Flexible Operation of Post-Combustion Amine-based CCS with a Co-located Wind Farm

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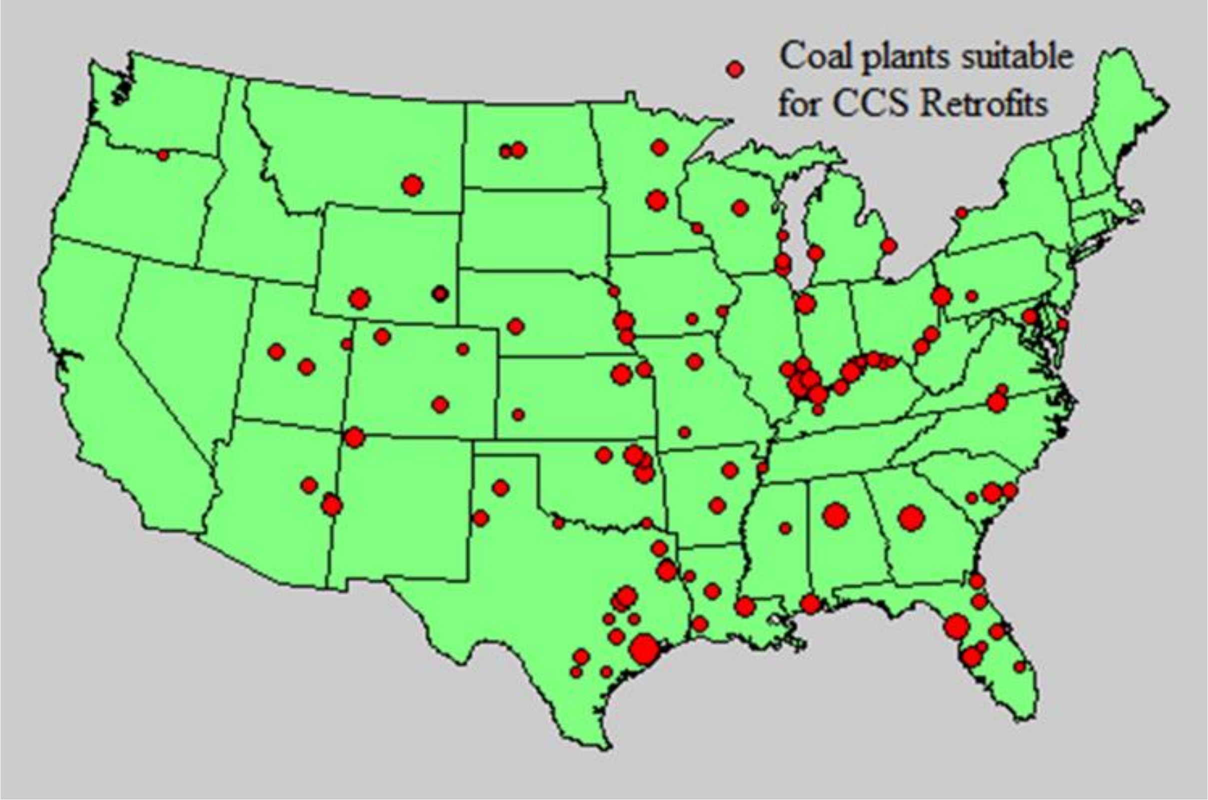
Location of Coal Plants Suitable for CCS Retrofit



Map generated based on data from eGrid Database: http://www.epa.gov/cleanenergy/energy-resources/egrid/

~35% of electricity sector CO_2 emissions come from plants suitable for CCS retrofits

Wind power (~11 TW) could cost effectively meet RPS goals if challenges from intermittency and access to transmission capacity are resolved

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Research Question

Can flexible operation of coal plants with CCS retrofits reduce:

a) **Cost of Capture of CO_2 (CoC)**
b) **Cost of integration of wind power**

The Hybrid System

http://blog.cleanenergy.org/2012/11/13/

Supply to the grid via already existing transmission lines

http://reneweconomy.com.au

Post-combustion amine based CCS unit with partial capture (Slide)

OR

Post-combustion amine based CCS unit with amine storage capabilities (Slide)

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Method

- Choose a existing coal plant location suitable for the hybrid system[1]
- Determine optimal size and dispatch schedule of the hybrid system to maximize revenue
- Measure hybrid system's performance:
  - Wind power integrated (MW) as % of nameplate capacity
  - Levelized cost of electricity ($/MWh)
  - Cost of CO_2 Capture ($/ton)
- Analysis of performance of the hybrid system in selected region for:
  - Electricity prices variability
  - Emissions rate limits (Imposed by regs. to Partial Capture)
  - Wind variability

1. Finkenrath M., Smith J., and Volk D. "CCS Retrofit: Analysis of the Globally Installed Coal-fired Power Plant Fleet". *International Energy Agency Information Report*. 2012

LP Optimization Model

Maximize

- $\Omega(\text{Net Revenue}) =$
  $\text{Revenue}_{\text{Coal Plant and Wind Farm}} - \text{Loss of Revenue}_{\text{CCS}} - \text{O\&M}_{\text{Coal}} - \text{Capital and O\&M Cost}_{\text{Wind Farm}} - \text{Variable Cost}_{\text{CCS}} - \text{Fixed Cost}_{\text{Amine Storage Configuration of CCS}}$

Decision Variables

- Size of Wind Farm
- Dispatch schedule of wind and coal unit
  - Partial capture → amount of flue gas vented
  - Amine storage → size of storage tank and rate of regeneration

Subject to physical constraints on operation of the hybrid system

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Data and Assumptions

- Perfect foresight for electricity price and wind speed forecasts
- Hourly electricity prices from PJM hubs year 2013
- 10-minutes synthetic wind power data from SynTiSe MCMC trained with EWITS data
- Capital costs of amine-storage from IECM (Integrated Environmental Control Model)
- No additional capital costs for partial capture
- Cost of wind power: NREL report '2011 Cost of Wind Energy Review'
- Coal plant specifications as in eGrid for Powerton (1786 MW plant)

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Metrics of performance

$$\text{Cost of } CO_2 \text{ Capture} (\$ \text{ per ton}) = \frac{LCOE_{\text{Hybrid System}} - LCOE_{\text{Coal Plant without CCS}}}{CO_2 \text{Emmissions}_{\text{Coal Plant without CCS}} - CO_2 \text{Emissions}_{\text{Hybrid System}}}$$

$$\text{Levelized Cost of Electricity (LCOE in \$ per MWh)} = \frac{\text{Capital \& Annual Operating Cost}_{\text{Wind Farm}} + \text{Capital \& O\&M Cost}_{\text{CCS}} + \text{Loss of Revenue}_{\text{CCS}} + \text{O\&M Cost}_{\text{Coal Plant}}}{\text{Net Power Dispatched by the Hybrid System}}$$

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Quantifying Ramp Characteristics in Wind Power

