Multi-Pollutant Emission Control at Electric Power Plants

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Motivation

- Electric power is the fastest-growing form of energy worldwide, and is strongly correlated with growth in GDP

- Electric power generation is a major source of environmental problems:
  - Air pollution
  - Global warming
  - Radioactive wastes
Energy Sources for Electricity
(U.S. 1999)

- Fossil Fuels  69%
  - Coal  52%
  - Natural Gas  14%
  - Petroleum  3%

- Uranium  20%

- Renewables  11%
  - Hydro  8%
  - Other  3%
Number of Federal U.S. Environmental Laws, 1870-1990

Source: EPRI
Environmental Emissions from Coal-Fired Power Plants

Particulate Matter

- Pre-NSPS
- 1971 NSPS
- 1979 NSPS
- 1999 TSP

Sulfur Dioxide

- Pre-NSPS
- 1971 NSPS
- 1979 NSPS
- 1999 FGD

Nitrogen Oxides

- Pre-NSPS
- 1971 NSPS
- 1979 NSPS
- 1997 NSPS

Lbs / 10^6 Btu

98%
99%
99.7%
99.9%
Red.
Red.
Red.
Red.

0%
75%
90%
98+% Red.
Red.
Red.
Red.
Red.

0%
30%
40%
85% Red.
Red.
Red.
Red.
Red.

Reduction
So What’s the Problem?

- Many existing plants are not covered by stringent federal standards for new sources.
- Regional emissions are still too high to achieve environmental quality standards for some health-related pollutants (esp. O$_3$, PM$_{2.5}$).
- Hazardous air pollutants (air toxics) from power plants are a growing new concern.
- Greenhouse gas emissions are not presently controlled.
## Problems and Emissions of Primary Concern

<table>
<thead>
<tr>
<th>Category</th>
<th>Pollutants</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acid deposition</td>
<td>SO$_2$, NO$_x$</td>
</tr>
<tr>
<td>Urban ozone</td>
<td>NO$_x$</td>
</tr>
<tr>
<td>Fine particles</td>
<td>SO$_2$, NO$_x$</td>
</tr>
<tr>
<td>Air toxics</td>
<td>Hg</td>
</tr>
<tr>
<td>Greenhouse gases</td>
<td>CO$_2$</td>
</tr>
</tbody>
</table>
The Current Policy Context

- **As of 2000**  
  SO$_2$ and NO$_x$ reduced to control acid rain

- **By 2004**  
  NO$_x$ further reduced to control summer ozone

- **By 2007**  
  New controls on mercury

- **By 2008 (?)**  
  Likely new reductions of SO$_2$ and NO$_x$ (for PM$_{2.5}$)

- **By 2010 (??)**  
  CO$_2$ reductions to control global warming
Recent Legislative Proposals for Multi-Pollutant Control

- U.S. Senate
  - S. 172
  - S. 1949
  - S. 1369

- House of Representatives
  - H.R. 25
  - H.R. 2645
  - H.R. 2900
  - H.R. 2980
**S. 1949. Clean Power Plant and Modernization Act of 1999**

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>NO\textsubscript{x}</td>
<td>90% removal at each plant</td>
</tr>
<tr>
<td>SO\textsubscript{2}</td>
<td>95% removal at each plant</td>
</tr>
<tr>
<td>Hg</td>
<td>90% below 1997 level</td>
</tr>
<tr>
<td>CO\textsubscript{2}</td>
<td>1.55 lbs/kWh (coal), 1.3 (oil), 0.9 (natural gas)</td>
</tr>
</tbody>
</table>
H.R. 2900.
Clean Smokestacks Act of 1999

$\text{NO}_x$  Cap at 1.55 Mt/yr ($75\% < 1997$)

$\text{SO}_2$  Cap at 2.32 Mt/yr ($75\% < 1997$)

Hg  90% below 1997 level

$\text{CO}_2$  Cap at 1914 Mt/yr (1990 level)

(Compliance by 2005)
Some Technical and Economic Questions

- What options are available to reduce these emissions individually?
- What interactions (if any) must be considered in evaluating the feasibility and cost of multi-pollutant controls?
- Are there any advantages to multi-pollutant control strategies?
A Hierarchy of Models for Policy Analysis

Options for a single facility (tech feasibility, efficiency, emissions, cost)

Multi-facility (or multi-sector) optimization or simulation (dynamic)

Integrated assessment models (including measures of impacts)
General Options for Reducing Power Plant Emissions

