ESSAYS IN RENEWABLE ENERGY AND EMISSIONS TRADING

By

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To My Parents, who have supported me through all of my academic achievements.
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# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACKNOWLEDGMENTS</td>
<td>4</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>9</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>10</td>
</tr>
<tr>
<td>ABSTRACT</td>
<td>12</td>
</tr>
</tbody>
</table>

## CHAPTER

### 1 EFFECTS OF STATE GOVERNMENT POLICIES ON ELECTRICITY CAPACITY FROM NON-HYDROPOWER RENEWABLE SOURCES

1.1 Introduction                                                        | 14    |
1.2 Literature Review                                                   | 16    |
1.3 Model                                                               | 18    |
1.4 Variables and Data                                                  | 21    |
1.5 Statistical Specifications and Empirical Analysis                   | 33    |
1.5.1 Economic and Political Variables: $W_{it}$                        | 34    |
1.5.2 Regulatory Policy Variables: $R_{it}$                            | 37    |
1.5.3 State Fixed-Effects Variables: $S_{it}$                          | 40    |
1.5.4 Year Variables: $T_{it}$                                         | 40    |
1.6 Conclusions                                                        | 41    |

### 2 EFFECTS OF COAL CONTRACT CONSTRAINTS ON SO₂ TRADING PROGRAM COMPLIANCE DECISIONS

2.1 Introduction                                                        | 47    |
2.2 Policy Background                                                   | 48    |
2.2.1 Title IV of the Clean Air Act Amendment                           | 48    |
2.2.1.1 Phase I of Title IV                                            | 49    |
2.2.1.2 Phase II of Title IV                                           | 50    |
2.2.2 Clean Air Interstate Rule                                         | 51    |
2.3 Literature Review                                                   | 52    |
2.3.1 Title IV: Phase I                                                | 52    |
2.3.2 Utility-Level Models of Compliance Costs                          | 55    |
2.3.3 Long-Term Coal Contracts                                         | 56    |
2.4 Inefficiencies Resulting from Coal Contract Constraints             | 57    |
2.5 Model and Parameters                                                | 60    |
2.6 Generating Unit Level Decision-Making Process                       | 62    |
2.6.1 Generating Unit’s Problem                                        | 63    |
2.6.2 First-Order Conditions                                           | 64    |
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.6.3 Characterizing a Unit’s Spot Market Fuel Choices and Marginal Cost of Abatement from Fuel Switching</td>
<td>65</td>
</tr>
<tr>
<td>2.6.3.1 Necessary conditions for using both high sulfur and low sulfur coal</td>
<td>65</td>
</tr>
<tr>
<td>2.6.3.2 Only high sulfur coal use: Necessary conditions</td>
<td>65</td>
</tr>
<tr>
<td>2.6.3.3 Only low sulfur coal use: Necessary conditions</td>
<td>66</td>
</tr>
<tr>
<td>2.6.4 Coal Use Under a High Sulfur Coal Contract Constraint</td>
<td>66</td>
</tr>
<tr>
<td>2.6.5 Coal Use under a Low Sulfur Coal Contract Constraint</td>
<td>68</td>
</tr>
<tr>
<td>2.6.6 Generating Unit-Level Compliance Costs</td>
<td>70</td>
</tr>
<tr>
<td>2.6.7 Generating Unit’s Net Allowance Position: Excess Demand</td>
<td>72</td>
</tr>
<tr>
<td>2.6.7.1 Cost savings of fuel switching versus allowance purchases when $P_A &gt; MCA_{s,s}^*$</td>
<td>74</td>
</tr>
<tr>
<td>2.6.7.2 Effects of high sulfur coal contracts on excess demand and costs</td>
<td>74</td>
</tr>
<tr>
<td>2.6.7.3 Cost savings of allowance purchases versus fuel switching when $P_A &lt; MCA_{s,s}^*$</td>
<td>80</td>
</tr>
<tr>
<td>2.6.7.4 Effects of low sulfur coal contracts</td>
<td>80</td>
</tr>
<tr>
<td>2.6.7.5 Fuel switching versus allowance purchases when $P_A = MCA_{s,s}^*$</td>
<td>85</td>
</tr>
<tr>
<td>2.6.8 Generating Unit’s Scrubber Installation Choice</td>
<td>86</td>
</tr>
<tr>
<td>2.6.8.1 When will a generating unit install a scrubber?</td>
<td>86</td>
</tr>
<tr>
<td>2.6.8.2 Different marginal costs of abatement</td>
<td>87</td>
</tr>
<tr>
<td>2.6.8.3 Excess demand correspondence</td>
<td>87</td>
</tr>
<tr>
<td>2.6.9 Impact of Coal Contracts on Excess Demand Correspondence</td>
<td>89</td>
</tr>
<tr>
<td>2.6.9.1 Impact of a binding high sulfur coal contract</td>
<td>90</td>
</tr>
<tr>
<td>2.6.9.2 Impact of a binding low sulfur coal contract</td>
<td>100</td>
</tr>
<tr>
<td>2.7 Possible Implications on the Allowance Market and Industry Compliance Costs</td>
<td>109</td>
</tr>
<tr>
<td>2.8 Conclusions</td>
<td>110</td>
</tr>
</tbody>
</table>

3 THE EFFECT OF FUEL CONTRACTING CONSTRAINTS ON SO₂ TRADING PROGRAM COMPLIANCE: EMPIRICAL EVIDENCE | 127  |

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1 Introduction</td>
<td>127</td>
</tr>
<tr>
<td>3.2 Review of Generating Unit Model</td>
<td>128</td>
</tr>
<tr>
<td>3.2.1 Generating Unit Problem</td>
<td>128</td>
</tr>
<tr>
<td>3.2.2 Optimal Compliance Choices</td>
<td>129</td>
</tr>
<tr>
<td>3.3 Allowance Market Equilibrium</td>
<td>132</td>
</tr>
<tr>
<td>3.4 Comparative Statics: Effects on the Allowance Market</td>
<td>134</td>
</tr>
<tr>
<td>3.4.1 Comparative Statics: Effect of Relative Fuel Cost on the Allowance Market</td>
<td>134</td>
</tr>
<tr>
<td>3.4.2 Comparative Statics: Effect of Coal Contracts on the Allowance Market Given the Scrubber Choice</td>
<td>135</td>
</tr>
<tr>
<td>3.4.2.1 Impact of high sulfur coal contract on allowance market</td>
<td>135</td>
</tr>
</tbody>
</table>
3.7.7.1 Characterization of “non-affected” generating units at an “affected” plant ........................................ 172
3.7.7.2 “Non-affected” generating units and high sulfur coal contracts ......................................................... 173
3.7.8 Scrubber Installation Choice ......................................................... 174
3.7.8.1 Marginal cost of abatement with and without a scrubber ................................................................. 174
3.7.9 A Plant’s Preferred Order of Scrubber Installation ................................................................. 176
3.7.9.1 At which generating units will a plant install a scrubber? ................................................................. 177
3.7.9.2 At what allowance price will a plant install a scrubber at a given generating unit? .............................. 178
3.7.9.3 Scrubber installation and high sulfur coal contracts ................................................................. 179
3.7.9.4 Scrubber installation and low sulfur coal contracts ................................................................. 181
3.7.10 Scrubber Installation Example: Plant with Two Affected Generating Units ........................................... 182
3.7.10.1 Case 1: Install no scrubbers ................................................................. 183
3.7.10.2 Case 2: Install one scrubber ................................................................. 184
3.7.10.3 Case 3: Install two scrubbers ................................................................. 185
3.7.11 Scrubber Installation Example: Plant with One Affected and One Non-Affected Generating Units ............. 186
3.7.12 Summary of Plant Level Results ................................................................. 187
3.8 CONCLUSIONS ................................................................................. 188

A CONTRACT IMPACTS ON COSTS AND SCRUBBER INSTALLATION
INDIFFERENCE PRICE ............................................................................. 199
A.1 Impacts on Total Costs and Compliance Costs from a Coal Contract Constraint ................................. 199
A.2 Derivation of Cost-Minimizing Input Use to Find $P^*_A$ ..................................................................... 205

B MARKET EQUILIBRIUM AND SIMULATION DESIGN ........................................ 206
B.1 Conditions for Existence of an Equilibrium ............................................................................. 206
B.2 Technical Details of Simulation Model Design ............................................................................. 208

REFERENCES ..................................................................................... 211

BIOGRAPHICAL SKETCH ........................................................................... 216
# LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-1</td>
<td>Dependent and Control Variables</td>
<td>43</td>
</tr>
<tr>
<td>1-2</td>
<td>Regressions Results</td>
<td>44</td>
</tr>
<tr>
<td>1-3</td>
<td>Policy Variables</td>
<td>45</td>
</tr>
<tr>
<td>1-4</td>
<td>Variable Effects of Significant Variables</td>
<td>46</td>
</tr>
<tr>
<td>2-1</td>
<td>Phase I Compliance Cost Estimates</td>
<td>113</td>
</tr>
<tr>
<td>2-2</td>
<td>High Sulfur Coal Contract: Assumptions</td>
<td>114</td>
</tr>
<tr>
<td>2-3</td>
<td>High Sulfur Coal Contract: Results</td>
<td>114</td>
</tr>
<tr>
<td>2-4</td>
<td>Low Sulfur Coal Contract Examples: Assumptions</td>
<td>114</td>
</tr>
<tr>
<td>2-5</td>
<td>Low Sulfur Coal Contract Examples: Results</td>
<td>115</td>
</tr>
<tr>
<td>2-6</td>
<td>Example Epsilon Magnitude: Case 1</td>
<td>116</td>
</tr>
<tr>
<td>2-7</td>
<td>Example Epsilon Magnitude: Case 2</td>
<td>117</td>
</tr>
<tr>
<td>2-8</td>
<td>Example Epsilon Magnitude</td>
<td>118</td>
</tr>
<tr>
<td>3-1</td>
<td>Example: Contract Coal Distribution</td>
<td>190</td>
</tr>
<tr>
<td>3-2</td>
<td>Sulfur Conversion by Fuel Type</td>
<td>190</td>
</tr>
<tr>
<td>3-3</td>
<td>Simulation Results</td>
<td>191</td>
</tr>
<tr>
<td>3-4</td>
<td>Impact of Contract Constraint on Scrubber Choice</td>
<td>192</td>
</tr>
<tr>
<td>3-5</td>
<td>Simulations with Engineering Data</td>
<td>192</td>
</tr>
<tr>
<td>3-6</td>
<td>Impacts of a Reduction in the Allowance Allocation of 10%</td>
<td>192</td>
</tr>
<tr>
<td>3-7</td>
<td>Math Example: Two Affected Units</td>
<td>192</td>
</tr>
</tbody>
</table>
LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-1</td>
<td>The SO$_2$ Allowance Price</td>
<td>119</td>
</tr>
<tr>
<td>2-2</td>
<td>Excess Demand Correspondence and Compliance Cost Savings from Fuel Switching</td>
<td>119</td>
</tr>
<tr>
<td></td>
<td>Over Allowance Purchasing</td>
<td></td>
</tr>
<tr>
<td>2-3</td>
<td>High Sulfur Contract: Shift in Minimum Excess Demand</td>
<td>120</td>
</tr>
<tr>
<td>2-4</td>
<td>No Contract: Compliance Costs</td>
<td>120</td>
</tr>
<tr>
<td>2-5</td>
<td>High Sulfur Contract: Compliance and Total Costs</td>
<td>120</td>
</tr>
<tr>
<td>2-6</td>
<td>High Sulfur Contract: Relative Savings from Contract Coal</td>
<td>121</td>
</tr>
<tr>
<td>2-7</td>
<td>Cost Savings from Using Allowances Over Fuel Switching</td>
<td>121</td>
</tr>
<tr>
<td>2-8</td>
<td>Low Sulfur Contract</td>
<td>121</td>
</tr>
<tr>
<td>2-9</td>
<td>No Contract: Compliance Costs</td>
<td>122</td>
</tr>
<tr>
<td>2-10</td>
<td>Low Sulfur Coal Contract: $MCA_{i}^{s,c}$</td>
<td>122</td>
</tr>
<tr>
<td>2-11</td>
<td>Low Sulfur Coal Contract: $MCA_{i}^{s,c}$</td>
<td>122</td>
</tr>
<tr>
<td>2-12</td>
<td>Compliance Costs: $P_A = MCA_{i}^{s,s}$</td>
<td>123</td>
</tr>
<tr>
<td>2-13</td>
<td>High Sulfur Coal Contract</td>
<td>123</td>
</tr>
<tr>
<td>2-14</td>
<td>Low Sulfur Coal Contract</td>
<td>123</td>
</tr>
<tr>
<td>2-15</td>
<td>Excess Demand Correspondence: $MCA_{i}^{s,s} &lt; P^S_A$</td>
<td>124</td>
</tr>
<tr>
<td>2-16</td>
<td>Excess Demand Correspondence: $MCA_{i}^{s,s} \geq P^S_A$</td>
<td>124</td>
</tr>
<tr>
<td>2-17</td>
<td>Impact of a High Sulfur Coal Contract: $MCA_{i}^{s,s} &lt; P^S_A$</td>
<td>125</td>
</tr>
<tr>
<td>2-18</td>
<td>Impact of a High Sulfur Coal Contract: $MCA_{i}^{s,s} &gt; P^S_A$</td>
<td>125</td>
</tr>
<tr>
<td>2-19</td>
<td>Impact of a Low Sulfur Coal Contract: $MCA_{i}^{NS} &gt; P^S_A$</td>
<td>125</td>
</tr>
<tr>
<td>2-20</td>
<td>Impact of a low sulfur Coal Contract: $MCA_{i}^{NS} &lt; P^S_A$</td>
<td>126</td>
</tr>
<tr>
<td>3-1</td>
<td>Excess Demand Correspondence</td>
<td>193</td>
</tr>
<tr>
<td>3-2</td>
<td>Impact of High Sulfur Coal Contract</td>
<td>193</td>
</tr>
<tr>
<td>3-3</td>
<td>Impact of Low Sulfur Coal Contract</td>
<td>194</td>
</tr>
<tr>
<td>3-4</td>
<td>Excess Demand Correspondence with Scrubber Choice</td>
<td>194</td>
</tr>
<tr>
<td>3-5</td>
<td>Impacts of High Sulfur Coal Contract</td>
<td>195</td>
</tr>
</tbody>
</table>
Environmental issues have become a key political issue over the past forty years and has resulted in the enactment of many different environmental policies. The three essays in this dissertation add to the literature of renewable energy policies and sulfur dioxide emissions trading.

The first essay ascertains which state policies are accelerating deployment of non-hydropower renewable electricity generation capacity into a state’s electric power industry. As would be expected, policies that lead to significant increases in actual renewable capacity in that state either set a Renewables Portfolio Standard with a certain level of required renewable capacity or use Clean Energy Funds to directly fund utility-scale renewable capacity construction. A surprising result is that Required Green Power Options, a policy that merely requires all utilities in a state to offer the option for consumers to purchase renewable energy at a premium rate, has a sizable impact on non-hydro renewable capacity in that state.

The second essay studies the theoretical impacts fuel contract constraints have on a electricity generating unit’s compliance costs of meeting the emissions compliance restrictions set by Phase I of the Title IV SO₂ Emissions Trading Program. Fuel contract constraints restrict a utility’s degrees of freedom in coal purchasing options, which can lead to the use of a more expensive compliance option and higher compliance costs.
The third essay analytically and empirically shows how fuel contract constraints impact the emissions allowance market and total electric power industry compliance costs. This paper uses generating unit-level simulations to replicate results from previous studies and show that fuel contracts appear to explain a large portion (65%) of the previously unexplained compliance cost simulations. Also, my study considers a more appropriate plant-level decisions for compliance choices by analytically analyzing the plant level decision-making process to show how cost-minimization at the more complex plant level may deviate from cost-minimization at the generating unit level.
CHAPTER 1
EFFECTS OF STATE GOVERNMENT POLICIES ON ELECTRICITY CAPACITY FROM NON-HYDROPOWER RENEWABLE SOURCES

1.1 Introduction

Renewable energy has recently become an important aspect in the U.S. electricity generation mix and a primary focus of government policy for environmental and energy security/price volatility reasons. First, the public’s growing concern for the environment and progressively stringent regulation of emissions in the electric power industry has driven policies to increase the amount of renewable energy in the electricity generation portfolio. Electricity production from renewable resources creates little, and often zero, emissions of the pollutants that result from traditional fossil fuel generating technologies. More renewable energy use helps utilities in their emissions compliance obligations. Moreover, the prospect of compliance with any future carbon emissions regulation would further strengthen the incentive to shift toward cleaner electricity generating technologies.¹

Second, recent uncertainty in the U.S. energy supply due to political concerns in the Middle East countries and other foreign oil producing countries as well as volatility in oil and natural gas prices have led to a push to increase U.S. energy independence through a greater domestic energy supply and to decrease the impacts on the economy from any price shocks in the fossil fuel markets, such as the natural gas price spikes in 2000-2001 and following the 2004 and 2005 hurricane seasons.²

¹ Smith et al. (2000) estimates the displacement of emissions from the Massachusetts Renewables Portfolio Standard.

² Bird et al. (2005) explains the market factors behind wind power deployment, which include the volatility of natural gas prices. GDS Associates (2001) supported this factor as well in the reasoning behind the enactment of Hawaii’s Renewables Portfolio Standard. The delivered price of natural gas to electric utilities has risen from $2.62/million cubic foot (MCF) in 1999 to $8.45/MCF in 2005 (EIA Annual Energy Review 2005).
Complementing federal policies such as the production tax credit, state governments have taken actions to increase renewable energy capacity and generation, with 41 of the 50 states enacting policies to encourage the use of renewable energy in their state. Individual state policies show a great deal of variance. The objective of this paper is to determine which state policies have led to increased deployment of aggregate non-hydro renewable energy capacity into a state’s electric power industry.\(^3\) The literature on state renewable energy policies consists mainly of case studies on policy effectiveness. Only one previous paper uses econometric methods to estimate the effects of various state policies on renewable capacity. Menz and Vachon (2006) measure the impacts on wind capacity in 39 states for 1998-2002. In contrast, my paper uses panel data from all 50 states for 1996-2003 to estimate the effects on total nonhydro renewable capacity deployment, not just wind power capacity deployment. It estimates the effects of additional policies, and also controls for differences in the market and political environments.

Three distinctly different types of policies are found to be effective at expanding non-hydro renewable capacity deployment: a command-and-control policy known as a Renewables Portfolio Standard (RPS), a tax-and-subsidy scheme facilitated through a Public Benefits Fund (PBF) or Clean Energy Fund (CEF), and a market-based policy where consumers can express their preferences to buy power from renewable resources at a premium price.

The command-and-control policy targets the utility by mandating a specified level of capacity that must come from renewable energy, and is generally referred to as a Renewables Portfolio Standard. The tax-and-subsidy scheme collects an additional charge per unit of electricity consumed from all customers in a state and places the proceeds into this Public Benefits Fund or Clean Energy Fund. Monies from the PBF/CEF are used to

\(^3\) The electric power industry accounted for 60% of renewable energy production in 2003.
subsidize renewable capacity deployment through grants, loans, or production incentives. The market-based policy creates a differentiated demand by mandating that utilities must offer their customers the choice to purchase green power, which allows consumers to express their preferences through paying an extra, utility commission-approved charge for green power.

The econometric results support many of the conclusions from various case studies with respect to Renewables Portfolio Standard and Clean Energy Fund policies. Moreover, the results presented here also show, unlike previous studies, that the potential for offering consumers the option to purchase renewable electricity at a higher price than conventionally produced electricity can increase renewable capacity in a state.

1.2 Literature Review

The bulk of the literature in this area uses case studies to determine the specific characteristics of effective state renewable energy policies. There are two main types of case studies: (1) analyses of a specific policy enacted in a particular state; and (2) a summary of the general impacts of a specific policy mechanism used across multiple states, including policy design characteristics that are effective across multiple states. Langniss and Wiser (2003) analyze the Texas Renewables Portfolio Standard, including the achievements of the policy mechanism and the design characteristics that allowed the policy to be effective at increasing renewable energy capacity. It was found that the clearly defined capacity requirements have been effective in increasing renewable capacity in Texas.

Wiser et al. (2004) considered all Renewables Portfolio Standards and found the pitfalls in the current policy designs. Some key problems in policy designs include insufficient duration and stability of targets, weak enforcement, and narrow applicability of the policy. Other conditions that may impact a policy’s effectiveness are the presence of long-term power purchasers and political and regulatory stability.
Petersik (2004) provides a non-econometric analysis of the effectiveness of different types of Renewables Portfolio Standards as of 2003 for the United States Energy Information Association (EIA). He finds that only Renewables Portfolio Standards that mandate a certain level of capacity (number of megawatts) have had any significant impact on renewable capacity deployment. Policies with renewable generation or sales requirements as well as voluntary policy programs were found to have no significant effect.

Chen et al. (2007) compares the results from 28 policy impact projections for state or utility-level Renewables Portfolio Standards and finds that (1) the impact on electricity prices is minimal, (2) wind power is expected to be the primary renewable used to meet policy requirements, and (3) the benefit-cost estimates rely heavily on uncertain assumptions, such as renewable technology costs, natural gas prices, and possible carbon emissions policy in the future.

Bolinger et al. (2001) describe in detail 14 different state Clean Energy Funds, enumerating the regulatory background, funding approaches, the current status of the fund, and the resulting impacts on renewable energy. Programs that fund utility-scale projects are found to be the most effective at increasing renewable capacity deployment.\(^4\) Bolinger et al. (2004, 2006) summarize the same 14 Clean Energy Funds. They find that due to delays and cancelled projects actual capacity often is much lower than initially obligated capacity.

Wiser and Olson (2004) examine participation in 66 utility green power programs. They find local green power programs have residential participation rates ranging from 0.02% to 6.45% and averaging 1.39%. However, this study does not look at any state-level Required Green Power Options that require all utilities in a state to offer consumers the option to purchase renewable energy. The paper focuses on participation rates of

\(^4\) Funding is usually based on actual production, but it is paid in a lump sum once the capacity has been constructed.
the utility-based programs, but does not analyze the impact of these local programs on renewable energy generation or capacity.

Bird et al. (2005) summarize federal renewable energy policies, general market factors, and state-specific factors, such as state policies, that are driving the deployment of wind power. The key market factors are the volatility in natural gas prices during the early 2000s and the lowered wind energy generation costs due to larger wind turbines, which have combined to make wind power more competitive with natural gas-fired generation.

Only one paper has attempted to econometrically estimate the effects of state renewable energy policy on renewable capacity. Menz and Vachon (2006) use ordinary least squares to estimate state policy effects on wind power capacity and generation with a panel dataset for 39 states for 1998-2002 while controlling for wind power availability, retail choice, and policy dummy variables for Public Benefits Fund, Renewables Portfolio Standard, Required Green Power Option, and fuel mix disclosure. Renewables Portfolio Standards, which require a minimum amount of renewable energy capacity or generation, and Required Green Power Options, which require all utilities in a state to offer renewable-based electricity to all consumers for a premium price, are found to have a statistically significant effect on wind capacity deployment. No statistically significant effects were found for Public Benefits Funds, which aid both the funding of energy efficiency, and for Clean Energy Funds, which fund renewable energy programs and projects.

1.3 Model

This paper uses an ordinary least squares approach as did Menz and Vachon (2006), but differs in many aspects. This paper includes state fixed-effects, a larger sample,

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5 Fuel mix disclosure is a policy that requires the fuel mix a power producer uses in its electricity generation to be disclosed to the public. It is believed that consumers will use this information to purchase electricity from power producers that use cleaner burning fuels or alternative energy.
and additional and more detailed policy variables as well as control variables for a state’s electricity market and political environment. Without controlling for differences in market size and political environments, omitted variables may bias the results and lead to incorrect policy interpretations. State fixed-effects are used to control for renewable availability and capacity constructed prior to 1996, which is in large part due to the implementation of prior federal policy at the state level as well as the effects of environmental preferences not captured by other variables.

\[ C_{it} = \alpha_0 + \beta \cdot R_{it} + \delta \cdot W_{it} + S_i + \epsilon_{it} \]

The model estimates total non-hydropower renewable capacity \((C_{it})\) for 1996-2003, where subscript \(i\) is the state and \(t\) is the year of the specific observation. \(R_{it}\) is the vector of seven regulatory policies (Clean Energy Fund, Renewables Portfolio Standard with Capacity Requirements, Renewables Portfolio Standard with Generation/Sales Requirements, Net Metering, Interconnection Standards, State Government Green Power Purchasing, and Required Green Power Option) and \(W_{it}\) is the vector of eight political and economic variables. Vector \(S_i\) is the state fixed-effects dummy variables and vector \(T_t\) are the year variables. The year variables, most of the control variables, and some of the policy variables are interacted with each state’s electricity generation level to control for market size in each state.

The dependent variable is the total non-hydropower renewable nameplate capacity in the electric power industry \((C_{it})\), which includes all nameplate capacity of utilities, independent power producers (IPPs), and industrial or commercial combined heat and power producers that use solar, wind, geothermal, or biomass as an energy source.\(^6\) The sum of all non-hydropower renewable energy in a state is used instead of the capacity

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\(^6\) Nameplate capacity is the amount of capacity the generator produces under ideal conditions. Non-hydro renewable nameplate capacity is derived from EIA Historical State Electricity Databases found on the EIA website in which solar, biomass, geothermal, and wind nameplate capacity are combined into a single category labeled Other Renewables.
of one specific type of renewable energy because using only one type would preclude any interesting cross-state comparison of policy effects of states with different available renewable energy resources. For example, comparing the effects of a policy on Maine and Texas using only wind power capacity excludes the policy effects on biomass capacity, which is a more likely renewable choice for Maine. Both types of renewable resources must be included to directly compare the effectiveness of policies across states.

The effects of state renewable energy policies are best estimated using total state non-hydro renewable capacity as the dependent variable because several policies mandate or fund a specific amount of renewable capacity. Policies that do not set specific renewable capacity requirements can be measured in capacity terms by controlling for each state’s market size, which will be discussed in more detail in Section 4.

A large amount of renewable capacity created before 1996 originated from the Public Utilities Regulatory Policy Act (PURPA), a federal policy passed in 1978 requiring utilities to purchase electricity from Qualifying Facilities (QFs), which are IPPs that meet specific requirements and include renewable-based facilities. For a variety of reasons, the effects of PURPA varied from state to state. State dummy variables (Si) measure these effects and other unchanging state factors, such as renewable resource availability.

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7 Hydropower is not included in the renewable energy capacity because most hydropower was created well before the mid-1990s, with few changes in capacity or costs over the time period being analyzed. These aspects allow hydropower to be considered a type of current generating technology, which includes steam or gas turbines fired by natural gas, coal, petroleum, or nuclear power. For hydropower to be a viable power option there must be an available river or stream as well as a significant change in elevation. Most of these sites in the U.S. already have hydropower capacity in place. Removing hydropower from the dependent variable allows the focus of the paper to be on the policy effects on the emerging technologies of wind, solar, biomass, and geothermal power.

8 (Morris, 2003). There is some concern that expiration and buyouts of PURPA contracts during the 1990s have led to decreases in renewable capacity, especially in California where deregulation in the early to mid-1990s created competition based on price
1.4 Variables and Data

1.4.1 Economic and Political Variables: \( W_{it} \)

Eight variables account for non-policy variability (Wit) in nameplate non-hydropower renewable capacity in the electric power industry of each state for 1996-2003. The economic variables measure the percentage of capacity from hydropower and nuclear power in a state, net generation, retail prices, fuel costs, renewable energy costs, and sugarcane production, while the political variable measures a state’s preferences for renewable capacity. These variables are interacted with generation to control for different market sizes across states.\(^9\) Table 1-1 summarizes the data for the dependent variable (RENEWABLE CAPACITY) and the control variables.\(^10\)

Total generation (GEN) is the total amount of electricity generated (in terawatthours) in a state for a given year.\(^11\) It is expected that more renewable capacity will be found in states that generate more electricity to help meet the higher demand for electricity found in those states.\(^12\) The other control variables as well as some of the policy variables are interacted with generation to account for market size across states. For example, without any consideration of costs or environmental impacts. Any capacity shut down due to PURPA contract expiration after 1996 will decrease the positive effects of any enacted policy. There is also the possibility of a state changing its interpretation and enforcement of PURPA after 1996, which would not be captured in the model.