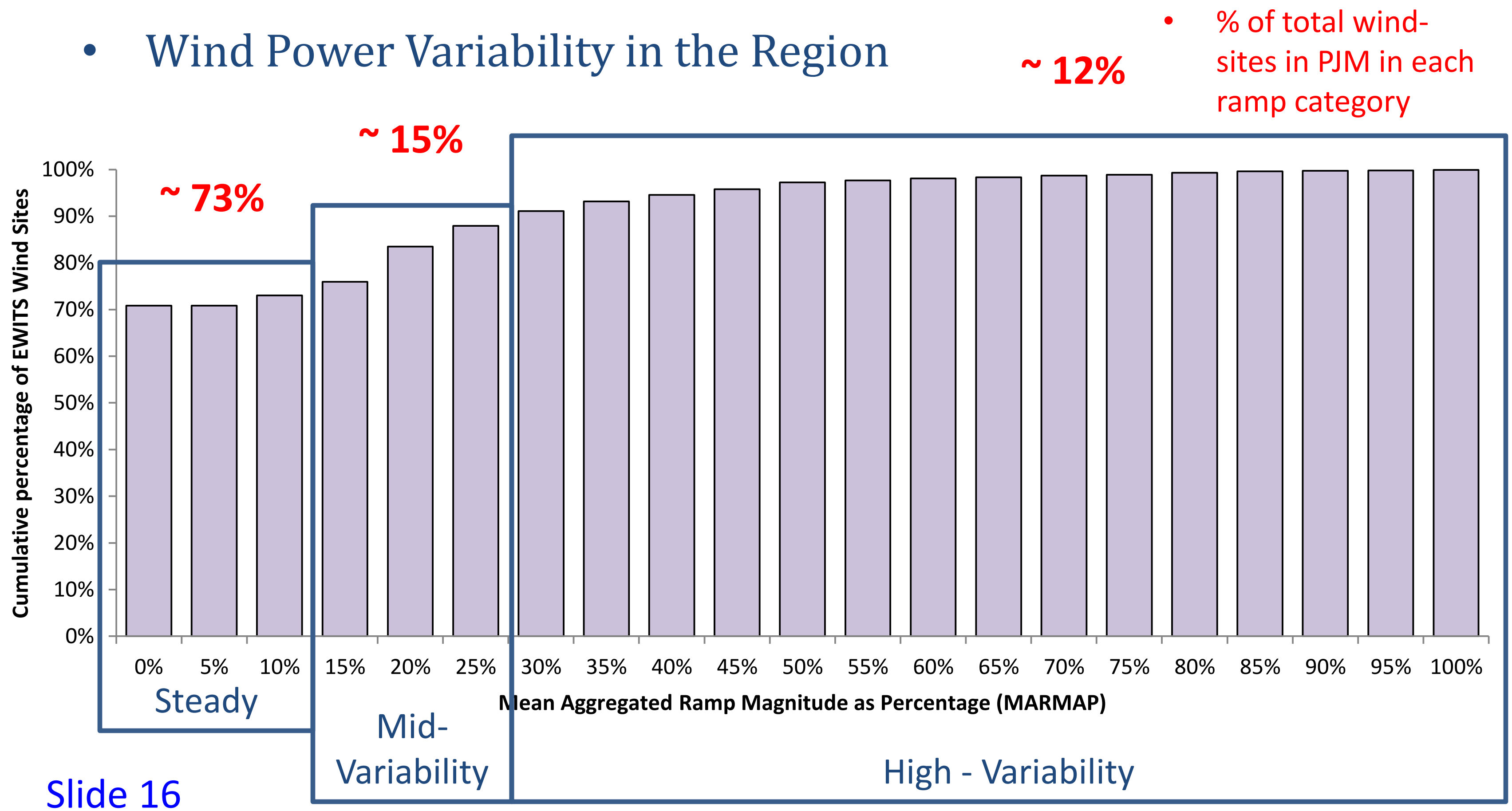
To characterize wind power variability the following metrics are defined:

- $Ramp_t = I_{|WP_t - WP_{t-1}| \geq Threshold} * |WP_t - WP_{t-1}|$ where I is the indicator function
- Aggregated Ramp Magnitude: $Ramp_{t_0, d_{t_0}}^{aggregated} = \left| WP_{t_0} - WP_{t_0 + d_{t_0}} \right|$
- Average Ramp Magnitude: $Ramp_{t_0, d_{t_0}}^{Rolling\ Avg} = \frac{\sum_{i=t_0}^{t_0 + d_{t_0}} Ramp_i}{d_{t_0}}$
- Mean Aggregated Ramp Magnitude as Percentage:

$MARMAP = \frac{\sum_{i \in I} Ramp_{t_i, d_{t_i}}^{Rolling\ Avg}}{Nameplate\ Capacity * |I|} * 100\%$ where I is the index set of all aggregated ramp start instances Example

Area of Study: PJM

- Wind Power Variability in the Region



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Results

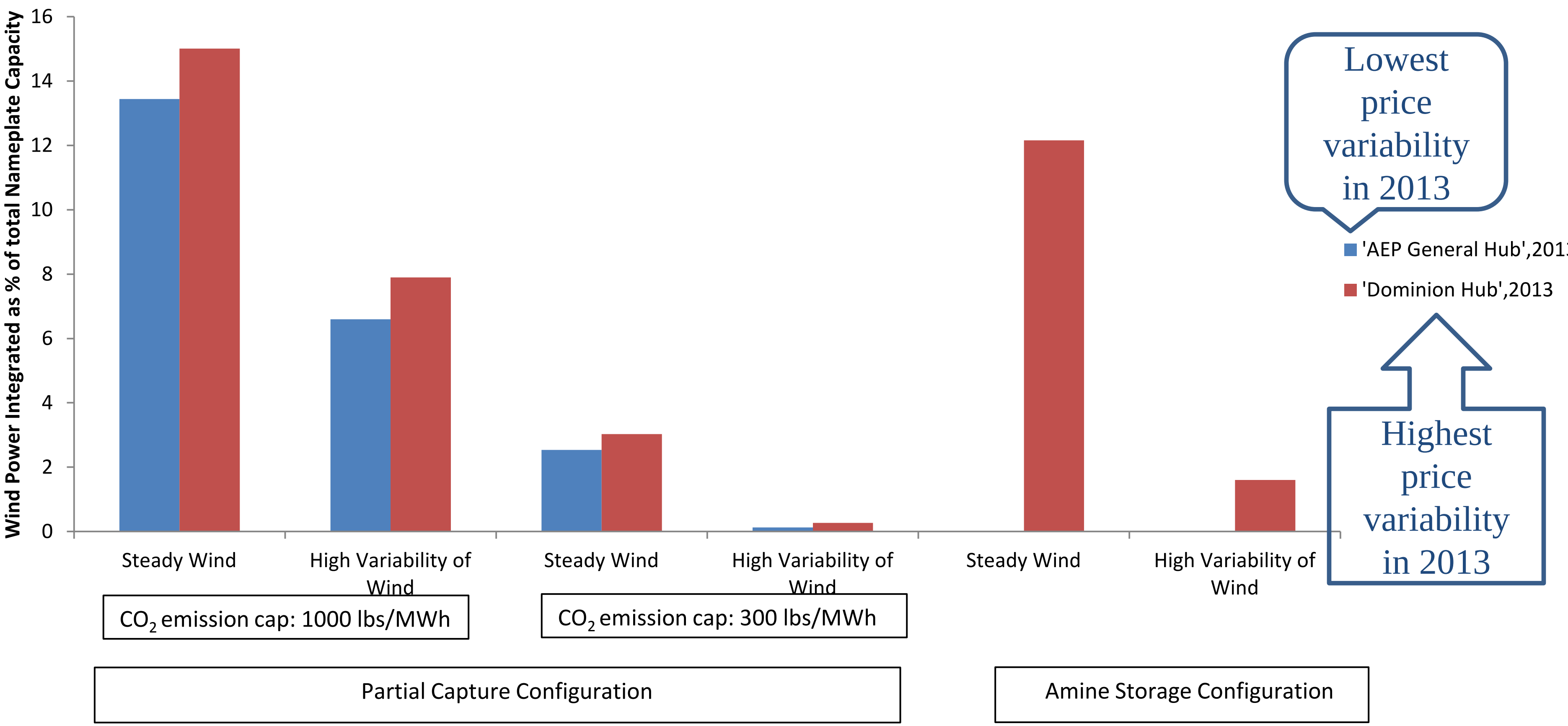
Assuming the hybrid system is required to perform as a base-load plant:

- Configuration (how much wind?)
- Cost of CO_2 capture

- For partial capture
- For amine -storage

Sensitivity to variability in prices and wind

Wind Power Integration for Base-load Operation



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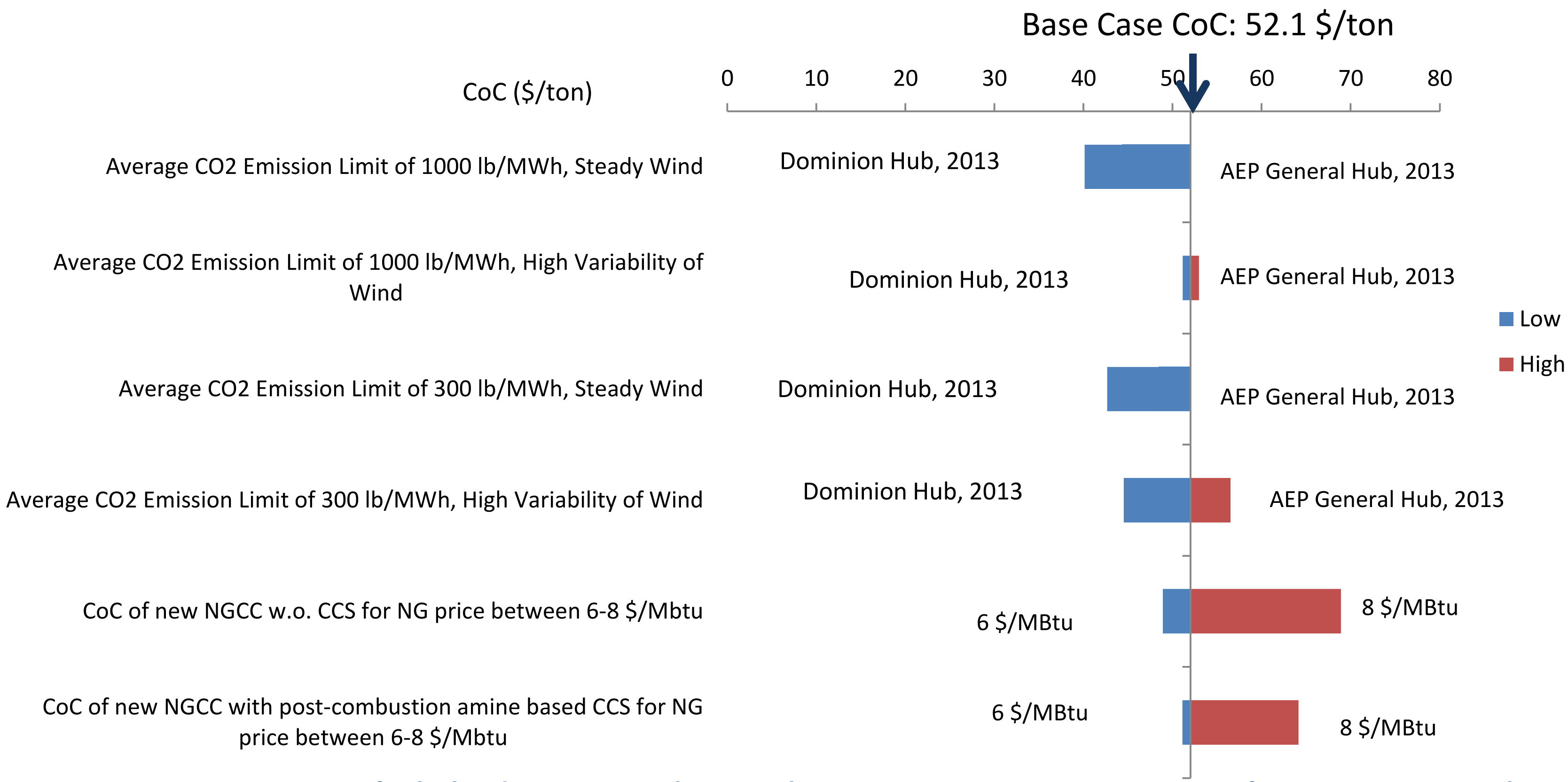
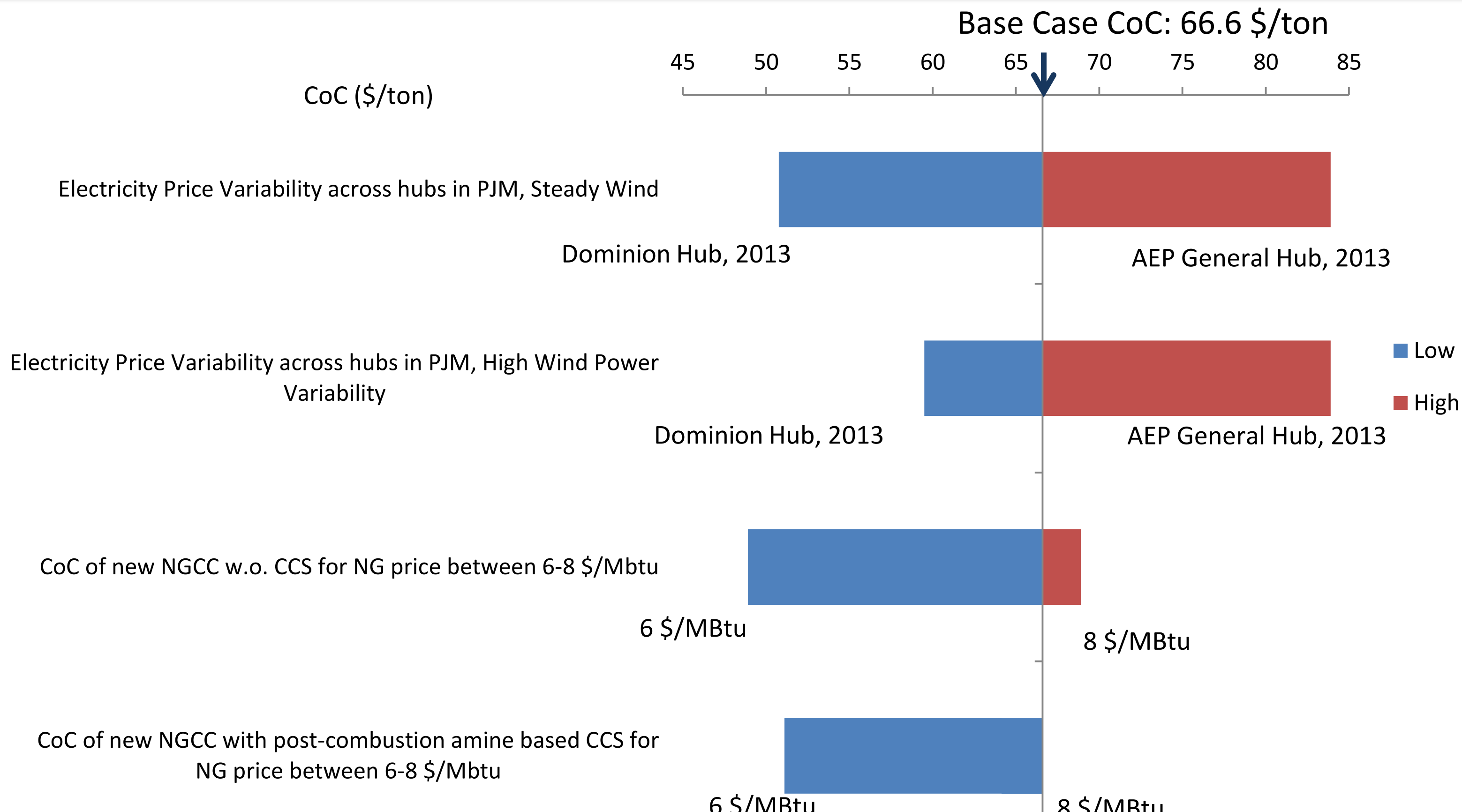
Cost of Capture (CoC) for Base-load Operation with Partial Capture Configuration