- Switch to a “cleaner” fuel
  - of the same type
  - of a different type
- Install control technology to capture or reduce emissions
- Switch to a different power plant technology with lower or no emissions
- Generate less electricity
Multi-Pollutant Interactions at Coal-Fired Power Plants

Criteria Air Pollutants
- PM
- SO₂
- NOₓ

Hazardous Air Pollutants
- Hg
- HCl
- H₂SO₄

Greenhouse Gas Emissions
- CO₂
- CH₄
Options for CO$_2$ Reductions

- Efficiency improvements
- Switch to low-C fuel
- Switch to zero-C energy
- Capture & sequester CO$_2$
CO\textsubscript{2} Capture Technologies

**CO\textsubscript{2} Separation and Capture**

- **Absorption**
  - Chemical
    - MEA
    - Caustic
    - Other
  - Physical
    - Selexol
    - Rectisol
    - Other
- **Adsorption**
  - Adsorber Beds
    - Alumina
    - Zeolite
    - Activated C
  - Regeneration Method
    - Pressure Swing
    - Temperature Swing
    - Washing
- **Cryogenics**
- **Membranes**
  - Gas Separation
    - Polyphenyleneoxide
    - Polydimethylsiloxane
  - Gas Absorption
    - Polypropylene
  - Ceramic Based Systems
- **Microbial/Algal Systems**
**Combustion Controls**
- **Furnace Type:** Tangential
- **NOx Control:** Low NOx Burners

**Post-Combustion Controls**
- **NOx Control:** Hot-Side SCR
- **Particulates:** Cold-Side ESP
- **SO2 Control:** Wet FGD
- **SO2/NOx:** None
- **CO2 Control:** Absorption - MEA

**By-Product Management**
- **Recovery:** None
- **Fly Ash Disposal:** mixed w/ Landfill
- **CO2 Storage:** Depleted Oil Wells
Concentrated CO2 (mton/yr) = 2.711e+06
Effect of CO₂ Capture on Emissions/kWh

<table>
<thead>
<tr>
<th>Net Power Gen. (BkWh/yr)</th>
<th>CO₂ Emission (g CO₂ /kWh&lt;sub&gt;net&lt;/sub&gt;)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ref. Plant</td>
<td>Ref. Plant</td>
</tr>
<tr>
<td>w/CO₂ Capture</td>
<td>w/CO₂ Capture</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>SOₓ Emission (g SOₓ /kWh&lt;sub&gt;net&lt;/sub&gt;)</th>
</tr>
</thead>
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<tr>
<td>Ref. Plant</td>
</tr>
<tr>
<td>w/CO₂ Capture</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>NOₓ Emission (g NOₓ /kWh&lt;sub&gt;net&lt;/sub&gt;)</th>
</tr>
</thead>
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<tr>
<td>Ref. Plant</td>
</tr>
<tr>
<td>w/CO₂ Capture</td>
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Current Work: A Menu of Technology Options

Choose Power System

Please Choose a Power System:
- Conventional Combustion
- Gasification Comb. Cycle
- Advanced Combustion
- Fuel Cells
- Vision 21 Plant
**Configure Plant**

**Goal:** Optimization

**Gasification Options**

**Plant Type:** Simple Cycle

**Post-Combustion Controls**

**NOx Control:** None

**CO2 Control:** None

**Solids Management**

**Slag:** Landfill

**Sulfur:** Landfill

**Plant Diagram**

Air → [Diagram showing the flow of air and components in the plant] → Product
Configure Plant

**Goal:** Optimization

**Gasification Options**
- **Plant Type:**
  - Simple Cycle
  - Combined Cycle

**Post-Combustion Controls**
- **NOx Control:** None
- **CO2 Control:** None

**Solids Management**
- **Slag:** Landfill
- **Sulfur:** Landfill

Plant Diagram:

- Air
- Streamlines connecting various components
- Output stream
Configure Plant

Goal: Optimization

Gasification Options
Plant Type: Combined Cycle

Post-Combustion Controls
NOx Control: SCR
CO2 Control: SCRE

Solids Management
Slag: Landfill
Sulfur: Landfill
**IECM Interface**

**Configure Plant**

**Goal:**
- Optimization

**Gasification Options**
- **Plant Type:** Combined Cycle

**Post-Combustion Controls**
- **NOx Control:** SCR
- **CO2 Control:** None
  - None
  - Absorption - MEA

**Solids Management**
- **Slag:** Landfill
- **Sulfur:** Landfill

**Plant Diagram**
Select Gasification Combined Cycle (IGCC) Options

Choose Power System

Please Choose a Power System:
- Conventional Combustion
- Gasification Comb. Cycle
- Advanced Combustion
- Fuel Cells
- Vision 21 Plant
Select KRW Gasifier

