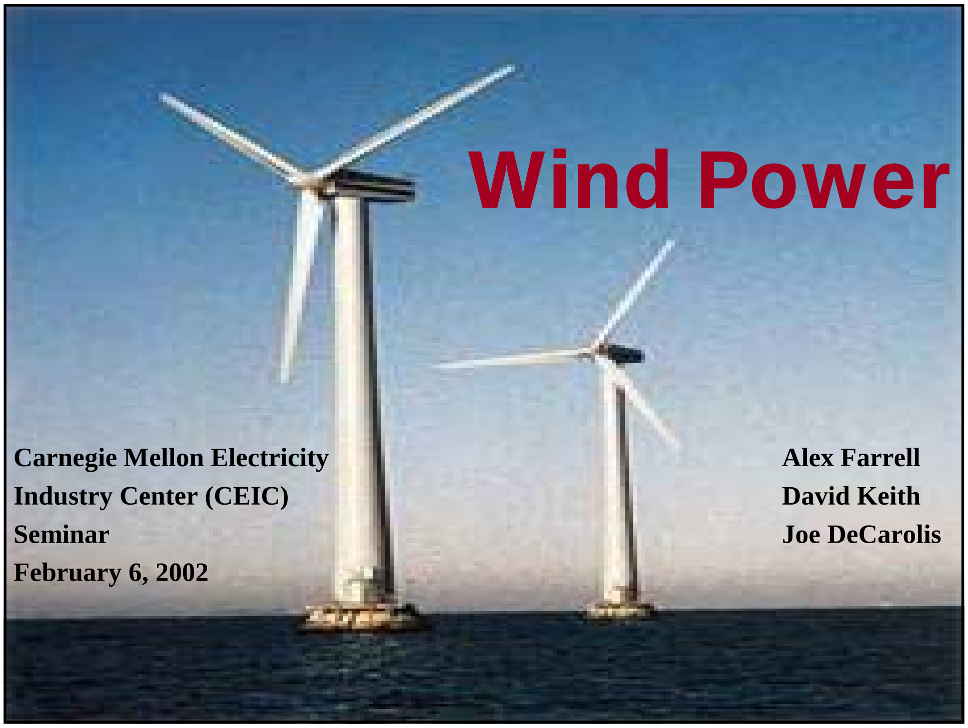
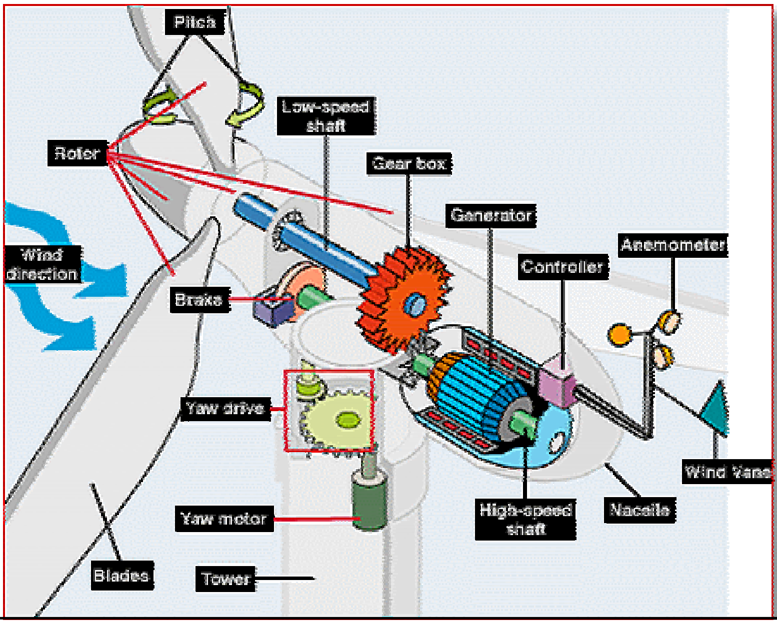