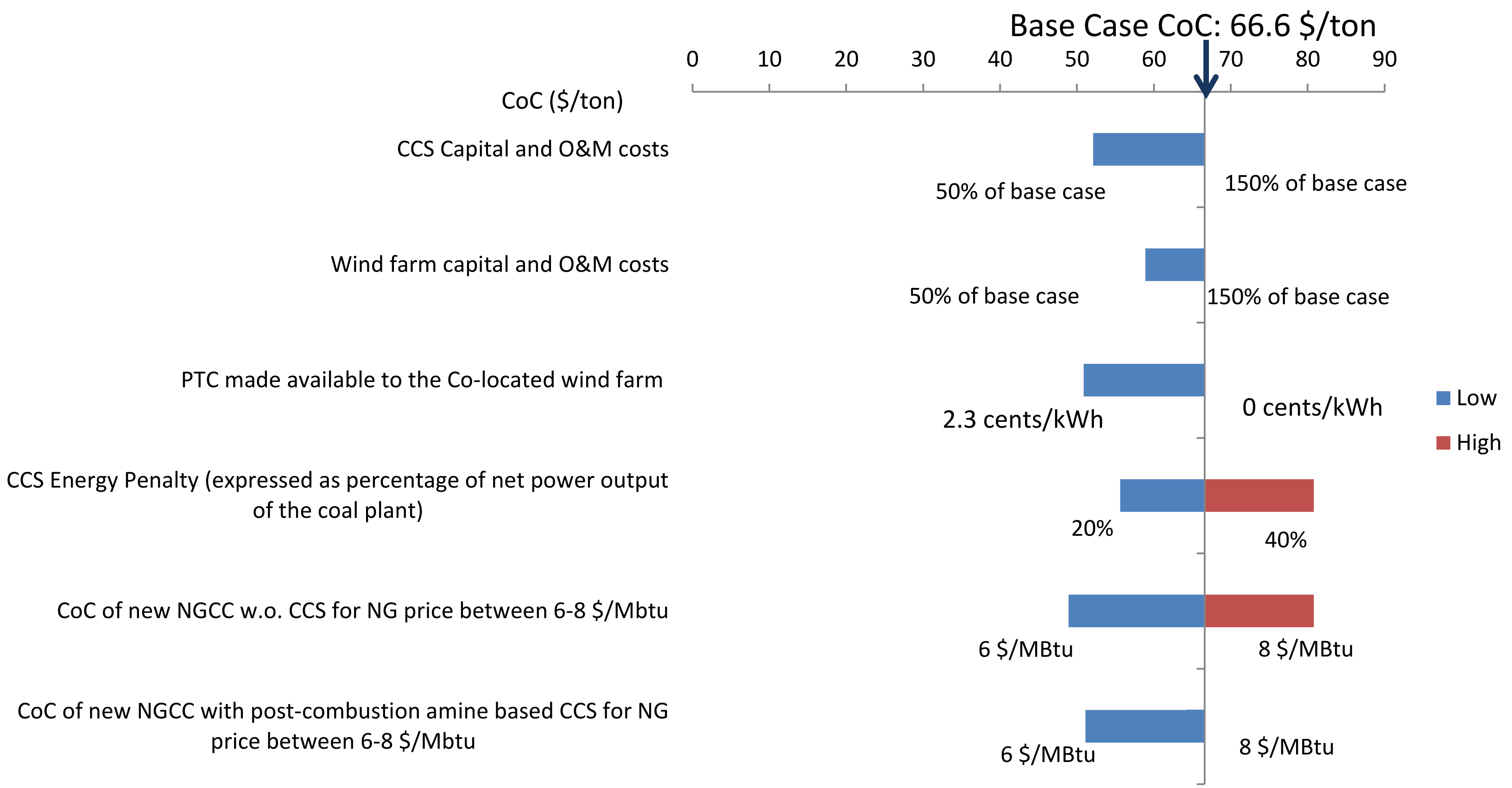
Base Case CoC : operation of a hybrid system with partial capture operation consisting of a 1785.6 MW sub-critical coal plant (with specs similar to the Powerton plant in IL), operating at the Chicago Hub with mid-level wind Power ramp characteristics. Annual average CO_2 emission limit: 300 lbs/MWh (Slide 17)

