REDESIGNING THE REGULATED POWER PLANT

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ADDRESSING GLOBAL GRAND CHALLENGES THROUGH ENGINEERING & PUBLIC POLICY

Science & Engineering
- Positive/objective
- Hypothesis
- Data
- Fundamental constraints

Engineering & Public Policy
- “Trans-science”
- Problem driven research
- Quantitative models
- Informed simplification
- Uncertainty analysis
- Data quality constraints

Public Policy
- Normative/subjective
- Tradeoffs
- Judgement
- Legal & political constraints
COAL FIRED POWER PLANTS ARE THE LARGEST POINT SOURCES OF AIR AND WATER EMISSIONS
GRID STABILITY AND CAPITAL COST OF ALTERNATIVES WILL LIMIT PACE OF TRANSITION
REGULATORY CHANGES REDUCE EXTERNALITIES OF COAL GENERATION, INCREASE LEVELIZED COST OF ELECTRICITY
**Tradeoffs in Air, Water, and Carbon Emissions Under Promulgated Regulation**

<table>
<thead>
<tr>
<th>CSAPR &amp; MATS</th>
<th>2015</th>
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<tbody>
<tr>
<td>Compliance Deadline</td>
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<tr>
<td>Criteria Air Pollution</td>
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<tr>
<td>Aqueous Emissions</td>
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<td>CO₂ Emissions</td>
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<td>Heat Rate</td>
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EPA Final Effluent Limitation Guidelines for Steam Electric Power Generation Facilities

Option 1. Chemical Precipitation and Biological Treatment (CPBT)

Option 2. Zero Liquid Discharge (ZLD)
AP2 ESTIMATES COUNTY-LEVEL HUMAN HEALTH AND ENVIRONMENTAL DAMAGES FROM NO$_X$, SO$_2$, AND PM$_{2.5}$

1.14 GW CFPP
G.G. Allen Steam Station in South Point Township, NC

Muller and Mendelsohn, American Economics Review; Gingerich et al., PNAS, under revision
SOCIAL COST OF CARBON APPROXIMATES CLIMATE DAMAGES

Benefit-Cost Analysis of FGD Wastewater Treatment

Significant risk of un-intended human health consequences where fuel switching is constrained.

ELG Technical Documentation

$600 Million / year in net costs of CPBT;

$2 Billion / year in net costs of ZLD

Gingerich et al., PNAS, under revision
WHAT HAVE WE LEARNED BY STUDYING THE AIR EMISSION IMPLICATIONS OF EXPANDED WASTEWATER TREATMENT?

1. Narrowly scoped and “median plant” analyses may miss important benefit-cost tradeoffs

2. Staged implementation of regulations precludes comprehensive systems-level redesign of capital intensive infrastructure
# TRADEOFFS IN AIR, WATER, AND CARBON EMISSIONS UNDER PROMULGATED REGULATION

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<tr>
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<td><strong>Compliance Deadline</strong></td>
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*Note: The table indicates the changes in emission levels and compliance deadlines for different pollutants under two regulatory schemes, CSAPR & MATS and ELGs.*
REDESIGNING THE REGULATED POWER PLANT: ALTERNATIVES FOR MINIMIZING THE COSTS OF REGULATORY COMPLIANCE
QUALITY, QUANTITY, AND SPATIAL-TEMPORAL AVAILABILITY OF WASTE HEAT IN THE US POWER SECTOR
REDESIGNING THE REGULATED POWER PLANT: ALTERNATIVES FOR MINIMIZING THE COSTS OF REGULATORY COMPLIANCE
Revenue Implications of Allocating Steam, Residual Heat, or Electricity to Environmental Controls

Maximize (Revenue = eE + cC + wW)

Models of Electricity Generation, Carbon Capture (221 kg/MWh CO\textsubscript{2} min), and Wastewater Treatment (ZLD)

Steam Allocation

Residual Heat Allocation

Electricity Allocation
Allocating residual heat for water treatment reduces the energy penalty of meeting FGD standard.
Optimal energy allocation depends upon the current regulatory environment.