\(^9\) Electricity generation in a state is has been chosen to represent market size instead of electricity sales in a state because some electricity sales originate from outside a particular state.

\(^10\) Data on capacity, generation, and price are found in the Historical Databases of the Electric Power Annual survey on the EIA website. Electricity summary data is available at the state level from the EIA.

\(^11\) A terawatt-hour (TWh) is the same as 1,000 GWh or 1 billion kWh.

\(^12\) Total generation was chosen instead of total sales because some of the electricity demand for a state’s power producers may come from other states. Generation is not contaminated with these interstate sales, which may otherwise inflate or deflate the market size measure. Generation and sales are highly correlated (0.952).
an increase in fuel costs will have a larger impact on renewable capacity in California than in Rhode Island. Larger states should have more funding to pay for projects to increase renewable capacity. Renewables Portfolio Standards with Sales Requirements set requirements on the percent of generation that must originate from renewable sources. States with more generation will have more total generation that is required to originate from renewable resources, which should lead to more renewable capacity in those states.

The following three variables are included in the model to control for market structure. Two of these variables are hydropower capacity (PCT HYDROPOWER) and nuclear power capacity (PCT NUCLEAR) as a percentage of total capacity excluding non-hydro renewables. Hydropower should lead to less non-hydro renewable capacity because hydropower has low marginal production costs, and the capacity typically was constructed many years ago. With lower marginal costs and sunk capital costs associated with hydropower, hydropower will be the first renewable energy to be implemented because it is more economically competitive than most non-hydropower renewables available to the electric power industry. Consumer and/or policy driven demand for renewable-based electricity may not differentiate between hydropower and other renewable sources, which allows hydropower to be a substitute of non-hydro renewables.

Similar to hydropower, nuclear power has low marginal costs of producing base load electricity, has sunk capital costs, and has no emissions. If non-hydro renewable capacity is deployed based on economic factors, given similar emissions profiles, greater nuclear or hydropower capacity should decrease the amount of non-hydro renewable capacity.

An alternative possibility is that regulators in states with large amounts of nuclear power encourage power producers to use other resource types to meet new demand. Renewable energy may be used by utilities to alleviate pressure from environmentalists over nuclear power, thus leading to greater deployment of renewable energy capacity in states with large amounts of nuclear capacity. The sign of PCT NUCLEAR will depend on which of these two factors has the larger effect on power producers.
A state’s annual weighted average real fuel cost (in 2002 dollars) per million Btus (FUEL COST) measures the impact of both a state’s composition of fossil fuel mix and a state’s average costs for each fossil fuel type: coal, natural gas, and fuel oil.\footnote{Fuel cost data can be found on the EIA website in the electricity databases section under Monthly Cost and Quality of Fuels for Electric Plants Database (FERC Form-423). The cost per unit, Btus per unit, and number of units purchased for every fuel purchase made by all public utilities are used to obtain a nominal average fuel cost measure. The data are aggregated and deflated using the Consumer Price Index for all goods from the Federal Reserve Bank of St. Louis to get the state’s annual average real fuel cost per million Btus in January 2002 dollars. FUEL COST has 30 missing observations for 8 different states. Idaho is the only state without any fossil fuel purchases. Estimates of the fuel costs are used to fill in the missing data. The non-Idaho missing observations are extrapolated from the existing data for a state from 1990-2003. Idaho’s observations are generated by using the average fuel costs of the states bordering Idaho. A missing data dummy variable is included in the model to capture any bias created through the extrapolation and approximation.} FUEL COST captures the effects of all these variables, which may have offsetting effects on renewable capacity. FUEL COST is used instead of creating separate variables for the cost and capacity of each fossil fuel for several reasons. First, using one variable instead of five variables simplifies the model. Second, data on specific fossil fuel costs are missing for many states.\footnote{There are missing fuel cost observations for coal (69), natural gas (65), and fuel oil (58). This might be due to no deliveries of a particular fuel to a state, or it could be the missing observations are due to changes in data reporting requirements during the sample period.}

Levelized cost of each renewable source is the estimated real cost of production per kilowatt-hour of electricity over the lifetime of the equipment, including all federal production incentives.\footnote{Levelized cost is calculated by a model that accounts for the initial capital costs of constructing the capacity, expected lifetime of the equipment, interest rates on debt, inflation rate, fuel costs, operational and maintenance costs, capacity factor of the equipment, and federal production incentives. Read McVeigh (1999) for a more detailed description of levelized cost used in this paper.} It captures the economic competitiveness of each renewable...
energy type. Renewable energy as well as nuclear and hydropower have little or no fuel cost and very high capital costs, while current generating technologies based on fossil fuel have large fuel costs but lower capital costs.\textsuperscript{16} As renewable energy has gotten cheaper to produce, it has become more economically competitive. This implies that decreases in the levelized cost of each type of renewable energy will lead to more renewable capacity. The levelized cost also includes federal production incentive policies that vary over time.\textsuperscript{17}

Many researchers have tried to estimate the levelized cost of energy for each renewable source. Making such an estimate is beyond the scope of this paper, so the data set being used for this variable is obtained from McVeigh et al. (1999). The estimated levelized cost of energy in the U.S. for each renewable energy source is in real 2002 dollars and is estimated for every five years, from 1980 to 2005.\textsuperscript{18} These data points are used to interpolate a polynomial curve that had the best fit (highest r-squared value). Due to this interpolation from estimated data, the cost of energy for each type of renewable energy is a reasonable though imprecise estimate of the decreasing cost of renewable energy over time in the U.S. The resulting trend lines for each type of renewable energy have a high correlation. So a weighted average of the levelized costs of wind, solar, biomass, and geothermal for the entire U.S. is used to create the new variable RENEW COST, which is an average national trend for renewable energy costs.\textsuperscript{19}

\begin{itemize}
\item \textsuperscript{16} Fossil fuel costs are uncertain for current generating technologies, and technical efficiency of capital equipment is uncertain for renewable energy generation.
\item \textsuperscript{17} The Renewable Energy Production Incentive (REPI) and Production Tax Credit (PTC) were passed in the Energy Policy Act (EPACT) of 1992. The level of the REPI is decided by Congress annually, while the PTC was reenacted in 1999 and 2001.
\item \textsuperscript{18} The data points for 1985, 1990, and 1995 were estimated based on actual cost information while 2000 and 2005 were forecasts made in 1999. The polynomial curves have an order of two for biomass and geothermal and three for solar and wind.
\item \textsuperscript{19} The weighted average for each year is based on the sources’ share of total non-hydropower net summer renewable capacity in the U.S in 2002. Net nameplate
\end{itemize}
If renewable capacity is being constructed on economic grounds, a rise in the retail price of electricity makes renewable energy more profitable and should have a positive effect on renewable capacity.\textsuperscript{20} However, retail prices in a state may be simultaneously determined with renewable capacity because using more renewable capacity increases the average costs of production, which could lead to higher prices. Using the state’s retail price could also lead to multicollinearity problems with fossil fuel costs because higher fuel costs will lead to higher electricity prices. To control for this endogeneity and possible multicollinearity, the model must use a proxy for a state’s retail price. A proxy must be correlated to the endogenous variable and have no impact itself on the dependent variable. The weighted average real retail price per kilowatt-hour of the bordering states (BORDER PRICE) is an ideal proxy for retail prices because it meets both of these requirements.\textsuperscript{21}

capacity data for each type of renewable energy are not available from the EIA, making net summer capacity the closest available alternative measure. Even though there is a cost of energy estimate for both solar thermal and solar Photovoltaic, the solar capacity data are not segregated into these two types. A non-weighted average of solar thermal and PV is taken to get the levelized cost for total solar capacity. Since all solar power accounts for less than 2.5\% of total non-hydro renewable capacity in the U.S., it is unlikely that using some weighted average of solar thermal and solar PV would make any significant difference. Summer capacity refers to the maximum output generating equipment is expected to supply to a system demonstrated by tests at the time of summer peak demand. Nameplate and summer capacity have high correlation, but are not identical due to different operating conditions across utilities. Definition of nameplate is in Footnote 7.

\textsuperscript{20} Average retail price is based on all sales in the market: residential, commercial, industrial, and other customers. Data are available from the EIA Historical Databases. Average retail price data are originally in nominal terms for each month. Two steps have to be taken to adjust the data into real terms for each year. First, the monthly data are divided by the CPI for all goods to get the monthly data into real terms. Second, monthly electricity sales are used to get a weighted average price for each year. The resulting variable is the real average retail price for each state and year in January 2002 dollars.

\textsuperscript{21} Bordering states are all states that either share a border, such as Arizona and New Mexico, or meet at a corner, such as Arizona and Colorado. The prices are weighted by sales in the bordering states. The correlation of retail price to BORDER PRICE is 0.836.
Using BORDER PRICE instead of the state’s retail price removes the possible collinearity with FUEL COST as well.

Florida, Hawaii, Louisiana, and Texas use the byproduct of sugar production from sugarcane as a biomass fuel. For example, in Hawaii sugarcane is one of the primary sources of biomass. Due to market conditions most of the sugarcane farms in Hawaii were shut down over the 1990s, removing the fuel source for much of the biomass capacity in the state. Changes in sugarcane production are likely to have an impact on the amount of biomass capacity in a state. The change in total tons of sugarcane production from 1996 levels (SUGARCANE PROD CHANGE) is included in the model to control for its impact on renewable capacity. SUGARCANE PROD CHANGE is the only control variable not interacted with generation.

A political variable is included to measure changes in renewable energy preferences in a state. The League of Conservation Voters (LCV) rating is used to determine if policy preferences for environmental protection increase renewable energy capacity independent from its policy effects. The League of Conservation Voters (LCV) annually publishes the National Environmental Scorecard, which rates all congressional votes on conservational issues by each representative. For example, if there are ten total votes in a year on environmental issues and a congressperson voted in favor of conservation six times, his or her LCV rating would be 60.

An average of all the votes by a state’s representatives is taken to get the average House of Representatives score (LCV SCORE). The scores from the House of Representatives are used instead of the Senate because representatives have a shorter term in office.

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22 Data from the National Environmental Scorecard is available from the League of Conservation Voters website, www.lcv.org. The LCV rating has been used in prior studies, including Baldwin and Magee (2000), Kalt and Zupan (1984), and Nelson (2002).
than senators, two years versus six years. The shorter term creates greater pressure on representatives to act according to their constituents’ preferences.

A high LCV rating for a state indicates that the state’s constituents are environmentally friendly and are more likely to demand electricity from renewable energy, all other things being equal. Consumers or environmental groups in states with higher LCV ratings may be more likely to pressure utilities to use greater amounts of renewable energy no matter which, if any, policies have been enacted by the state.

Policies may be endogenous to higher LCV ratings because states with congresspersons who vote for federal pro-environmental policies may be more likely to enact state pro-environmental policies. The policy endogeneity issue is not addressed in the body of this paper because LCV SCORE is not a strong enough predictor of state policies to be a satisfactory instrument. Note also that removing LCV SCORE from the regression does not change the other results.

1.4.2 Regulatory Policy Variables: $R_{it}$

Seven of the independent variables are policy variables capturing the effects of different types of renewable energy regulation, either by a state’s legislature or Public Utility Commission ($R_{it}$). Most policies are enacted through state legislation, and then enforced by the Public Utility Commission (PUC). There are a few instances, however, in which a PUC adopts guidelines without state legislation. No legislation or PUC action is required for state governors to use executive orders to create a state government green power purchasing agreement or to set voluntary goals for generation.

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23 Information on renewable policies is available on the Database of State Incentives for Renewable Energy (DSIRE) website, www.dsireusa.org, which is a project of the Interstate Renewable Energy Council and funded by the U.S. Department of Energy. The information is compiled from many different sources, including federal and state officials, public utility commissions, and renewable energy organizations. The source of the information is included within each policy description. Bollinger et al. (2001) includes additional information on the enactment and design of Public Benefits Funds.
Policy dummy variable values are determined by a policy’s enactment date, zero before enactment and one after enactment. The enactment date is the year that the policy is passed by the state legislator, created through an executive order, or announced as a mandate under new PUC guidelines. Some of these policies allow a grace period for power producers to meet the new regulations. The effective date is the year that the policy requirements must be met. The average lag from the enactment to effective date is a little over one year, but can be longer for Renewables Portfolio Standards. The enactment year is a better choice to determine when the policy begins to impact the power producers. Once a power producer becomes aware of a future requirement, it may begin to construct any necessary renewable capacity. These actions could lead to large amounts of renewable capacity being constructed between the enactment date and effective date.

Regulatory policies described below include a Renewables Portfolio Standard with a Capacity Requirement, Renewables Portfolio Standard with a Generation/Sales Requirement, Clean Energy Fund, Net Metering, Interconnection Standards, State Government Green Power Purchasing, and Required Green Power Options. Table 3-2 summarizes the data for the policy variables.

The first policy that will be discussed is a Renewables Portfolio Standard, which specifies an amount of a state’s electricity production, sales, or capacity that must be renewable-based. Renewables Portfolio Standards can be differentiated into three main structural forms, policies that set (1) mandatory renewable generation or sales levels, (2) voluntary renewable generation or sales goals, and (3) mandatory renewable energy capacity requirements.

The first type of Renewables Portfolio Standard sets a percentage of total generation or sales for each power producer/retailer that must originate from renewable sources, usually increasing every year or every few years. For example, Arizona’s tiered renewable levels that have to be met began at 0.2% in 2001 and increased by 0.2% each year,
resulting in a requirement of one percent in 2005. Most other states’ Renewables Portfolio Standards have similar structures, but vary in percentage levels and enforcement dates.\textsuperscript{24}

Iowa, Minnesota, Texas, and Wisconsin have mandated utilities to install a certain level of megawatts of renewable capacity.\textsuperscript{25} As long as the requirements are implemented effectively, renewable capacity requirements should increase renewable capacity by the same number of megawatts required by the mandate. These capacity requirements will make this type of Renewables Portfolio Standards more effective in this model because they target actual capacity construction versus generation or sales based Renewables Portfolio Standards.

The differences between Renewables Portfolio Standards can be accounted for in the model by two variables: a variable that measures the size of the renewable generation or sales requirement (RPS: SALES REQ) and a variable that measures the size of the capacity requirement (RPS: CAP REQ).\textsuperscript{26} The capacity requirement size and date are used to extrapolate the expected requirement for each year assuming a linear function, where the power producers increase capacity by the same amount each year until they meet the final requirements, to form the variable RPS: CAP REQ.

\textsuperscript{24} In 1998, Wisconsin introduced mandatory capacity levels before it enacted a Renewables Portfolio Standard with mandatory generation or sales in 1999. Two states (Illinois and Hawaii) with Renewables Portfolio Sales Goals (not requirements) are counted as Renewables Portfolio Standards with a sales requirement. The only result that changes when these non-mandatory goals are treated as a requirement of zero is the coefficient on RPS: SALES REQ becomes smaller and becomes less significant for all specifications. All other coefficients remain relatively unchanged.

\textsuperscript{25} Minnesota has had both types of Renewables Portfolio Standard since 2001. A voluntary generation goal was enacted in 2001, while the capacity requirement was enacted in 1994.

\textsuperscript{26} Capacity requirements range from 50 to 2000 MW, and generation/sales requirements range from 0-30\%.
RPS: SALES REQ is an even more complex variable. The generation/sales requirement, which usually sets a target about five years after enactment, is linearly interpolated backwards to the enactment date of the policy. For example, a policy enacted in 1996 with a sales requirement of 1.0% beginning in 2000 would be linearly interpolated to be 0.2% in 1996 and increase by 0.2% each year until it reaches 1.0% in 2000. Although the requirement is not enforced until 2000, it would be necessary for power producers to begin construction at least several years before 2000 to get the necessary capacity constructed in time to meet the sales requirement.

Although this policy does not directly require the construction of renewable capacity, an increase in the required amount of renewable generation may lead to a need for more renewable capacity. If current levels of renewable capacity cannot meet a future generation/sales requirement, additional capacity will need to be constructed.\textsuperscript{27}

A Clean Energy Fund is a state-level program that is often, but not always, created through the restructuring of the electricity market and is used to fund grants, loans, and production incentives for both research and development and actual deployment of alternative energy. Many Clean Energy Funds focus on funding actual renewable capacity deployment, which should lead to more renewable capacity in a state.

Clean Energy Funds are paid for through System Benefits Charges (SBCs), which are additional charges paid by all consumers on their electricity consumption. SBCs can be

\textsuperscript{27} Some state Renewables Portfolio Standards a with generation/sales requirement allow the use of some hydropower electricity to meet the requirement. However, there are normally specific requirements as to which facilities will be eligible, including restrictions on a unit’s maximum capacity, type of hydropower, and year of installation. For example, some states do not allow generating units greater than 30 MW to be eligible. One state does not allow any hydropower to originate from dammed hydropower plants. Another state only allows electricity from new hydropower capacity to be eligible. These restrictions will decrease the effectiveness of these policies to increase renewable capacity in a state. However, the complexities of the restrictions make it difficult to create an appropriate measure for these effects.
considered a consumption tax on electricity to fund deployment of renewable capacity in the industry. In Minnesota, a settlement with the electric utility Xcel Energy created a similar fund that is paying for renewable energy research and deployment. Maine created a voluntary fund similar to a Clean Energy Fund for the state’s customers to donate money.\textsuperscript{28}

Similar to Renewables Portfolio Standards, Clean Energy Funds must be differentiated to understand how effective these policies are at increasing renewable deployment in a state. The variable used in this model is a variable that measures the amount of capacity that is being funded for utility-scale projects from Clean Energy Funds (CEF: CAP FUNDED).\textsuperscript{29}

Some customers may prefer to build generating capacity to provide their home with some of their own electricity. Net Metering (NET METERING) allows customers that are able to produce more electricity than they consume in a given month to sell any excess to the utility to offset the charges for electricity in months the customer is a net purchaser. The effect of net metering is expected to be negative because if renewable energy demanders produce their own renewable electricity through a solar PV system or small wind turbine, they will demand less renewable capacity from power producers. From a utility perspective, if it is required to reach a renewable capacity or sales target, these customer-owned facilities may serve to offset a utility’s needs to build renewable

\textsuperscript{28} Database of State Incentives for Renewable Energy (DSIRE) does not include New Mexico as having a Clean Energy Fund, while Bolinger et al. (2001) verifies that New Mexico does have a Clean Energy Fund.

\textsuperscript{29} The capacity obligations as of 2003 are interpolated backwards linearly to the enactment year so that an equal amount of additional capacity obligations are made each year and total the overall obligations as of 2003. The data for is variable originated from the Database of Utility-Scale Renewable Energy Projects from the Clean Energy States Alliance (CESA).
capacity. NET METERING is interacted with GEN to control for the policy’s effect based on market size.

Interconnection standards (INTERCON STANDARDS) are a set of guidelines used to safely and effectively connect individual renewable generating units to the electric utility power grid. Some have technical requirements, such as generator type and size limits, mandatory safety and performance standards, and insurance requirements that must be met before a net metering customer can connect to the utility’s network. Interconnection standards must be met by any commercial, industrial, residential, or government customer that decides to connect to the grid. Without these state policies, the net metering connections could cause major problems for the grid, power producers, and other purchasers. Interconnection standards increase the costs of hooking up to the grid for net metering and may offset some of the negative effect from net metering. INTERCON STANDARDS is also interacted with GEN to control for market size.\(^\text{30}\)

State Government Green Power Purchasing policies require that some percentage of a state government’s electricity purchases be from renewable sources. These purchase agreements range from 5% to 50% of a state government’s electricity purchases. Similar to Renewables Portfolio Standards with Sales Requirements, a State Government Green Power Purchasing agreement increases the need for renewable-based electricity generation. As state government electricity use rises, the renewable generation needed to meet the requirement increases. If the new generation needs cannot be met by current renewable capacity, power producers will need to construct new renewable energy capacity. The size of the State Government Green Power Purchasing requirement, in terms of a percentage of the state government’s electricity purchases, is interacted with GEN to

\(^{30}\) Since only four observations have interconnection standards and no net metering, the interaction term measures the effect of interconnection standards on states that already have net metering policies. Only 86 of the 187 observations (46%) with net metering also have interconnection standards, which removes concerns of multicollinearity.
control for both the state’s purchase requirement and the state’s market size (PCT STATE PURCHASING*GEN).

A Required Green Power Option requires utilities to offer customers the option to purchase renewable power at a premium. There are two versions of how these options are implemented. The most common type gives consumers the option to make voluntary contributions, called voluntary renewable energy tariffs in return for the guarantee that some of the consumer’s electricity consumption is produced from renewable sources. Consumers purchase electricity at the market price and then pay a premium for blocks of green electricity, usually about $2 per 100 kWh. The second type allows the producers to charge consumers a higher rate per kilowatt-hour, but only to cover the additional costs for electricity from renewable sources. Both the premium block rate and premium per kilowatt-hour rate must be approved by the state’s Public Utilities Commission (PUC).

Required Green Power Options elicit customer preferences and a crude measure of willingness to pay for renewable energy by allowing consumers to voluntarily pay higher prices for the knowledge that they are supporting renewable-based electricity. The creation of this niche market for renewable energy generation should have a positive impact on renewable capacity. The variable REQ GREEN POWER OPT is a dummy variable, which is interacted with GEN in the model to measure the effect of the policy based on the state’s market size (REQ GREEN POWER OPT*GEN).

1.5 Statistical Specifications and Empirical Analysis

Ordinary Least Square regressions with state fixed-effects and robust standard errors are used in this paper to estimate total non-hydro renewable capacity. Robust standard errors are used to account for heteroskedasticity, which was found to exist in the model by using a Breusch-Pagan/Cook-Wesiberg Heteroskedasticity Test. \(^\text{31}\) Table 3 reports

\(^{31}\) The result was a Chi-Sq=448 and P(\(\cdot\))>Chi-Sq=0.0000, so there is a significant difference in the variance of the dependent variable, which creates heteroskedasticity.
the regression results. Specification 1 includes only the policy variables. Specification 2 includes the economic market and political control variables, and Specification 3 replaces RENEW COST with year dummies interacted with GEN. The following subsections describe the results using the coefficients from Specification 3.\textsuperscript{32}

1.5.1 Economic and Political Variables: \( W_{it} \)

The coefficient for GEN is insignificant, which cannot be easily interpreted because of how many different ways that a state’s generation can impact a state’s level of renewable capacity. Although the coefficient is insignificant, generation levels do have effects through other variables that are interacted with GEN, which are explained below.

The percentage of other capacity comprised of hydropower interacted with generation (PCT HYDRO*GEN) is not statistically significant. However, the coefficient for the percentage of other capacity comprised of nuclear power interacted with generation (PCT NUCLEAR*GEN) is positive and statistically significant. A one standard deviation (12.46\%) increase in the percentage of non-renewable capacity comprised of nuclear power leads to an increase of 2.09 MW per terawatt-hour of generation in a state. So this one standard deviation change in a state with a median generation level (51.15 TWh) leads to an increase of 107 MW. It is possible that utilities with more nuclear power are deploying more renewable capacity because the utilities are focused on diversifying its generation mix, either to decrease the utilities’ use of fossil fuels and lower emissions or to alleviate pressure from environmentalists who are upset about the use of nuclear power.

The coefficients on the average LCV score for the House of Representatives interacted with generation (LCV SCORE*GEN) are positive and significant. A one standard deviation increase (26.51 points) in a state’s LCV score leads to an increase of 0.663 MW per terawatt-hour of generation. A one standard deviation increase in a state with median

\textsuperscript{32} Results from Specification 2 are nearly identical to results from Specification 3 with the same interpretations.
generation leads to an increase of 34 MW. Preferences for renewable energy capacity do in fact lead to a small amount of deployment of some renewable capacity, holding policies fixed.

As expected, renewable energy cost interacted with generation (RENEW COST*GEN) has a negative and statistically significant coefficient. A one-cent per kWh decrease in renewable energy cost leads to an increase of 0.712 MW per terawatt-hour of generation. In a state with median generation, a one cent decrease in RENEW COST leads to an increase of 36 MW. RENEW COST decreased by 1.79 cents from 1996 to 2003, which implies an increase of 65 MW for a state with median generation. This effect does not just include the technological changes in renewable energy. As mentioned in Section 4, all federal production incentives are included in the costs of production for each renewable source, capturing the federal policy changes as well as the technological advances. The year variable coefficients, which explain the same impacts as RENEW COST, are explained in detail in Section 5.4.

The coefficient on average border state retail price interacted with generation (BORDER PRICE*GEN) is negative and is marginally statistically significant only in Specification 3 of Table 3. Higher electricity prices do not appear to result in more renewable energy capacity construction. In fact, the negative coefficient implies that an increase of one cent in the price of electricity leads to a small decrease in renewable capacity by 13 MW in a state with median generation. A one standard deviation (2.07 cents) increase in price leads to a decrease of only 27 MW. It is possible that consumers in a state with high electricity prices have less of an appetite for further increases in prices through more expensive renewable generation.33

33 High electricity prices may be one of the factors driving the enactment of state renewable energy policies. However, high prices by themselves do not appear to lead to renewable capacity deployment in a state.
The coefficient for average fuel cost interacted with generation (FUEL COST*GEN) is statistically significant. It is difficult to interpret the meaning of the coefficient, since the components of the variable may lead to opposite effects. Higher costs should make renewable energy capacity more competitive. But the variable also reflects differences in fuel type use in a state. To take one example, since natural gas is more expensive than coal, more natural gas use would lead to a higher average fossil fuel cost and make renewable energy more competitive in the market. On the other hand, natural gas results in lower emissions than using coal or oil. All else equal, a state with more natural gas capacity will have lower emissions than if a state had higher amounts of coal capacity, which lowers the need for non-emitting renewable capacity to meet emissions reduction goals. If this holds true, a higher average fossil fuel cost will be correlated with less renewable capacity construction.

To alleviate any concerns about FUEL COST, an additional specification is estimated replacing FUEL COST with five variables: average cost of coal, average cost of oil, average cost of natural gas, percent of non-renewable capacity comprised of coal, and percent of non-renewable capacity comprised of natural gas. Natural gas and coal capacity are treated in the same manner as hydropower and nuclear power capacity in the model. Each variable is interacted with GEN, just like the other control variables.

A higher percentage of total non-renewable capacity comprised of coal is correlated with more renewable capacity, which gives some support that states with dirtier conventional capacity use more renewable capacity. As the price of coal increases, less renewable capacity is constructed. These two results support the idea that the emissions requirements utilities must meet are a driving force to renewable deployment, while economic competitiveness in the market does not have much of an impact. Caution is necessary in interpreting the results with the additional set of fuel variables because there are many missing observations that must be extrapolated. The dummy variables that control for missing observations for coal and natural gas are both statistically
significant, which brings up concerns about the variable coefficients and any possible biases due to the missing data. The most important result from this specification is that the additional variables have no effect on the policy variable coefficients, which remain relatively unchanged relative to the original model.

The coefficient on SUGARCANE PROD CHANGE is insignificant. The missing fuel cost dummy variable interacted with generation (MISSING FUEL COST*GEN) controls for any measurement error caused by the extrapolation of the 38 missing data points and is insignificant as well.

1.5.2 Regulatory Policy Variables: $R_{it}$

Table 4 estimates the statistically significant effects from both the control variables and the policy variables based on a state with median generation levels. Clean Energy Funds, Renewables Portfolio Standards with Capacity Requirements, and Required Green Power Options have statistically significant effects on renewable capacity in the electric power industry. Renewables Portfolio Standards with Generation/Sales Requirements and State Green Power Purchasing Programs are marginally significant in Specification 1, but lose their significance once control variables are introduced into the model.

