Weather Determined Geographic Characteristics of Wind and Solar Energy Generation Systems

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Study Basics

- Weather Assimilation Model to obtain PV Generation and Wind Generation:
  - RUC 13km 0-hour
  - Hourly
  - 2006, 2007, 2008 (each treated independently)

- Wind and Solar Features
  - Onshore turbines
    - 3 MW each (90 m)
  - Offshore turbines
    - 5 MW each (90 m)
  - PV Utility plants
    - 20 MW each
  - Natural Gas backup
    - Determined by System
  - Nuclear
    - 100.4 GW
  - Hydroelectric Dams
    - 74.4 GW
Rapid Update Cycle (RUC) Hourly Assimilation

Cycle hydrometeor, soil temp/moisture/snow plus atmosphere state variables

11
12
13 Time (UTC)

Hourly obs

<table>
<thead>
<tr>
<th>Data Type</th>
<th>~Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rawinsonde (12h)</td>
<td>150</td>
</tr>
<tr>
<td>NOAA profilers</td>
<td>35</td>
</tr>
<tr>
<td>VAD winds</td>
<td>120-140</td>
</tr>
<tr>
<td>PBL – prof/RASS</td>
<td>~25</td>
</tr>
<tr>
<td>Aircraft (V, temp)</td>
<td>3500-10000</td>
</tr>
<tr>
<td>TAMDAR (V, T, RH) (*)</td>
<td>200-3000</td>
</tr>
<tr>
<td>Surface/METAR</td>
<td>2000-2500</td>
</tr>
<tr>
<td>Buoy/ship</td>
<td>200-400</td>
</tr>
<tr>
<td>GOES cloud winds</td>
<td>4000-8000</td>
</tr>
<tr>
<td>GOES cloud-top pres</td>
<td>10 km res</td>
</tr>
<tr>
<td>GPS precip water</td>
<td>~300</td>
</tr>
<tr>
<td>Mesonet (temp, dpt)</td>
<td>~8000</td>
</tr>
<tr>
<td>Mesonet (wind)</td>
<td>~4000</td>
</tr>
<tr>
<td>METAR-cloud-vis-wx</td>
<td>~1800</td>
</tr>
<tr>
<td>AMSU-A/B/GOES radiances</td>
<td></td>
</tr>
<tr>
<td>– RR only</td>
<td></td>
</tr>
<tr>
<td>Radar reflectivity/ lightning</td>
<td>1km</td>
</tr>
</tbody>
</table>

Electrical Load

Electricity Demand in MW

Y-axis: 0, 1, 2, 3, 4, 5, 6, 7

X-axis: Hours

x100000
Electrical Load

- Electricity load from the three years (2006-2008) is grown using GDP until 2011 and then 0.7% per year to obtain 2030 levels.
- Load split into 16 sub-divisions based on largest cities in each balancing authority.

Price Parameter Space

- Costs parameter space:

<table>
<thead>
<tr>
<th>TECHNOLOGY</th>
<th>LOW</th>
<th>MID</th>
<th>HIGH</th>
</tr>
</thead>
<tbody>
<tr>
<td>ONSHORE WIND</td>
<td>$1.35 / W</td>
<td>$1.61 / W</td>
<td>$1.87 / W</td>
</tr>
<tr>
<td>OFFSHORE WIND</td>
<td>$3.50 / W</td>
<td>$4.15 / W</td>
<td>$4.80 / W</td>
</tr>
<tr>
<td>PHOTOVOLTAICS</td>
<td>$1.23 / W</td>
<td>$2.13 / W</td>
<td>$3.02 / W</td>
</tr>
<tr>
<td>CORRESPONDING NATURAL GAS</td>
<td>$8.63 / mmBtu</td>
<td>$6.60 / mmBtu</td>
<td>$4.56 / mmBtu</td>
</tr>
</tbody>
</table>

- Costs are converted to mortgage costs @ 5% for 30 years. Natural gas capital is $1 / W.
- Transmission costs are $1300 / MW-mile.
Classification Maps

- The type and amount of electricity generation installed in each RUC box is constrained by:
  - Spacing between facilities
  - Topography of the land
  - Land Use (residential, commercial, protected lands, etc.)

Weather Data to Power

- The solar radiation is created by performing a multivariate regression of RUC model data and GOES satellite images.
- The solar realization number is calculated by modeling single axis tracking “standard” PV panels.