Wind Power

Carnegie Mellon Electricity
Industry Center (CEIC)
Seminar
February 6, 2002

Alex Farrell
David Keith
Joe DeCarolis

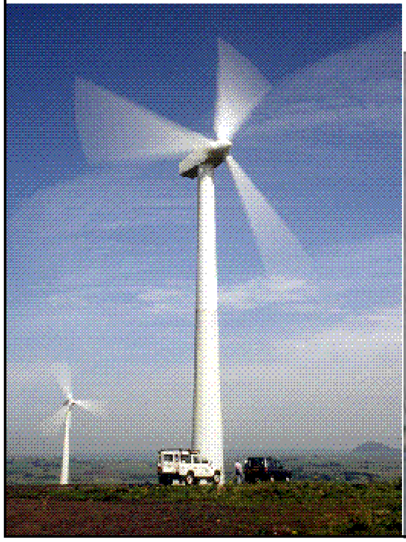
Wind Turbine basics



Contemporary wind turbines

Vestas V39 500kW

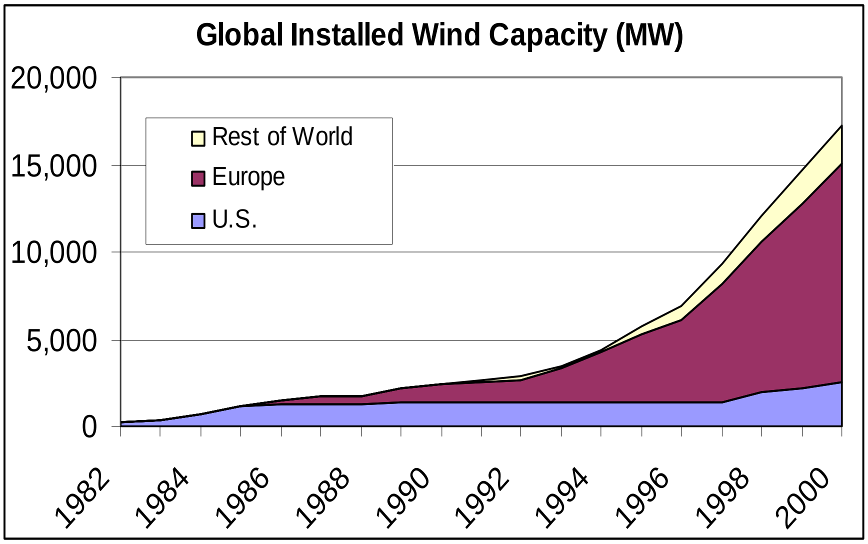
39m diameter rotor, 43m tower



NEG Micon 2MW

72m diameter rotor, 68m tower

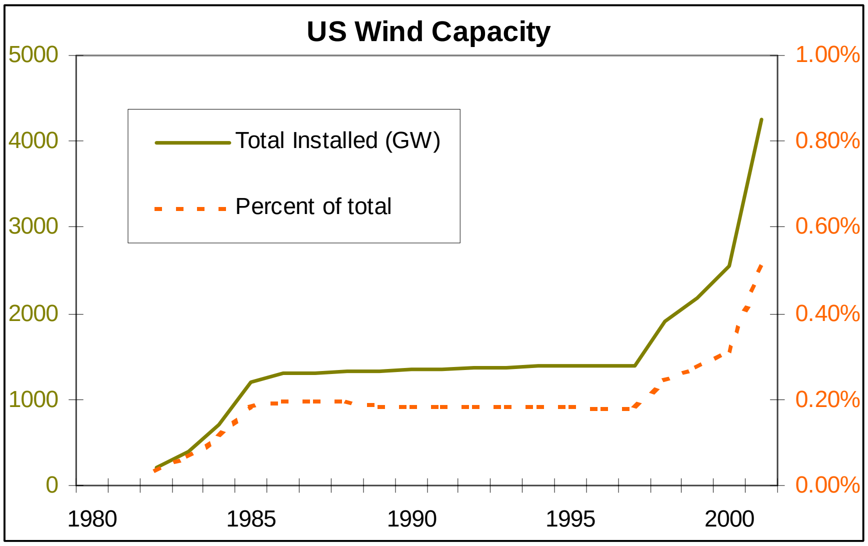
Recent growth: 20%-30% annually



Note: Total global capacity = 3Million MW

Source: Swisher et al. 2002

Rapid growth, but a small fraction



Renewable Portfolio Standard (RPS)

- Mandatory government requirement
- Production
- Consumption
- Credits
- Definitions
  - Solar
  - Wind
  - Biomass
  - Landfill gas
  - Municipal solid waste
  - Tidal and wave
  - Geothermal

Targets and RPS around the world

- **Australia** – Mandatory additional 2% renewables by 2010– ~900MW wind
- **Denmark** – Plan 21: 20% renewables by 2003 (*more later*)
- **Germany** – Two Länder have RPS
- **Greece** – Target of doubling renewable contribution by 2010 – ~2,500MW wind
- **Netherlands** – Target of 10% renewables by 2020 – ~2,750MW wind
- **Spain** – Subisides, Target of 12% by 2010 – ~9,000MW wind

RPS in the U.S.