CEF: CAP FUNDED, which measures the amount of capacity that the fund has agreed to help finance, has a marginally statistically significant coefficient. This includes capacity that has been agreed upon, but has not yet been built, either because the project has not been finished or the project is later canceled. For each megawatt of capacity that the Clean Energy Fund has funded or agreed to fund in the near future, approximately 0.206 MW has been constructed. This is not significantly different than the fraction of capacity that has actually been constructed as of 2003, which was 0.33 MW per 1 MW. Even though actual renewable capacity is probably not constructed linearly over the lifetime of the policy, the estimates from the linear interpolation seem to be representative of actual capacity construction due to the Clean Energy Funds.
The coefficient on RPS: CAP REQ is positive and significant, and about the same size as would be expected. For each megawatt of capacity required by the Renewables Portfolio Standard, approximately 1.14 MW is constructed. The coefficient is not significantly different than one. Similar to CEF: CAP FUNDED, the linear interpolation approach taken in designing RPS: CAP REQ is effective at capturing the policy effects by allowing variation in the timing of capacity construction.

The most interesting result from the model is the effect that Required Green Power Options have on renewable capacity. The coefficient for REQ GREEN POWER OPT*GEN has a positive and statistically significant coefficient and has some of the largest effects on renewable capacity of any variable, where enactment leads to renewable capacity increasing by 3.46 MW per terawatt-hour of generation. A state with a median generation level (51.15 TWh) that enacts a Required Green Power Option would have an increase of 177 MW. Washington has the largest electricity market of states that have enacted a Required Green Power Option (100.1 TWh), which would lead to an increase in renewable capacity of 346 MW. To give some perspective on these results, the estimated impacts in total renewable capacity can be expressed in terms of a percentage of total capacity in a state. Depending on the state, a Required Green Power Option leads to an increase of about 1.2-1.6%.

The statistically and economically significant increase implies that Required Green Power Options, which create a niche market for green power by requiring states to offer renewable-based electricity to their consumers at a premium, are very useful in increasing the amount of renewable energy capacity in a state.

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34 These estimates are made by taking the estimated effect of a Required Green Power Option in a state on total renewable capacity in 2003, and then dividing that value by total capacity in the state for 2003. The resulting impact is a measure of the change in renewable capacity in percentage terms of total capacity.

35 This estimation is in the range of the average participation rate for all local green power programs of 1.4% (Wiser and Olson, 2004).
The coefficients for both STATE PURCHASING: PCT REQ*GEN and RPS: SALES REQ*GEN are marginally statistically significant in Specification 1. However, once control variables are included in the regressions, the coefficients are no longer statistically significant. Initial state government purchase levels are minimal and account for a relatively small portion of the electricity market in a state. The low demand can still be met by current renewable generation in a state. Given the size and statistical significance of the coefficient in Specification 3, it is unlikely that state government purchases of renewable energy will result in any significant increase in renewable capacity in a state.

There are multiple reasons for the insignificance of RPS: SALES REQ*GEN. First, most Renewables Portfolio Standards with sales requirements have been enacted fairly recently and currently have low requirements. Power suppliers may be able to meet their low initial requirements by using current renewable capacity. Second, some of the states implementing these policies have available hydropower capacity already in place that is considered eligible to meet a portion of these currently low mandates, which decreases the policies’ effectiveness in encouraging new non-hydro renewable capacity deployment in a state. Third, some states allow the purchase of Renewable Energy Credits (RECs), which are certificates that represent the environmental rights of renewable electricity, instead of actual generation. Many of these same states allow power producers/retailers to purchase RECs from out-of-state power producers to meet their in-state requirements. All three of these factors will decrease the policy’s impacts on in-state renewable capacity deployment. A few more years of data should result in RPS: SALES REQ*GEN to have statistically significant impacts on renewable capacity in its state.

Neither net metering nor interconnection standards appear to have an impact on renewable capacity. The coefficients on NET METERING and INTERCON STANDARDS are statistically insignificant.
1.5.3 State Fixed-Effects Variables: $S_{it}$

Forty-nine state fixed-effects variables are included in Specification 3 in Table 3 to control for state interpretation of federal policies enacted prior to 1996 as well as any time-invariant differences across states.\(^{36}\) Time-constant variation across states includes the availability of renewable energy resources and the initial level of a state’s preferences for renewable energy use. The coefficients should be highly correlated to the amount of renewable capacity that existed in 1996. The correlation between a state’s initial renewable capacity and its state-fixed effect coefficient is 0.978. The state fixed-effects seem to effectively control for the impact of existing regulation and the market environment prior to 1996.

1.5.4 Year Variables: $T_{it}$

The third specification replaces the national renewable energy cost trend variable (RENEW COST) with year variables interacted with GEN. The coefficients are statistically insignificant for all years except for 2003, where the impact is 0.530 MW per terawatt-hour of generation in a state. A state with median generation has an increase of 27 MW from 1996 to 2003. These year variables measure the impact of renewable energy becoming more economically viable as well as federal policy implemented to encourage renewable energy use. The federal Renewable Energy Production Tax Credit (PTC) and federal Renewable Energy Production Incentive (REPI) were enacted in 1992. The federal PTC was renewed in both 1999 and 2001, while the funding for the REPI changes from year to year based on congressional appropriations. Each year coefficient controls for the impact of these policies on each state as funding for these production incentives change as well as the improvements in the technology behind renewable energy.

\(^{36}\) One state must be dropped from the model to remove multicollinearity of the fixed-effects variables.
1.6 Conclusions

States have enacted many policies to increase the deployment of non-hydro renewable capacity into the electric power industry in that state. The literature evaluating the effectiveness of these programs consists of case studies and one statistical study, which explains the use of wind power. My statistical study utilizes a larger panel, more policies, and more control variables to explain the deployment of total renewable capacity in a state.

Three regulatory policies appear to be effective at increasing renewable capacity deployment in a state. The significant results from these regulatory policies confirm many of the findings from prior case studies, which find Renewables Portfolio Standards with Capacity Requirements and Clean Energy Funds have increased renewable capacity. An additional policy, Mandatory Green Power Options, is also found to increase capacity deployment in a state as well.

The previous empirical study found Public Benefits Funds, which include any Clean Energy Fund in a state, to be insignificant in their model. My paper finds that Clean Energy Funds with utility-scale projects increase the deployment of renewable capacity in a state. By using System Benefits Charges (SBCs) a state can effectively make consumers pay for cleaner energy without creating a different market for renewable energy demand. Similar to the case study findings by Bolinger et al. (2001, 2004, 2005), larger utility-scale projects make Clean Energy Funds more effective at increasing renewable capacity deployment in a state.

This paper finds that different types of Renewables Portfolio Standards have different effects on renewable capacity. Each megawatt of capacity mandated by Renewables Portfolio Standards with Capacity Requirements results in the deployment of one megawatt of additional renewable capacity in a state. But recent Renewables Portfolio Standards that mandate generation or sales levels appear not to have statistically significant effects. These results mirror Petersik’s case study in that only Renewables
Portfolio Standards with Capacity Requirements have increased renewable capacity, but expand on the case study by finding evidence on the size of the policy effect holding other policies fixed.

Statewide Required Green Power Options appear to have been as effective as any other policy. Forcing utilities to offer customers the option to purchase renewable-based electricity at a reasonable premium rate drastically increases renewable capacity in a state. The policy has a greater impact in larger electricity markets and appears to be effective regardless of a state’s political environment.

There are major renewable policy implications if these results hold when additional years are eventually included in the model. Only five states have currently implemented Required Green Power Options even though creating a statewide green power market appears to be as effective at increasing renewable energy capacity in a state as a command-and-control scheme of a Renewables Portfolio Standards or tax-and-subsidy scheme of a Clean Energy Fund. State government purchasing agreements of renewable energy appear to be no more than window dressing for politicians to show their support to the environmental community, and additional funding to renewable power producers.

The remaining policies in the model do not appear to impact renewable energy capacity construction in the electric power industry. State government green power purchasing does not increase renewable electricity demand enough to drive capacity construction. Net metering and interconnection standards target residential and commercial capacity and do not impact electric power industry decisions.

The important policy implications that arise from the results indicate policymakers have a wide array of tools at their disposal to promote renewable energy deployment in a state to meet environmental and energy security policy goals. The array of policy mechanisms will become even more useful to state governments if the prospect of U.S. climate change/carbon emissions policy becomes a reality.
<table>
<thead>
<tr>
<th>Variable</th>
<th>Mean</th>
<th>Std. Dev.</th>
<th>Min.</th>
<th>Max.</th>
<th>Median</th>
</tr>
</thead>
<tbody>
<tr>
<td>RENEWABLE CAPACITY (MW)</td>
<td>348.7</td>
<td>827.6</td>
<td>0.00</td>
<td>6177.4</td>
<td>178.5</td>
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<tr>
<td>GEN (TWh)</td>
<td>73.82</td>
<td>64.98</td>
<td>4.95</td>
<td>385.63</td>
<td>51.15</td>
</tr>
<tr>
<td>PCT HYDROPOWER (Percentage)</td>
<td>14.14</td>
<td>20.68</td>
<td>0.00</td>
<td>91.59</td>
<td>6.26</td>
</tr>
<tr>
<td>PCT NUCLEAR (Percentage)</td>
<td>11.13</td>
<td>12.46</td>
<td>0.00</td>
<td>56.20</td>
<td>7.54</td>
</tr>
<tr>
<td>BORDER PRICE (2002 cents/kWh)</td>
<td>7.58</td>
<td>2.07</td>
<td>4.82</td>
<td>14.49</td>
<td>6.68</td>
</tr>
<tr>
<td>RENEW COST (2002 cents/kWh)</td>
<td>6.93</td>
<td>0.585</td>
<td>6.00</td>
<td>7.79</td>
<td>6.94</td>
</tr>
<tr>
<td>FUEL COST (2002 dollars/MMBtu)</td>
<td>2.086</td>
<td>0.987</td>
<td>0.601</td>
<td>7.431</td>
<td>1.861</td>
</tr>
<tr>
<td>LCV SCORE (0 to 100)</td>
<td>43.06</td>
<td>26.51</td>
<td>0.00</td>
<td>100.0</td>
<td>38.0</td>
</tr>
<tr>
<td>SUGARCANE PROD CHANGE</td>
<td>88.95</td>
<td>599.33</td>
<td>-1707.0</td>
<td>4882.0</td>
<td>0.0</td>
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**Table 1-2. Regressions Results**

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<th></th>
<th>(1)</th>
<th>(2)</th>
<th>(3)</th>
</tr>
</thead>
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<tr>
<td><strong>Total Non-Hydro Renewable Capacity</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CEF: CAP FUNDED (MW)</td>
<td>0.198</td>
<td>0.144</td>
<td>0.206</td>
</tr>
<tr>
<td></td>
<td>(0.107)*</td>
<td>(0.145)</td>
<td>(0.124)*</td>
</tr>
<tr>
<td>RPS: CAP REQ (MW)</td>
<td>1.245</td>
<td>1.144</td>
<td>1.142</td>
</tr>
<tr>
<td></td>
<td>(0.175)**</td>
<td>(0.168)***</td>
<td>(0.168)***</td>
</tr>
<tr>
<td>RPS: EFFECTIVE GEN REQ</td>
<td>0.153</td>
<td>0.108</td>
<td>0.100</td>
</tr>
<tr>
<td></td>
<td>(0.056)**</td>
<td>(0.077)</td>
<td>(0.071)</td>
</tr>
<tr>
<td>PCT STATE GREEN POWER PURCHASING*GEN</td>
<td>0.026</td>
<td>0.013</td>
<td>-0.002</td>
</tr>
<tr>
<td></td>
<td>(0.014)*</td>
<td>(0.017)</td>
<td>(0.016)</td>
</tr>
<tr>
<td>REQUIRED GREEN POWER OPT*GEN</td>
<td>3.539</td>
<td>3.318</td>
<td>3.457</td>
</tr>
<tr>
<td></td>
<td>(0.667)**</td>
<td>(1.207)***</td>
<td>(1.166)***</td>
</tr>
<tr>
<td>NET METERING*GEN</td>
<td>0.093</td>
<td>-0.237</td>
<td>-0.033</td>
</tr>
<tr>
<td></td>
<td>(0.205)</td>
<td>(0.214)</td>
<td>(0.227)</td>
</tr>
<tr>
<td>INTERCON STANDARD*GEN</td>
<td>-0.246</td>
<td>-0.241</td>
<td>-0.240</td>
</tr>
<tr>
<td></td>
<td>(0.211)</td>
<td>(0.195)</td>
<td>(0.210)</td>
</tr>
<tr>
<td>SUGAR CANE PRODUCTION CHANGE (Tons)</td>
<td>-0.011</td>
<td>-0.007</td>
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</tr>
<tr>
<td></td>
<td>(0.023)</td>
<td>(0.023)</td>
<td></td>
</tr>
<tr>
<td>GEN (1 TWh)</td>
<td></td>
<td>-0.184</td>
<td>(1.150)</td>
</tr>
<tr>
<td>FUEL COST ($/mmBtu)*GEN</td>
<td>-0.154</td>
<td>-0.124</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.107)</td>
<td>(0.109)</td>
<td></td>
</tr>
<tr>
<td>FUEL COST MISSING*GEN</td>
<td>-1.261</td>
<td>-1.167</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.843)</td>
<td>(0.802)</td>
<td></td>
</tr>
<tr>
<td>BORDER PRICE (Cents/kWh)*GEN</td>
<td>0.199</td>
<td>-0.259</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.207)</td>
<td>(0.117)**</td>
<td></td>
</tr>
<tr>
<td>RENEW COST (Cents/kWh)*GEN</td>
<td>-0.712</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.211)**</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LCV SCORE*GEN</td>
<td>0.024</td>
<td>0.025</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.011)</td>
<td>(0.011)</td>
<td></td>
</tr>
<tr>
<td>PCT HYDRO*GEN</td>
<td>0.018</td>
<td>-0.027</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.028)</td>
<td>(0.024)</td>
<td></td>
</tr>
<tr>
<td>PCT NUCLEAR*GEN</td>
<td>0.143</td>
<td>0.168</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.043)</td>
<td>(0.052)**</td>
<td></td>
</tr>
<tr>
<td>YR1997*GEN</td>
<td></td>
<td>-0.048</td>
<td>(0.151)</td>
</tr>
<tr>
<td>YR1998*GEN</td>
<td></td>
<td>-0.142</td>
<td>(0.186)</td>
</tr>
<tr>
<td>YR1999*GEN</td>
<td></td>
<td>-0.187</td>
<td>(0.182)</td>
</tr>
<tr>
<td>YR2000*GEN</td>
<td></td>
<td>-0.269</td>
<td>(0.199)</td>
</tr>
<tr>
<td>YR2001*GEN</td>
<td></td>
<td>0.322</td>
<td>(0.247)</td>
</tr>
<tr>
<td>YR2002*GEN</td>
<td></td>
<td>0.250</td>
<td>(0.199)</td>
</tr>
<tr>
<td>YR2003*GEN</td>
<td></td>
<td>0.530</td>
<td>(0.226)**</td>
</tr>
<tr>
<td>CONSTANT</td>
<td>309.103</td>
<td>413.745</td>
<td>267.888</td>
</tr>
<tr>
<td></td>
<td>(7.689)***</td>
<td>(55.340)***</td>
<td>(50.741)***</td>
</tr>
<tr>
<td>Observations</td>
<td>400</td>
<td>400</td>
<td>400</td>
</tr>
<tr>
<td>State Fixed-Effects</td>
<td>50</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>R-squared</td>
<td>0.598</td>
<td>0.634</td>
<td>0.646</td>
</tr>
</tbody>
</table>

Robust Standard Errors in Parentheses; * significant at 10%; ** significant at 5%; *** significant at 1%
<table>
<thead>
<tr>
<th>Variable</th>
<th>States with Policy</th>
<th>Non-Zero Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>CEF: CAP FUNDED</td>
<td>8</td>
<td>51</td>
</tr>
<tr>
<td>RENEWABLES PORTFOLIO STANDARD</td>
<td>14</td>
<td>66</td>
</tr>
<tr>
<td>RPS: CAP REQ</td>
<td>4</td>
<td>27</td>
</tr>
<tr>
<td>RPS: SALES REQ</td>
<td>6</td>
<td>39</td>
</tr>
<tr>
<td>NET METERING</td>
<td>31</td>
<td>187</td>
</tr>
<tr>
<td>INTERCON STANDARDS</td>
<td>21</td>
<td>90</td>
</tr>
<tr>
<td>STATE PURCHASING: PCT REQ</td>
<td>6</td>
<td>14</td>
</tr>
<tr>
<td>REQ GREEN POWER OPT</td>
<td>5</td>
<td>16</td>
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</table>
Table 1-4. Variable Effects of Significant Variables

<table>
<thead>
<tr>
<th>Variable</th>
<th>Mean</th>
<th>Std. Dev.</th>
<th>Increase Per Unit per TWh</th>
<th>Std. Dev. in Median Gen. State</th>
</tr>
</thead>
<tbody>
<tr>
<td>RENEW COST (2002 cents/kWh)</td>
<td>6.93</td>
<td>0.59</td>
<td>-0.725 MW</td>
<td>-36 MW</td>
</tr>
<tr>
<td>BORDER PRICE (2002 cents/kWh)</td>
<td>7.58</td>
<td>2.07</td>
<td>-0.235 MW</td>
<td>-27 MW</td>
</tr>
<tr>
<td>PCT NUCLEAR</td>
<td>11.13</td>
<td>12.46</td>
<td>0.170 MW</td>
<td>107 MW</td>
</tr>
<tr>
<td>LCV SCORE (0-100)</td>
<td>43.06</td>
<td>26.51</td>
<td>0.025 MW</td>
<td>34 MW</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Effect of Enacting a Policy</th>
<th>Mean</th>
<th>Std. Dev.</th>
<th>Per Unit Effect</th>
<th>Impact in Median Gen. State</th>
</tr>
</thead>
<tbody>
<tr>
<td>PBF: CAP FUNDED</td>
<td>8.20</td>
<td>61.21</td>
<td>0.206 MW per 1.0 MW</td>
<td>20.6% of Funded Capacity</td>
</tr>
<tr>
<td>RPS: CAP REQ</td>
<td>14.05</td>
<td>78.30</td>
<td>1.142 MW per 1.0 MW</td>
<td>114% of Req. Cap.</td>
</tr>
<tr>
<td>REQ GREEN POWER OPT</td>
<td>0.02</td>
<td>0.15</td>
<td>3.457 MW per TWh</td>
<td>177 MW</td>
</tr>
</tbody>
</table>

Note 1: Results are for Spec. 3 excluding RENEW COST, which is from Spec. 2.
Note 2: All other variables are statistically insignificant.
CHAPTER 2
EFFECTS OF COAL CONTRACT CONSTRAINTS ON SO₂ TRADING PROGRAM COMPLIANCE DECISIONS

2.1 Introduction

Title IV of the 1990 Clean Air Act Amendments (CAAA) introduced the first sulfur dioxide (SO₂) emissions cap-and-trade program in the United States (U.S.). The program was claimed to be a success by the Clinton Administration due to a lower than projected allowance prices, and total compliance costs well below the estimated costs under an alternative command-and-control policy.¹

A growing body of evidence suggests that much of the potential cost savings have not been achieved by the Title IV SO₂ Trading Program.² State public utility commission (PUC) regulations, adjustment costs, and long-term coal contracts have all been cited as leading to non-cost-minimizing actions taken by many electric utilities.³ There is a body of evidence indicating state PUC regulation has led to compliance costs that are in excess of least-cost compliance in cap-and-trade programs as had been previously conjectured. However, these estimates appear not to account for much of the excess compliance costs that resulted during Phase I of Title IV.⁴

No work has been done to date to show the effects long-term coal or other fuel contracts have on the ability of cap-and-trade programs to achieve the least-cost compliance solution. Fuel contract constraints decrease the degrees of freedom in

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¹ Burtraw et al. (2005); Sotkiewicz and Holt (2005)

² Carlson et al. (2000); Ellerman et al. (1997); Sotkiewicz and Holt (2005)

³ Carlson et al. (2000), Ellerman et al. (1997), Ellerman et al. (2000), Bohi (1994); Bohi and Burtraw (1997), Fullerton et al. (1997), and Swift (2001) all listed either state regulations or long-term coal contracts or both as possible reasons for the apparent or potential sub-optimal behavior.

⁴ Sotkiewicz and Holt (2005) found actual compliance costs to be much higher than their estimated costs while controlling for the effects of state regulation.
compliance choices on which pollution markets rely to improve cost-effectiveness in utility
decision-making. It may well be the case the presence of long-term contracts are driving
part, or most, of the deviations from least-cost that have been simulated or estimated in
the literature for Phase I. If long term coal contracts did in fact lead to inefficiencies under
Phase I, contracts could have similar effects under the newly enacted Clean Air Interstate
Rule (CAIR) of 2005 that further restricts SO\textsubscript{2} emissions.

In this paper a model of unit-level SO\textsubscript{2} compliance is constructed that incorporates
the presence of coal contracts to examine how long-term coal contracts affect utility
compliance choices and a unit’s compliance costs. As expected, the presence of coal
contract constraints leads to compliance costs in excess of the hypothetical least-cost
solution. The presence of binding high sulfur contract constraints that were likely in Phase
I of the Title IV SO\textsubscript{2} Program may explain the lower than expected allowance prices
in Phase I that accompanied compliance costs that were above the least-cost solution.
It is also found that the presence of binding low sulfur coal constraints that may exist
under CAIR, which may lead to allowance prices that are higher than without the binding
constraint. The effects of the contract constraint seem counter-intuitive: binding high
sulfur coal constraints leading to lower excess demand for allowances, which could reduce
the allowance market price. Binding low sulfur coal constraints leading to higher excess
demand for allowances, which could increase the allowance market price. The interaction
between the contract constraints and the discrete nature of the scrubber choice leads to
these unexpected results.

2.2 Policy Background

2.2.1 Title IV of the Clean Air Act Amendment

Under the Title IV SO\textsubscript{2} emission trading program, affected units are allocated
allowances, which permit the holder to emit one ton of SO\textsubscript{2} in the year in which the
allowance is issued or any year thereafter, and that may be traded (bought or sold) in the
market or banked for future use. At the end of each year, generating units are required to
hold at least enough allowances to cover their yearly emissions to be in compliance. The program allows generating units several degrees of freedom in choosing how to best meet its compliance obligations: switch from high sulfur to low sulfur fuels; install scrubbers; and buy or sell allowances; or any combination thereof.\(^5\)

### 2.2.1.1 Phase I of Title IV

Phase I of Title IV, which ran from 1995-1999, capped the initial level of emissions at 8.7 million tons of SO\(_2\) per year for the 110 largest polluting plants, which included 263 generating units. The EPA allocated allowances *gratis* to these affected units based on average heat input during 1985-1987 multiplied by an emissions rate of 2.5 lbs. SO\(_2\)/mmBtu.

An additional 168 units participated in Phase I in 1996 based on the rules established by EPA allowing a plant to “opt-in” units (7 units), designate substitution units (160 units), or designate compensating units (1 unit) as part of their Phase I compliance plans. The voluntary participation of these additional units resulted in a total of 431 affected generating units under Phase I. A “substitution unit” is a unit that would eventually be affected in Phase II that voluntarily enrolled into Phase I to meet some or all of the required emissions reductions for a Phase I unit (Sotkiewicz and Holt, 2005). Substitution units receive an allowance allocation based on its historical heat input. A utility may decide to reduce its electricity production at a Phase I affected unit. To do so, the utility must have a “compensation unit” from the Phase II units the utility operates to cover the necessary additional electricity. This compensation unit is then brought into Phase I and given an allowance allocation based on its historical heat input. Industrial sources of SO\(_2\) emissions could use the opt-in provision and voluntarily enroll into Phase I and receive

\(^5\) There are additional compliance options, including shutting down the affected unit and shifting dispatch away from the affected unit (Energy Information Association, 1997)
allowance allocations similar to substitution and compensation units. There were seven units that entered the program through this opt-in provision (Ellerman et al., 2000).

Allowance prices were low compared to initial marginal abatement cost estimates, and relatively stable throughout Phase I and the beginning of Phase II. Initial marginal cost estimates used by the EPA ranged from $199-$226 (Smith and Ellerman, 1998). The market opened in 1995 at a price of $150, soon hit a low of $70 in early 1996, and then slowly rose back to around $150. Other than a slight spike in 1999 as utilities positioned themselves for the start of Phase II, the allowance price remained relatively stable around $150 (Burtraw et al., 2005).

2.2.1.2 Phase II of Title IV

Phase II, which began in 2000 and will continue until the implementation of CAIR in 2010, includes all units over 25 MW in generating capacity. The more than 2,000 affected generating units throughout the U.S. were allocated allowances based on an emissions rate of 1.2 lbs. SO2/mmBtu of heat input, multiplied by the unit’s baseline heat input during 1985-1987. New generating units were given no allowances and were required to purchase any necessary allowances in the allowance market. Phase II allocations were capped at 10.0 million tons annually in 2000, have decreased to 9.5 in 2002 where it will remain until 2010, when it drops to 8.95 million tons.

The banking provision has allowed utilities to trade intertemporally with utilities using the substantial allowance bank accumulated through Phase I for compliance in Phase II leading to annual emission levels in excess of 10 million tons in each year from 2000 to 2005.

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6 There was an incentive to opt-in generating units voluntarily if it is beneficial to the utility. Opting Phase II units into Phase I give utilities additional ways to decrease emissions and sell allowances and, apparently more importantly, bank allowances for future use in Phase II. Actual SO2 emissions by Phase I units were much lower during Phase I than the total allowance allocation during Phase I, which allowed utilities to bank additional allowances for use during Phase II (Ellerman et al., 1997).
The allowance prices remained fairly stable through the beginning of 2004. A large spike up to over $700 took place in 2004, which according to Burtraw et al. (2005) has been associated with several factors: an increase in natural gas prices, increased electricity demand, and the proposal of future emissions control legislation now referred to as the Clean Air Interstate Rule (CAIR).

2.2.2 Clean Air Interstate Rule

In 2005, the EPA issued the Clean Air Interstate Rule (CAIR) that further restricts the emissions of SO$_2$ in 25 eastern states and the District of Columbia effective in 2010. The states under CAIR are the same states that had affected units under Phase I.

Generating units still receive their allowance allocation as defined under Phase II. Beginning in 2010, the emissions value of the allowances for units in the CAIR region is cut in half from 1.2 to 0.6 lbs. SO$_2$/MMBtu of heat input which implies a unit must hold two Title IV allowances for each ton of actual emissions. Starting in 2015 units must hold 2.86 Title IV allowances for every ton of emissions, which translates to an allocation of approximately 0.4 lbs. SO$_2$/MMBtu. Meanwhile generating units outside the CAIR region will continue operate under the Title IV, Phase II Program with trades allowed to take place between CAIR and Phase II units. Units under Phase II and CAIR participate in the same allowance market and face the same market allowance price.

The spike in allowance prices up to over $1,600 in 2006 seen in Figure 2.8 may have been a result of the proposal and enactment of CAIR. Utilities could have chosen to bank allowances instead of selling allowances in the market to ensure their ability to cover requirements at the beginning of CAIR. It is still uncertain what led to the temporary spike in allowance prices, but it appears likely that it was a temporary reaction to the policy environment or other market conditions as the allowance price has quickly decreased to its current price of less than $600/ton.
2.3 Literature Review

2.3.1 Title IV: Phase I

There has been significant research done on the Title IV SO\textsubscript{2} Cap-and-Trade Program, both for Phase I and Phase II (Ellerman et al. (2000); Burtraw et al. (2005)). From Table 2-1, it can be seen that, in general, the compliance cost estimates before Phase I took effect were higher than the estimates made after Phase I became effective and actual data could be used in the estimates. The pre-policy estimates range as high as $1.34$ billion/year with most estimates at least $860$ million/year. The actual cost estimates are towards the lower end of this range between $730$-$990$ million/year.

There are several reasons for the differences between initial estimates and actual aggregate industry compliance costs. The most important factor was the decrease in delivered low sulfur coal prices. At the unit level, lower low sulfur coal prices decreased the marginal cost of reducing emissions through fuel switching, which was the compliance option chosen by 52% of all affected units, while 32% of affected units chose to purchase allowances, 10% installed a scrubber, 3% shut down, and 3% chose other methods.\footnote{Energy Information Association, The Effects of Title IV of the Clean Air Act Amendments of 1990 on Electric Utilities: An Update}

Several of these studies have estimated the cost savings resulting from the allowance trading system. Carlson, et. al. (2000) used an econometric-based simulation model to estimate the potential cost savings from trading in the program compared to a uniform emissions rate standard. The potential savings was estimated at $250$ million, 80% of which is a result of switching from high to low sulfur coal and 20% from technical change, such as improved scrubber technology (Burtraw et al., 2005).

