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

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~35% of electricity sector CO₂ 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.
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

Supply to the grid via already existing transmission lines

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

Post-combustion amine based CCS unit with partial capture [Slide]

http://reneweconomy.com.au

OR

Post-combustion amine based CCS unit with amine storage capabilities [Slide]
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

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Maximize

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

Decision Variables

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

Subject to physical constraints on operation of the hybrid system
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
- Coal plant specifications as in eGrid for Powerton (1786 MW plant)
Metrics of performance

Cost of CO₂ Capture ($ per ton) =

\[
\frac{\text{LCOE}_{\text{Hybrid System}} - \text{LCOE}_{\text{Coal Plant without CCS}}}{\text{CO}_2 \text{Emissions}_{\text{Coal Plant without CCS}} - \text{CO}_2 \text{Emissions}_{\text{Hybrid System}}}
\]

Levelized Cost of Electricity (LCOE in $ per MWh) =

\[
\frac{\text{Capital & Annual Operating Cost}_{\text{Wind Farm}} + \text{Capital & O&M Cost}_{\text{CCS}} + \text{Loss of Revenue}_{\text{CCS}} + \text{O&M Cost}_{\text{Coal Plant}}}{\text{Net Power Dispatched by the Hybrid System}}
\]
Quantifying Ramp Characteristics in Wind Power

To characterize wind power variability the following metrics are defined:

- **Ramp_t**: \( I_{|WP_t - WP_{t-1}| \geq \text{Threshold}} \cdot |WP_t - WP_{t-1}| \) where I is the indicator function

- **Aggregated Ramp Magnitude**: \( \text{Ramp}_{t_0, d_{t_0}}^{\text{aggregated}} = |WP_{t_0} - WP_{t_0+d_{t_0}}| \)

- **Average Ramp Magnitude**: \( \text{Ramp}_{t_0, d_{t_0}}^{\text{Rolling Avg}} = \frac{\sum_{i=t_0}^{t_0+d_{t_0}} \text{Ramp}_{i}}{d_{t_0}} \)

- **Mean Aggregated Ramp Magnitude as Percentage**: \( \text{MARMAP} = \frac{\sum_{i \in I} \text{Ramp}_{i}^{\text{Rolling Avg}}}{\text{Nameplate Capacity} \cdot |I|} \cdot 100\% \) where I is the index set of all aggregated ramp start instances  

Example
Area of Study: PJM

- Wind Power Variability in the Region

- % of total wind-sites in PJM in each ramp category

10%
20%
30%
40%
50%
60%
70%
80%
90%
100%

Cumulative percentage of EWITS Wind Sites

Mean Aggregated Ramp Magnitude as Percentage (MARMAP)

• ~ 73% Steady
• ~ 15% Mid-Variability
• ~ 12% High - Variability
• % of total wind-sites in PJM in each ramp category

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Background Information and Objectives
Method
Partial Capture
Amine Storage
Conclusions
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

**Background Information and Objectives**

- **Method**
- **Partial Capture**
- **Amine Storage**
- **Conclusions**

**Steady Wind**
- High Variability of Wind

**Partial Capture Configuration**
- CO₂ emission cap: 300 lbs/MWh

**Amine Storage Configuration**
- CO₂ emission cap: 1000 lbs/MWh

**AEP General Hub',2013**
- Lowest price variability in 2013

**Dominion Hub',2013**
- Highest price variability in 2013
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 CO₂ 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

**Background Information and Objectives**

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

- CCS Capital and O&M costs
  - 50% of base case
  - 150% of base case

- Wind farm capital and O&M costs
  - 50% of base case
  - 150% of base case

- PTC made available to the Co-located wind farm
  - 2.3 cents/kWh
  - 0 cents/kWh

- CCS Energy Penalty (expressed as percentage of net power output of the coal plant)
  - 20%
  - 40%

- CoC of new NGCC w/o. CCS for NG price between 6-8 $/MBtu
  - 6 $/MBtu
  - 8 $/MBtu

- CoC of new NGCC with post-combustion amine based CCS for NG price between 6-8 $/MBtu
  - 6 $/MBtu
  - 8 $/MBtu

Background Information and Objectives

Method

Partial Capture

Amine Storage

Conclusions
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
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
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

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2. “Eastern Wind Integration & Transmission Study”, prepared by EnerNex Corporation for the National Renewable Energy Laboratory, February 2011
Questions?

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Flexible Operation of Post-Combustion Amine based CCS

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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Background Information and Objectives

Method

Partial Capture

Amine Storage

Conclusions

Back-up Slide:
Wind Power Potential in the US

United States - Annual Average Wind Speed at 80 m

Background Information and Objectives
Method
Partial Capture
Amine Storage
Conclusions
Quantifying LMP Variability

- Trend Block 1
  \[ PD_{0.2}^{\text{Rolling Average}} = \frac{1 + 2}{2} = 1.5 \]
- Trend Block 2
  \[ PD_{2.4}^{\text{Rolling Average}} = \frac{1 + 1}{2} = 1 \]
- PD_{1}^{\text{Rolling Average}} = \frac{1.5 + 1}{2} = 1.25

Back-up Slide
Quantifying Variability of Electricity Prices (LMP)
## Back-up Slide

Quantifying Variability of Electricity Prices (LMP)

<table>
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<th>Hub Name</th>
<th>Mean Annual PD&lt;sub&gt;Rolling Avg&lt;/sub&gt; ($/MWh)</th>
<th>Mean Annual PD&lt;sub&gt;t&lt;/sub&gt;</th>
<th>∑&lt;sub&gt;i=1&lt;/sub&gt;&lt;sup&gt;8760&lt;/sup&gt; d&lt;sub&gt;i&lt;/sub&gt; / 8760</th>
<th>Standard Deviation (LMP&lt;sub&gt;t&lt;/sub&gt;)</th>
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Quantifying Ramp Characteristics in Wind Power

Wind Power

- Nameplate Capacity = 10
- Ramp Threshold = 2
- \( \text{Ramp}_{1} = 2 \), \( \text{Ramp}_{3} = 2 \), \( \text{Ramp}_{4} = 2 \), \( \text{Rolling Average}_{3,2} = 2 \)
- \( \text{Ramp}_{1,1}^a = 2 \), \( \text{MARMAP} = \frac{4 + 2}{2 \times 10} = 2.0\% \)

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