Wind, Solar and Geothermal Power: Research at Carnegie Mellon University

Jay Apt

Tepper School of Business and Department of Engineering & Public Policy
Carnegie Mellon University

May 19, 2011
Overview
Carnegie Mellon Electricity Industry Center (CEIC)

• We are in our 10th year
  – Created jointly with A.P. Sloan Foundation and EPRI in August 2001
  Close partnership with industry principals and field-intensive research.

• We define ‘Electricity Industry’ broadly to include the companies that supply the equipment, all the organizations that build and operate the nation’s electric power system, agencies that shape and regulate the system as well as customers who use the power.

• Support
  – 38% from federal & state government, 32% from foundations, 30% from industry.

• 22 Faculty, 29 Ph.D. Students, and 2 post-doctoral fellows.

• 21 PhDs granted.

• 184 peer-reviewed publications (as of June 2010)
Carnegie Mellon is unique…

…in conducting systems studies that combine engineering, economics and regulatory and other analysis that results in policy that really changes the world, because it is sensible, affordable and robust.

184 refereed publications from CEIC as of June 2010.
Examples of recent CEIC research

- **Environmental Science & Technology**
  - Net Air Emissions from Electric Vehicles: The Effect of Carbon Price and Charging Strategies

- **Editors' Choice**
  - Engineering: The Pros (and Cons) of Plugging In
  - The adage out of sight, out of mind has some resonance as the first big crop of plug-in hybrid cars hits the road in the United States. People live and sometimes small gasoline plug-in car into a socket may not seem like the energy is coming from the ether. Of course, power plants actually burn the harder, and Peterson et al. are among the growing number of researchers gauging the implications. They have examined the net effect on carbon, nitrogen, and sulfur emissions of replacing a fraction of load in a number of Eastern and Midwestern U.S. states with plug-in hybrids. They modeled several different scenarios, such as when cars were charged and whether carbon dioxide emissions were priced or captured and sequestered. For a 20% hybrid fleet scenario, they found significant reductions in CO2 emissions across the board, and NOx reductions in most cases. The potential downside was an increase in sulfur dioxide emissions as demand for coal combustion rose. — Dorin, Donald, Sci. Technol. 10, 182, 32-34 (2013).

- **Compensating for wind variability using co-located natural gas generation and energy storage**

- **Foreign Affairs**
  - MARCH/APRIL 2009
  - The Geoengineering Option
  - A Last Resort Against Global Warming?

- **Air Emissions Due To Wind And Solar Power**

- **Implications of Compensating Property Owners for Geologic Sequestration of CO2**

- **Near-Term Implications of a Ban on New Coal-Fired Power Plants in the United States**

- **The variability of interconnected wind plants**

- **Lithium-ion battery cell degradation resulting from realistic vehicle and vehicle-to-grid utilization**

- **The economics of using plug-in hybrid electric vehicle battery packs for grid storage**

- **Large blackouts in North America: Historical trends and policy implications**

- An economic welfare analysis of demand response in the PJM electricity market

- The air quality and human health effects of integrating utility-scale batteries into the New York State electricity grid
The CCSReg Project: Authoritative research-based policy guidance
The RenewElec Project

www.RenewElec.org
Current RenewElec projects

• Network reconfiguration to integrate solar/wind
• Public engagement for EGS
• Grid stability with large-scale wind
• Can demand-side management buffer wind?
• Hurricane risk to offshore wind plants
• Solar-thermal integration cost differences from PV
• The costs of forecast uncertainty
• Balancing area consolidation
• Reserve requirements (using non-Gaussian statistics)
• Environmental implications of coal ramping to follow wind
• Integrated solar – natural gas plants
• G2V
• Decommissioning requirements
Why de-carbonize electric power?

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

Source: U.S. EIA 2009
Why de-carbonize electric power?