Cost of Capture (CoC) for Base-load Operation with Amine Storage Configuration



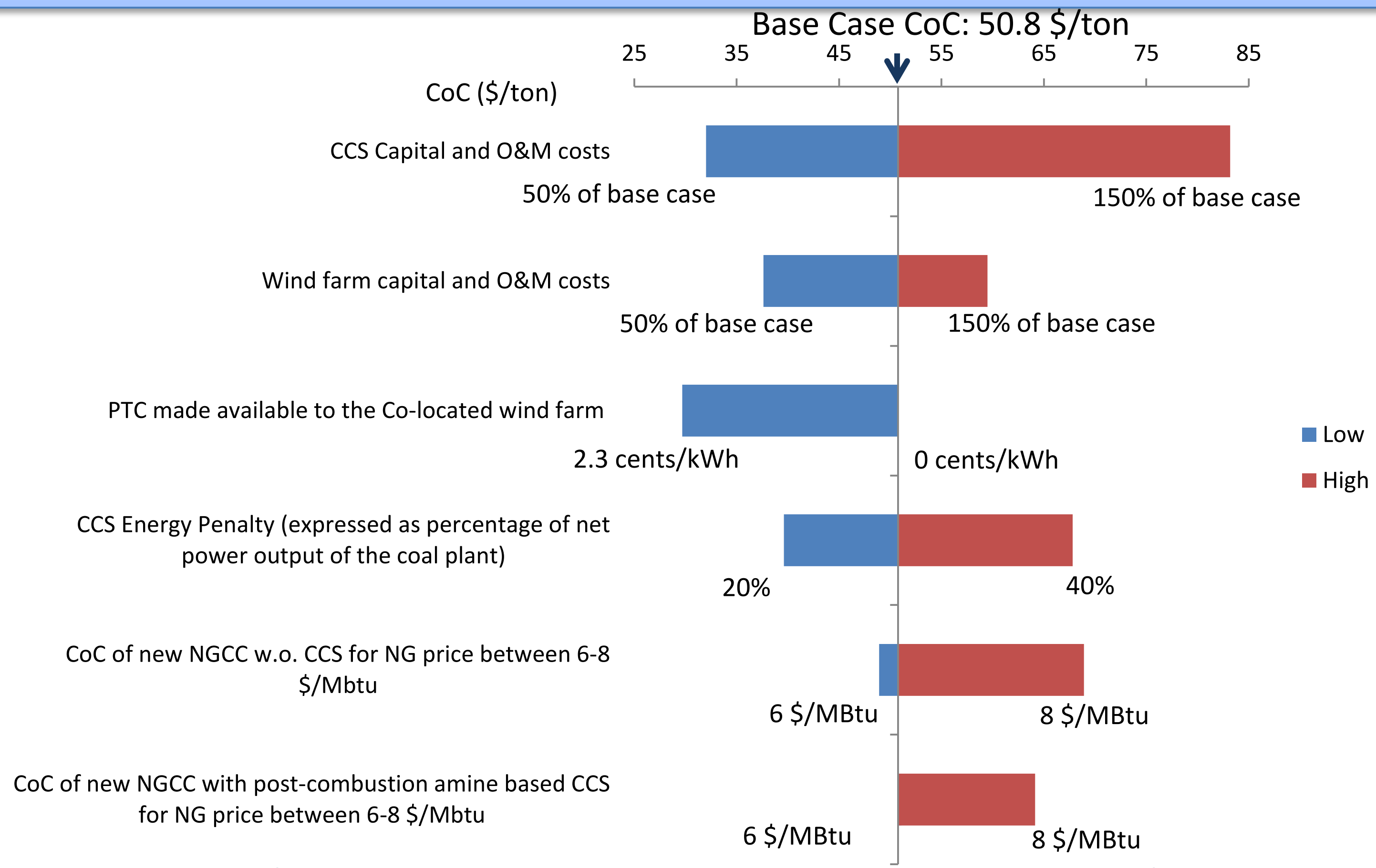
Base Case CoC : operation of a hybrid system with amine storage operation consisting of a 1785.6 MW sub-critical coal plant (with specs similar to the Powerton plant in IL), operating at the Chicago Hub with mid-level wind Power ramp characteristics **(Slide 17)**

Cost of Capture (CoC) for Base-load Operation with Amine Storage Configuration



Base Case CoC : Operation of a hybrid system with amine storage operation consisting of a 1785.6 MW sub-critical coal plant (with specs similar to the Powerton plant), operating at the Chicago Hub with mid-level wind power ramp characteristics

Cost of Capture (CoC) for Base-load Operation with Amine Storage Configuration



Base Case CoC : Operation of a hybrid system with amine storage operation consisting of a 1785.6 MW sub-critical coal plant (with specs similar to the Powerton plant), operating at the Dominion Hub with steady wind power ramp characteristics

Scope of Implementation for Partial Capture Configuration

- The potential for wind power integration depends on:
  - Variability of the wind power
  - Variability of electricity prices

- For PJM in 2013, the hybrid system's CoC is comparable to CoC for replacement with a new NGCC plant

- For highly variable wind (i.e. ramp >98%), base-load operation of hybrid system is not profitable

Scope of Implementation for Amine Storage Configuration

- The potential for wind power integration depends on:
  - Variability of the wind power
  - Variability of electricity prices
- Low price variability (e.g. AEP General Hub in 2013) does not allow cost-effective integration of wind for base-load power operation
- High price variability, (e.g. Dominion Hub in 2013), and 'Steady' wind, can integrate wind farms of capacities of up to 12.5%. If wind sites have 'Mid Variability' the wind farm size decreases to 2%
- Wind sites with "high" variability can not be profitably integrated with the hybrid system with base-load operation (ramp characteristics)

Effect of relaxing the base-load operation constraint

- Increase in percent of wind power in the system ↑
- Reductions in the CoC values for both the partial capture and amine storage configurations. ↓
- Partial capture (net power allowed to vary beyond 10% of rated capacity) :
  - 5-21% increase in wind power integration
  - 1.5 – 4.2 $/ton decrease in CoC is
- Amine Storage (net power allowed to vary beyond 10% of rated capacity) :
  - 18-32 % increase in wind power integration
  - 2-10.7 $/ton decrease in CoC

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Conclusions

- Provides a viable method of transitioning to a power system with lower carbon emissions
- Facilitates renewable power integration
- Provides a hedge against uncertainty of natural gas prices and carbon emissions constraints
- Allows significant increase in profits relative to a CCS retrofitted coal plant operating continuously
- For the amine storage configuration, the hybrid system has lower CoC relative to new NGCC plants if natural gas prices are at least:
  - 'Steady' wind and high price variability: 5.8 $/MBtu
  - Low price variability (e.g. AEP hub): 14.5 $/MBtu

Conclusions

- At least three additional benefits have not been considered:
  - Avoided costs of procuring additional transmission capacity for wind power: Median value estimated at 15$/MWh[1]
  - Avoided costs of integration of intermittent resources to the grid: Estimated at 3.10 – 5.13 $/MWh for up to 30% of penetration of wind power in the Eastern Interconnect[2]
  - Increased ramp-capability of the hybrid system: Analysis of our test system operation indicates ramp-capability payments of 110-430 $/MW to enable the system to operate without losses even in the absence of price variability

1. Mills A., Wiser R., and Porter K. "The Cost of Transmission of Wind Energy: A Review of Transmission Planning Studies". Renewable and Sustainable Energy Reviews 16 (2012) 1– 19
2. "Eastern Wind Integration & Transmission Study", prepared by EnerNex Corporation for the National Renewable Energy Laboratory, February 2011

Questions?