Keohane (2002) simulates which generating units would have installed scrubbers under a uniform emissions-rate standard and finds that the total number of scrubbers would have been one-third higher than the actual number of installed scrubbers under the
cap-and-trade approach. Sotkiewicz and Holt (2005) find that due to PUC regulation, not only is there a greater number of scrubbers actually installed at the beginning of Phase I relative to the least cost solution (18 scrubbers), but only nine of those actually installed are at units that install scrubbers under the least cost solution. An increase in the number and inefficient location of scrubber installations increases the total costs of compliance because installing a scrubber is the most expensive compliance option under Phase I.

In the initial years of Phase I, many firms were not active participants in the allowance market, choosing to switch fuels and bank allowances or shift allowances between only their own units (Hart (1998); Ellerman et al. (1998)). The firms that did participate mainly traded allowances within the same utility company. Bohi and Burtraw (1997) find that intra-utility trading accounts for two-thirds of the allowance transactions while the remaining one-third were inter-utility trades. Since most trades were made between units owned by the same company, trading between two generating units at the same plant would be a common occurrence. Many studies suggested state public utility regulations and other state laws as a reason for the inefficiencies resulting from this self-sufficient behavior (Bohi (1994); Bohi and Burtraw (1997); Swift (2001)).

Arimura (2002) uses econometric approaches to study the impact of PUC regulation on compliance choices, and finds that utilities that face PUC regulation are more likely to switch fuels instead of purchasing allowances for compliance.

Winebrake et al. (1995) estimated the cost inefficiencies from state government restrictions on a utility’s allowance trading, and estimates the total cost estimates for the first ten years of Title IV (1995-2005). A command-and-control approach was estimated to result in compliance costs of $4.19 billion greater than in the unrestricted permit trading system ($5.02 billion, or an average of $502 million/year) and an estimated allowance price of $143/ton.

Winebrake et al. (1995) simulates the additional costs from restrictions on between-state trading that were under consideration by both New York and Wisconsin. Both states were
trying to minimize allowance sales to states whose emissions will eventually reach New York/Wisconsin and result in hotspots, which are areas with extreme emissions levels that result in greater damages in a particular area relative to damages throughout the rest of the region. Preventing utilities in New York and Wisconsin from selling allowances to utilities outside their state would have resulted in more than double the compliance costs in both states, and increased nationwide compliance costs. Some of the additional costs from these restrictions would have been offset by lower costs for utilities not in New York or Wisconsin that would have been able to sell more allowances due to the additional demand no longer being met by allowances sales from New York and Wisconsin utilities.

Some studies further explain the inefficiencies by examining the actual lost cost savings that are specifically a result of state PUC regulation under Phase I. Carlson et al. (2000) find that the actual compliance costs were $339 million (59%) greater in 1996 than the least-cost solution. The study concludes the difference between actual compliance costs and the least-cost compliance may be attributable to “adjustment costs associated with changing fuel contracts and capital expenditures as well as regulatory policies.” Sotkiewicz and Holt (2005) find that PUC regulations resulted in $131 million of the additional compliance costs relative to the least cost solution. However, there is a significant amount of compliance costs that remained unexplained. My study conjectures long-term coal contracts may be responsible for what appears to be inefficient behavior resulting in additional compliance costs.

8 Sotkiewicz and Holt model the possibility of ex post “prudence”, which assumes that there is some cost, such as future state PUC cost disallowance, to the generating unit for choosing a less cost-effective option. If PUC regulations allow for total pass-through of costs without threat of ex-post prudence, then a generating unit is indifferent to costs and may not make the lowest cost compliance option.
2.3.2 Utility-Level Models of Compliance Costs

Previous studies have estimated the compliance costs at the generating unit or utility-level, and focus on the impacts of state regulation on utility-level compliance choices. Swinton (2002) calculates the shadow prices of emissions reductions for seven Florida power plants from 1990 to 1998 and compares their optimal choices to their actual actions. Several factors were discussed as the reasons for some utilities making sub-optimal decisions: state PUC regulations, program learning curve, small magnitude of potential gains from trade, and uncertainty over the program’s longevity.

Swinton (2004) follows the same approach except it expands the study to 40 plants with data from 1994 to 1998, and introduces the possibility that long-term coal contracts may prohibit utilities from switching coal types, although it is not modeled. Both studies find the actual utility-level compliance costs to be much higher than the estimated least-cost solution.

Coggins and Swinton (1996) use an output distance function to estimate the shadow price of SO\(_2\) emissions abatement for electric power plants in Wisconsin. The study estimated the allowance shadow price to be greater than the observed allowance prices at the time, which they assert may be partially explained by Wisconsin’s strict state regulations on SO\(_2\) emissions.

Several studies have shown analytically or through simulation models that state PUC regulations can lead to inefficiencies at the utility-level. Bohi and Burtraw (1992) develop a model of utility decision-making given two compliance options, purchasing allowances or installing emissions control technology. Bohi and Burtraw derive two recommendations so that state regulation does not result in inefficient compliance choices by a utility. First, if a utility’s allowed return is less than its cost of capital with respect to both compliance options, symmetrical cost recovery rules are recommended as uneven treatment of cost recovery may create incentives for a utility to make suboptimal compliance choices. Second, if a utility is allowed to earn more than its cost of capital with regard to both
compliance options, Bohi and Burtraw recommend the more expensive be treated less favorably. Fullerton et al. (1997) uses a numerical model to determine the impact state regulation will have on a utility’s compliance costs by modeling the cost-minimizing utility compliance choices and a utility’s compliance choices under its Public Utility Commission rules. The study finds that asymmetrical cost recovery rules can lead to utility compliance costs much higher than the least-cost solution, and possibly higher than a command-and-control approach.

2.3.3 Long-Term Coal Contracts

Joskow (1985, 1988) states that coal contracts decrease transaction costs in coal purchasing that result from uncertainty and complexity in future coal markets. A utility may be willing to pay more than the current spot market price for coal to protect itself from unexpected higher rates in the future.

Joskow (1988, 1990) finds that during periods in which the spot market coal prices were lower than the contracted prices, the contract prices failed to adjust downward. This downward rigidity of coal prices can lead to utility coal costs being higher than is optimal in the short run. Some renegotiation, breach of contract, and litigation has occurred, but nearly all contracts appear to have continued unchanged. The main reason for the constraints in altering these coal contracts is that less than 15% of coal consumed by utilities is supplied by a coal company owned by the same utility (Joskow, 1987). Firms have high legal or negotiation costs of breaking a coal contract when the agreement is made with a firm that has no financial ties to the utility. Coal contracts may also be a result of regulations protecting the local coal industry (Arimura 2002). Due to the inability of contracted coal prices to decrease with spot market prices, large coal price
reductions can lead to significant differences between coal contract prices and spot market coal prices.\(^9\)

Ellerman and Montero (1998) found that investment and innovation in coal production and delivery as well as greater competition between railroads due to the Staggers Rail Act of 1980 created lower coal prices during the first year of Phase I, especially for low sulfur coal from the Powder River Basin. These lower coal prices led to lower marginal costs of abating SO\(_2\) emissions through fuel switching, which is reflected in the lower than expected allowance price in 1995 (Burtraw et al., 2005). Considering the downward rigidity of contract coal prices, the same coal price reductions also resulted in lower spot market prices for both high sulfur and low sulfur coal relative to the coal prices under contract.

2.4 Inefficiencies Resulting from Coal Contract Constraints

There are three plausible scenarios where binding contract constraints results in sub-optimal compliance choices. First, during Phase I a utility with high sulfur coal contracts may be unable to switch to low sulfur coal for compliance when it is

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\(^9\) A utility cannot sell contracted coal on the spot market because of the transaction costs involved in selling to another utility from both its contract for coal purchases and its contract for coal transportation. A coal contract sets a given type and amount of coal for an agreed upon price from a particular coal source. A transportation contract sets a given price for delivery of coal purchases from a coal source. The combination of these two contracts results in the delivered cost of a coal purchase. For one utility to sell coal to another utility, it would need to either buy out its contract with a provision to deliver the coal to the other utility or it would need to pay for the shipment of the coal from its facility to the other utility. There are large additional costs associated with either of these actions. As shown in Joskow, few contracts were bought out, breached, or renegotiated. Also, there does not appear to be any sales of coal from one utility to another.
cost-effective to do so. Consequently, the utility is forced to sub-optimally install a scrubber or purchase allowances.\textsuperscript{10}

Second, during Phase I spot coal prices were declining and often were lower than the price of contract coal of similar characteristics (heat and sulfur content). Contract constraints may have prevented utilities from switching to lower priced spot market coal alternatives of similar sulfur and heat content than was being utilized under contract.

Third, under CAIR some utilities may be locked into low sulfur coal contracts entered into for Title IV compliance and may be unable switch back to high sulfur coal and scrub if it is cost-effective to do so. Consequently, the contract constraint pushes a utility into sub-optimal compliance choices such as allowance purchases or scrubber installation while using low sulfur coal.

An examination of the data for Phase I affected units indicates that of the 26 scrubbers installed by the end of 1996 in response to the passage of the 1990 Clean Air Act Amendments, 23 of those scrubbers were installed at facilities with 40 percent or more of its coal deliveries by contract and with 20 of them having a weighted average SO\textsubscript{2} emission rates greater than the \textit{Phase I allowed level} of 2.5 lbs. SO\textsubscript{2}/mmBtu (pounds per million Btus of heat).\textsuperscript{11} Additionally, the 14 generating units with scrubbers and greater than 75\% of coal under contract all have emissions rates over 2.5 lbs. SO\textsubscript{2}/mmBtu. This indicates the possibility that high sulfur coal contract constraints are driving some

\textsuperscript{10} The actual purchasing of allowances is not what increases industry-wide compliance costs. It is the sub-optimality of the allowance purchase that increases the total compliance costs in an industry.

\textsuperscript{11} A total of 29 scrubbers were installed between 1990 and 1996. Three of the scrubbers are not considered to have been installed for compliance of Phase I. Two were installed on Port Washington units in Wisconsin to meet New Source Review requirements while a third was installed on a Yates unit as results of a pilot program.
compliance decisions. The idea that spot market purchases may have been preferred can be indicated in the fact that many Phase I facilities in 1996 had allowed both long-term high and low sulfur coal contracts to expire during the 1990-1995 period and replaced those with spot market coal of an equivalent or lower sulfur content. This may also be an indication of potentially binding low sulfur contract constraints as utilities face future compliance decisions under CAIR.

Contract constraints will continue to bind a generating unit’s decisions until the expiration of the contract. The average length of coal supply contracts (weighted by tonnage) in 1996 was 16.5 years with 53.3% of delivered coal under contracts signed for greater than 10 years and 22.1% of greater than 30 years. The impacts of coal contract rigidities will dissipate over time. However, the impacts of these contracts on compliance decisions could continue to linger for years due to the length of many of these contracts.

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12 Data used is available from the EIA FERC-423 database and Electric Power Annual 1996.

13 Data from the EIA FERC-423 Database and Coal Transportation Rate Database show the percentage of coal purchased through contract agreements. Of the 93 Phase I Affected Units with contract expirations between 1990-1995, 62 did not sign any new contracts, 13 replaced high sulfur contracts with low sulfur contracts, and only 18 replaced old contracts with new contracts for the same sulfur content. Contracts were shifted from 11-30 years (decrease of 48 to 33%) to contracts of 5 or fewer years (increase from 13 to 24%). Low sulfur contracted coal deliveries increased by 389% and high sulfur contracted coal deliveries decreased by 50% for Phase I affected units between 1988 and 1997 while non-affected units saw an increase of 82% and a decrease of 42%, respectively. From the available FERC-423 data for 133 plants with at least one affected unit, 34 reduced the percentage of coal under contract by greater than 25 percent: 12 switched from high contract coal to high spot market coal, 12 switched from low sulfur contract coal to low sulfur spot market coal, 8 switched from high sulfur contract coal to low sulfur spot market coal, and 2 switched from low sulfur contract coal to high sulfur spot market coal.

14 The length of the contract does not represent the years remaining on the length of the contract. There will be variation in the time frame under which these contracts expire.
2.5 Model and Parameters

The model is a static production cost model that draws heavily from Sotkiewicz (2003) and Fullerton et al. (1997), which simulates production costs at the *generating unit* level with constraints on demand for electricity and emissions levels, and introducing high sulfur coal and low sulfur coal contract constraints. It would seem that adding contract constraints to the model would not cause any major disruptions. However, the model results in rather complex interpretations due to how the contract constraints interact with the non-convexities of a unit’s scrubber choice. Let “i” be the index of units. The parameters in the model are described below.

**Technology Parameters:**

- \( z_i \in \{0, 1\} \) represents a generating unit’s discrete scrubber choice where \( z_i = 1 \) if a unit installs a scrubber and \( z_i = 0 \) if a unit does not install a scrubber.

- \( P_{iz} \) represents the levelized yearly cost of a scrubber, which are the average annual costs from depreciation and use of capital plus the operation and maintenance costs of installing and operating a scrubber.\(^{15}\)

- \( r_i \in [0, 1] \) represents the scrubber emissions capture rate or emissions removal efficiency rate, which is the fraction of emissions that the scrubber removes from the exhaust stream. The removal rate is independent of the sulfur content of the coal used by a utility because it removes some percentage of emissions after production. Depending on the scrubber technology and vintage, it can remove 25-99% of \( \text{SO}_2 \) emissions.\(^{16}\)

**Demand Parameter:**

- \( D_i \) represents electricity demand, in million Btus of heat input, for a given generating unit. Demand is derived by taking the total kilowatt-hours of electricity

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\(^{15}\) The capital costs are assumed to be $260/kW under Phase I and $141.34/kW under CAIR. Capital costs are discounted at a 10% rate based on a 20 year equipment lifespan \( \left(\frac{d(1+d)^t}{(1+d)^2-1}\right) \). The operation and maintenance costs are assumed to be 2.0 mills/kWh under Phase I and 1.23 mills/kWh under CAIR.

\(^{16}\) Table 30: “Flue Gas Desulfurization (FGD) Capacity in Operation at U.S. Electric Utility Plants as of December 1996” from the 1996 Electric Power Annual Vol. II
demand multiplied by the heat input required to generate one kilowatt-hour of electricity. Demand at the unit level is assumed to be fixed. Modeling each generating unit’s hourly dispatch and hourly costs in the context of varying loads and dispatch are not easily modeled, and would require arbitrary assumptions about how units would be utilized. For these reasons, it is assumed in this paper that utilities do not have the option to shift electricity production across generating units to meet demand.

Coal Parameters:

- $C_{ih}^s, C_{il}^s$ are the quantities, in tons, of high sulfur and low sulfur spot market coal use for a given unit, respectively.
- $C_{ih}^c, C_{il}^c$ are the quantities, in tons, of high sulfur and low sulfur contract coal use for a given unit, respectively.
- $P_{ih}^s, P_{ih}^c$ are the delivered prices, in dollars/ton, of high sulfur and low sulfur spot market coal for a given unit, respectively.
- $P_{ih}^c, P_{ih}^c$ are the delivered prices, in dollars/ton, of high sulfur and low sulfur contract coal for a given unit, respectively. Delivered coal prices will differ across regions of the U.S. due to the location of coal mines across the country. It is assumed that generating units are price takers in purchasing coal.
- $H_{ih}^s, H_{il}^s$ are the heat content for high sulfur and low sulfur spot market coal for a given unit, respectively. Heat content is the average amount of heat, in million Btus, in one ton of coal. The delivered price is the dollars/mmBtu paid for coal.
- $H_{ih}^c, H_{il}^c$ are the heat content for high sulfur and low sulfur contract coal for a given unit, respectively. The heat content will differ across regions of the U.S. due to the heat content of coal from different coal mines across the country.
- $S_{ih}^s, S_{il}^s$ are the sulfur content for high sulfur and low sulfur spot market coal for a given unit, respectively. Sulfur content is the percentage of a ton of coal comprised of sulfur.

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17 For example, a generating unit in Wisconsin will have different delivered coal prices for a particular coal type relative to a unit in Georgia. Wisconsin is closer to the low sulfur coal mines in the Powder River Basin in the Western U.S., which results in a much lower delivered price to Wisconsin than to Georgia.
- $S^c_{th}, S^c_{il}$ are the sulfur content for high sulfur and low sulfur contract coal for a given unit, respectively. The sulfur content will differ across regions of the U.S. due to the heat content of coal from different coal mines across the country.

- $m$ represents the rate at which sulfur is transformed into $\text{SO}_2$, which is assumed to be a constant (1.9) for simplicity.\textsuperscript{18}

- $\overline{C}^c_{th}, \overline{C}^c_{il}$ represent the contract constraints for a given unit, which requires the use of a minimum amount of each coal type.

**Allowance Parameters:**

- $E_i$ represents a generating unit’s tons of $\text{SO}_2$ emissions.

- $A^e_i$ represents a generating unit’s initial allowance allocation in tons of $\text{SO}_2$ emissions.

- $A_i$ represents a generating unit’s net allowance position in tons of $\text{SO}_2$ emissions, which is the difference between the actual allowances used and a unit’s initial allowance allocation. A unit is a net buyer of allowances (positive excess demand) if it uses more allowances than its initial allocation ($A_i > 0$), a net seller (negative excess demand) if it uses fewer allowances than its initial allocation ($A_i < 0$), and neither if it uses exactly the same amount of allowances as its initial allocation ($A_i = 0$).

- $P_A$ is the allowance price, which is endogenously determined in the model by the decisions of the utilities. Each allowance that is bought (sold) will increase (decrease) the utility’s production costs by $P_A$. Each generating unit takes $P_A$ as given.

### 2.6 Generating Unit Level Decision-Making Process

The model is a static model with decisions made at the generating unit level where each generating unit chooses its coal use, net allowance position, and scrubber choice to

\textsuperscript{18} Sulfur content is the tons of sulfur per ton of coal. In this paper, any coal that results in emissions greater than 2.5 lbs. $\text{SO}_2$/MMBtu is considered high sulfur coal. Under Phase II of Title IV and CAIR, the high sulfur-low sulfur cut-off value is reduced from 2.5 to 1.2 lbs./MMBtu. Under CAIR the new allowance allocation is based on 0.6 lbs./MMBtu, which cannot be met by fuel switching alone because low sulfur coal normally ranges from 0.7-1.2 lbs./MMBtu with few shipments of low sulfur coal resulting in emissions of 0.6 lbs./MMBtu. $m = 1.9$ for bituminous and anthracite coal, $m = 1.75$ for subbituminous coal, $m = 1.5$ for lignite coal. These differ due to each coal types composition.
minimize its costs based on its constraints for emissions, electricity demand, and coal use
for both high sulfur and low sulfur contract coal.

### 2.6.1 Generating Unit’s Problem

\[
\min_{z_i, A, C_{s_i}, C_{c_i}} z_i P_i + P_A A_i + P_{s_i} C_{s_i}^s + P_{c_i} C_{c_i}^c + P_{sc_i} C_{sc_i}^c + P_{s_il} C_{s_i}^s + P_{c_il} C_{c_i}^c
\]

(2–1)

subject to...

\[
A_e + A_i \geq (1 - z_i r_i)(m)(C_{s_i} S_{s_i} + C_{c_i} S_{c_i}^c + C_{s_i} S_{s_i} + C_{c_i} S_{c_i}^c)
\]

(2–2)

\[
(C_{s_i} H_{s_i} + C_{c_i} H_{c_i}^c + C_{s_i} H_{s_i}^c + C_{c_i} H_{c_i}^c) \geq D_i
\]

(2–3)

\[
C_{c_i} = C_{c_i}^c \quad \mu_{ci}
\]

(2–4)

\[
C_{c_i} = C_{c_i}^c \quad \mu_{ci}
\]

(2–5)

\[
C_{s_i}, C_{c_i} \geq 0
\]

(2–6)

\[
z_i \in \{0, 1\}
\]

(2–7)

Equation (3–1) represents the unit’s cost function. These costs include the cost of scrubber installation \((z_i P_i)\), net costs of allowance purchases \((P_A A_i)\), and costs of coal purchases \((P_{s_i} C_{s_i}^s + P_{c_i} C_{c_i}^c + P_{sc_i} C_{sc_i}^c + P_{s_il} C_{s_i}^s + P_{c_il} C_{c_i}^c)\). The emissions constraint is shown in (3–2), where the number of allowances held \((A_e + A_i)\) must be as large as the amount of total emissions by the generating unit \([(1 - z_i r_i)(m)(C_{s_i} S_{s_i} + C_{c_i} S_{c_i}^c + C_{s_i} S_{s_i} + C_{c_i} S_{c_i}^c)]\). Total emissions is a function of the amount of each coal type used as well as the emissions reduction due to a scrubber, if one is installed. The Lagrange multiplier on the emissions constraint is represented by \(\lambda_{i1}\). The demand constraint requires that the amount of heat input to generate electricity \((C_{s_i} H_{s_i} + C_{c_i} H_{c_i}^c + C_{s_i} H_{s_i}^c + C_{c_i} H_{c_i}^c)\) must cover the consumer demand \((D_i)\) for electricity expressed as heat input, which is seen in (3–3). The Lagrange multiplier on the demand constraint is represented by \(\lambda_{i2}\). Coal contract constraints require the unit to use a specific amount of each contract coal type, \(C_{c_i}^c\) for high sulfur coal in (3–4) and \(C_{c_i}^c\) for low sulfur coal in (3–5). A unit will use exactly the contracted amount because (1) if the contract coal is more expensive than spot market coal, then a
unit will not want to use any more contract coal than is necessary and (2) if contract coal is cheaper than spot market coal, the coal producer would prefer to sell any additional non-contracted coal through the spot market. The Lagrange multiplier for each contract constraint on each coal type is represented by $\mu_{ih}$ for high sulfur contract coal and $\mu_{il}$ for low sulfur contract coal.

### 2.6.2 First-Order Conditions

The partial derivative with respect to $A_i$ yields the impact of a one unit change in the net allowances purchased on the unit’s total costs.

\[ P_A - \lambda_{i1} = 0 \quad (2-8) \]

Since $A_i$ can be either positive or negative based on the net allowance position, (2–8) will hold with equality. The additional cost to the firm of emitting one more ton of emissions is equivalent to the allowance price, $\lambda_{i1} = P_A$.

Let $f \in \{h, l\}$ represent the type of coal and $g \in \{s, c\}$ represent the type of purchase. Each coal type has its own sulfur content ($S_{gf}^s$), heat content ($H_{gf}^c$), and delivered price ($P_{gf}^d$). The partial derivatives with respect to $C_{gf}^s$ represent the impact a one unit change in “f” type sulfur coal (high or low) from a “g” type purchasing agreement (spot market or contract) has on the unit’s total costs.

\[ P_{ih}^s + \lambda_{i1}(1 - z_i r_i)(m)(S_{ih}^s) - \lambda_{i2}H_{ih}^s \geq 0, = 0 \text{ if } C_{ih}^s > 0 \quad (2-9) \]

\[ P_{il}^s + \lambda_{i1}(1 - z_i r_i)(m)(S_{il}^s) - \lambda_{i2}H_{il}^s \geq 0, = 0 \text{ if } C_{il}^s > 0 \quad (2-10) \]

\[ P_{ih}^c + \lambda_{i1}(1 - z_i r_i)(m)(S_{ih}^c) - \lambda_{i2}H_{ih}^c - \mu_{ih} = 0 \quad (2-11) \]

\[ P_{il}^c + \lambda_{i1}(1 - z_i r_i)(m)(S_{il}^c) - \lambda_{i2}H_{il}^c - \mu_{il} = 0 \quad (2-12) \]

The cost of using one more unit of $C_{if}^g$ can be disaggregated into four different cost changes: $P_{if}^g$ is the additional costs of purchasing one more unit of coal, $\lambda_{i1}(1 - z_i r_i)(m)(S_{if}^g)$ is the additional costs of the extra emissions from one more unit of coal,
\[ \lambda_{i2} H_{ij} \] is the benefit from meeting the demand remaining from using the additional unit of coal, and \( \mu_{ij} \) represents the reduction in costs from meeting the contract constraint. If \( C_{ij}^s > 0 \), then (3–37) or (2–10) holds with equality. Since the contract constraint holds with equality, (2–11) and (2–12) always hold with equality.

### 2.6.3 Characterizing a Unit’s Spot Market Fuel Choices and Marginal Cost of Abatement from Fuel Switching

A generating unit’s choice of fuel type is based on its scrubber installation choice as well as its marginal cost of abatement relative to the allowance price. In this section, the scrubber choice is taken as given and the focus is solely on comparing the allowance price to the marginal cost of abatement of switching from high sulfur coal to low sulfur coal.

#### 2.6.3.1 Necessary conditions for using both high sulfur and low sulfur coal

If a generating unit uses both high sulfur and low sulfur spot market coal \( (C_{ih}^s > 0, C_{il}^s > 0) \), the additional costs of using each coal type are equal and (3–37) and (2–10) hold with equality, or

\[
\frac{P_{ih}^s + \lambda_{i1}(1 - z_i r_i)(m)(S_{ih}^s)}{H_{ih}^s} = \frac{P_{il}^s + \lambda_{i1}(1 - z_i r_i)(m)(S_{il}^s)}{H_{il}^s}
\]

\[
(2–13)
\]

(2–13) can be rearranged to isolate the shadow price of allowances or emissions, \( \lambda_{i1} \), to derive the Marginal Cost of Abatement from Switching Fuels from high sulfur spot to low sulfur spot market coal \( (MCA_{i}^{s,s}) \) in (2–14). Exploiting (2–8), the allowance price equals \( MCA_{i}^{s,s} \):

\[
P_A = \lambda_{i1} = MCA_{i}^{s,s} = \frac{P_{il}^s - P_{ih}^s}{(1 - z_i r_i)(m)(\frac{S_{il}^s}{H_{il}^s} - \frac{S_{ih}^s}{H_{ih}^s})}
\]

\[
(2–14)
\]

The shadow price is equal to the difference in price per unit of heat divided by the difference in emissions per unit of heat.

#### 2.6.3.2 Only high sulfur coal use: Necessary conditions

If a generating unit uses only high sulfur spot market coal \( (C_{ih}^s > 0) \), the additional costs to the generating unit of using high sulfur spot market coal is weakly less than using
low sulfur spot market coal and (3–37) holds with equality while (2–10) holds with weak inequality, or

$$\frac{P^s_{i_l} + \lambda_1 (1 - z_ir_i)(m)(S^s_{i_l})}{H^s_{i_l}} \leq \frac{P^s_{i_l} + \lambda_1 (1 - z_ir_i)(m)(S^s_{i_l})}{H^s_{i_l}}$$  \hspace{1cm} (2–15)

(2–15) can be rearranged to show the allowance price is weakly less than $MCA^{s,s}$:

$$P_A \leq MCA_i^{s,s} = \frac{P^s_{i_l} - P^s_{i_h}}{(1 - z_ir_i)(m)(S^s_{i_l} - S^s_{i_h})}$$  \hspace{1cm} (2–16)

### 2.6.3.3 Only low sulfur coal use: Necessary conditions

If a generating unit chooses to use only low sulfur spot market coal ($C^s_{i_l} > 0$), the additional costs of using low sulfur spot market coal is weakly less than using high sulfur spot market coal and (2–10) holds with equality while (3–37) holds with weak inequality, or

$$\frac{P^s_{i_l} + \lambda_1 (1 - z_ir_i)(m)(S^s_{i_l})}{H^s_{i_l}} \geq \frac{P^s_{i_l} + \lambda_1 (1 - z_ir_i)(m)(S^s_{i_l})}{H^s_{i_l}}$$  \hspace{1cm} (2–17)

(2–17) can be rearranged to show that the allowance price is weakly greater than $MCA^{s,s}$:

$$P_A \geq MCA_i^{s,s} = \frac{P^s_{i_l} - P^s_{i_h}}{(1 - z_ir_i)(m)(S^s_{i_l} - S^s_{i_h})}$$  \hspace{1cm} (2–18)

### 2.6.4 Coal Use Under a High Sulfur Coal Contract Constraint

$\mu_{i_h}$ is the shadow price of the high sulfur contract constraint, which includes both the change in costs due to fuel costs and emissions. If contract coal is more expensive than spot market coal, then $\mu_{i_h} > 0$ and it increases fuel costs. If contract coal is cheaper than spot market coal, then $\mu_{i_h} < 0$ and it decreases fuel costs.