FGD Wastewater Treatment Only

Water: 35 GJ of Residual Heat for FO

FGD Wastewater and Carbon Capture

Carbon: 243 GJ of Residual Heat
       61 GJ of Low Pressure Steam
Water: 2.3 MWh of Electricity for MVC
Optimal energy allocation depends upon the current regulatory environment...

...and the market price of carbon.
1. CFPPs maximize their revenue by generating as much electricity as possible, thus minimizing dispatch of steam and auxiliary electricity to environmental controls.

2. Revenue maximizing case fully utilizes residual heat resources for water treatment or carbon capture.
GEOLOGIC CARBON STORAGE (GCS) EXTRACTS BRINE FOR PRESSURE MANAGEMENT
Reservoir water quality varies widely, with median TDS exceeding 100,000 ppm.

TDS (g/L)
- 4-12
- 12-22
- 22-48
- 48-90
- 90-160
- 160-226
- 226-321
PORTFOLIO OF WATER DESALINATION TECHNOLOGIES

- Reverse Osmosis
- Capacitive Deionization
- Forward Osmosis
- Multiple Effect Distillation/Multistage Flash Distillation
- Membrane Distillation/Crystallization
- Mechanical Vapor Recompression
- Thermal Vapor Recompression

Energy Quality:
- Low (10 g/L)
- High (100 g/L)

Energy Intensity:
- Low
- High

Electrical Energy
REDUCE WATER TREATMENT ISSUES BY LENTHENING PIPELINE TRANSPORT OF CO$_2$?
Minimum TDS of extracted water salinity depends on economically viable transport distances.
REDESIGNING THE REGULATED POWER PLANT

• Emissions tradeoffs underscores the imperative of low energy separations;

• Plant process modeling aids in optimizing energy allocation under changing regulatory scenarios;

• Clear regulatory guidance and comprehensive analysis reduce burden of system retro-fit.
ACKNOWLEDGEMENTS
U.S. ELECTRICITY GENERATION BY FUEL

THOUSAND MEGAWATT HOURS PER DAY

Forecast

Coal 48.2% 44.4% 44.8% 42.3% 37.4% 38.9% 38.6% 33.2% 30.1% 31.0%
Natural gas 21.4% 23.3% 23.9% 24.7% 30.3% 27.7% 27.5% 32.7% 34.5% 33.3%
Petroleum 23.3% 23.3% 23.3% 23.3% 23.3% 23.3% 23.3% 23.3% 23.3% 23.3%
Nuclear 23.3% 23.3% 23.3% 23.3% 23.3% 23.3% 23.3% 23.3% 23.3% 23.3%
Hydropower 21.4% 23.3% 23.9% 24.7% 30.3% 27.7% 27.5% 32.7% 34.5% 33.3%
Non-hydro 21.4% 23.3% 23.9% 24.7% 30.3% 27.7% 27.5% 32.7% 34.5% 33.3%
renewables 21.4% 23.3% 23.9% 24.7% 30.3% 27.7% 27.5% 32.7% 34.5% 33.3%
Other sources 21.4% 23.3% 23.9% 24.7% 30.3% 27.7% 27.5% 32.7% 34.5% 33.3%

WATER QUALITY BENEFITS OF CHEMICAL PRECIPITATION AND BIOLOGICAL TREATMENT OF FGD WASTEWATER TREATMENT

Annual Discharges [lbs]

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<thead>
<tr>
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<tr>
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<tr>
<td>Selenium</td>
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<td>Arsenic</td>
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<tr>
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<td>1,000</td>
</tr>
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- Boron
- Mercury
- Selenium
- Arsenic
- Lead
- Chlorides
AVERAGE AIR EMISSIONS/m³ OF ZLD WASTEWATER TREATMENT

![Bar chart showing emissions of NO\textsubscript{x}, SO\textsubscript{2}, PM\textsubscript{2.5}, and CO\textsubscript{2} for Auxiliary Electricity and Chemical Manufacturing.]
AIR EMISSION IMPLICATIONS OF FGD WASTEWATER TREATMENT