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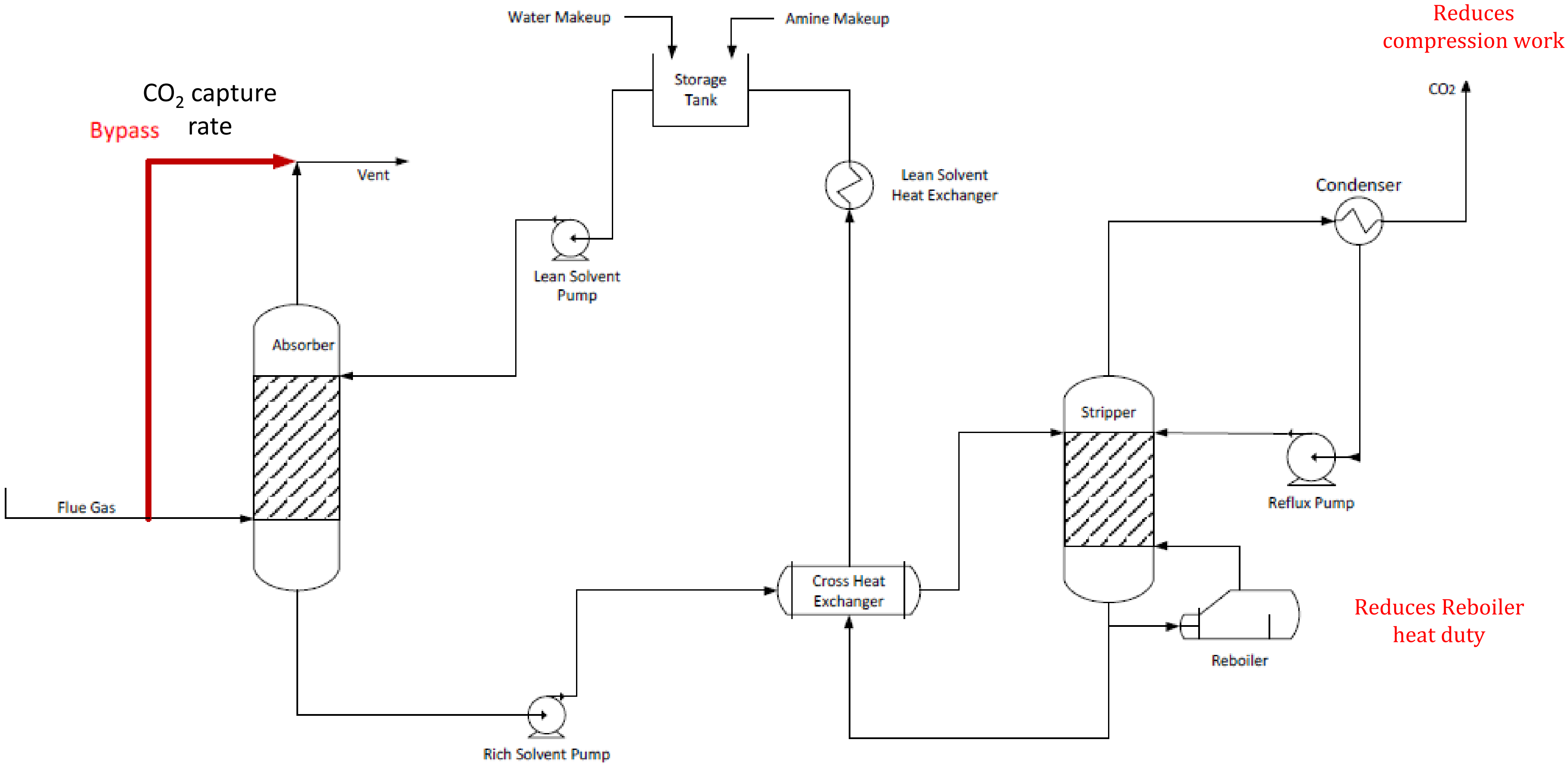
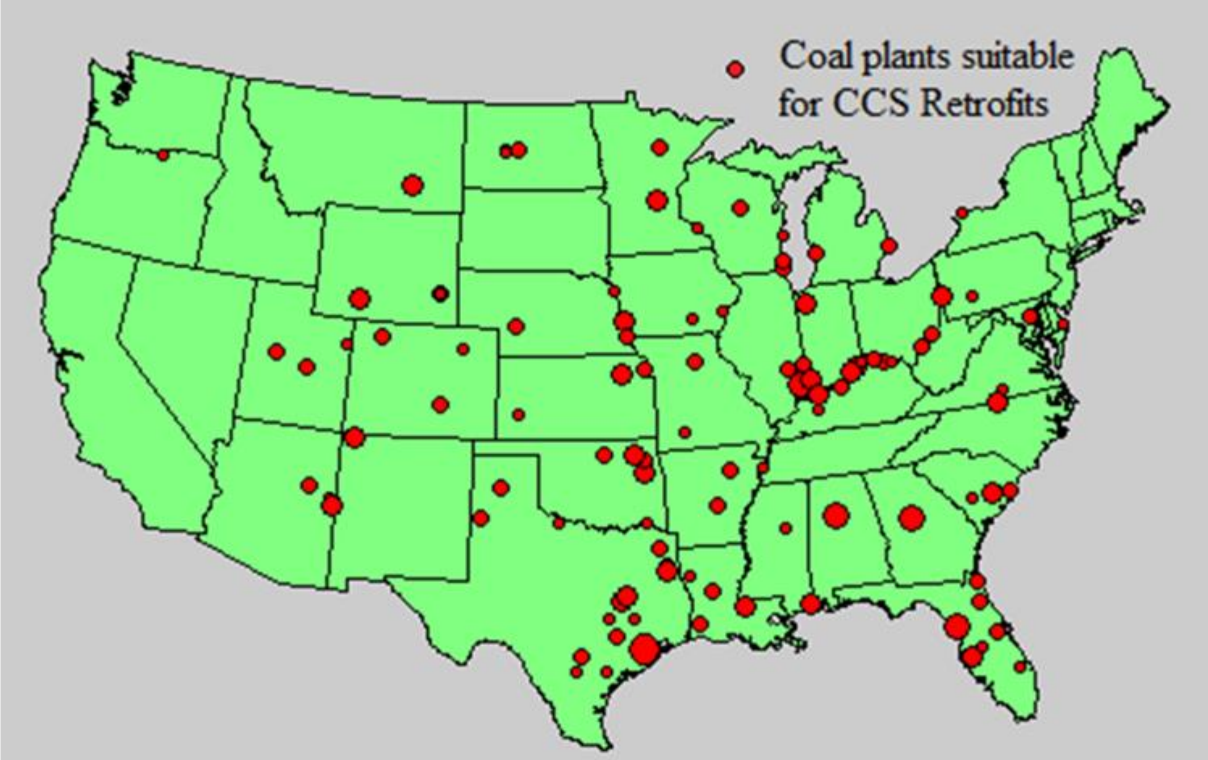


Brasington R.D. Integration and Operation of Post-Combustion Capture System on coal-fired power generation: Load following and Peak Power.MS Thesis at MIT. June, 2012 Previous Slide

Location of Coal Plants Suitable for CCs Retrofit



Map generated based on data from eGrid Database: http://www.epa.gov/cleanenergy/energy-resources/egrid/