Assume a unit has a high sulfur coal contract and uses only low sulfur spot market coal (no high sulfur spot market coal). So (2–10) and (2–11) hold with equality. It has been shown in (2–17) that if a unit uses only low sulfur spot market coal, $P_A \geq MCA^{s,s}$:

$$\frac{P^c_{i_l} + \lambda_1 (1 - z_ir_i)(m)(S^c_{i_l}) - \mu_{i_h}}{H^c_{i_l}} = \frac{P^s_{i_l} + \lambda_1 (1 - z_ir_i)(m)(S^s_{i_l})}{H^s_{i_l}}$$  \hspace{1cm} (2–19)
By rearranging (2–19) and exploiting (2–8), it can be shown that the allowance price is equal to Marginal Cost of Abatement of switching from high sulfur contract to low sulfur spot market coal ($MCA_{i}^{c,s}$) plus an additional term representing the benefits of meeting the contract constraint, which is weakly greater than $MCA_{i}^{s,s}$:

$$\lambda_{i1} = P_A = MCA_{i}^{c,s} + \frac{\mu_{ih}}{H_{ih}^c} \geq MCA_{i}^{s,s}$$  \hspace{1cm} (2–20)

From (2–20), if $MCA_{i}^{s,s} - MCA_{i}^{c,s} > 0$, then $\mu_{ih} > 0$ and high sulfur contract coal is more expensive than spot market high sulfur coal. If $MCA_{i}^{s,s} - MCA_{i}^{c,s} < 0$, then $\mu_{ih}$ can be positive or negative. If $\mu_{ih} < 0$, then contract coal is cheaper than spot market coal and the additional compliance costs due to emissions dominate the savings from the lower fuel costs. If $\mu_{ih} > 0$, then contract coal is cheaper than spot market coal and the savings from the lower fuel costs dominate the increased compliance costs due to emissions.

$$\frac{\mu_{ih}}{H_{ih}^c} \geq MCA_{i}^{s,s} - MCA_{i}^{c,s}$$  \hspace{1cm} (2–21)

Now assume a unit has a high sulfur coal contract and uses only high sulfur spot market coal (no low sulfur spot market coal). (2–11) and (2–12) hold with equality while (2–10) holds with weak inequality. Also, it has been shown that when a unit uses only high sulfur spot market coal, $P_A \leq MCA_{i}^{s,s}$. Using the same approach as in the previous case, it can be found that the allowance price is weakly less than $MCA_{i}^{c,s}$ plus an additional term representing the benefits of meeting the contract constraint:

$$\Rightarrow P_A \leq MCA_{i}^{c,s} + \frac{\mu_{ih}}{H_{ih}^c} \geq \frac{P_{s}^c + \lambda_{i1}(1 - z_{ir})m(S_{ih}^s)}{H_{ih}^c}$$  \hspace{1cm} (2–22)

The sign of $\mu_{ih}$ cannot be determined by comparing $MCA_{i}^{s,s}$ and $MCA_{i}^{c,s}$, but the first-order conditions for high sulfur contract and spot market coal can be used to determine its sign.

$$\frac{P_{s}^c + \lambda_{i1}(1 - z_{ir})m(S_{ih}^s)}{H_{ih}^c} = \frac{P_{s}^c + \lambda_{i1}(1 - z_{ir})m(S_{ih}^c) - \mu_{ih}}{H_{ih}^c}$$
\[
\mu_{ih} = \frac{P_{ih}^c + \lambda_{i1}(1 - z_ir_i)(m)(S_{ih}^c)}{H_{ih}^c} - \frac{P_{ih}^s + \lambda_{i1}(1 - z_ir_i)(m)(S_{ih}^s)}{H_{ih}^s}
\]

If the additional costs, both from fuel costs and emissions, of using high sulfur contract coal is more expensive than using high sulfur spot market coal, then \(\mu_{ih} > 0\). If the additional costs, both from fuel costs and emissions, of using high sulfur contract coal is less than using high sulfur spot market coal, then \(\mu_{ih} < 0\). If the additional costs, both from fuel costs and emissions, of using high sulfur contract coal is the same as using high sulfur spot market coal, then \(\mu_{ih} = 0\).

Now assume a unit has a high sulfur coal contract and uses both high sulfur and low sulfur spot market coal. So (2–10) and (2–11) hold with equality. Also, it has been shown in (2–15) that when a unit uses both high and low sulfur spot market coal, \(P_A = MCA_i^{s,s}\):

\[
\Rightarrow P_A = MCA_i^{s,s} = MCA_i^{c,s} + \frac{\mu_{ih} H_{ih}^c}{(1 - z_ir_i)(m)(S_{ih}^c - S_{ih}^s)}
\]

By solving for \(\mu_{ih}\) in (2–24), the sign of \(\mu_{ih}\) can be determined. If \(MCA_i^{s,s} - MCA_i^{c,s} = 0\), then \(\mu_{ih} = 0\) and high sulfur contract coal has the same cost as high sulfur spot market coal. If \(MCA_i^{s,s} - MCA_i^{c,s} > 0\), then \(\mu_{ih} > 0\) and contract coal is more expensive to use than spot market coal. If \(MCA_i^{s,s} - MCA_i^{c,s} < 0\), then \(\mu_{ih} < 0\) and contract coal is cheaper to use than spot market coal.

\[
\frac{\mu_{ih} H_{ih}^c}{(1 - z_ir_i)(m)(S_{ih}^c - S_{ih}^s)} = MCA_i^{s,s} - MCA_i^{c,s}
\]

### 2.6.5 Coal Use under a Low Sulfur Coal Contract Constraint

\(\mu_{il}\) is the shadow price of the low sulfur contract constraint, which includes both the change in costs due to fuel costs and emissions. If contract coal is more expensive than spot market coal, then \(\mu_{il} > 0\) and it increases fuel costs. If contract coal is cheaper than spot market coal, then \(\mu_{il} < 0\) and it decreases fuel costs.

Assume a unit has a low sulfur coal contract and uses only high sulfur spot market coal. It has already been shown in (2–16) that when a unit uses only high sulfur spot coal.
market coal, $P_A \leq MCA_i^{s,s}$. (3–37) and (2–12) hold with equality while (2–10) holds with a weak inequality. Using the same approach as in the previous section yields:

$$\lambda_{il} = P_A = MCA_i^{s,c} - \frac{\mu_{il}}{H_{il}} \leq MCA_i^{s,s}$$  \hspace{1cm} (2–26)

Using (2–26), the sign of $\mu_{il}$ can be determined. If $MCA_i^{s,s} - MCA_i^{c,s} > 0$, then $\mu_{il} > 0$ and low sulfur contract coal is more expensive to use than low sulfur spot market coal. If $MCA_i^{s,s} - MCA_i^{c,s} < 0$, then $\mu_{il}$ can either be negative or positive. If $MCA_i^{s,s} - MCA_i^{c,s} < 0$ and $\mu_{il} > 0$, then the higher fuel costs dominate the lower costs from emissions. If $MCA_i^{s,s} - MCA_i^{c,s} < 0$ and $\mu_{il} < 0$, then the lower costs from emissions dominate higher fuel costs.

$$\frac{\mu_{il}}{H_{il}} \geq MCA_i^{s,c} - MCA_i^{s,c} \hspace{1cm} (2–27)$$

Now assume a unit has a low sulfur coal contract and uses only low sulfur spot market coal. So (2–10) and (2–12) hold with equality while (3–37) holds with a weak inequality. It has already been shown in (2–17) that when a unit uses only low sulfur spot market coal, $P_A \geq MCA_i^{s,s}$.

$$P_A \geq MCA_i^{s,c} - \frac{\mu_{il}}{H_{il}} \leq (1 - z_i r_i)(m)(S_{il}^s H_{si}^s - S_{il}^c H_{ci}^c) \hspace{1cm} (2–28)$$

Although the sign of $\mu_{il}$ cannot be determined by comparing $MCA_i^{s,s}$ and $MCA_i^{s,c}$. The first order conditions for low sulfur contract and spot market coal can be used to determine its sign.

$$\begin{align*}
\frac{P_s^s + \lambda_{il}(1 - z_i r_i)(m)(S_{il}^s)}{H_{il}^s} &= \frac{P_c^c + \lambda_{il}(1 - z_i r_i)(m)(S_{il}^c)}{H_{il}^c} - \frac{\mu_{il}}{H_{il}} \\
\Rightarrow \frac{\mu_{il}}{H_{il}} &= \frac{P_c^c + \lambda_{il}(1 - z_i r_i)(m)(S_{il}^c)}{H_{il}^c} - \frac{P_s^s + \lambda_{il}(1 - z_i r_i)(m)(S_{il}^s)}{H_{il}^s} \hspace{1cm} (2–29)
\end{align*}$$

If the additional costs, both from fuel costs and emissions, of using low sulfur contract coal is more expensive than using low sulfur spot market coal, then $\mu_{il} > 0$. If the
additional costs, both from fuel costs and emissions, of using low sulfur contract coal is less than using low sulfur spot market coal, then \( \mu_{il} < 0 \). If the additional costs, both from fuel costs and emissions, of using low sulfur contract coal is the same as using low sulfur spot market coal, then \( \mu_{il} = 0 \).

Now assume a generating unit has a low sulfur coal contract and uses both high sulfur and low sulfur spot market coal. So (3–37), (2–10), and (2–12) hold with equality and 

\[
P_A = MCA^{s,s}_i:
\]

\[
P_A = MCA^{s,s}_i = MCA^{s,c}_i - \frac{\mu_{il}}{H^i_{il}} \left(1 - z_ir_i\right)(m)\left(\frac{S_{ih}^s}{H^i_{ih}} - S_{il}^s\right)
\]

(2–30)

By solving for \( \mu_{il} \), the sign of \( \mu_{il} \) can be determined. If \( MCA^{s,c}_i - MCA_i^{s,s} = 0 \), then \( \mu_{il} = 0 \) and contract coal is as costly to use as spot market coal. If \( MCA_i^{s,c} - MCA_i^{s,s} > 0 \), then \( \mu_{ih} > 0 \) and contract coal is more expensive to use than spot market coal. If \( MCA_i^{s,c} - MCA_i^{s,s} < 0 \), then \( \mu_{ih} < 0 \) and contract coal is cheaper to use than spot market coal.

\[
MCA_i^{s,s} = MCA^{s,c}_i - \frac{\mu_{il}}{H^i_{il}} \left(1 - z_ir_i\right)(m)\left(\frac{S_{ih}^s}{H^i_{ih}} - \frac{S_{il}^s}{H^i_{il}}\right)
\]

(2–31)

### 2.6.6 Generating Unit-Level Compliance Costs

Total compliance costs for a generating unit are the additional costs due to satisfying the emissions constraint, including costs from switching fuels, the costs from its net allowance position, and scrubber installation costs. Compliance costs may be positive or negative depending on its compliance decisions and its initial allowance allocation.

The scrubber installation costs are represented by \( P_{iz} \), and will only attribute to a unit’s compliance costs if a scrubber is installed (\( z_i = 1 \)).

The costs of a unit’s net allowance position is the difference between a generating unit’s initial allowance allocation and its actual emissions multiplied by the allowance price (\( P_A A_i \)).

The costs of switching fuels is the larger of two values: (1) total costs of actual coal purchases (\( P_{ih}^s C_{ih}^s + P_{il}^s C_{il}^s + P_{ih}^c C_{ih}^c + P_{il}^c C_{il}^c \)) minus the costs of purchasing only high sulfur
spot market coal given any contracted coal \((P_{ish}^s \hat{C}_{ish}^{s,MAX} + P_{ish}^c \bar{C}_{ish}^c + P_{ili}^c \bar{C}_{ili}^c)\), or (2) zero where:

\[
\hat{C}_{ish}^{s,MAX} = D_i - \frac{C_{ish}^c H_{ish}^c - C_{ili}^c H_{ili}^c}{H_{ish}^s}
\]  

(2–32)

The latter will only occur if it is weakly cheaper for the generating unit to use low sulfur coal without the emissions restrictions \((\frac{P_{ish}^s}{H_{ish}^s} \geq \frac{P_{ili}^s}{H_{ili}^s})\). Notice that the contracted coal will be used regardless and will cancel out.

\[
z_i P_{iz} + P_A A_i + \max\{(P_{ili}^s C_{ili}^s + P_{ish}^s C_{ish}^s - P_{ish} \hat{C}_{ish}^{s,MAX}), 0\}
\]  

(2–33)

Combining each of the three cost components results in a unit’s total net compliance costs. Even though the contract coal has no direct affect, the contracts will indirectly affect compliance costs through a unit’s allowance position and scrubber choice. Proposition 1 shows the sufficient conditions under which a coal contract will either increase or decrease compliance costs.

**Proposition 1:** Given the scrubber choice

(i) If \(P_A > MCA_{i}^{s,s}\) and the sulfur to heat content ratio of high sulfur contract coal \((\frac{S_{ih}^s}{H_{ish}^s})\) is greater than the sulfur to heat content ratio of high sulfur spot market coal \((\frac{S_{ih}^s}{H_{ish}^s})\), then a high sulfur coal contract *increases* compliance costs.

(ii) If \(P_A \leq MCA_{i}^{s,s}\) and the sulfur to heat content ratio of high sulfur contract coal \((\frac{S_{ih}^s}{H_{ish}^s})\) is greater than the sulfur to heat content ratio of high sulfur spot market coal \((\frac{S_{ih}^s}{H_{ish}^s})\), then a high sulfur coal contract *increases* compliance costs.

(iii) If \(P_A \geq MCA_{i}^{s,s}\) and the sulfur to heat content ratio of low sulfur contract coal \((\frac{S_{il}^s}{H_{ili}^s})\) is greater than the sulfur to heat content ratio of low sulfur spot market coal \((\frac{S_{il}^s}{H_{ili}^s})\), then a low sulfur coal contract *increases* compliance costs.

(iv) If \(P_A < MCA_{i}^{s,s}\), then a low sulfur coal contract *decreases* compliance costs.

See the Appendix A for detailed proofs of Proposition 1. Proposition 1(iv) may seem counter-intuitive, but it shows the importance of being careful about defining a unit’s
compliance costs versus a unit's total costs, which is something to keep in mind for the remainder of the paper.

2.6.7 Generating Unit’s Net Allowance Position: Excess Demand Correspondence

Assume there are no contract constraints \((C_{ih}^c = 0, C_{il}^c = 0)\). A generating unit’s net allowance position, or excess demand, is the difference between a unit’s initial allowance allocation and the unit’s actual allowance use as governed by (3–2). From (3–2) and (3–3), the minimum and maximum excess demand for allowances can be formally derived.

If \(P_A < MCA_i^{s,s}\), a unit will use the maximum amount of high sulfur spot market coal which can be derived from (3–3):

\[
C_{ih}^{s,MAX} = \frac{D_i}{H_{ih}}
\]  

The use of all high sulfur spot market coal leads to the maximum emissions level:

\[
E_i^{MAX} = (1 - z_ir_i)(m)(S_{ih}^s)(\frac{D_i}{H_{ih}^s})
\]  

Inserting \(C_{ih}^{s,MAX}\) in for \(C_{ih}^s\) in (3–2) gives an expression for the maximum allowance excess demand, which is the difference between the maximum emissions level \((E_i^{MAX})\) and the initial allowance allocation \((A_i^e)\):

\[
A_i^{MAX} = E_i^{MAX} - A_i^e = (1 - z_ir_i)(m)(S_{ih}^s)(\frac{D_i}{H_{ih}^s}) - A_i^e
\]  

If a unit’s initial allocation cannot cover its maximum possible emissions, then it will have a positive net allowance position and be a net buyer of allowances.

If \(P_A > MCA_i^{s,s}\), a unit will use the maximum amount of low sulfur spot market coal, which can be derived from (3–3):

\[
C_{il}^{s,MAX} = \frac{D_i}{H_{il}}
\]  

The use of all low sulfur spot market coal leads to the minimum emissions level:

\[
E_i^{MIN} = (1 - z_ir_i)(m)(S_{il}^s)(\frac{D_i}{H_{il}^s})
\]
Inserting $C_{s,MAX}^i$ in (2–37) for $C_s^i$ in (3–3) gives an expression for the minimum allowance excess demand, which is the difference between the minimum emissions level ($E_i^{MIN}$) and the initial allowance allocation ($A_i^e$):

$$A_i^{MIN} = E_i^{MIN} - A_i^e = (1 - z_ir_i)(S_{il}^e)(D_i^l) - A_i^e$$

(2–39)

If a unit’s initial allocation can cover its minimum possible emissions, then it will have a negative net allowance position and be a net seller of allowances.

If $P_A = MCA_i^{s,s}$, a unit may use any combination of high sulfur spot market coal and low sulfur spot market coal, which leads to any level of excess demand in the range ($E_i^{MIN} - A_i^e, E_i^{MAX} - A_i^e$). The allowance excess demand can be represented by $A_i = (\theta E_i^{MAX} - (1 - \theta)E_i^{MIN} - A_i^e)$ where the constant $\theta \in [0, 1]$. A unit that is indifferent between fuel switching and allowances purchases could be either a net buyer or a net seller.

Combining the excess demands for each of the three cases creates the Excess Demand Correspondence:

$$A_i = \begin{cases} 
A_i^{MAX} & \text{if } P_A > MCA_i^{s,s} \\
\theta A_i^{MAX} - (1 - \theta)A_i^{MIN} & \text{if } P_A = MCA_i^{s,s} \forall \theta \in [0, 1] \\
A_i^{MIN} & \text{if } P_A < MCA_i^{s,s}
\end{cases}$$

A generating unit’s excess demand correspondence can be seen graphically in Figure 2.8(i). High sulfur spot market coal use corresponds to the right-hand vertical line where $P_A < MCA_i^{s,s}$. Low sulfur spot market coal use corresponds to the left-hand vertical line where $P_A > MCA_i^{s,s}$. The case where a generating unit uses some combination of low sulfur spot market coal and high sulfur spot market coal is represented by the horizontal line at which $P_A = MCA_i^{s,s}$. 
2.6.7.1 Cost savings of fuel switching versus allowance purchases when $P_A > MCA_{i}^{s,s}$

Assuming that high sulfur spot market coal is cheaper than low sulfur spot market coal ($\frac{P_s}{M_H} < \frac{S_s}{M_H}$), a generating unit that does not have an emissions constraint prefers to use high sulfur spot market coal to meet electricity demand.\textsuperscript{19} Allowing generating units to have a choice in their compliance options can lead to costs savings in several cases. First, consider the case that $P_A > MCA_{i}^{s,s}$. Using low sulfur spot market coal leads to the minimum number of allowances used by the unit ($A_{i}^{MIN}$). Assuming that the initial allocation by the firm is larger than the minimum possible allowance use, the unit will sell its remaining allowances after meeting its allowance requirement. The excess demand for such a unit can be seen in (2–39), where the excess demand will actually be negative.

The unit’s cost savings from switching fuels over purchasing allowances is $(P_A - MCA_{i}^{s,s})(A_{i}^{MAX} - A_{i}^{MIN})$, which is the area “a+b” seen in Figure 2.8(ii). The dark-shaded area (a) is the cost savings for the generating unit from abating emissions through fuel switching instead of purchasing additional allowances. The light-shaded area (b) is the cost savings from abating more than its initial allocation and selling the extra allowances.

2.6.7.2 Effects of high sulfur coal contracts on excess demand and costs

Now consider how a high sulfur coal contract will impact a generating unit’s allowance excess demand correspondence in Figure 2.8, which is summarized in Proposition 2.

Proposition 2: Given the scrubber choice,

(i) For the range of allowance prices $P_A \geq MCA_{i}^{s,s}$, a high sulfur coal contract will weakly increase a unit’s allowance excess demand.

(ii) For the range of allowance prices $P_A \leq MCA_{i}^{s,s}$, a high sulfur coal contract will weakly decrease excess demand if $\frac{S_s}{M_H} \leq \frac{S_s}{M_H}$.

\textsuperscript{19} The assumption that high sulfur coal is cheaper than low sulfur coal is supported by actual coal prices.
(iii) For the range of allowance prices $P_A \leq MCA_{i}^{s,s}$, a high sulfur coal contract will weakly increase excess demand if $\frac{S_{ih}^c}{H_{ih}^c} \geq \frac{S_{ih}^s}{H_{ih}^s}$.

**Proof of Proposition 2(i):**

For allowance prices $P_A > MCA_{i}^{s,s}$, a unit prefers to use all low sulfur coal, which leads to the minimum allowance excess demand ($A_{i}^{MIN}$). A high sulfur coal contract forces some high sulfur coal use and decreases low sulfur coal use from $C_{il}^{s,MAX}$ to $\hat{C}_{il}^{s,MAX}$, which is the maximum amount of low sulfur coal a unit will use given its high sulfur coal contract:

$$C_{il}^{s,MAX} > \hat{C}_{il}^{s,MAX} = \frac{D_i}{H_{il}^s} - \frac{C_{ih}^c H_{ih}^s}{H_{il}^s}$$ (2–40)

The decrease in low sulfur spot market coal use increases emissions from $E_{i}^{MIN}$ to $\hat{E}_{i}^{MIN}$, which is the minimum emissions given the high sulfur coal contract constraint:

$$\Rightarrow E_{i}^{MIN} < \hat{E}_{i}^{MIN} = (1 - z_i r_i)(m)(S_{il}^{s} \hat{C}_{il}^{s,MAX} + S_{ih}^{c} \overline{C}_{ih}^{c})$$ (2–41)

Higher emissions must be covered by additional allowances, which results in the minimum excess demand with a high sulfur coal contract to be greater than the minimum excess demand with no high sulfur coal contract:

$$\Rightarrow A_{i}^{MIN} < \hat{A}_{i}^{MIN} = \hat{E}_{i}^{MIN} - A_{i}^{e}$$ (2–42)

Therefore, a high sulfur coal contract will increase excess demand for allowance prices $P_A > MCA_{i}^{s,s}$.

**Proof of Proposition 2(ii) and 2(iii):**

For allowance prices $P_A < MCA_{i}^{s,s}$, a unit prefers to use all high sulfur coal, which leads to the maximum allowance excess demand ($A_{i}^{MAX}$). A high sulfur coal contract forces a unit to decrease its high sulfur spot market coal use from $C_{il}^{s,MAX}$ to $\hat{C}_{il}^{s,MAX}$ where:

$$C_{ih}^{s,MAX} > \hat{C}_{ih}^{s,MAX} = \frac{D_i}{H_{ih}^s} - \frac{C_{ih}^c H_{ih}^s}{H_{il}^s}$$ (2–43)
If \( \frac{S^s}{H^s} > \frac{S^c}{H^c} \), the sulfur content per unit of heat content is greater for high sulfur contract coal than high sulfur spot market coal and will increase the maximum emissions from \( E_i^{MAX} \) to \( \hat{E}_i^{MAX} \):

\[
\Rightarrow E_i^{MAX} > \hat{E}_i^{MAX} = (1 - z_i r_i)(m)(S^s_{ih} \hat{C}^{s,MAX}_{ih} + S^c_{ih} \hat{C}^{c}_{ih}) \quad (2-46)
\]

Greater emissions result in an increase in a unit’s maximum excess demand from \( A_i^{MAX} \) to \( \hat{A}_i^{MAX} \) in Figure 2.8(ii):

\[
\Rightarrow A_i^{MAX} > \hat{A}_i^{MAX} = \hat{E}_i^{MAX} - A_i^e \quad (2-47)
\]

Therefore, a high sulfur coal contract for coal with a higher sulfur to heat content ratio will increase excess demand for allowance prices \( P_A < MCA_i^{s,s} \). ■

A binding high sulfur coal contract that restricts a unit’s ability to switch to low sulfur coal can force a net seller of allowances to decrease their allowance sales from \( A_i^{MIN} \) to \( \hat{A}_i^{MIN} \) and abate fewer emissions than the generating unit would prefer as shown in Figure 2.8(i). If the contract constraint is large enough it will shift \( \hat{A}_i^{MIN} \) to the right of \( A_i = 0 \) and force a unit to be a net buyer. If the contract constraint forces the generating unit to use all high sulfur coal, then the excess demand is a vertical line where the unit’s only choice is to purchase the maximum amount of allowances. This case may have
occurred during Phase I because some generating units purchased 100% high sulfur coal through contracts in 1996.\textsuperscript{20}

High sulfur coal is assumed to be the preferred coal to use prior to Title IV as units would wish to use the cheapest coal regardless of sulfur content, which was usually high sulfur coal. In Figure 2.8, a unit prefers to use low sulfur coal because $P_A > MCA_i^{s,s}$, and the compliance costs from switching fuels to abate emissions can be seen in area $(a + b)$. Area $(b + c)$ is the revenue gained (negative cost) from selling the remaining allowances that are available due to abating emissions below a unit’s initial allowance allocation. The net compliance costs for a unit will be the costs of switching fuels minus the revenues from allowance sales, or $(a + b) - (b + c) = (a - c)$. If $(a - c) < 0$, then a unit will have negative compliance costs.

Now consider how a high sulfur coal contract will impact the excess demand correspondence, compliance costs, and total costs. As has already been shown above and can be seen in Figure 2.8, a high sulfur coal contract will increase the minimum excess demand from $A_i^{MIN}$ to $\hat{A}_i^{MIN}$ and may increase or decrease the maximum excess demand depending on the relative sulfur to heat content ratio of contract to spot market coal.

These shifts in a unit’s excess demand may have three distinct effects on a unit’s costs. The first cost impact is the additional compliance costs to a unit from lost allowance sales, which is represented by area $(d)$ in Figure 2.8. A unit must use some high sulfur coal, which results in a unit covering additional emissions through more expensive allowances instead of switching to low sulfur coal.

The second impact results from the difference in the sulfur to heat content ratio between high sulfur contract and spot market coal. If \( \frac{S_c}{H_{ih}} < \frac{S_s}{H_{ih}} \), then the maximum emissions a unit can create will decrease and $\hat{A}_i^{MAX} < A_i^{MAX}$. This will decrease the compliance costs by $(f)$ in Figure 2.8(i) for reducing emissions to the allowance allocation.

\textsuperscript{20} Available from FERC-423 Data.
emissions level. If \( \frac{S_{ch}^i}{H_{ch}^i} > \frac{S_{sh}^i}{H_{sh}^i} \), then the maximum emissions a unit can create will increase and \( \tilde{A}_{i}^{MAX} > A_{i}^{MAX} \). This will increase the compliance costs by area \((f)\) in Figure 2.8(ii) for reducing emissions to the allowance allocation emissions level.

Consider how these shifts in excess demand will impact a unit’s *net compliance costs*. The increase in the minimum excess demand will increase net compliance costs by decreasing area \((b)\) and area \((c)\). If maximum excess demand decreases, net compliance costs decrease by area \((f)\) in Figure 2.8(i). Combining the two impacts results in net compliance costs of \((a - c)\) in Figure 2.8(i). If maximum excess demand increases, net compliance costs increase by area \((f)\) in Figure 2.8(ii). Combining the two impacts results in net compliance costs of \((a + f - c)\) in Figure 2.8(ii).

The third cost impact results from different prices for high sulfur spot market and contract coal, which is represented by area \((e)\). Higher priced contract coal causes a unit to have additional fuel costs to meeting electricity demand, which is an increase a unit’s *total costs*.

The graphical description of a high sulfur coal contract’s impacts on excess demand and costs can be seen in the example defined in Table 3-1. Given the coal characteristics, demand, allowance allocation, and allowance price, and using a high sulfur contract coal price of $1.50/mmBtu, the minimum and maximum allowance use and \( MCA_{i}^{c,s} \) can be computed if a unit faces no high sulfur coal contract \((C_{ch}^i = 0)\). For this example, high sulfur contract and spot market coal are assumed to have the same characteristics, which isolates the effect that high sulfur coal contracts have on excess demand for allowance prices \( P_A > MCA_{i}^{c,s} \).