- **AZ** – Regulated utilities generate at least 1.1% of total retail energy sales from renewable sources by 2007. Emphasis on solar. $0.000875/kwh Environmental Portfolio Surcharge (with caps).
- **CT** – from 5% (now) to 7% in 2009.
- **ME** – 30% standard (now 50% - hydro, biomass, WTE)
- **MA** – 1% in 2003, addition 0.5% annually through '09 and an additional 1% annually thereafter. (4.5% in 2010)
- **NV** – 1% by 2010, half of which must be solar
- **NJ** – 6.5% by 2012
- **PA** – 2% now, additional 0.5% annually subject to cost caps
- And then there's Texas . . . .

RPS in Texas

- Signed into law in 1999 by Gov. Bush as part of overall restructuring legislation.
  - Target – from 850MW in 2000 to 2,850MW in 2009
  - Total capacity ~77MW (implies ~3.6% renewables)
- Electricity retailers responsible for holding proportional number of Renewable Energy Credits (RECs) each year.
- Enforcement – lesser of 5¢/kWh or mean value of REC.
- So far
  - Over ten wind farms for 930MW constructed
  - 12 new landfill gas plants (44MW) announced
  - 50MW hydro renovations announced
  - 2650MW of wind projects have applied for grid access.

Denmark

Plan 21 goals: 2003 – 20% Renewable electricity by 2003, 2030 – 5,500MW (of which 4,000MW offshore) and exports

Ireland

20 Million MWh/yr production

94% fossil-fueled (all imports)

Arklow

- 200 turbines, 520MW
- 10% of capacity (?)
- 80km offshore
- 5-25m water
- capital cost €630M
- displace €330M/year in fuel

Is the Answer to Effective Climate Change Mitigation Blowing in the Wind?

Joe DeCarolis

Advisors: David Keith

Alex Farrell

Motivation

How much will wind energy cost if it serves as baseload and comprises a large fraction of US electricity supply?

Why Care?

- Interest in a clean and affordable electricity supply.
- More specifically, concern over:
  - ⇨ Air pollution
  - ⇨ Climate change
  - ⇨ Impacts from fossil fuel extraction
  - ⇨ Sustainability of fuel supplies

But Why Care About Wind?

Technology	**Cost (¢ / kWh)**
Wind	4-8
Biomass	6-8
Solar thermal	10-12
Photovoltaics	20-30
Coal	**3-4**
Natural Gas	**3-4**

Adapted from Cassedy and Grossman, “Introduction To Energy”.

The Benefits

- Mature technology with competitive capital costs.
- Environmental benefits.
- Renewable energy source.

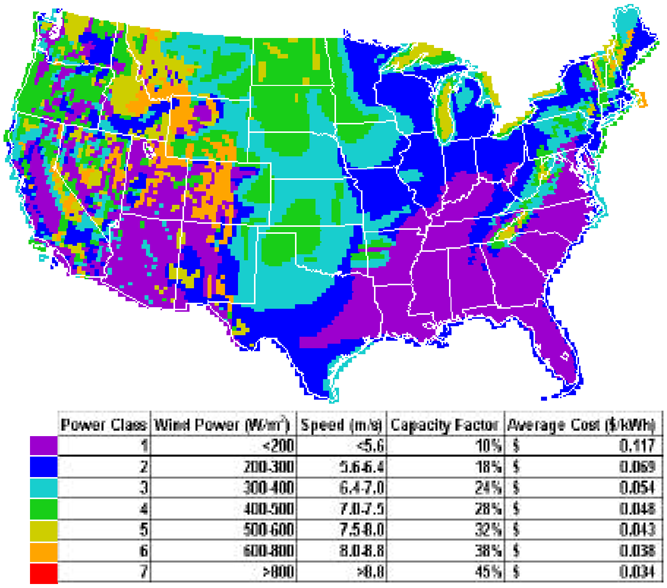
The Catch

- Where, when, and how hard the wind blows determines the cost-effectiveness of wind projects.