Electric Power CO₂ emissions in metric tons per MWh

Source: U.S. EIA 2009
US Electrical Net Generation 1950 - 2009

Trillion kWh


Carnegie Mellon
45% Demand Growth by 2030?

US Electrical Net Generation

(or more, with plug-in hybrid electric vehicles)
What percent of US electricity is now generated by renewables?

10.5 %
US Net Electric Generation 2009

- Coal: 44.7%
- Natural and other gas: 23.6%
- Nuclear: 20.2%
- Hydro: 6.9%
- Wind: 1.8%
- Solar: 0.02%
- Wood: 0.9%
- Geothermal: 0.4%
- Waste: 0.5%

Oil: 1.0%
US Renewables Net Generation 2009
10.5% of total electric net generation

- Hydro: 6.9%
- Wind: 1.8%
- Wood: 0.9%
- Waste: 0.5%
- Geothermal: 0.4%
- Solar: 0.02%
Operating Wind Farms

Wind farms > 5 MW
USA Wind Production

Billion kWh

Land use can be benign
Or, Not so Benign
Land Use Requirements for Electric Power Generation

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.
Data are good!
2008 ERCOT Wind Hourly Output

29.2% Annual Capacity Factor
2009 ERCOT Wind Hourly Output

Installed Wind Capacity
Hourly Wind Output

24.4% Yearly Capacity Factor

MW

Onshore Texas Wind and Load have a correlation of -0.9
Monthly electricity demand and wind generation capacity factors in the Mid-Atlantic Highlands.
Source: National Research Council
Wind sometimes fails for many days
15 Days of 10-Second Time Resolution Data

Power output (MW)

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

Frequency $^{-5/3}$

Turbine upper level of response

Turbine inertia (low-pass filter)

30 Seconds

Sensor Noise Floor

Log (kW)

Log (Frequency)
We can learn some important things from the power spectrum.
Smoothing by Adding Wind Farms

24 Hours

Power Spectral Density

Frequency (Hz)
Smoothing by Adding Wind Farms

24 Hours

Power Spectral Density

Frequency (Hz)
Smoothing by Adding Wind Farms

![Graph showing power spectral density vs. frequency for different number of wind plants. The x-axis represents frequency in Hz, and the y-axis represents power spectral density on a log scale. Three curves are shown: 1 Wind Plant, 4 Wind Plants, and 20 Wind Plants. The x-axis ranges from $10^{-7}$ to $10^{-3}$, and the y-axis ranges from $10^{-4}$ to $10^3$.}]
Smoothing by Adding Wind Farms

Smoothing by Adding Wind Farms
... has diminishing returns

Each hour decompose wind energy into the following components:

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

Wind Energy:

- **Load Following Component**
- **Regulation Component**
- **Hourly Energy Component**

Forecasted energy $q_{\text{Forecasted}}$ and $q_H$ are shown in the diagram. Capacity adjustments are indicated by arrows.
Hydroelectric Power has Droughts
Wind Probably Does Too

Operating Solar PV
Units > 5 MW
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)
Solar
Comparison of Wind with Solar PV
4.6 MW TEP Solar Array (Arizona)
Capacity Factor: 19%
Comparison of wind and solar PV

We have data showing that

• Solar thermal has substantially better intermittency characteristics than PV. But, solar thermal capital costs are rising, and solar thermal is now more expensive than PV.
• We are quantifying whether the benefit of smaller intermittency costs makes solar thermal competitive with PV.
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 + 1 + 2 + n = Firm Power

- Variable Power
- Compensating Power
- Firm Power

Diagram:
- Wind power
- Gas power
- Time axis
Model with GE LM6000

Wind + CT Operating Parameters

![Graph showing Power Levels (MW) and Time (hours) with Ideal Fill Power, Wind Power, and Actual Fill Power curves.]

![Graph showing Ramp Rates (MW/min) and Time (hours) with Ramp Rates curve.]