The minimum allowance use based on the low sulfur coal characteristics is 11,400 tons while the maximum allowance use based on the high sulfur spot market coal characteristics is 38,000 tons. The \( MCA_{i}^{c,s} \) is $270.68, which is lower than the allowance price of $300.00. So a unit will switch to all low sulfur coal to minimize its total costs. In doing so, it will use use 11,400 of its allowance allocation to cover its minimum emissions
level and sell the remaining 8,600 allowances at $300.00 each. *Net compliance costs* are the additional costs from switching to low sulfur spot market coal plus the costs of allowance purchases, which is $4.62 million. *Total costs* are the total cost of fuel purchases minus allowance sales, which is $35.82 million.

Now consider the same unit with a high sulfur coal contract for 500,000 tons of coal, which accounts for half of the required heat input. The maximum allowance use remains at 38,000 tons, but the minimum allowance use decreases to 24,700 tons because of the coal contract. The $MCA_{C,s}^i$s is $90.23, which is much lower than the allowance price of $300.00 and $MCA_{S,s}^i$s of $270.68. The coal contract results in compliance costs (costs of switching fuels minus allowance sales) of $5.01 million and total costs to meeting electricity demand (low sulfur spot market coal purchases plus high sulfur contract coal purchases plus allowance purchases) of $38.61 million. Compliance costs increased by $390,000 because the unit could not switch all its coal use to low sulfur coal. Total costs to the unit increased by $2.79 million because of the higher price for the contract coal.

Another possibility is that the high sulfur contract coal could actually be cheaper, which is reasonable because the main reason for making a coal contract agreement is for protection against future coal price fluctuations. This case can be seen in Figure 2.8, where $MCA_{C,s}^i > MCA_{S,s}^i$ and there is actually a cost savings to the unit from using high sulfur contract coal over high sulfur spot market coal. The *net compliance costs* remain the same as in the previous example, area \((a - c)\).\(^{21}\) However, the *total costs* to the unit will decrease relative to not having coal under the contracted price. Area \((d + e)\) is the additional compliance costs to the unit for not being able to switch to low sulfur coal. Area \((e)\) are the “cost savings” of using lower priced high sulfur contract coal over high sulfur spot market coal.

\(^{21}\) For simplicity, the sulfur to heat content ratio is assumed to be equal for high sulfur contract and spot market coal.
By using the same assumptions as in Example 1 except changing the price of high sulfur contract coal to $1.20/mmBtu, compliance costs and total costs to a unit when contract coal is cheaper can be computed. $MCA_i^{c,s}$ is $561.40. The change in net compliance costs remain the same at $390,000 while the costs due to the lower priced coal actually decrease by about $1.2 million. The unit actually has benefits by lowering its total costs by $810,000 through the coal contract even though it must increase its compliance costs.

### 2.6.7.3 Cost savings of allowance purchases versus fuel switching when $P_A < MCA_i^{c,s}$

Assuming that high sulfur spot market coal is cheaper than low sulfur spot market coal ($\frac{P_{h}^{s}}{\bar{H}_{h}} < \frac{S_{h}^{s}}{\bar{H}_{h}}$), a generating unit that does not have an emissions constraint prefers to use high sulfur spot market coal to meet electricity demand. Consider the case that $P_A < MCA_i^{c,s}$. Using high sulfur spot market coal leads to the maximum number of allowances used by the unit ($A_i^{MAX}$). Assuming that the initial allocation to the unit is smaller than the maximum possible allowance use, the unit will purchase additional allowances to meet its allowance requirement. The excess demand for such a unit can be seen in (2–36), where the excess demand will be positive.

Given that a unit preferred to use high sulfur coal before $SO_2$ constraints, the unit’s cost savings from using allowances over switching fuels is $(MCA_i^{c,s} - P_A)(A_i^{MAX} - A_i^{MIN})$, which is the area “a+b” seen in Figure 2.8. The dark-shaded area (a) is the cost savings for the generating unit from purchasing additional allowances instead of switching fuels. The light-shaded area (b) is the cost savings from using the allocated allowances instead of abating emissions and selling the extra allowances.

### 2.6.7.4 Effects of low sulfur coal contracts

Now consider how a low sulfur coal contract will impact a generating unit’s allowance excess demand correspondence in Figure 2.8, which is summarized in Proposition 3.

**Proposition 3:** Give the scrubber choice,
(i) For the range of allowance prices $P_A \leq MCA_{i}^{s,s}$, a low sulfur coal contract will weakly decrease a unit’s allowance excess demand.

(ii) For the range of allowance prices $P_A \geq MCA_{i}^{s,s}$, a low sulfur coal contract will decrease excess demand if $\frac{S^{u}_{si}}{H^{u}_{ih}} \leq \frac{S^{s}_{si}}{H^{s}_{ih}}$.

(iii) For the range of allowance prices $P_A \geq MCA_{i}^{s,s}$, a low sulfur coal contract will increase excess demand if $\frac{S^{u}_{si}}{H^{u}_{ih}} \geq \frac{S^{s}_{si}}{H^{s}_{ih}}$.

Proof of Proposition 3(i):

For allowance prices $P_A < MCA_{i}^{s,s}$, a unit prefers to use all high sulfur coal, which leads to the maximum allowance excess demand ($A_{i}^{MAX}$). A low sulfur coal contract forces some low sulfur coal use and decreases high sulfur coal use from $C_{ih}^{s,MAX}$ to $\hat{C}_{ih}^{s,MAX}$, which is the maximum amount of high sulfur spot market coal a unit will use given the low sulfur coal contract constraint:

$$C_{ih}^{s,MAX} > \hat{C}_{ih}^{s,MAX} = \frac{D_{i}}{H^{s}_{ih}} - \frac{C^{c}_{il}H^{c}_{il}}{H^{s}_{ih}}$$ (2–48)

The decrease in maximum high sulfur coal use decreases a unit’s maximum emissions from $E_{i}^{MAX}$ to $\hat{E}_{i}^{MAX}$:

$$\Rightarrow E_{i}^{MAX} > \hat{E}_{i}^{MAX} = (1 - z_{ir}) (m) (S^{s}_{si} \hat{C}_{ih}^{s,MAX} + S^{u}_{si}C^{c}_{il})$$ (2–49)

Lower emissions decrease the allowances used, which results in the maximum excess demand with a low sulfur coal contract to be lower than the maximum excess demand with no low sulfur coal contract:

$$\Rightarrow A_{i}^{MAX} > \hat{A}_{i}^{MAX} = \hat{E}_{i}^{MAX} - A_{i}^{e}$$ (2–50)

Therefore, a high sulfur coal contract will increase excess demand for allowance prices $P_A < MCA_{i}^{s,s}$. ■

Proof of Proposition 3(ii) and 3(iii):

For allowance prices $P_A > MCA_{i}^{s,s}$, a unit prefers to use all low sulfur coal, which leads to the minimum allowance excess demand ($A_{i}^{MIN}$). A low sulfur coal contract
decreases the maximum amount of low sulfur spot market coal use from \(C_{s,\text{MAX}}\) to \(\hat{C}_{s,\text{MAX}}\):

\[
C_{s,\text{MAX}} > \hat{C}_{s,\text{MAX}} = \frac{D_i}{H_{s,ih}^e} - \frac{C_{s,il}^e}{H_{s,il}^e}
\] (2–51)

If \(\frac{S_{il}^e}{H_{s,il}^e} < \frac{S_{il}^s}{H_{s,il}^s}\), the sulfur content per unit of heat content is lower for low sulfur contract coal than low sulfur spot market coal and will decrease the minimum emissions from \(E_{i,\text{MIN}}\) to \(\hat{E}_{i,\text{MIN}}\):

\[
\Rightarrow E_{i,\text{MIN}} > \hat{E}_{i,\text{MIN}} = (1 - z_i r_i)(m)(S_{il}^e \hat{C}_{s,MAX}^e + S_{il}^c \tilde{C}_{il}^e)
\] (2–52)

Lower emissions result in a decrease in a unit’s minimum excess demand from \(A_{i,\text{MAX}}\) to \(\hat{A}_{i,\text{MAX}}\) in Figure 2.8(i):

\[
\Rightarrow A_{i,\text{MIN}} > \hat{A}_{i,\text{MIN}} = \hat{E}_{i,\text{MIN}} - A_i^e
\] (2–53)

Therefore, a low sulfur coal contract for coal with a lower sulfur to heat content ratio will decrease excess demand for allowance prices \(P_A > MCA_{i,s,s}\).

If \(\frac{S_{il}^e}{H_{s,il}^e} > \frac{S_{il}^s}{H_{s,il}^s}\), the sulfur content per unit of heat content is greater for low sulfur contract coal than low sulfur spot market coal and will increase the minimum emissions from \(E_{i,\text{MIN}}\) to \(\hat{E}_{i,\text{MIN}}\):

\[
\Rightarrow E_{i,\text{MIN}} < \hat{E}_{i,\text{MIN}} = (1 - z_i r_i)(m)(S_{il}^e \hat{C}_{s,MAX}^e + S_{il}^c \tilde{C}_{il}^e)
\] (2–54)

Greater emissions result in an increase in a unit’s minimum excess demand from \(A_{i,\text{MIN}}\) to \(\hat{A}_{i,\text{MIN}}\) in Figure 2.8(ii):

\[
\Rightarrow A_{i,\text{MIN}} > \hat{A}_{i,\text{MIN}} = \hat{E}_{i,\text{MIN}} - A_i^e
\] (2–55)

Therefore, a high sulfur coal contract for coal with a higher sulfur to heat content ratio will increase excess demand for allowance prices \(P_A > MCA_{i,s,s}\).

A binding low sulfur coal contract that restricts a unit’s ability to use allowance can force a net buyer of allowances to decrease their allowance purchases from \(A_{i,\text{MAX}}\) to \(\hat{A}_{i,\text{MAX}}\) and abate more emissions than the generating unit would prefer as shown in Figure 2.8. If
the contract constraint is large enough it will shift $\hat{A}_i^{MAX}$ to the left of $A_i = 0$ and force a unit to be a net seller. If the contract constraint forces the generating unit to use all low sulfur coal, then the excess demand is a vertical line where the unit’s only choice is to purchase the minimum amount of allowances. This case may occur during Phase II if some generating units purchased 100% low sulfur coal through contracts.

In Figure 2.8, the *net compliance costs* can be seen in the shaded area $(a)$ that represents the costs of purchasing allowances to cover the unit’s emissions above its allowance allocation.

Now consider how a low sulfur coal contract will impact the excess demand correspondence, compliance costs, and total costs. As has already been shown above and can be see in Figure 2.8, a low sulfur coal contract will decrease the maximum excess demand from $A_i^{MAX}$ to $\hat{A}_i^{MAX}$ and may increase or decrease the minimum excess demand depending on the relative sulfur to heat content ratio of contract to spot market coal.

These shifts in a unit’s excess demand may have two distinct effects on a unit’s costs. The first cost impact is the additional compliance costs to a unit from switching from high sulfur spot market to low sulfur contract coal instead of purchasing allowances, which is represented by area $(c)$ in Figure 2.8. A unit must use some low sulfur coal, which results in a unit abating additional emissions instead of purchasing allowances. Area $(c)$ is the difference between the costs of switching fuels to decrease emissions, area $(b + c)$, and the decrease in costs from allowance purchases, area $(b)$. Net compliance costs increase from $(a + b)$ to $(a + b + c)$.

The second cost impact results from different prices for low sulfur contract and spot market coal, which is represented by area $(d)$. Higher priced contract coal causes a unit to have additional fuel costs to meeting electricity demand, which increases a unit’s *total costs*.

The graphical description of coal contract impacts on excess demand and costs can be seen in the example defined in Table 2-4. Given the coal characteristics, demand,
allowance allocation, and allowance price, and low sulfur contract coal price of $1.80/mmBtu, the minimum and maximum allowance use and $MCA^{s,s}_i$ can be found if a unit faces no low sulfur coal contract ($\overline{C}_{ih} = 0$). For this example, low sulfur contract and spot market coal are assumed to have the same characteristics, which isolates the effect that low sulfur coal contracts have on excess demand for allowance prices $P_A < MCA^{s,s}_i$.

The minimum allowance use based on the low sulfur coal characteristics is 11,400 tons while the maximum allowance use based on the high sulfur spot market coal characteristics is 38,000 tons. The $MCA^{s,s}_i$ is $270.68$, which is higher than the allowance price of $200.00$. So a unit will purchase allowances to minimize its total costs. In doing so, it will use use the entire 20,000 ton allowance allocation and purchase an additional 18,000 allowances to cover its maximum emissions level. Net compliance costs are the additional costs from purchasing allowances, which is $3.6 million. Total costs are the total cost of fuel purchases plus allowance purchases, which is $34.8 million.

Now consider the same unit with a low sulfur coal contract for 500,000 tons of coal, which accounts for half the required heat input to meet demand. The minimum allowance use remains at 11,400 tons, but the maximum allowance use decreases to 24,700 tons because of the coal contract. The $MCA^{s,c}_i$ is $451.13$, which is much higher than the allowance price of $200.00$ and $MCA^{s,s}_i$ of $270.68$. The coal contract results in net compliance costs (additional costs of allowance purchases and fuel switching) of $4.54 million and total costs to meeting electricity demand (high sulfur spot market coal purchases plus low sulfur contract coal purchases plus allowance purchases) of $38.14 million. Compliance costs increased by $940,000 because the unit could not use all high sulfur coal. Total costs to the unit increased by $3.34 million because of the higher price for the contract coal.

Another possibility is that the low sulfur contract coal could actually be cheaper than low sulfur spot market coal, which is reasonable because the main reason for making a coal contract agreement is for protection against future coal price fluctuations. This case can
be seen in Figure 2.8, where $MCA^{c,s}_i < MCA^{s,s}_i$ and there is actually a cost savings to the unit from using low sulfur contract coal over low sulfur spot market coal. The compliance costs remain the same as in the previous example, area $(a + b + c)$. However, the total costs to the unit will decrease relative to not having coal under the contracted price. Area $(c + d)$ is additional costs to the unit for not being able to switch to low sulfur coal. Area $(d)$ is the cost savings of using lower priced high sulfur contract coal over high sulfur spot market coal.

By making the same assumptions as in Example 1 except changing the price of low sulfur contract coal to $1.50/mmBtu, we can solve for compliance costs and total costs to a unit. $MCA^{s,c}_i$ is $180.45. The change in compliance costs remain the same at $940,000 while the costs due to the lower priced coal actually decrease by $1.2 million.\textsuperscript{22} The unit actually gains by lowering its total costs by $260,000 through the coal contract even though it must increase its compliance costs.

**2.6.7.5 Fuel switching versus allowance purchases when $P_A = MCA^{s,s}_i$**

In the knife-edge case a generating unit has no strict preference between purchasing allowances and abating emissions because $P_A = MCA^{s,s}_i$. The unit’s excess demand may be any value in the range $[A^{MIN}_i - A^{e}_i, A^{MAX}_i - A^{e}_i]$. The generating unit has no preference in compliance options because any combination of abatement and allowance purchases result in the same compliance costs of area $(a)$ in Figure 2.8.

A high sulfur coal contract will have the same impacts on the excess demand correspondence when $P_A = MCA^{s,s}_i$ as in Section 5.7.2 where $P_A > MCA^{s,s}_i$. However, the impacts on compliance costs and total costs will be different. The reasoning for this is that the contract does not force a unit to use a more expensive compliance option. By comparing Figure 2.8 to Figure 2.8, these differences can be derived. The shift in a unit’s

\textsuperscript{22} For simplicity, the sulfur to heat content ratio is assumed to be equal for low sulfur contract and spot market coal.
minimum excess demand has no impact on compliance costs. Total costs will still increase by area (c) if the relative price of high sulfur contract coal is more expensive than high sulfur spot market coal. The shift in maximum excess demand will still impact compliance costs by area (f).

A low sulfur coal contract will have the same impacts on the excess demand correspondence when \( P_A = MCA_i^{s,s} \) as in in Section 5.7.3 where \( P_A < MCA_i^{s,s} \). However, the impacts on compliance costs and total costs will be different. The reasoning for this is that the contract does not force a unit to use a more expensive compliance option. By comparing Figure 2.8 to Figure 2.8, these differences can be derived. The shift in a unit’s minimum excess demand has no impact on compliance costs. Total costs will still increase by area (c) if the relative price of high sulfur contract coal is more expensive than high sulfur spot market coal. The shift in maximum excess demand will not impact compliance costs because the additional costs of abating emissions are offset by the decrease in allowance purchases.

2.6.8 Generating Unit’s Scrubber Installation Choice

It is not possible to completely characterize a generating unit’s decision based on \( MCA_i \) and allowance price alone because of the non-convexities of scrubber installation. In this section a unit’s decisions with the option of installing a scrubber are examined, the allowance price at which a unit will install a scrubber is derived, the change in the excess demand correspondence shown, and the effect of coal contracts on the excess demand examined.

2.6.8.1 When will a generating unit install a scrubber?

Let \((\tilde{C}_{ih}^s, \tilde{C}_{il}^s, \tilde{A}_i)\) and \((\hat{C}_{ih}^s, \hat{C}_{il}^s, \hat{A}_i)\) be the cost minimizing combination of spot coal and allowances with and without a scrubber installed, respectively. A unit is indifferent to installing a scrubber if the total costs with a scrubber installed are equal to the total costs without a scrubber installed:

\[
P_{iz} + P_A^s \tilde{A}_i + P_{ih}^s \tilde{C}_{ih}^s + P_{il}^s \tilde{C}_{il}^s = P_A^s \hat{A}_i + P_{ih}^s \hat{C}_{ih}^s + P_{il}^s \hat{C}_{il}^s
\]  

\hspace{1cm} \text{(2-56)}

86
$P^S_A$ is the allowance price at which the unit is indifferent between installing a scrubber or not. The amount of high sulfur and low sulfur contract coal will be the same both with and without a scrubber and will cancel out, but the contract coal still affects the allowance position.\footnote{See Appendix A for the derivation of this equation.}

A generating unit’s decisions will hinge on this allowance price. (2–56) can be used to solve for $P^S_A$, the minimum allowance price at which a generating unit will install a scrubber:

$$P^S_A \geq \frac{P_{iz} + P^s_{ih}(\hat{C}^s_{ih} - \hat{C}^s_{ih}) + P^s_{il}(\hat{C}^s_{il} - \hat{C}^s_{il})}{(A_i - \hat{A}_i)}$$  \hspace{1cm} (2–57)

A unit will prefer to install a scrubber at $P^S_A$ if the average costs of abatement from using a scrubber is weakly less than the costs of purchasing an allowance.

2.6.8.2 Different marginal costs of abatement

The installation of a scrubber leads to an increase in the unit’s marginal abatement cost of switching from high sulfur spot market to low sulfur spot market coal relative to the marginal abatement cost without a scrubber installed:

$$MCA^s_{i} = \frac{P^s_{il}H_{si}H_{il} - P^s_{ih}H_{si}H_{ih}}{(m)(S^s_{ih}H_{ih} - S^s_{il}H_{il})}$$

$$MCA^s_{i} = \frac{P^s_{il}H_{si}H_{il} - P^s_{ih}H_{si}H_{ih}}{(m)(S^s_{ih}H_{ih} - S^s_{il}H_{il})}$$

Scrubber installation decreases the size of the denominator of $MCA^s_{i}$ by $(r_i)(m)(S^s_{ih}H_{ih} - S^s_{il}H_{il})$, which is due to the fact that only a fraction (based on the scrubber’s reduction rate) of the emissions reduction from switching fuels is realized.

2.6.8.3 Excess demand correspondence

A generating unit’s excess demand correspondence becomes significantly more complicated when a unit’s scrubber installation choice is introduced into its decision-making process. The excess demand correspondence is a combination of a unit’s excess demand
correspondences with and without a scrubber with a discontinuity representing the discrete choice separating the two pieces.

A generating unit’s excess demand correspondence can be derived from its optimal compliance choices as the market allowance price changes. For allowance prices \( M\tilde{CA}_i^{s,s} < P_A \), a generating unit installs a scrubber because \( P^S_A < P_A \), and switches fuels from high sulfur spot market to low sulfur spot market coal because \( M\tilde{CA}_i^{s,s} < P_A \). So a generating unit will have minimum excess demand when a scrubber is installed \( (A_i^{SMIN}) \), which has already been derived in (2–36) given that \( z_i = 1 \).

For allowance prices \( P^S_A < P_A < M\tilde{CA}_i^{s,s} \), a generating unit installs a scrubber because \( P^S_A < P_A \), and uses high sulfur coal because \( P_A < M\tilde{CA}_i^{s,s} \). So a generating unit will have maximum excess demand when a scrubber is installed \( (A_i^{SMAX}) \), which has already been derived in (2–39) given \( z_i = 1 \).

For allowance prices \( MCA_i^{s,s} < P_A < P^S_A \), a generating unit does not install a scrubber because \( P_A < P^S_A \), and switches fuels from high to low sulfur coal because \( MCA_i^{s,s} < P_A \). So a generating unit will have minimum excess demand without a scrubber installed \( (A_i^{MIN}) \), which has already been derived in (2–36) given \( z_i = 0 \).

For allowance prices \( 0 < P_A < MCA_i^{s,s} \), a generating unit does not install a scrubber because \( P_A < P^S_A \), and high sulfur coal because \( P_A < MCA_i^{s,s} \). So a generating unit will have maximum excess demand without installing a scrubber \( (A_i^{MAX}) \), which has already been derived in (2–39).

\[
A_i = \begin{cases} 
A_i^{MAX} & \text{if } 0 < P_A < MCA_i^{s,s} < P^S_A \text{ or } 0 < P_A < P^S_A < MCA_i^{s,s} \\
\theta A_i^{MAX} - (1 - \theta)A_i^{MIN} & \text{if } (MCA_i^{s,s} = P_A < P^S_A) \forall \theta \in [0, 1] \\
A_i^{MIN} & \text{if } MCA_i^{s,s} < P_A \leq P^S_A \\
A_i^{SMAX} & \text{if } P_A \leq P_A < M\tilde{CA}_i^{s,s} \\
\theta A_i^{SMAX} - (1 - \theta)A_i^{SMIN} & \text{if } M\tilde{CA}_i^{s,s} = P_A \forall \theta \in [0, 1] \\
A_i^{SMIN} & \text{if } M\tilde{CA}_i^{s,s} < P_A 
\end{cases}
\]
Using these four different excess demands for each allowance price range and the
knife-edge allowance prices, it is possible to mathematically derive the excess demand
correspondence.

The excess demand correspondence seen in Figure 2.8(i) includes a generating unit’s
net allowance position under the four different allowance price ranges if \( \left( \frac{P_{si}^h}{H_{si}^h} < \frac{P_{si}^l}{H_{si}^l} \right) \). If
\( \left( \frac{P_{si}^h}{H_{si}^h} \geq \frac{P_{si}^l}{H_{si}^l} \right) \) a generating unit faces negative marginal abatement costs and will use only
low sulfur coal, which will result in a special case of only two price ranges where the only
choice a unit makes is whether to install a scrubber in Figure 2.8(ii).^24

If a generating unit never prefers to switch fuels before installing a scrubber because
\( MCA_i^{s,s} \geq P_A^s \), there is a special case in which the allowance price range \( MCA_i^{s,s} < P_A < P_A^s \) does not exist for the excess demand correspondence. The excess demand
correspondence under this case can be seen in Figure 2.8.

2.6.9 Impact of Coal Contracts on Excess Demand Correspondence

Given the scrubber choice, a coal contract restricts the available coal use options,
which affects the excess demand correspondence as shown in Section 6.7. A contract
constraint also changes the allowance price at which a generating unit will optimally
install a scrubber, which alters the excess demand correspondence as well. Under Phase
I, a generating unit without a scrubber may prefer to use low sulfur coal, but when facing
a high sulfur coal contract constraint it would install a scrubber and prefer to use high
sulfur spot market coal. The opposite may occur under CAIR, where generating units may
face low sulfur coal contract constraints. A unit may wish to install a scrubber and use
all high sulfur coal, but the low sulfur contract constraint may result in no scrubber being
installed and allowance purchases occurring instead. The combination of these two effects
may change the excess demand correspondence for all allowance prices.

^24 An example where \( \frac{P_{si}^h}{H_{si}^h} \geq \frac{P_{si}^l}{H_{si}^l} \) in the actual data is the delivered prices of coal to
generating units in the state of Wisconsin.
First, it is important to generalize the indifference price at which a generating unit will install a scrubber ($P^S_A$), which can be derived by setting a unit’s costs when it does not install a scrubber, which includes net allowance purchases ($A_i$) and fuel costs ($P^s_{ih}C^s_{ih} + P^s_{il}C^s_{il}$), to a unit’s costs when it does install a scrubber, which includes net allowance purchases ($A^{s,MAX}_i$), fuel costs ($P^s_{ih}C^s_{ih,MAX} + P^s_{il}C^s_{il}$), and costs of a scrubber ($P^i_z$).

Assuming that high sulfur spot market coal is cheaper than low sulfur spot market coal, a unit uses all high sulfur spot market coal if it installs a scrubber because $M\tilde{CA}^s,s_i > P_A$. It is uncertain if a unit will use high or low sulfur coal if it does not install a scrubber, and will depend on the relationship between $P_A$ and $MCA^s,s_i$.

$$P^S_A A^s_{i} + P^s_{ih}C^s_{ih} + P^s_{il}C^s_{il} = P^S_A A^s_{i} + P^s_{ih}C^s_{ih} + P^s_{il}C^s_{il}$$ (2–59)

A unit that faces a coal contract will face a different indifference allowance price of $(P^S_A - \epsilon)$ because parameters values on both sides of the equality will change. $\epsilon$ could be positive or negative depending on several conditions, including the type of coal under contract. The new values that solve this equality are the contract constrained cost minimizing parameter values. The fuel costs for the contract coal will be the same both with and without a scrubber and will cancel out.

$$P^i_z + (P^S_A - \epsilon)\tilde{A}_i^{s,MAX} + P^s_{ih}\tilde{C}^s_{ih} + P^s_{il}\tilde{C}^s_{il} = (P^S_A - \epsilon)\tilde{A}_i + P^s_{ih}\tilde{C}^s_{ih} + P^s_{il}\tilde{C}^s_{il}$$ (2–60)

By solving for the constant $P^i_z$ in (2–59) and (2–60) and setting the two expressions equal to each other, the sign and value of $\epsilon$ can be derived.

### 2.6.9.1 Impact of a binding high sulfur coal contract

The impacts of a high sulfur coal contract on the two pieces of the excess demand correspondence will be the same as in Section 6.7 where the scrubber choice is given except there will be an additional impact on excess demand from the contract on the allowance price at which a unit is indifferent to installing a scrubber.
There are two cases for which the value of $\epsilon$ must be derived to determine the contracts impact on the allowance indifference price, the first of which will have two subcases. As will be shown for each of the cases, if $(\frac{S_{ih}}{H_{ih}} \geq \frac{S_{ih}'}{H_{ih}'})$, then $\epsilon$ will be positive and may decrease the allowance price at which a unit will prefer to install a scrubber.

In the first case, without a high sulfur coal contract, a unit prefers to use low sulfur spot market coal without a scrubber and high sulfur coal with a scrubber. The two subcases will be determined by the generating unit’s characteristics and the size of the contract constraint.

In the first subcase, both with or without a high sulfur coal contract, a unit prefers to use low sulfur spot market coal if it does not install a scrubber and high sulfur spot market coal it does install a scrubber. For this to hold, $(MCA_{i}^{s,s} < P_{A} < \tilde{MCA}_{i}^{s,s})$ and $(MCA_{i}^{s,s} < P_{A} - \epsilon < P_{A}^{S})$.