Can Wind Serve As Baseload?

- Almost all debate focuses on wind farms serving a small fraction of total demand.
- The cost that matters for wind at the margin is the average cost per kWh.
- Given the prices on the previous table, one might assume that under moderate climate control wind should dominate electricity supply.
- But remoteness and intermittency of the wind resource raise the real cost of wind energy.
- These problems can be neglected on a small scale, but must be addressed on a large scale.
- Therefore economic performance of current small scale wind farms can not be extrapolated to baseload.

Where Does the Wind Blow? Remotely.



	Power Class	Wind Power (W/m^2)	Speed (m/s)	Capacity Factor	Average Cost ($/kWh)	
🟪	1	<200	<5.6	10%	$	0.117
🟦	2	200-300	5.6-6.4	18%	$	0.069
🟦	3	300-400	6.4-7.0	24%	$	0.054
🟩	4	400-500	7.0-7.5	28%	$	0.048
🟨	5	500-600	7.5-8.0	32%	$	0.043
🟧	6	600-800	8.0-8.8	38%	$	0.038
🟥	7	>800	>8.8	45%	$	0.034

Map adapted from NREL and capacity factors drawn from McGowan *et al.*

When and How Hard Does the Wind Blow? Unpredictably and Intermittently.

- Wind speed is highly variable and difficult to predict more than an hour or two in advance.
- System operators forced to utilize spinning reserves and dispatchable capacity to complement periods of low wind power output.
- As wind capacity increases in size relative to the overall generation capability (>10%), the amplitude of power fluctuations from wind increase, making it difficult for system operators to maintain system stability.

3 Solutions to Remoteness and Intermittency

Problem	Solution
Remoteness	• Long-distance transmission.
Intermittency	• Long-distance transmission. • Backup gas turbine capacity. • Large-scale storage.

Long-Distance Electricity Transmission

- Link remote, dispersed sites via transmission lines to demand centers.
- To connect Great Plains wind with distant demand centers, high voltage direct current (HVDC) lines will in many cases be more cost-effective than high voltage AC.
- HVDC is a proven technology:

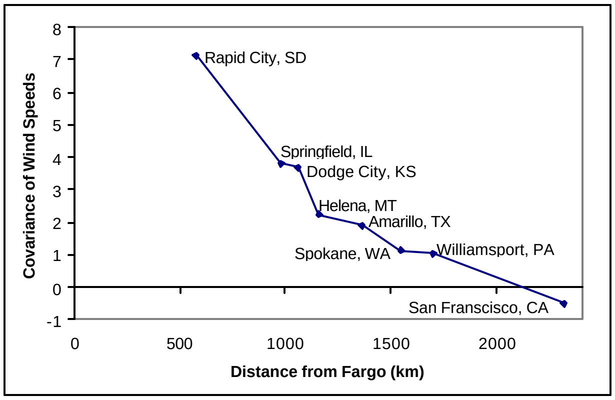
  Itaipu Brazil – operating voltage is ±600 kV, which transmits 6,300 MW in 2 bipoles over 800 km (Foz do Iguacu, Paraguay to Ibiuna, Brazil).

  Hydro Quebec – operating voltage is ± 450 kV, which transmits 2,000 MW in a bipole line over 1500 km (James Bay, Quebec to Boston, MA).

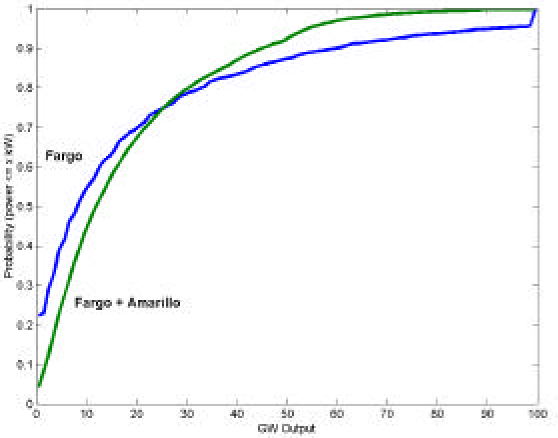
  Pacific Intertie – operating voltage is ± 400 kV, which transmits 1,400 MW in a bipole line over 1500 km (Columbia River to Los Angeles, CA).