  - Regression is done on 13 independent variables: 5 satellites, top of atmosphere radiation, zenith angle and the 6 hydrometeors from the RUC assimilation model.
  - The regressed data is from the seven SURFRAD sites for 2006 – 8.
  - Correlation between the 48,000 data points is 0.9303.
Weather Data to Power

- The wind speed data is interpolated from the RUC assimilation model heights to hub height at 90 m.
- The wind speed is then applied to a generic “power” curve for a 3 MW wind turbine to produce the realization number.

<table>
<thead>
<tr>
<th>Wind Tower Location</th>
<th>50 m height</th>
<th>70 m height</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tower 1</td>
<td>-1.57 m/s</td>
<td>-1.30 m/s</td>
</tr>
<tr>
<td>Tower 2</td>
<td>-0.48 m/s</td>
<td>-0.35 m/s</td>
</tr>
<tr>
<td>Tower 3</td>
<td>-1.38 m/s</td>
<td>-1.19 m/s</td>
</tr>
<tr>
<td>Tower 4</td>
<td>-1.38 m/s</td>
<td>-1.12 m/s</td>
</tr>
<tr>
<td>Tower 5</td>
<td>-1.56 m/s</td>
<td>-0.37 m/s</td>
</tr>
</tbody>
</table>

- Bias calculations performed at 5 wind tower sites.
- The bias calculations suggest that the RUC has a low bias, and as such the RUC data will give a lower estimate of the wind power potential.

Wind Capacity: Fraction of Rated Power realized

Average Wind Capacity Factor - 2006-2008

[Map showing average wind capacity factor across the United States]
Minimization Procedure

- A cost optimization procedure creates a large-scale electricity generation system composed of wind, solar, natural gas backup, with Nuclear and Hydroelectric base load.

- Costs considered:
  - Installing a Wind Farm or Solar PV Utility
  - Natural gas plant installation
  - Natural gas fuel and variable O/M
  - Cost of transmission, both construction and electrical losses

- The cost is subject to:
  - It must meet the load at all times, in all areas
  - The placement of wind and solar must be less than upper bounds
  - Satisfy natural gas reserves requirement
  - Satisfy transmission between nodes
The Minimization Procedure

ALL OTHER EQUATIONS CONSTRAIN THE MAGNITUDE OF ANY OF THE TERMS

Linear Solution of Wind and Solar Installations (MW)
Full CONUS Solution

- Installed capacity:

<table>
<thead>
<tr>
<th>Technology</th>
<th>Capacity (GW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Onshore Wind</td>
<td>975.63</td>
</tr>
<tr>
<td>Offshore Wind</td>
<td>3.21</td>
</tr>
<tr>
<td>Photovoltaic</td>
<td>199.53</td>
</tr>
<tr>
<td>Natural Gas</td>
<td>503.22</td>
</tr>
</tbody>
</table>

TOTAL CAPACITY (INC NUKE & HYDRO): **1886.992 GW**
TODAY: 1137.3 GW [470.3 GW NATURAL GAS]

Full CONUS Solution

- Mean Capacity factors:
  - Onshore Wind: 33.47%
  - Offshore Wind: 51.33%
  - Photovoltaic: 17.29%
  - **Natural Gas**: 19.46%

- Transmission losses: 1.15%
- Electricity production curtailed: 9.81%
Full CONUS Solution

Generation vs Load

- Natural Gas
- Non-fossil fuel generation
- Load

Time (Hrs)

Generation / Load (GW)

Half CONUS Solution

Linear Solution of Wind and Solar Installations (MW)

Map of the United States with wind and solar installations indicated.
What the study demonstrates

- The utilization and cost effectiveness of combined wind and solar power generation is optimized for larger geographic (this scaling is more critical for low gas prices).
- The location of optimal wind and solar generating capacity far from demand would require a upgraded power transmission systems.
- Placement of wind in solar generation in an optimal national system is very different than the current ad hoc bottom-up approach.
- A national wind-solar generation system could supply a large percentage of US power (this is sensitive to costs).
- Such a system would result in large CO2 emission reductions.
What the study does not demonstrate

- Does not show exact locations of wind and solar placement. The resolution of the model is 13 km by 13 km.
- Grid integration is not included in the model.
- Local transmission and distribution is not in the model.
- The cost optimization, by definition, only outputs the most economical system. Other systems with higher and lower utilization can occur in reality.
- The transmission from the model is only a proxy.

QUESTIONS?