If a unit that has no high sulfur contract coal ($C_{c}^{ih} = 0$), a unit uses the maximum amount of high sulfur coal with a scrubber and the maximum amount of low sulfur coal without a scrubber, and is indifferent to installing a scrubber at allowance price $P_{A}^{S}$:

$$P_{iz} + P_{A}^{S}A_{i}^{SMAX} + P_{ih}^{s}C_{ih}^{s,MAX} = P_{A}^{S}A_{i}^{MIN} + P_{il}^{s}C_{il}^{s,MAX} \quad (2-61)$$

$(2-61)$ can be rearranged to find an expression for $P_{iz}$:

$$\Rightarrow P_{iz} = P_{A}^{S}(A_{i}^{MIN} - A_{i}^{SMAX}) - P_{ih}^{s}C_{ih}^{s,MAX} + P_{il}^{s}C_{il}^{s,MAX} \quad (2-62)$$

A high sulfur coal contract will change the optimal values of the other parameters, which will change the indifference allowance price by some value $\epsilon$:

$$P_{iz} + (P_{A}^{S} - \epsilon)\tilde{A}_{i}^{SMAX} + P_{ih}^{s}\tilde{C}_{ih}^{s,MAX} + P_{il}^{c}\tilde{C}_{il}^{c} = (P_{A}^{S} - \epsilon)\tilde{A}_{i}^{MIN} + P_{il}^{s}\tilde{C}_{il}^{s,MAX} + P_{ih}^{c}\tilde{C}_{ih}^{c} \quad (2-63)$$

$(2-63)$ can be rearranged to find an expression for $P_{iz}$:

$$\Rightarrow P_{iz} = (P_{A}^{S} - \epsilon)(\tilde{A}_{i}^{MIN} - \tilde{A}_{i}^{SMAX}) + P_{il}^{s}\tilde{C}_{il}^{s,MAX} - P_{ih}^{s}\tilde{C}_{ih}^{s,MAX} \quad (2-64)$$
Since $P_{iz}$ is a constant, the two expressions for $P_{iz}$ in (2–62) and (2–63) can be set equal to solve for the value of $\epsilon$:

$$
\epsilon = \frac{P_A^S(A_i^{\text{MIN}} - A_i^{\text{MIN}} + A_i^{\text{S MAX}} - \tilde{A}_i^{\text{S MAX}}) + P_i^d(C_{ih}^{\text{S MAX}} - C_{ih}^{\text{S MAX}}) - P_{ih}(\tilde{C}_{ih}^{\text{S MAX}} - C_{ih}^{\text{S MAX}})}{(A_i^{\text{MIN}} - \tilde{A}_i^{\text{S MAX}})} \tag{2–65}
$$

Filling in for allowances and coal use parameters, it is possible to determine the sign of $\epsilon$.

$$
A_i^{\text{MIN}} = \left(\frac{D_i}{H_{ih}^s}\right)(S_{ih}^s)(m) - A_i^c \\
\tilde{A}_i^{\text{MIN}} = (C_{ih}^cS_{ih}^c + \frac{D_i - C_{ih}^cH_{ih}^cS_{ih}^a}{H_{ih}^s})(m) - A_i^c
$$

$$
A_i^{\text{S MAX}} = \left(\frac{D_i}{H_{ih}^s}\right)(S_{ih}^s)(1-r_i) - A_i^c \\
\tilde{A}_i^{\text{S MAX}} = \left[\tilde{C}_{ih}^cS_{ih}^c + \frac{D_i - \tilde{C}_{ih}^cH_{ih}^c}{H_{ih}^s}\right](m)(1-r_i) - A_i^c
$$

$$
C_{ih}^{\text{S MAX}} = \frac{D_i}{H_{ih}^s} - A_i^c \\
\tilde{C}_{ih}^{\text{S MAX}} = \frac{D_i - \tilde{C}_{ih}^cH_{ih}^c}{H_{ih}^s}
$$

By filling these expressions into (2–65), the expression for $\epsilon$ can be simplified to parameters for coal price, sulfur content, heat content, and scrubber capture rate.

$$
\epsilon = \frac{C_{ih}^cH_{ih}^c\left[(P_A^S)(m)\left[(r_i)\left(\frac{S_{ih}^c}{H_{ih}^s} - \frac{S_{ih}^a}{H_{ih}^s}\right) + \left(\frac{S_{ih}^s}{H_{ih}^s} - \frac{S_{ih}^a}{H_{ih}^s}\right)\right] - \left(P_i^d - \frac{P_{ih}^s}{H_{ih}^s}\right)\right]}{(A_i^{\text{MIN}} - \tilde{A}_i^{\text{S MAX}})} \tag{2–66}
$$

An interpretable form is derived by separating terms, multiplying though by $(\tilde{A}_i^{\text{MIN}} - \tilde{A}_i^{\text{S MAX}})$, and dividing through by $m(\frac{S_{ih}^a}{H_{ih}^s} - \frac{S_{ih}^a}{H_{ih}^s})$.

$$
\Rightarrow \epsilon(\tilde{A}_i^{\text{MIN}} - \tilde{A}_i^{\text{S MAX}}) = C_{ih}^cH_{ih}^c\left[P_A^S\tilde{r}_i\left(\frac{S_{ih}^s}{H_{ih}^s} - \frac{S_{ih}^a}{H_{ih}^s}\right) + P_A^d - \frac{P_{ih}^s}{H_{ih}^s}\right] + m(\frac{S_{ih}^a}{H_{ih}^s} - \frac{S_{ih}^a}{H_{ih}^s})
$$

$$
\Rightarrow \epsilon(\tilde{A}_i^{\text{MIN}} - \tilde{A}_i^{\text{S MAX}}) = C_{ih}^cH_{ih}^c\left[P_A^S\tilde{r}_i\left(\frac{S_{ih}^s}{H_{ih}^s} - \frac{S_{ih}^a}{H_{ih}^s}\right) + \left(P_A^d - MCA_i^{s,s}\right)\right] \tag{2–67}
$$

From the initial assumption that a unit uses low sulfur coal when it does not install a scrubber, it is known that $P_A^S > MCA_i^{s,s}$. So if $\frac{S_{ih}^c}{H_{ih}^s} \geq \frac{S_{ih}^a}{H_{ih}^s}$, then $\epsilon > 0$ and $\epsilon$ increases as the size of the high sulfur coal contract $(\tilde{C}_{ih}^c)$ increases. If $\frac{S_{ih}^c}{H_{ih}^s} < \frac{S_{ih}^a}{H_{ih}^s}$, then the sign of $\epsilon$ is unknown.
An example reflective of Phase I data will help to explain which sign is most likely for $\epsilon$. The example in Table 2-6 is based on data from the a unit that installed a scrubber under Phase I. The first example will consider $\epsilon$ given that a unit uses low sulfur coal from the Southern Appalachian Mountains and high sulfur coal from the Northern Appalachian Mountains. Southern Appalachian coal has a low average sulfur content (0.65%). In this example, high sulfur spot market coal is assumed to have both a lower sulfur content and price than high sulfur contract coal. Given the assumptions in Table 2-6, a unit will prefer to use low sulfur coal if it does not install a scrubber because $MCA_{i,s,s}^s = $244.26 and $P_A = $250. If a scrubber is installed, a unit prefers to use high sulfur spot market coal because the marginal cost of abatement increases above the allowance price to $MCA_{i,s,s}^s = $4,885.20. The annualized scrubber costs are $P_{iz} = $15.886 million, which results in $P_A^S = $1,572.56. A high sulfur coal contract for 50% of coal use results in a decrease in the indifference allowance price of $\epsilon = $1,210.61 to $(P_A - \epsilon) = $382.00 (a 76% decrease in $P_A^S$). Although a unit’s compliance choices are not altered at $P_A = $250, the large decrease in $\epsilon$ encourages scrubbing at much lower allowance prices than without the coal contract. This subcase will hold for a contract constraint of less than 73.5% of coal use. This example shows that for many units, high sulfur coal contracts would not have enough of an impact to result in scrubber installation in Phase I. Only about 10% of units actually installed scrubbers to comply with Phase I, but these units account for over half of total abatement by affected units.

In the second subcase, assume that without a high sulfur coal contract, a unit prefers to use low sulfur spot market coal if it does not install a scrubber and high sulfur spot market coal if it does install a scrubber because $(MCA_{i,s,s}^s < P_A < MCA_{i,s,s}^s)$ and $(MCA_{i,s,s}^s < P_A^S)$. However, with a high sulfur coal contract, a unit prefers to use high sulfur spot market coal both with and without a scrubber because $(P_A^S - \epsilon < MCA_{i,s,s}^s)$.

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25 Gen. JM Gavin had 100% coal under contract.
If a unit that has no high sulfur contract coal ($C_{ih} = 0$), a unit uses the maximum amount of low sulfur coal if a scrubber is not installed, but uses the maximum amount of high sulfur coal if a scrubber is installed. The unit is indifferent to installing a scrubber at allowance price $P_A^S$:

$$P_{iz} + P_A^S A_i^{S MAX} + P_{ih}^s C_{ih}^{s MAX} = P_A^S A_i^{MIN} + P_{ih}^s C_{ih}^{s MAX}$$

(2–68) shows that the costs with and without a scrubber are equal for a given $P_A^S$, and can be rearranged to find an expression for $P_{iz}$:

$$\Rightarrow P_{iz} = P_A^S (A_i^{MIN} - A_i^{S MAX}) - P_{ih}^s C_{ih}^{s MAX} + P_{ih}^s C_{ih}^{s MAX}$$

(2–69)

(2–70) can be rearranged to find an expression for $P_{iz}$:

$$\Rightarrow P_{iz} = (P_A^S - \epsilon)(A_i^{MAX} - \tilde{A}_i^{S MAX})$$

(2–71)

The two expressions for $P_{iz}$ in (2–69) and (2–71) can be set equal to solve for the value of $\epsilon$:

$$\epsilon = \frac{P_A^S (A_i^{MAX} - A_i^{MIN} + A_i^{S MAX} - \tilde{A}_i^{S MAX}) - P_{ih}^s C_{ih}^{s MAX} + P_{ih}^s C_{ih}^{s MAX}}{(A_i^{MAX} - \tilde{A}_i^{S MAX})}$$

(2–72)

By filling in for allowances and coal use, it is possible to determine the sign of $\epsilon$.

$$A_i^{MIN} = \left(\frac{D_i}{H_{ih}^s}\right) (S_{ih}^s(m) - A_i^{e})$$

$$A_i^{MAX} = \left(\frac{D_i - \overline{C}_{ih} H_{ih}^c}{H_{ih}^s} S_{ih}^s + \overline{C}_{ih} S_{ih}^c\right) m - A_i^{e}$$

$$A_i^{S MAX} = \left(\frac{D_i}{H_{ih}^s}\right) (S_{ih}^s(m)(1-r_i) - A_i^{e})$$

$$\tilde{A}_i^{S MAX} = \left(\frac{D_i - \overline{C}_{ih} H_{ih}^c}{H_{ih}^s} S_{ih}^s + \overline{C}_{ih} S_{ih}^c\right) (m)(1-r_i) - A_i^{e}$$
By filling into (2–72), the expression for $\epsilon$ can be simplified to parameters for coal price, sulfur content, heat content, and scrubber capture rate:

$$\Rightarrow \epsilon(\hat{A}_{i}^{MAX} - \hat{A}_{i}^{SMAX}) = mP_{A}^{S}[r_{i}\mathcal{C}_{ih}^{c}H_{ih}^{c}(S_{c}^{c}H_{c}^{c} - S_{s}^{s}H_{s}^{s}) + D_{i}(\frac{S_{s}^{s}H_{s}^{s}}{H_{s}^{s}_{ih}} - \frac{S_{s}^{s}H_{s}^{s}}{H_{s}^{s}_{il}})] - D_{i}(\frac{P_{s}^{s}H_{s}^{s}}{H_{s}^{s}_{ih}} - \frac{P_{s}^{s}H_{s}^{s}}{H_{s}^{s}_{il}})$$

(2–73)

The new form in (2–73) is easier to determine the sign of $\epsilon$ because the sign of the left-hand side is unchanged while simplifying the right-hand side. Now get the right-hand side into a form that is interpretable by separating terms and dividing through by $m\left(\frac{S_{s}^{s}H_{s}^{s}}{H_{s}^{s}_{ih}} - \frac{S_{s}^{s}H_{s}^{s}}{H_{s}^{s}_{il}}\right)$.

$$\Rightarrow \epsilon(\hat{A}_{i}^{MIN} - \hat{A}_{i}^{SMAX}) = P_{A}^{S}r_{i}\mathcal{C}_{ih}^{c}H_{ih}^{c}\left(\frac{S_{s}^{s}H_{s}^{s}}{H_{s}^{s}_{ih}} - \frac{S_{s}^{s}H_{s}^{s}}{H_{s}^{s}_{il}}\right) + P_{A}^{S}D_{i} - D_{i}\left(\frac{P_{s}^{s}H_{s}^{s}}{H_{s}^{s}_{ih}} - \frac{P_{s}^{s}H_{s}^{s}}{H_{s}^{s}_{il}}\right)$$

(2–74)

The last two terms in (2–74) can be combined to get $D_{i}(P_{A}^{S} - MCA_{i}^{s,s})$:

$$\Rightarrow \epsilon(\hat{A}_{i}^{MIN} - \hat{A}_{i}^{SMAX}) = P_{A}^{S}r_{i}\mathcal{C}_{ih}^{c}H_{ih}^{c}\left(\frac{S_{s}^{s}H_{s}^{s}}{H_{s}^{s}_{ih}} - \frac{S_{s}^{s}H_{s}^{s}}{H_{s}^{s}_{il}}\right) + D_{i}(P_{A}^{S} - MCA_{i}^{s,s})$$

(2–75)

From our initial assumption that a unit uses all low sulfur spot market coal if it does not install a scrubber, if it does not have a high sulfur coal contract, then $P_{A}^{S} > MCA_{i}^{s,s}$. If $(\frac{S_{s}^{s}H_{s}^{s}}{H_{s}^{s}_{ih}} \geq \frac{S_{s}^{s}H_{s}^{s}}{H_{s}^{s}_{il}})$, then the first term is non-negative, which makes $\epsilon > 0$. As in Case 1, an increase in the size of the high sulfur coal contract ($\mathcal{C}_{ih}^{c}$) increases the value of $\epsilon$. However, if $(\frac{S_{s}^{s}H_{s}^{s}}{H_{s}^{s}_{ih}} < \frac{S_{s}^{s}H_{s}^{s}}{H_{s}^{s}_{il}})$ then it is uncertain whether $\epsilon$ is positive or negative.

Assuming the data in Table 2-6, this case will occur if the contract is greater than 73.5% of coal use. For this case to occur, a high sulfur coal contract must result in a unit preferring to use high sulfur coal without a scrubber installed when, without a contract, it initially prefers to use low sulfur coal without a scrubber ($P_{A}^{S} > MCA_{i}^{s,s}$ and $P_{A}^{S} - \epsilon < MCA_{i}^{s,s}$). A unit must also prefer to use high sulfur coal with a scrubber both with and without a high sulfur coal contract ($P_{A}^{S} - \epsilon < P_{A}^{S} < M\tilde{C}A_{i}^{s,s}$). The allowance
price at which a unit will initially install a scrubber is $P_A^S = 1,592.61$, which is much higher than the assumed allowance price ($P_A = 250.00$). As the size of a contract coal increases from 50% to 75% of coal use, $\epsilon$ increases from $\epsilon = 1,210.61$ to $\epsilon = 1,349.82$, respectively. With a coal contract of 50%, a unit still prefers to use low sulfur coal if it does not install a scrubber because $(P_A^S - \epsilon) = 382.00 > MCA_i^{s,s} = 244.26$. However, as the coal contract increases in size to 75%, a unit now prefers to use high sulfur coal if it does not install a scrubber because $(P_A^S - \epsilon) = 242.79 < MCA_i^{s,s} = 244.26$. Also, a unit will now install a scrubber because $(P_A^S - \epsilon < P_A)$, which may have a large impact on compliance costs.

In the third case, assume that a unit, both with and without a high sulfur coal contract, prefers to use high sulfur coal both with and without a scrubber because $(P_A < MCA_i^{s,s})$ and $(P_A^S - \epsilon < P_A^S < MCA_i^{s,s})$. Given that a unit that has no high sulfur contract coal ($\overline{C}_{ih}^c = 0$), a unit is indifferent to installing a scrubber at allowance price $P_A^S$: 

$$P_{iz} + P_A^S A_i^{MAX} + P_{ih} C_{ih}^{s,MAX} = P_A^S A_i^{MAX} + P_{ih} C_{ih}^{s,MAX}$$  \hspace{1cm} (2-76)$$

(2-76) can be rearranged to find an expression for $P_{iz}$ where the only change in costs is the change in a unit’s net allowance position:

$$\Rightarrow P_{iz} = P_A^S (A_i^{MAX} - A_i^{SMAX})$$  \hspace{1cm} (2-77)$$

A high sulfur coal contract will change the indifference allowance price by some value $\epsilon$ because it alters the costs from net allowance purchases and fuel costs:

$$P_{iz} + (P_A^S - \epsilon) \hat{A}_i^{SMAX} + P_{ih} \hat{C}_{ih}^{s,MAX} + P_{ih} \overline{C}_{ih}^c = (P_A^S - \epsilon) \hat{A}_i^{MAX} + P_{ih} \hat{C}_{ih}^{s,MAX} + P_{ih} \overline{C}_{ih}^c$$  \hspace{1cm} (2-78)$$

(2-78) can be rearranged to find an expression for $P_{iz}$:

$$\Rightarrow P_{iz} = (P_A^S - \epsilon)(\hat{A}_i^{MAX} - \hat{A}_i^{SMAX})$$  \hspace{1cm} (2-79)$$

96
The two expressions for \( P_{iz} \) in (2–77) and (2–79) can be set equal to solve for the value of \( \epsilon \):

\[
\Rightarrow \epsilon = \frac{P_S^A (\hat{A}_{i}^{MAX} - A_{i}^{MAX} + A_{i}^{SMAX} - \hat{A}_{i}^{SMAX})}{(\hat{A}_{i}^{MAX} - \hat{A}_{i}^{SMAX})} \quad (2–80)
\]

Filling in for allowances and coal use, it is possible to determine the sign of \( \epsilon \).

\[
A_{i}^{MAX} = \left( \frac{D_i}{H_{ih}^s} \right) (S_{ih}^s)(m) - A_i^e \quad \hat{A}_{i}^{MAX} = \left( \frac{D_i - C_{ih}^e H_{ih}^c}{H_{ih}^s} S_{ih}^s + C_{ih}^e C_{ih}^c} \right) (m) - A_i^e
\]

\[
A_{i}^{SMAX} = \left( \frac{D_i}{H_{ih}^s} \right) (S_{ih}^s)(m)(1-r_i) - A_i^e \quad \hat{A}_{i}^{SMAX} = \left( \frac{D_i - C_{ih}^e H_{ih}^c}{H_{ih}^s} S_{ih}^s + C_{ih}^e C_{ih}^c} \right) (m)(1-r_i) - A_i^e
\]

By filling into (2–80), the expression for \( \epsilon \) can be simplified to parameters for coal price, sulfur content, heat content, and scrubber capture rate:

\[
\Rightarrow \epsilon (\hat{A}_{i}^{MAX} - \hat{A}_{i}^{SMAX}) = P_S^A m_{r_i} C_{ih}^e H_{ih}^c (S_{ih}^c / H_{ih}^e - S_{ih}^s / H_{ih}^s) \quad (2–81)
\]

If high sulfur contract coal has a weakly higher sulfur to heat content ratio than high sulfur spot market coal \((S_{ih}^c / H_{ih}^e \geq S_{ih}^s / H_{ih}^s)\), then \( \epsilon > 0 \) and as the amount of coal under contract \((C_{ih}^e) \) increases, the size of \( \epsilon \) increases. If \((S_{ih}^c / H_{ih}^e < S_{ih}^s / H_{ih}^s)\), then \( \epsilon < 0 \).

Under the initial assumptions, \( P_S^A < MCA_i^{s,s} \). The example in Table 2-7 uses data representative of a unit that installed a scrubber under Phase I.\(^{26}\) A unit facing these coal characteristics prefers to use high sulfur coal with or without a scrubber installed because \( MCA_i^{s,s} = $1,137.74 > P_A = 250.00 \) and \( MCA_i^{s,s} = $1,137.74 > P_A^S = 460.80 \). In this case, \( \epsilon \) is much smaller than in the previous examples at \( \epsilon = $44.66 \) because a unit does not prefer to use low sulfur coal without a scrubber. There are no additional compliance costs from not being able to switch from high to low sulfur coal. Although the size of \( \epsilon \) is smaller than in other examples, the initial size of \( P_A^S \) is much smaller than in the previous two cases. So a smaller value of \( \epsilon \) may still alter a unit’s compliance choices.

\(^{26}\) BL England had 94% of coal under contract.
Based on the above two cases, the sign of epsilon can be summarized in the following Proposition 4.

**Proposition 4:** Given a high sulfur coal contract,

(i) \( \epsilon \geq 0 \) if \( \frac{S_{ch}}{H_{ch}} \geq \frac{S_{s h}}{H_{s h}} \).

(ii) The sign of \( \epsilon \) is unknown if \( \frac{S_{ch}}{H_{ch}} < \frac{S_{s h}}{H_{s h}} \).

Given the impact a high sulfur coal contract has on excess demand defined in Proposition 2 and the sign of \( \epsilon \) defined in Proposition 4, the impact of a high sulfur coal contract is derived in Proposition 5(a) and 5(b).

**Proposition 5(a):** Assuming \( \frac{S_{ch}}{H_{ch}} \geq \frac{S_{s h}}{H_{s h}} \) and allowing for the scrubber choice

(i) For the range of allowance prices \( P_A \geq M\tilde{C}A_i^{s,s} \), a high sulfur coal contract will weakly increase a unit’s excess demand.

(ii) For the range of allowance prices \( P^S_A \leq P_A \leq M\tilde{C}A_i^{s,s} \), a high sulfur coal contract will weakly increase excess demand.

(iii) For the range of allowance prices \( (P^S_A - \epsilon) \leq P_A \leq P^S_A \), a high sulfur coal contract will weakly decrease excess demand if \( A^{MIN}_i \geq \hat{A}^{SMAX}_i \) and weakly increase excess demand if \( A^{MIN}_i \leq \hat{A}^{SMAX}_i \).

(iv) For the range of allowance prices \( M\tilde{C}A_i^{s,s} \leq P_A \leq (P^S_A - \epsilon) \), a high sulfur coal contract will weakly increase a unit’s excess demand.

(v) For the range of allowance prices \( 0 \leq P_A \leq MCA_i^{s,s} \), a high sulfur coal contract will weakly increase a unit’s excess demand.

**Proof of Proposition 5(a):**

(i) When a unit faces \( P_A \geq M\tilde{C}A_i^{s,s} \), a unit prefers to install a scrubber and use all low sulfur coal. From Proposition 2(i), a high sulfur coal contract increases the minimum emissions level, which will weakly increase a unit’s allowance excess demand.

(ii) When a unit faces \( P^S_A \leq P_A \leq M\tilde{C}A_i^{s,s} \), a unit prefers to install a scrubber and use all high sulfur coal. From Proposition 2(iii), given \( \frac{S_{ch}}{H_{ch}} \geq \frac{S_{s h}}{H_{s h}} \), a high sulfur coal contract increases the maximum emissions level, which will weakly increase a unit’s allowance excess demand.

(iii) From Proposition 4(i), when a unit faces \( (P^S_A - \epsilon) \leq P_A \leq P^S_A \), a high sulfur coal contract decreases a unit’s indifference allowance price of installing a scrubber.
below the allowance price by $\epsilon > 0$, which leads to a unit installing a scrubber where it initially would not and decreases a unit’s emissions and a unit’s excess demand. From Proposition 2(iii), given the scrubber choice and $\left(\frac{S_{ih}}{H_{ih}} \geq \frac{S_{ih}}{H_{ih}}\right)$, a high sulfur coal contract will weakly increase a unit’s emissions and excess demand. If $A_i^{MIN} \geq \hat{A}_i^{S MAX}$, the combined net effect of the countering shifts is weakly negative and weakly decreases excess demand. If $A_i^{MIN} \leq \hat{A}_i^{S MAX}$, the combined net effect is weakly positive and weakly increases excess demand.

(iv) When a unit faces $\left(\frac{S_{ih}}{H_{ih}} \geq \frac{S_{ih}}{H_{ih}}\right)$, a unit does not install a scrubber and prefers to use low sulfur coal. From Proposition 2(i), a high sulfur coal contract increases a unit’s minimum emissions level and excess demand.

(v) When a unit faces $0 \leq P_A \leq MCA_i^{s,s}$, a unit does not install a scrubber and prefers to use high sulfur coal. From Proposition 2(iii), given $\left(\frac{S_{ih}}{H_{ih}} \geq \frac{S_{ih}}{H_{ih}}\right)$, a high sulfur coal contract increases a unit’s maximum emissions level and excess demand. ■

Proposition 5(a) is shown graphically in Figure 2.8(i). Proposition 5(b) expresses the impact a high sulfur coal contract will have on a unit’s excess demand correspondence by assuming that $\epsilon > 0$.

**Proposition 5(b):** Assuming $\left(\frac{S_{ih}}{H_{ih}} \leq \frac{S_{ih}}{H_{ih}}\right)$, $\epsilon \geq 0$, and allowing for the scrubber choice

(i) For the range of allowance prices $P_A \geq M\tilde{C}A_i^{s,s}$, a high sulfur coal contract will weakly increase a unit’s excess demand.

(ii) For the range of allowance prices $P_A^{S} \leq P_A \leq M\tilde{C}A_i^{s,s}$, a high sulfur coal contract will weakly decrease excess demand.

(iii) For the range of allowance prices $(P_A^{S} - \epsilon) \leq P_A \leq P_A^{S}$, a high sulfur coal contract will weakly decrease excess demand.

(iv) For the range of allowance prices $M\tilde{C}A_i^{s,s} \leq P_A \leq (P_A^{S} - \epsilon)$, a high sulfur coal contract will weakly increase a unit’s excess demand.

(v) For the range of allowance prices $0 \leq P_A \leq MCA_i^{s,s}$, a high sulfur coal contract will weakly decrease excess demand.

**Proof of Proposition 5(b):**

(i) When a unit faces $P_A \geq M\tilde{C}A_i^{s,s}$, a unit prefers to install a scrubber and use all low sulfur coal. From Proposition 2(i), a high sulfur coal contract increases the minimum emissions level, which will weakly increase a unit’s allowance excess demand.
When a unit faces $P_A^S \leq P_A \leq M\tilde{C}A_{i}^{s,s}$, a unit prefers to install a scrubber and use all high sulfur coal. From Proposition 2(ii), given $(S_{ih}^{s} / H_{ih}^{s} \leq S_{ih}^{h} / H_{ih}^{h})$, a high sulfur coal contract decreases the maximum emissions level, which will weakly decrease a unit’s allowance excess demand.

If $\epsilon > 0$, when a unit faces $(P_A^S - \epsilon) \leq P_A \leq P_A^S$, a high sulfur coal contract decreases a unit’s indifference allowance price of installing a scrubber below the allowance price, which leads to a unit installing a scrubber where it initially would not and decreases a unit’s emissions and a unit’s excess demand. From Proposition 2(ii), Given the scrubber choice and $(S_{ih}^{s} / H_{ih}^{s} \leq S_{ih}^{h} / H_{ih}^{h})$, a high sulfur coal contract will weakly decrease a unit’s emissions and excess demand. The combined net effect is weakly negative and weakly decreases excess demand.

From Proposition 2(i), when a unit faces $M\tilde{C}A_{i}^{s,s} \leq P_A \leq (P_A^S - \epsilon)$, a unit does not install a scrubber and prefers to use low sulfur coal. A high sulfur coal contract increases a unit’s minimum emissions level and excess demand.

From Proposition 2(ii), when a unit faces $0 \leq P_A \leq MCA_{i}^{s,s}$, a unit does not install a scrubber and prefers to use high sulfur coal. Given $(S_{ih}^{s} / H_{ih}^{s} \leq S_{ih}^{h} / H_{ih}^{h})$, a high sulfur coal contract decreases a unit’s maximum emissions level and excess demand.