Transmission Can Help With Intermittency Too

- Geographic dispersion of wind farms can reduce the overall variance in wind power output.
- The wind speed covariances demonstrate that the correlation between wind patterns decreases as the distance between sites increases.



Quantification of Diversity Benefit



Case 1: Fargo

Fargo: 100 GW

Case 2: Fargo+Amarillo

Fargo: 50 GW

1400 km

Amarillo: 50 GW

Gas Turbine Backup

Advantages

- Capital costs and CO_2 emissions are low.
- Fast ramp rates suited to following wind.

Disadvantages

- Introduces emissions that wind is trying to mitigate in the first place.
- Adds additional capital costs.

Large-Scale Storage (Compressed Air, Pumped Hydro)

Advantages

- Flattens the wind energy supply curve without using additional generating units.

Disadvantages

- Adds additional capital costs.
- Installation of storage requires specific geologic structures.

Pumped hydro - 2 reservoirs at different heights in close proximity

Compressed Air – naturally occurring aquifers, solution-mined salt caverns, mechanically-formed reservoirs in rock formations.

My Contribution: A Greenfield Analysis of Baseload Wind Energy

Objective

To estimate the cost of baseload wind while characterizing the relative benefits of backup gas turbines, storage systems, and geographically dispersed wind farms.

Plan

Perform a greenfield analysis that assumes no preexisting energy infrastructure and optimizes the amount of wind, gas, transmission, and storage capacity to build using projected capital costs and wind speed vectors from potential wind farm sites as inputs.

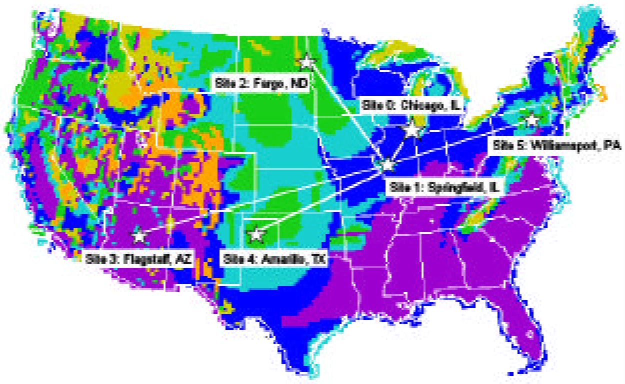
Implementation

Create a nonlinear constrained optimization model in MatLab.

Model Inputs

- Hourly wind speed recordings downloaded from the National Climatic Data Center.
- All data recorded at WBAN (Weather Bureau Army-Navy) stations (airports).
- Resultant wind speed vectors contain 45,000 hourly measurements, but only the first 10,000 elements were used in the model for computational efficiency.

Wind Site Configuration



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🟨	5	500-600	7.5-8.0
🟧	6	600-800	8.0-8.8
🟥	7	>800	>8.8

Decision Variables

12 decision variables, summarized as follows:

- Wind capacity at each of the five sites.
- Transmission line capacities between Fargo, Flagstaff, Amarillo, Williamsport and Springfield.
- Transmission line capacity between Springfield and Chicago.
- Onsite storage, located at Springfield, IL.
- GT capacity (GTCC capacity not a decision variable, determined by wind and GT capacities).

Model Parameters

Parameters	**Values**	**Units**
Natural gas cost	3.5	$ / GJ
GT capital cost	350	$ / kW
GTCC capital cost	500	$ / kW
Wind capital cost	700	$ / kW
Transmission line cost[1] Transmission substation cost	530,000 100	$ / mile $ / kW
CAES capital cost[2]	500	$ / kW
GT Efficiency (HHV)	0.35	
GTCC Efficiency (HHV)	0.55	

[1] Taken from ORNL "HVDC Power Transmission Technology Assessment

[2] Taken from Cavallo "Energy Storage Technologies For Utility Scale Intermittent Renewable Energy Systems" JSEE, Nov. 2001.