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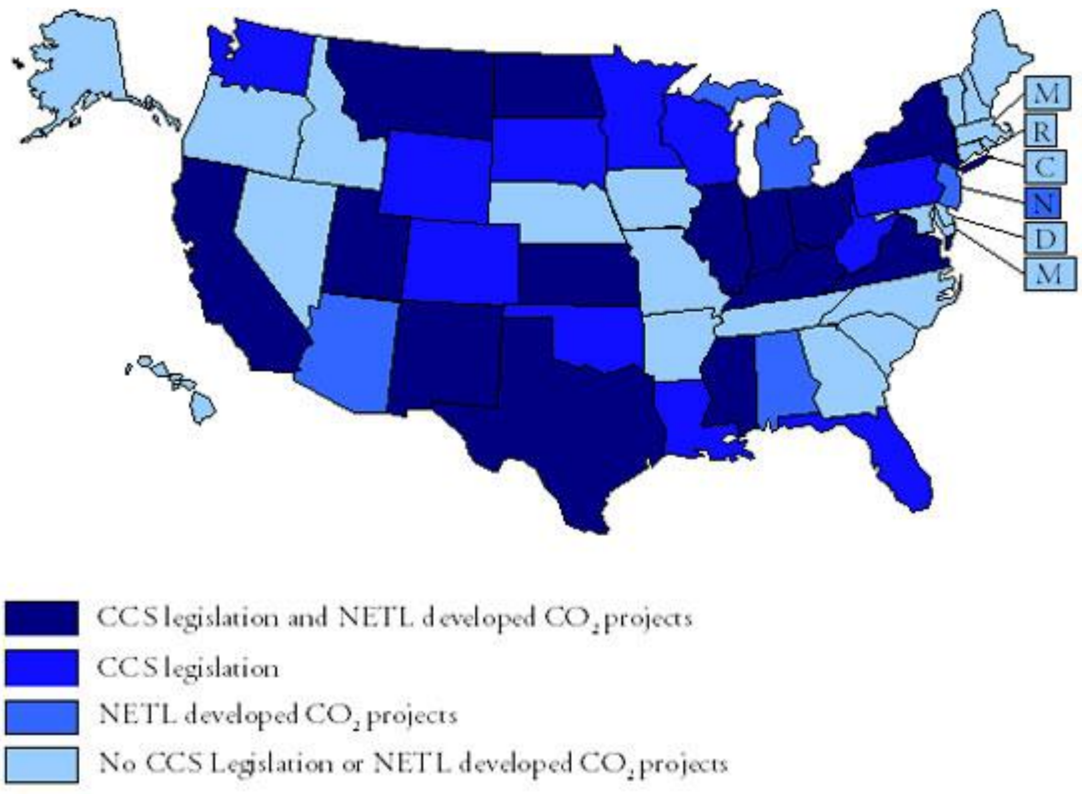
Back-up Slide:

CCS Legislation in the US



Carbon Capture & Storage in the States. http://www.ncsl.org/research/energy/carbon-capture-and-storage-in-the-states.aspx . Accessed 14th March, 2014.

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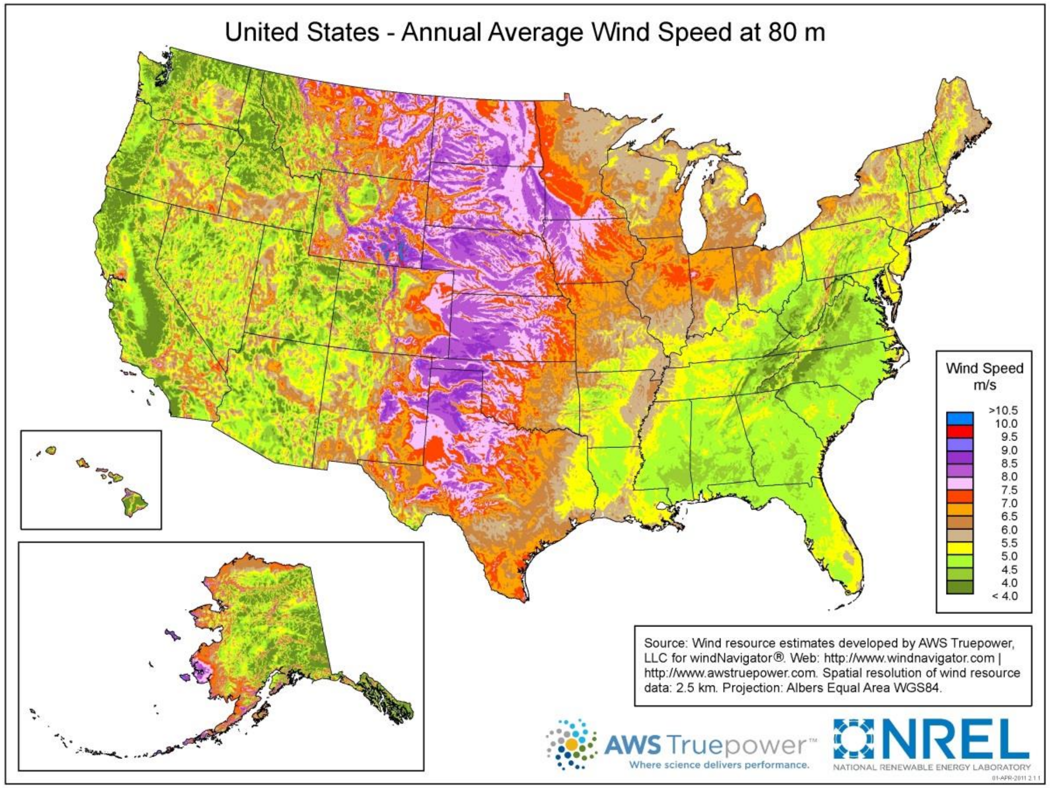
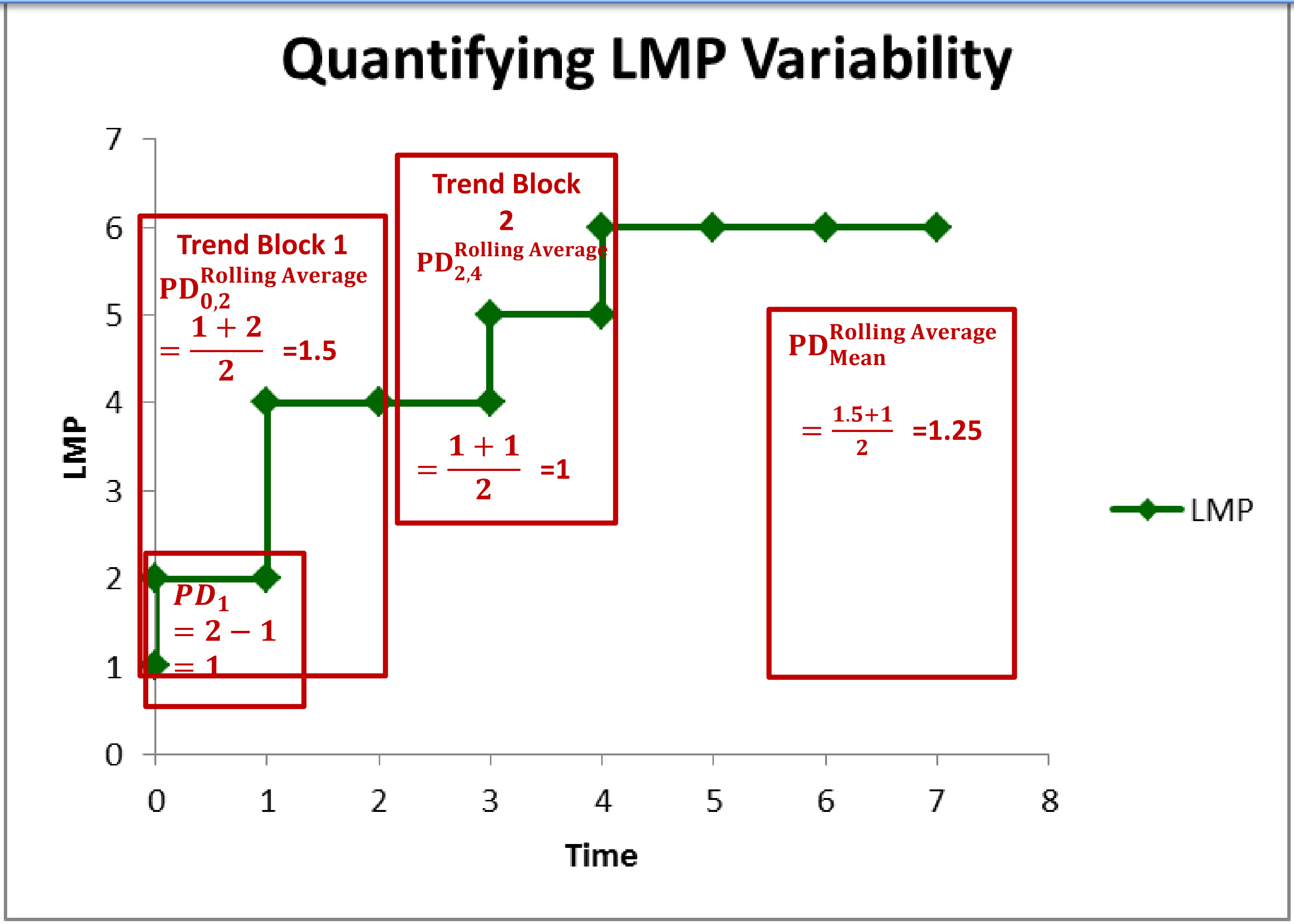
Back-up Slide:

Wind Power Potential in the US



Back-up Slide

Quantifying Variability of Electricity Prices (LMP)



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Back-up Slide

Quantifying Variability of Electricity Prices (LMP)

Hub Name	Mean Annual $PD^{Rolling\ Avg}$ ($/MWh)	Mean Annual PD_t	$\frac{\sum_{i=1}^{8760} d_i}{8760}$	Standard Deviation (LMP_t)
'AEP GEN HUB'	7.049	4.795	0.198	14.44
'OHIO HUB'	7.277	5.070	0.201	15.25
'AEP-DAYTON HUB'	7.644	5.196	0.200	15.76
'CHICAGO GEN HUB'	7.684	5.514	0.212	15.37
'N ILLINOIS HUB'	7.875	5.680	0.213	15.92
'CHICAGO HUB'	8.210	6.002	0.213	16.88
'WEST INT HUB'	8.393	6.045	0.199	31.52
'ATSI GEN HUB'	8.501	6.481	0.198	73.35
'WESTERN HUB'	9.200	6.512	0.201	20.90
'EASTERN HUB'	9.439	7.010	0.203	23.27
'NEW JERSEY HUB'	9.553	7.031	0.203	23.55
'DOMINION HUB'	10.060	7.159	0.207	22.63

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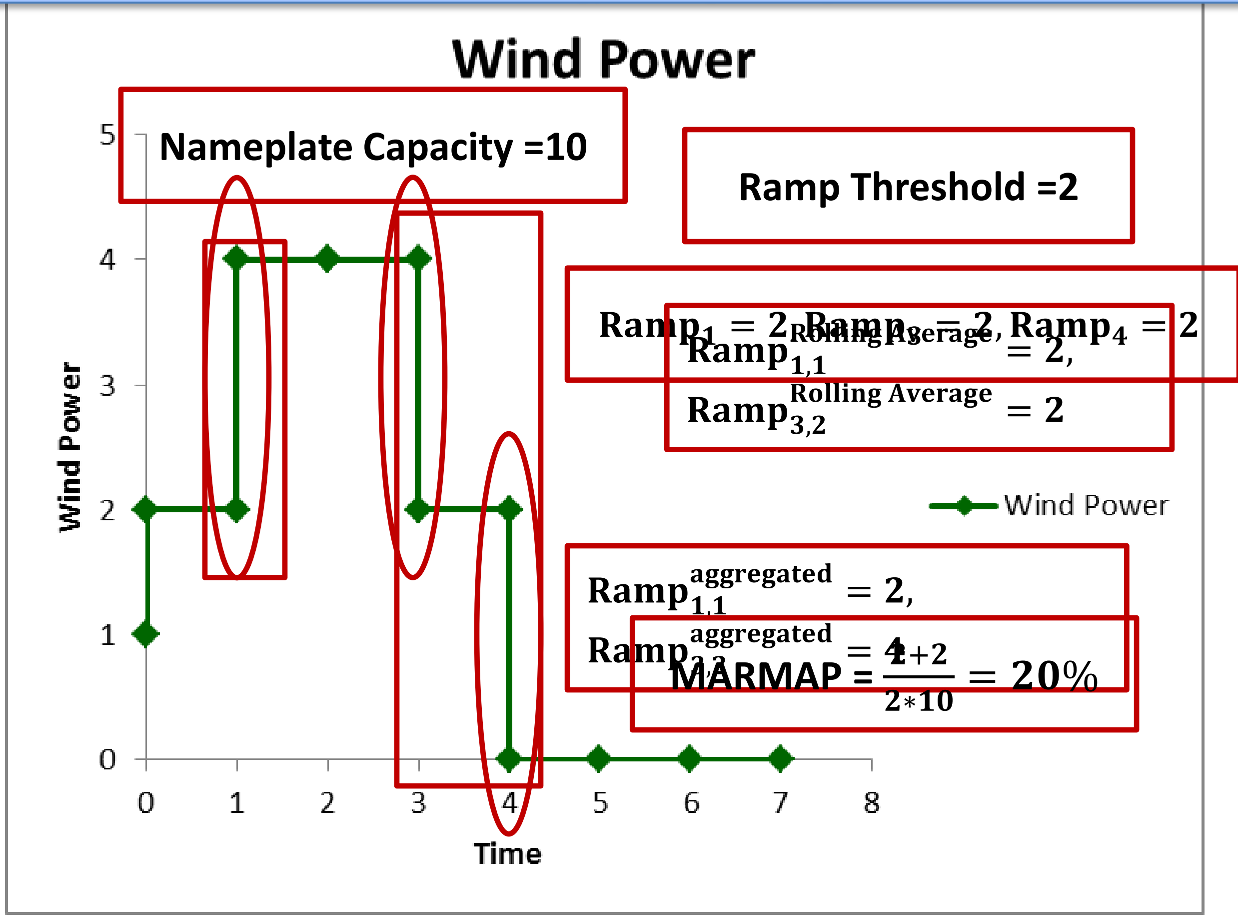

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