Power Levels (MW)

Ramp Rate (MW/min)

Time (hours)
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
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 Mgas+renewable then the fraction of expected emissions reductions that are achieved is
  \[(M_{\text{gas}} - M_{\text{gas+renewable}}) / (M_{\text{gas}} \times P)\]
Emissions Factors

(a) LM6000

CO₂ Emissions (tonnes/MWh)

0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1

0 0.05 0.1 0.15 0.2 0.25 0.3 0.35

α (Penetration Factor)

Predicted

Expected

LM6000 Steam, no SCR

(b) LM6000

NOₓ Emissions (kg/MWh)

0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1

0 0.05 0.1 0.15 0.2 0.25 0.3 0.35

α (Penetration Factor)

Predicted

Expected

(c) 501FD

CO₂ Emissions (tonnes/MWh)

0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1

0 0.05 0.1 0.15 0.2 0.25 0.3 0.35

α (Penetration Factor)

Predicted

Expected

501FD DLN, SCR

(d) 501FD

NOₓ Emissions (kg/MWh)

0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1

0 0.05 0.1 0.15 0.2 0.25 0.3 0.35

α (Penetration Factor)

Predicted

Expected
Operating Geothermal February 21, 2011

Units > 5 MW
Enhanced Geothermal

1. Cold water is pumped under pressure down an injection well and is heated in the geothermal reservoir.
2. The hot water returns to the surface under pressure.
3. The hot water heats up a secondary working fluid via a heat exchanger.
4. The vapour from that fluid spins a turbine to generate electricity.

The 2% recoverable EGS heat-in-place resource estimates are 2,800 times the 2005 total US energy consumption.*
HAZUS can simulate natural disasters...

- Buildings
- Facilities
- Infrastructure

- Repair & Reconstruction Costs
- Business Interruptions

- Casualties & Injuries
- Shelter Requirements

Physical Damage  
Economic Loss  
Social Impacts

The EGS resources are heterogeneously distributed.
The damage map shows where EGS activity can raise public concerns.

The regions correspond to the high EGS potential regions in purple color in the MIT/Google map.
AltaRock is preparing to drill near Bend, OR*

The map corresponds to the high EGS region in purple in Oregon from the MIT/Google map.

*Source: http://online.wsj.com/article/SB20001424052748704133804575198362283533710.html
Only a small portion of locations involve high DEL and number of injuries

Graph:
- Y-axis: % of Resource Base
- X-axis: $ Million
- Legend:
  - Blue: Direct Economic Loss
  - Green: Injuries

Chart:
- # of People Injured
- Scale: 0 to 30

Inset:
- $ Million scale: 0 to 200
EGS can be deployed in many areas in the US if geothermal power companies and regulatory bodies cooperate with the public to select socially acceptable sites.
CMU Utility-Scale Battery Research

The Device

- Activated carbon
- NaMnO₂

- Anode is low cost activated carbon
  - Electrochemical Double Layer Capacitor Effect
- Cathode is NaMnO₂
  - Alkali ion intercalation material
- Electrolyte is Na₂SO₄ in water (~1 M)
Cycle Life

• Deep discharging of current point design shows little to no fade over 100 cycled to 100% DoD.

• Rapid cycling of indicative coin cell shows stability to at least 5000 cycles.

Round Trip Energy Efficiency

> 95% Energy Efficient Using KEMA Efficiency Test Protocol

• Stable cycle life during internal testing at Aquion
• Cells to be on test at KEMA 3rd week of October
Energy storage is used only to smooth the sharpest wind fluctuations

Eric Hittinger
Average Cost of Electricity is relatively constant over a wide range of wind penetrations for the Wind/Gas/NaS Battery Systems.
Final Comments

• None of this means that wind, geothermal, or solar (if costs ever come down) can't be used at large scale, but wind/solar will require a portfolio of fill-in power (some with very high ramp rates, some with slow) and R&D is required to optimize emissions control for fast and deep ramping.
Thank you.

Jay Apt
apt@cmu.edu