Configure Plant

Goal: Optimization

Gasification Options
Gasifier: KRW
Oxidant: KRW
Gas Cleanup: Lurgi, Texaco

Post-Combustion Controls
NOx Control: None

Solids Management
Slag: Landfill
Sulfur: Landfill

Plant Diagram
Select Oxygen Plant

Configure Plant

- Goal: Optimization
- Gasification Options
  - Gasifier: KRW
  - Oxidant: Oxygen
  - Gas Cleanup: Oxygen
- Post-Combustion Controls
  - NOx Control: None
- Solids Management
  - Slag: Landfill
  - Sulfur: Landfill

Plant Diagram
Select Cold Gas Cleanup

Configure Plant

- **Goal:** Optimization
- **Gasification Options**
  - **Gasifier:** KRW
  - **Oxidant:** Oxygen
  - **Gas Cleanup:** Cold
   - None
   - Hot
- **Post-Combustion:** Cold
- **NOx Control:** None

Solids Management

- **Slag:** Landfill
- **Sulfur:** Landfill

Plant Diagram
Select NO\textsubscript{x} Control

Configure Plant

**Goal:** Optimization

**Gasification Options**
- **Gasifier:** KRW
- **Oxidant:** Oxygen
- **Gas Cleanup:** Cold

**Post-Com bustion**
- **NO\textsubscript{x} Control:** SCR, None, SCR

**Solids Management**
- **Slag:** Landfill
- **Sulfur:** Landfill

Plant Diagram
Select Byproduct Recovery

Configure Plant

Set Objectives

Set Parameters

Get Results

**Goal:**
Optimization

**Gasification Options**

- **Gasifier:** KRW
- **Oxidant:** Oxygen
- **Gas Cleanup:** Hot

**Post-Combustion Controls**

- **NOx Control:** SCR

**Solids Management**

- **Slag:** Landfill
- **Sulfur:** Sulfur, Landfill, Sulfuric Acid
# Coal vs. Natural Gas

<table>
<thead>
<tr>
<th>Constituent</th>
<th>kg/GJ in Coal</th>
<th>kg/GJ in Gas</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon</td>
<td>24</td>
<td>14</td>
</tr>
<tr>
<td>Sulfur</td>
<td>0.6</td>
<td>trace</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>0.6</td>
<td>0.0</td>
</tr>
<tr>
<td>Ash</td>
<td>3.5</td>
<td>0.0</td>
</tr>
</tbody>
</table>

$/GJ (1999)     | $0.9          | $2-3         |

$/GJ (2001)     | $0.9          | $7-8         |
Needed: A Life Cycle Assessment of Greenhouse Gas Emissions

**Natural Gas**

- **Gas Well** (Raw Gas) → **Gas Processing Plant**
- **Power Plant** (Energy for Compressor)
- **Pipeline** (CO₂ Leakage)
- **Energy for Transport**
- **CH₄ offgas**

**Coal**

- **Coal Mine** (CH₄ offgas) → **Prep Plant**
- **Power Plant** (Energy for Transport)
- **Energy for Transport**
- **CO₂**
Take-Home Message #1

The hip bone’s connected to the leg bone!
Take-Home Message #2

The head bone’s connected to the foot bone!
Take-Home Message #3

Ignoring these connections can give you the wrong answers for policy analysis.
Some Factors Affecting Control Strategy Choices

- Regulatory/policy requirements
  - Stringency
  - Timetable
  - Flexibility
- Availability and cost of technology
- Availability and cost of alternative fuels
- Human dimensions
The IECM is Available for Downloading

- Web Access:
Power Generation Options Using Fossil Fuels

Power Generation Technologies

- Fuel
  - Coal
    - Combustion-based
      - Gasification-based
  - Gas
    - Direct Combustion
      - Gas Reforming

- Oxidant
  - Air
  - Pure Oxygen

- Technology
  - Simple Cycle
    - Pulverized Coal Gas Turbines
  - Combined Cycle
    - Gas Turbines
    - Coal Gasification
    - Fuel Cells
    - Other