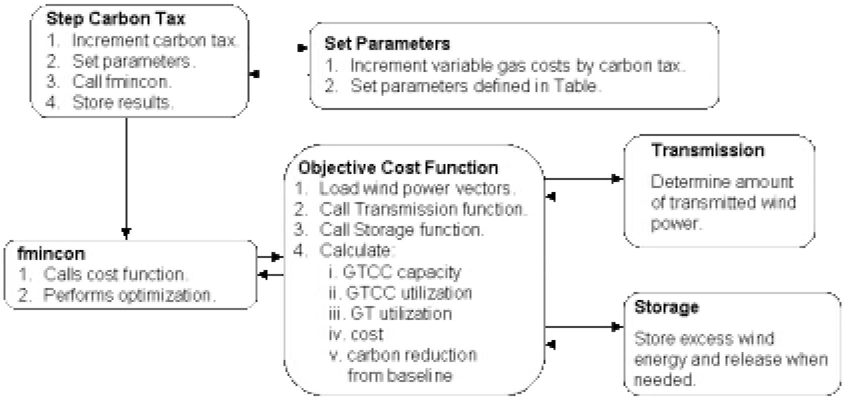
The Objective Function

The objective function minimizes the fixed and variable costs associated with the various technologies as a function of carbon tax.

- **Fixed costs** include the capital costs from wind, GT, GTCC, and transmission.
- **Variable costs** include the cost of gas for the GT and GTCC systems, and depend on utilization. Variable O&M costs for the various technologies were not considered explicitly, but were folded into the fixed costs.

- GTCC is the baseline at zero carbon tax.

Model Structure



Step Carbon Tax
1. Increment carbon tax.
2. Set parameters.
3. Call fmincon.
4. Store results.

Set Parameters
1. Increment variable gas costs by carbon tax.
2. Set parameters defined in Table.

fmincon
1. Calls cost function.
2. Performs optimization.

Objective Cost Function
1. Load wind power vectors.
2. Call Transmission function.
3. Call Storage function.
4. Calculate:
   - i. GTCC capacity
   - ii. GTCC utilization
   - iii. GT utilization
   - iv. cost
   - v. carbon reduction from baseline

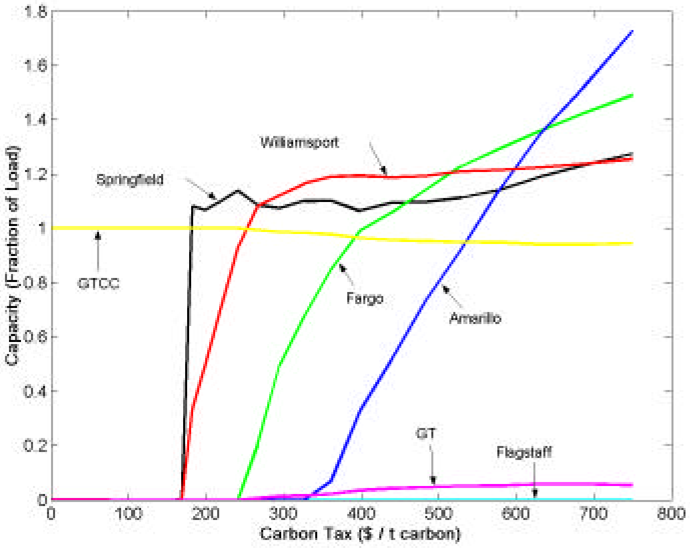
Transmission

Determine amount of transmitted wind power.

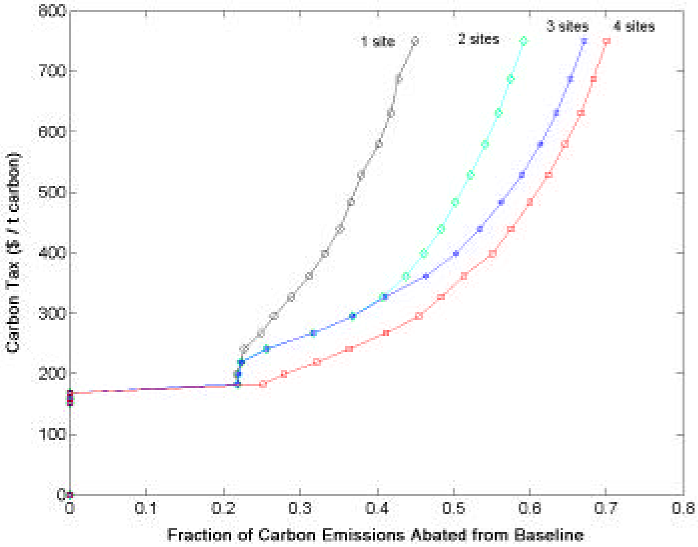
Storage

Store excess wind energy and release when needed.