1. Quantify the air emissions (criteria pollutants and greenhouse gases) associated with FGD wastewater treatment;

2. Estimate human health, environmental, and climate change damages resulting from these emissions;
LIFE-CYCLE EMISSIONS OF WASTEWATER TREATMENT

Emissions from FGD Wastewater Treatment

- Emissions from Auxiliary Electricity Consumption

Emissions from Chemical Manufacturing

- Emissions from Energy Consumed in Chemical Manufacturing
- Direct Emissions from Chemical Manufacturing
POWER MODEL BASED UPON NETL 550 MW CFPP

Legend

B: Boiler  
G: Generator  
WT: Water Treatment  
CC: Carbon Capture

m: mass flow rate [kg/hr]  
h: steam enthalpy [kJ/kg]  
$S_E$: dispatch to Turbine [%]  
$S_W$: dispatch to WT [%]  
$S_C$: dispatch to CC [%]
Using Cansolv to capture carbon imposes a parasitic loss of 21 MW.
MECHANICAL VAPOR RECOMPRESSION IS MORE EFFICIENT THAN THERMAL TECHNOLOGIES

MVC – 21 kWh/m³
FORWARD OSMOSIS PROCESS OVERVIEW

Feedwater → Pump → Feed Side (Dilute Draw Solution) → Preheater/Condenser → Pump → Concentrated Draw Solution → Compressor (in case of vacuum) → Draw Solute

Concentrated Brine → Pump → Draw Side (Draw Solution) → Pump → Condensate → Reboiler → Distillation Column → Fresh Water

Electrical Energy

Steam (Thermal Energy)
There is sufficient exhaust heat to meet in-plant water treatment demands using FO processes.

Sorek Desalination Plant = 415,000 m³/day
REDESIGNING THE REGULATED POWER PLANT: ALTERNATIVES FOR MINIMIZING THE COSTS OF REGULATORY COMPLIANCE

1. What is the revenue maximizing allocation of energy sources to combinations of power generation and emissions controls?

2. How will the optimal energy allocation change under future regulations?
ALTERNATIVE FIGURE

![Box plot of TDS (g/L) for different geological units.]

- Eocene
- Oligocene
- Miocene
- Washita
- Paluxy
- Mission Canyon
- Mt. Simon
- San Andres
- Wasatch
- Tertiary
THIS IS JUST TO SHOW YOU THE BRINE MANAGEMENT ENERGY PENALTY FOR THE 5 CASES
INTEGRATE RESERVOIR COSTS INTO REGIONAL ASSESSMENTS

Saline reservoirs have large CO$_2$ storage capacities, but we lack resolved estimates of water quality.
APPROXIMATE EXTRACTED WATER COMPOSITION USING USGS PRODUCED WATER TDS DATABASE
Significant variability in salinity estimates, but TDS of most large reservoirs is greater than seawater.
SUFFICIENT SHORT TERM STORAGE VOLUMES AT LOWER EXTRACTED WATER SALINITIES

25 years of CFPPs

25 years of stationary emissions sources
19 BGJ of waste heat discharged from US power plants annually, mostly at very low temperatures.

Gingerich and Mauter, ES&T, 2015
Zhou, Gingerich, and Mauter, I&ECR, 2015
Gingerich and Mauter, ES&T, submitted
Models of Electricity Generation, Carbon Capture (221 kg/MWh CO$_2$ min), and Wastewater Treatment (ZLD)

Maximize (Revenue = eE + cC + wW)
SIGNIFICANT PARASITIC LOSSES ASSOCIATED WITH STEAM WITHDRAWAL, ESPECIALLY FROM HP AND IP TURBINES

MVC – 21 kWh/m³
Models of Electricity Generation, Carbon Capture (221 kg/MWh CO₂ min), and Wastewater Treatment (ZLD)

Maximize (Revenue = eE + cC + wW)
Allocating residual heat for water treatment reduces the energy penalty of meeting FGD standard.
ENERGY PENALTY OF EXTRACTED WATER TREATMENT

Energy use (kWh/tonne of CO₂)

- CO₂ Transport
- Brine Management

Energy Use (kWh/tonne of CO₂)

Carbon Capture
Carbon Transport
Brine Management

Parasitic Loss (%)