-3568G
<table>
<thead>
<tr>
<th>Data Set</th>
<th>Power Plant Type</th>
<th>Data Set Resolution</th>
<th>Data Set Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eastern</td>
<td>Wind</td>
<td>1 second</td>
<td>240 hours</td>
</tr>
<tr>
<td>Northern Great Plains</td>
<td>Wind</td>
<td>10 second</td>
<td>15 hours</td>
</tr>
<tr>
<td>Central Great Plains</td>
<td>Wind</td>
<td>10 second</td>
<td>83 hours</td>
</tr>
<tr>
<td>Southern Great Plains</td>
<td>Wind</td>
<td>10 second</td>
<td>222 hours</td>
</tr>
<tr>
<td>Southwest</td>
<td>Solar</td>
<td>1 minute</td>
<td>732 days</td>
</tr>
</tbody>
</table>
Results

• Penetration $P$ of renewables from 0 to 100%

• Emissions factor (kg of CO$_2$ or NO$_x$ per MWh)

• Expected reductions vs. our model's predictions:
   If the actual system emissions are $M_{\text{gas+renewable}}$ then the fraction of expected emissions reductions that are achieved is
   \[
   \frac{(M_{\text{gas}} - M_{\text{gas+renewable}})}{(M_{\text{gas}} \times P)}
   \]
Emissions Factors

(a) LM6000

LM6000
Steam, no SCR

(b) LM6000

(c) 501FD

501FD
DLN, SCR

(d) 501FD

Final Comments

• Smart integration of large-scale wind or solar will use a portfolio of fill-in power (some with high ramp rates, much more with slow ramp rates).
• The amount of smoothing by interconnection is very dependent on the time scale considered.
• Large area connections don’t substantially change the variability.
• There are likely to be years of good wind, and not such good wind.
• Although solar thermal capital costs are currently higher than PV, variability costs are about half that of PV, comparable to wind.
Thank you.

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