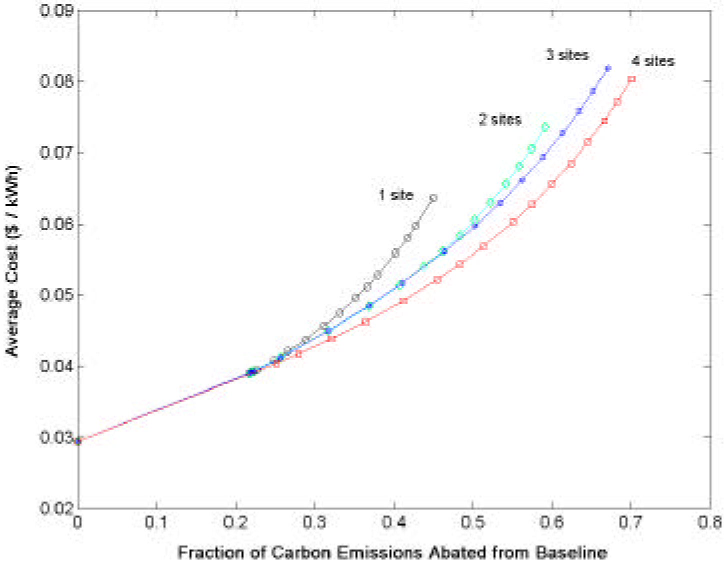
Optimal Wind and Gas Capacities As a Function of Carbon Tax



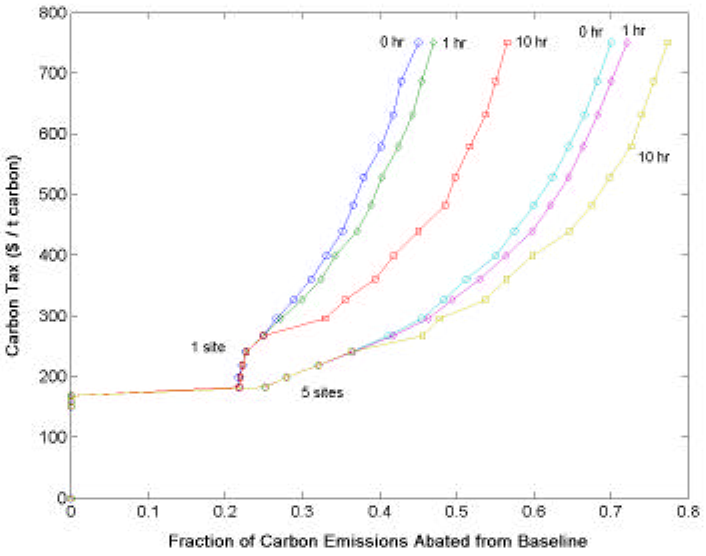
Marginal Cost of Carbon Mitigation as a Function of Site Diversity



Average Cost as a Function of Site Diversity



The Effect of Storage



Reconciling Model Predictions with Market Realities

Even if a carbon tax is imposed, do regulatory barriers exist for wind power development? …YES

- **Transmission line siting.** Overlapping federal, state, and local transmission line siting processes make new line construction very difficult.
- **Embedded transmission costs.** Charges based on:
  1. distance between the generator and load center
  2. peak use of transmission system

  penalize wind.
- **Real-time balancing markets.** Charge or credit generators based upon the value of energy at the time of deviation.
- **Rate pancaking.** Payment of multiple access rates as transmitted power crosses ownership lines.

Conclusions

1. Baseload wind is more costly than current small-scale wind applications because remoteness and intermittency must be addressed – but costs are in the ballpark.
2. In addition, baseload wind utilizing storage and geographic site diversity is capable of effecting deep cuts in carbon emissions.
3. Significant regulatory impediments exist, which prevent the results of the greenfield analysis from becoming reality in the short-term.

Future Work

- Include coal in the greenfield analysis.
- Perform detailed sensitivity analysis on the transmission costs.
- Use model insight to inform the back-of-the-envelope arguments made in *Science* regarding large-scale wind.
- Take my model to the Rolling Thunder developers – apply it to a work-in-progress.