Proposition 5(b) is shown graphically in Figure 2.8(ii). There are conditions under which some of these allowance price ranges do not exist. For example, $P_A^S < MCA_{i}^{s,s}$ in the third case described above. So there is no price range $(MCA_{i}^{s,s}, P_A^S)$ in Figure 2.8. However, Propositions 5(a) and 5(b) still hold for the price ranges that do exist. In Case 2, $\epsilon$ is large enough to shift the allowance price from $P_A > MCA_{i}^{s,s}$ to $(P_A - \epsilon) < MCA_{i}^{s,s}$ and causes the visual representation of the excess demand correspondence to shift from Figure 2.8 to 2.8.

**2.6.9.2 Impact of a binding low sulfur coal contract**

Proposition 5 can be proven using the same approach that was used to determine the sign of $\epsilon$ with a high sulfur coal contract is used to show that $\epsilon$ is always less than or equal to zero, and may increase the allowance price at which a unit is indifferent to installing a scrubber. Once again there will be three case under consideration.

In the first case, assume that both with and without a low sulfur coal contract, a unit prefers to use low sulfur spot market coal if it does not install a scrubber and high sulfur
spot market coal if it does install a scrubber because \((MCA_i^{s,s} < P_A < \tilde{MCA}_i^{s,s})\) and \((MCA_i^{s,s} < P_A^S)\).

If a unit has no low sulfur contract coal \((C_{cil} = 0)\), a unit uses the maximum amount of high sulfur coal with a scrubber and the maximum amount of low sulfur coal without a scrubber, and is indifferent to installing a scrubber at allowance price \(P_A^S\):

\[
P_{iz} + P_A^S A_i^{SMAX} + P_{ih}^s C_{ih}^{s,MAX} = P_A^S A_i^{MIN} + P_{ih}^s C_{ih}^{s,MAX}
\]

(2–82) can be rearranged to find an expression for \(P_{iz}\):

\[
\Rightarrow P_{iz} = P_A^S (A_i^{MIN} - A_i^{SMAX}) - P_{ih}^s C_{ih}^{s,MAX} + P_{ih}^s C_{ih}^{s,MAX}
\]

(2–83)

A low sulfur coal contract will change a unit’s coal use and allowance purchases, which changes the indifference allowance price by some value \(\epsilon\):

\[
P_{iz} + (P_A^S - \epsilon) \tilde{A}_i^{SMAX} + P_{ih}^s \tilde{C}_{ih}^{s,MAX} + P_{ih}^s \tilde{C}_{il}^c = (P_A^S - \epsilon) \tilde{A}_i^{MIN} + P_{ih}^s \tilde{C}_{il}^{s,MAX} + P_{ih}^s \tilde{C}_{il}^c
\]

(2–84) can be rearranged to find an expression for \(P_{iz}\):

\[
\Rightarrow P_{iz} = (P_A^S - \epsilon) (\tilde{A}_i^{MIN} - \tilde{A}_i^{SMAX}) + P_{ih}^s \tilde{C}_{il}^{s,MAX} - P_{ih}^s \tilde{C}_{ih}^{s,MAX}
\]

(2–85)

The two expressions for \(P_{iz}\) in (2–83) and (2–85) can be set equal to solve for the value of \(\epsilon\):

\[
\Rightarrow \epsilon = \frac{P_A^S (\tilde{A}_i^{MIN} - A_i^{MIN} + A_i^{SMAX} - \tilde{A}_i^{SMAX}) - P_{ih}^s (C_{ih}^{s,MAX} - \tilde{C}_{ih}^{s,MAX}) + P_{ih}^s (C_{ih}^{s,MAX} - \tilde{C}_{ih}^{s,MAX})}{(A_i^{MIN} - A_i^{SMAX})}
\]

(2–86)

Filling in for allowances and coal use, it is possible to determine the sign of \(\epsilon\).

\[
A_i^{MIN} = \left(\frac{D_i}{H_{il}}\right) (S_{il}^s) (m) - A_i^e \quad \tilde{A}_i^{MIN} = \left[\left(\frac{D_i - \tilde{C}_{il}^e H_{il}^c}{H_{il}^s}\right) (S_{il}^s) + \tilde{C}_{il}^e S_{il}^c\right] (m) - A_i^e
\]

\[
A_i^{SMAX} = \left(\frac{D_i}{H_{ih}}\right) (S_{ih}^s) (m)(1-r_i) - A_i^e \quad \tilde{A}_i^{SMAX} = \left[\left(\frac{D_i - \tilde{C}_{il}^e H_{il}^c}{H_{il}^s}\right) (S_{il}^s) + \tilde{C}_{il}^e S_{il}^c\right] (m)(1-r_i) - A_i^e
\]
\[ C_{i\text{h}}^{s,\text{MAX}} = \frac{D_i}{H_{i\text{h}}^s} \]
\[ \tilde{C}_{i\text{h}}^{s,\text{MAX}} = \frac{D_i - C_{i\text{h}}^{s,\text{ih}}}{H_{i\text{h}}^s} \]
\[ C_{i\text{il}}^{s,\text{MAX}} = \frac{D_i}{H_{i\text{il}}^s} \]
\[ \tilde{C}_{i\text{il}}^{s,\text{MAX}} = \frac{D_i - C_{i\text{il}}^{s,\text{ih}}}{H_{i\text{il}}^s} \]

By filling these expressions into (2–86), the expression for \( \epsilon \) can be simplified to parameters for coal price, sulfur content, heat content, and scrubber capture rate.

\[ \Rightarrow \epsilon = \frac{C_{i\text{il}}^{s,\text{il}}}{(\tilde{A}_{i\text{MIN}}^{i} - \tilde{A}_{i\text{SMAX}}^{i})} \left( \frac{P_{A}^{s}}{m} \right) \left( \frac{S_{i\text{il}}^{s} - S_{i\text{ih}}^{s}}{S_{i\text{il}}^{s} - S_{i\text{ih}}^{s}} - \frac{S_{i\text{il}}^{s} - S_{i\text{il}}^{s}}{S_{i\text{il}}^{s} - S_{i\text{il}}^{s}} \right) + \left( \frac{P_{A}^{s}}{m} - \frac{P_{A}^{s}}{m} \right) \left( \frac{S_{i\text{il}}^{s} - S_{i\text{il}}^{s}}{S_{i\text{il}}^{s} - S_{i\text{il}}^{s}} \right) \right] \] (2–87)

A more interpretable expression is derived by multiplying through by \((\tilde{A}_{i\text{MIN}}^{i} - \tilde{A}_{i\text{SMAX}}^{i})\) and dividing through by \(m(S_{i\text{il}}^{s} - S_{i\text{il}}^{s})\).

\[ \Rightarrow \epsilon(\tilde{A}_{i\text{MIN}}^{i} - \tilde{A}_{i\text{SMAX}}^{i}) = C_{i\text{il}}^{s,\text{il}} \left( \frac{P_{A}^{s}}{m} \right) \left( \frac{S_{i\text{il}}^{s} - S_{i\text{il}}^{s}}{S_{i\text{il}}^{s} - S_{i\text{il}}^{s}} - 1 \right) + \left( \frac{P_{A}^{s}}{m} - \frac{P_{A}^{s}}{m} \right) \left( \frac{S_{i\text{il}}^{s} - S_{i\text{il}}^{s}}{S_{i\text{il}}^{s} - S_{i\text{il}}^{s}} \right) \] (2–88)

\[ \Rightarrow \epsilon(\tilde{A}_{i\text{MIN}}^{i} - \tilde{A}_{i\text{SMAX}}^{i}) = C_{i\text{il}}^{s,\text{il}} \left( \frac{P_{A}^{s}}{m} \right) \left( \frac{S_{i\text{il}}^{s} - S_{i\text{il}}^{s}}{S_{i\text{il}}^{s} - S_{i\text{il}}^{s}} - (P_{A}^{s} - MCA_{i}^{s,s}) \right) \] (2–89)

From the initial assumption that a unit uses low sulfur coal when it does not install a scrubber, it is known that \((P_{A}^{s} > MCA_{i}^{s,s})\). Since \((S_{i\text{il}}^{s} < S_{i\text{il}}^{s})\), then \(\epsilon < 0\) and its magnitude increases as the size of the low sulfur coal contract \(C_{i}^{s,s} \) increases.

A binding low sulfur coal contract is more likely to impact units under CAIR. An example using recent data reflective of the coal availability and delivered prices for a unit in Alabama in 2000 will help to show \(\epsilon < 0\). Under the assumptions, a unit will prefer to switch fuels to abate emissions if it does not install a scrubber because \(MCA_{i}^{s,s} = 561.40\), which is much lower than the assumed allowance price \(P_{A} = 700.00\).

If a scrubber is installed, a unit prefers to use high sulfur spot market coal because the marginal cost of abatement is much greater than the allowance price \((MCA_{i}^{s,s} = 11,228)\). A unit will not install a scrubber because the allowance price at which a unit is indifferent to installing a scrubber \((P_{A}^{s} = 731.46)\) is higher than \(P_{A}\). A low sulfur coal contract

\[27\] The data can be found in Table 15.A of the 2000 Electric Power Annual Volume II.
for 50% of coal use results in $\epsilon = -42.00$, which increases the indifference price to $(PA - \epsilon) = 773.46$. The example shows that some units will not be impacted by a low sulfur coal contract because the increase in the indifference price does not alter the scrubber choice.

In the second case, assume that without a low sulfur coal contract, a unit prefers to use high sulfur spot market coal both if it does or does not install a scrubber because $(PS < MCA_{i,s}^s)$. However, with a low sulfur coal contract, a unit prefers to use low sulfur spot market coal if it does not install a scrubber and high sulfur spot market coal if it does install a scrubber because $(MCA_{i,s}^s < PA - \epsilon < \hat{MAC}_{i,s})$.

If a unit has no low sulfur contract coal ($C_{cil} = 0$), a unit uses the maximum amount of high sulfur coal both with and without a scrubber, and the unit is indifferent to installing a scrubber at allowance price $PS_A$:

$$P_{iz} + P_A^S A_{i}^{SMAX} + P_{ih}^S C_{ih}^{s,MAX} = P_A^S A_{i}^{MAX} + P_{ih}^S C_{ih}^{s,MAX}$$

(2–90) shows that the costs with and without a scrubber are equal for a given $PA$, and can be rearranged to find an expression for $P_{iz}$:

$$\Rightarrow P_{iz} = P_A^S (A_{i}^{MAX} - A_{i}^{SMAX})$$

(2–91)

Since a unit uses high sulfur coal both with and without a scrubber, a low sulfur coal contract will change the coal use by a unit both with and without a scrubber and change the indifference allowance price by some value $\epsilon$: 

$$P_{iz} + (PS_A - \epsilon) \hat{A}_{i}^{SMAX} + P_{ih}^S \hat{C}_{ih}^{s,MAX} + P_{il}^S \hat{C}_{il}^{c} = (PS_A - \epsilon) \hat{A}_{i}^{MIN} + P_{il}^S \hat{C}_{il}^{s,MAX} + P_{ih}^S \hat{C}_{ih}^{c}$$

(2–92) can be rearranged to find an expression for $P_{iz}$:

$$\Rightarrow P_{iz} = (PS_A - \epsilon) (\hat{A}_{i}^{MIN} - \hat{A}_{i}^{SMAX}) + P_{il}^S \hat{C}_{il}^{s,MAX} + P_{ih}^S \hat{C}_{ih}^{s}$$

(2–93)
The two expressions for \( P_{iz} \) in (2–91) and (2–93) can be set equal to solve for the value of \( \epsilon \):

\[
\Rightarrow \epsilon = \frac{P^S \left( \hat{A}_i^{MIN} - A_i^{MAX} + A_i^{SMAX} - \hat{A}_i^{SMAX} \right) + P_d \hat{C}_{il}^{MAX} - P_{ih} \hat{C}_{ih}^{SMAX}}{(\hat{A}_i^{MIN} - \hat{A}_i^{SMAX})} \tag{2–94}
\]

By filling in for allowances and coal use, it is possible to determine the sign of \( \epsilon \).

\[
A_i^{MAX} = \left( \frac{D_i}{H_{il}^s} \right) (S_{il}^s)(m) - A_i^e \quad \hat{A}_i^{MIN} = \left( \frac{D_i - \overline{C}_{ih}^c H_{il}^c}{H_{il}^s} \right) S_{il}^s + \overline{C}_{il}^c S_{il}^c m - A_i^e
\]

\[
A_i^{SMAX} = \left( \frac{D_i}{H_{il}^s} \right) (S_{il}^s)(m)(1 - r_i) - A_i^e \quad \hat{A}_i^{SMAX} = \left( \frac{D_i - \overline{C}_{ih}^c H_{il}^c}{H_{il}^s} \right) S_{il}^s + \overline{C}_{il}^c S_{il}^c (m)(1 - r_i) - A_i^e
\]

\[
\hat{C}_{il}^{SMAX} = \frac{D_i - \overline{C}_{il}^c H_{il}^c}{H_{il}^s} \quad \hat{C}_{ih}^{SMAX} = \frac{D_i - \overline{C}_{ih}^c H_{il}^c}{H_{ih}^s}
\]

By filling into (2–94), the expression for \( \epsilon \) can be simplified to parameters for coal price, sulfur content, heat content, and scrubber capture rate:

\[
\Rightarrow \epsilon \left( \hat{A}_i^{MIN} - \hat{A}_i^{SMAX} \right) = mP^S A H_{il}^c C_{il}^c \left( \frac{S_{il}^s}{H_{il}^s} - \frac{S_{il}^d}{H_{il}^d} \right) + r_i \left( \frac{S_{il}^c}{H_{il}^s} - \frac{S_{il}^d}{H_{il}^d} \right) - H_{il}^c C_{il}^c \left( \frac{P_d}{H_{il}^d} - \frac{P_{ih}}{H_{ih}^d} \right)
\]

\[
- D_i \left[ mP^S \left( \frac{S_{ih}^s}{H_{ih}^s} - \frac{S_{il}^d}{H_{il}^d} \right) - \left( \frac{P_d}{H_{il}^d} - \frac{P_{ih}}{H_{ih}^d} \right) \right] \tag{2–95}
\]

An interpretable form is derived by multiplying through by \( (\hat{A}_i^{MIN} - \hat{A}_i^{SMAX}) \) and dividing through by \( m \left( \frac{S_{ih}^s}{H_{ih}^s} - \frac{S_{il}^d}{H_{il}^d} \right) \) and combining like terms:

\[
\Rightarrow \epsilon \left( \hat{A}_i^{MIN} - \hat{A}_i^{SMAX} \right) = P^S_A r_i \left( \frac{S_{il}^c}{H_{il}^s} - \frac{S_{il}^d}{H_{il}^d} \right) + (D_i - H_{il}^c C_{il}^c) \left( P_A - \frac{\left( \frac{P_d}{H_{il}^d} - \frac{P_{ih}}{H_{ih}^d} \right)}{m \left( \frac{S_{ih}^s}{H_{ih}^s} - \frac{S_{il}^d}{H_{il}^d} \right)} \right) \tag{2–96}
\]

\[
\Rightarrow \epsilon \left( \hat{A}_i^{MIN} - \hat{A}_i^{SMAX} \right) = P^S_A r_i \left( \frac{S_{il}^c}{H_{il}^s} - \frac{S_{il}^d}{H_{il}^d} \right) + (D_i - H_{il}^c C_{il}^c)(P_A - MCA_{i,s,s}) \tag{2–97}
\]

From our initial assumption that a unit uses all high sulfur spot market coal if it does not install a scrubber if it does not have a high sulfur coal contract, then \( P_A^S < MCA_{i,s,s} \).

The total amount of heat content from the contract coal \( (S_{il}^c H_{il}^c) \) is weakly less than the total heat content needed to meet demand \( (D_i) \). So the second term is weakly negative. Meanwhile, the first term is negative because \( \left( \frac{S_{il}^c}{H_{il}^s} \right) < \left( \frac{S_{il}^d}{H_{il}^d} \right) \) and \( \left( \frac{S_{il}^c}{H_{il}^s} \right) > \left( \frac{S_{il}^d}{H_{il}^d} \right) \), which means.
\( \epsilon < 0 \) and an increase in the size of the high sulfur coal contract \( (C^c_{ih}) \) increases the magnitude of \( \epsilon \).

The second example in Table 2-8 uses data that reflects this case. Without a coal contract, \( P^S_A = 520.35 \), which is less than \( MCA^{s,s}_i = 657.90 \) and \( P_A = 700.00 \), and a unit will use high sulfur coal both with and without a scrubber installed. In this case, a unit will install a scrubber because \( P^S_A < P_A = 700.00 \). Now consider a low sulfur coal contract for 50\% of all coal use, which results in \( \epsilon = -352.99 \) and will increase the indifference price above both \( MCA^{s,s}_i \) and \( P_A \) to \( (P^S_A - \epsilon) = 873.34 \). With the low sulfur coal contract, a unit will now not install a scrubber and prefers to use low sulfur spot market coal.

In the third case, assume that a unit, both with and without a low sulfur coal contract, prefers to use high sulfur coal with and without a scrubber because \( P^S_A < (P^S_A - \epsilon) < MCA^{s,s}_i \). Given that a unit has no low sulfur contract coal \( (C^c_{il} = 0) \), a unit is indifferent to installing a scrubber at allowance price \( P^S_A \):

\[
P_{iz} + P^S_A A_i^{sMAX} + P^s_{il} C^{sMAX}_{il} = P^S_A A_i^{MAX} + P^s_{il} C^{sMAX}_{il} \tag{2-98}
\]

(3-26) can be rearranged to find an expression for \( P_{iz} \) where the only change in costs are the price of a scrubber and the change in a unit’s net allowance position. \( P^S_A \) is equal to the average cost of reducing a unit of emissions from scrubber installation:

\[
\Rightarrow P_{iz} = P^S_A (A_i^{MAX} - A_i^{sMAX}) \tag{2-99}
\]

A low sulfur coal contract will change the indifference allowance price by some value \( \epsilon \) because it alters the costs from net allowance purchases and fuel costs:

\[
P_{iz} + (P_A - \epsilon) \widehat{A}_i^{sMAX} + P^s_{ih} \widehat{C}^{sMAX}_{ih} + P^c_{il} \widehat{C}^c_{il} = (P^S_A - \epsilon) \widehat{A}_i^{MAX} + P^s_{ih} \widehat{C}^{sMAX}_{ih} + P^c_{il} \widehat{C}^c_{il} \tag{2-100}
\]

(2-100) can be rearranged to find an expression for \( P_{iz} \):

\[
\Rightarrow P_{iz} = (P^S_A - \epsilon)(\widehat{A}_i^{MAX} - \widehat{A}_i^{sMAX}) \tag{2-101}
\]
The two expressions for \( P_{iz} \) in (2–99) and (2–101) can be set equal to solve for the value of \( \epsilon \):

\[
\epsilon = \frac{P_A^{S}(\hat{A}^{MAX}_i - A^{MAX}_i + A^{SMAX}_i - \hat{A}^{SMAX}_i)}{(\hat{A}^{MAX}_i - \hat{A}^{SMAX}_i)} \quad (2–102)
\]

Filling in for allowances and coal use, it is possible to determine the sign of \( \epsilon \).

\[
A^{MAX}_i = \left( \frac{D_i}{H_{ih}} \right) (S_{ih}^s)(m) - A_i^e \quad \hat{A}^{MAX}_i = \left( \frac{D_i - C_{cil}^c H_{cil}^c}{H_{ih}^s} S_{ih}^s + C_{cil}^c S_{cil}^c \right) (m) - A_i^e
\]

\[
A^{SMAX}_i = \left( \frac{D_i}{H_{ih}^s} \right) (S_{ih}^s)(m)(1-r_i) - A_i^e \quad \hat{A}^{SMAX}_i = \left( \frac{D_i - C_{cil}^c H_{cil}^c}{H_{ih}^s} S_{ih}^s + C_{cil}^c S_{cil}^c \right) (m)(1-r_i) - A_i^e
\]

By filling into (2–102), the expression for \( \epsilon \) can be simplified to parameters for coal price, sulfur content, heat content, and scrubber capture rate.

\[
\Rightarrow \epsilon(\hat{A}^{MAX}_i - \hat{A}^{SMAX}_i) = P_A^{S} m r_i C_{cil}^c H_{cil}^c (S_{cil}^c \frac{S_{ih}^s}{H_{ih}^s} - \frac{S_{ih}^s}{H_{ih}^s}) \quad (2–103)
\]

Since \( \frac{S_{cil}^c}{H_{cil}^c} < \frac{S_{ih}^s}{H_{ih}^s} \), \( \epsilon < 0 \) and an increase in the size of the coal contract \( (C_{cil}^c) \) increases the magnitude of \( \epsilon \).

The third example in Table 2-8 uses data reflective of delivered costs and coal characteristics for a unit in Florida. A unit initially prefers to use high sulfur coal both with and without a scrubber because \( (P_A = 600.00) < (MCA_i^{s,s} = 3,887.56) \). A unit will prefer to install a scrubber in this example because the indifferent price is \( P_A^{S} = 565.60 \).

A low sulfur coal contract for 50% of coal use will increase the indifference price to \( (P_A^{S} - \epsilon) = 642.42 \), which will result in a unit not installing a scrubber.

Based on the above three cases, the sign of epsilon can be summarized in Proposition 6.

**Proposition 6:** Given a low sulfur coal contract, \( \epsilon \leq 0 \).

Given Proposition 3 and Proposition 6, the impact of a low sulfur coal contract is derived in Proposition 7(a) and 7(b).

**Proposition 7(a):** Assuming \( \frac{S_{cil}^c}{H_{cil}^c} \geq \frac{S_{ih}^s}{H_{ih}^s} \) and allowing for the scrubber choice...
For the range of allowance prices $P_A \geq M\tilde{C}A_i^{s,s}$, a low sulfur coal contract will \textit{weakly increase} excess demand.

For the range of allowance prices $(P_A^S - \epsilon) \leq P_A \leq M\tilde{C}A_i^{s,s}$, a low sulfur coal contract will \textit{weakly decrease} excess demand.

For the range of allowance prices $P_A^S \leq P_A \leq (P_A^S - \epsilon)$, a low sulfur coal contract will \textit{weakly increase} excess demand.

For the range of allowance prices $M\tilde{C}A_i^{s,s} \leq P_A \leq P_A^S$, a low sulfur coal contract will \textit{weakly increase} excess demand.

For the range of allowance prices $0 \leq P_A \leq MCA_i^{s,s}$, a low sulfur coal contract will \textit{weakly decrease} excess demand.

\textbf{Proof of Proposition 7(a):}

(i) When a unit faces $P_A \geq M\tilde{C}A_i^{s,s}$, a unit prefers to install a scrubber and use all low sulfur coal. From Proposition 3(iii), given $\frac{S_i^c}{H_i^c} \geq \frac{S_i^h}{H_i^h}$, a low sulfur coal contract increases the minimum emissions level, which will weakly increase a unit’s allowance excess demand.

(ii) When a unit faces $(P_A^S - \epsilon) \leq P_A \leq M\tilde{C}A_i^{s,s}$, a unit prefers to install a scrubber and use all high sulfur coal. From Proposition 3(i), a low sulfur coal contract decreases the maximum emissions level, which will weakly decrease a unit’s allowance excess demand.

(iii) From Proposition 6, when a unit faces $P_A^S \leq P_A \leq (P_A^S - \epsilon)$, a low sulfur coal contract increases a unit’s indifference allowance price of installing a scrubber above the allowance price, which leads a unit to not install a scrubber where it initially would have done so and increases a unit’s emissions and a unit’s excess demand. From Proposition 3(iii), given the scrubber choice and $\frac{S_i^c}{H_i^c} \geq \frac{S_i^h}{H_i^h}$, a low sulfur coal contract will weakly increase a unit’s emissions and excess demand. The combined net effect is weakly positive and weakly increases excess demand.

(iv) When a unit faces $M\tilde{C}A_i^{s,s} \leq P_A \leq P_A^S$, a unit does not install a scrubber and prefers to use low sulfur coal. From Proposition 3(iii), given $\frac{S_i^c}{H_i^c} \geq \frac{S_i^h}{H_i^h}$, a low sulfur coal contract increases a unit’s minimum emissions level and excess demand.

(v) When a unit faces $0 \leq P_A \leq MCA_i^{s,s}$, a unit does not install a scrubber and prefers to use high sulfur coal. From Proposition 3(i), a low sulfur coal contract decreases a unit’s maximum emissions level and excess demand.

Proposition 7(a) is shown graphically in Figure 2.8(i).

\textbf{Proposition 7(b):} Assuming that $(\frac{S_i^c}{H_i^c} < \frac{S_i^h}{H_i^h})$ and allowing for the scrubber choice...
(i) For the range of allowance prices $P_A \geq M\bar{C}A_i^{s,s}$, a low sulfur coal contract will weakly decrease excess demand.

(ii) For the range of allowance prices $(P_A^S - \epsilon) \leq P_A \leq M\bar{C}A_i^{s,s}$, a low sulfur coal contract will weakly decrease excess demand.

(iii) For the range of allowance prices $P_A^S \leq P_A \leq (P_A^S - \epsilon)$, a low sulfur coal contract will increase excess demand $A_i^{SMAX} \leq \hat{A}_i^{MIN}$ and weakly decrease excess demand if $A_i^{SMAX} \geq \hat{A}_i^{MIN}$.

(iv) For the range of allowance prices $M\bar{C}A_i^{s,s} \leq P_A \leq P_A^S$, a low sulfur coal contract will weakly decrease excess demand.

(v) For the range of allowance prices $0 \leq P_A \leq MCA_i^{s,s}$, a low sulfur coal contract will weakly decrease excess demand.

Proof of Proposition 7(b):

(i) When a unit faces $P_A \geq M\bar{C}A_i^{s,s}$, a unit prefers to install a scrubber and use all low sulfur coal. From Proposition 3(ii), given $\frac{S_i}{H_i} < \frac{S_i}{H_i}$, a low sulfur coal contract decreases the minimum emissions level, which will weakly decrease a unit’s allowance excess demand.

(ii) When a unit faces $(P_A^S - \epsilon) \leq P_A \leq M\bar{C}A_i^{s,s}$, a unit prefers to install a scrubber and use all high sulfur coal. From Proposition 3(i), a low sulfur coal contract decreases the maximum emissions level, which will weakly decrease a unit’s allowance excess demand.

(iii) From Proposition 6, when a unit faces $P_A^S \leq P_A \leq (P_A^S - \epsilon)$, a low sulfur coal contract increases a unit’s indifference allowance price of installing a scrubber above the allowance price, which leads a unit to not install a scrubber where it initially would have done so and increases a unit’s emissions and a unit’s excess demand. From Proposition 3(ii), given the scrubber choice and $\frac{S_i}{H_i} < \frac{S_i}{H_i}$, a high sulfur coal contract will weakly decrease a unit’s emissions and excess demand. If $\hat{A}_i^{MIN} \geq A_i^{SMAX}$, the combined net effect of the countering shifts is weakly positive and weakly increases excess demand. If $\hat{A}_i^{MIN} \leq A_i^{SMAX}$, the combined net effect is weakly negative and weakly decreases excess demand.

(iv) When a unit faces $M\bar{C}A_i^{s,s} \leq P_A \leq P_A^S$, a unit does not install a scrubber and prefers to use low sulfur coal. From Proposition 3(ii), given $\frac{S_i}{H_i} < \frac{S_i}{H_i}$, a low sulfur coal contract decreases a unit’s minimum emissions level and excess demand.

(v) When a unit faces $0 \leq P_A \leq MCA_i^{s,s}$, a unit does not install a scrubber and prefers to use high sulfur coal. From Proposition 3(i), a low sulfur coal contract decreases a unit’s maximum emissions level and excess demand.
Proposition 7(b) is shown graphically in Figure 2.8(ii). As with a high sulfur contract, some of the price ranges may not exist for a particular case. However, the remaining parts of the propositions hold.

2.7 Possible Implications on the Allowance Market and Industry Compliance Costs

Under Phase I of Title IV, there were many generating units facing high sulfur coal contracts for at least a fraction of their total coal use. If a binding high sulfur coal contract leads a unit to choose a suboptimal compliance choice, such as purchasing additional permits or installing a scrubber instead of switching fuels, and results in weakly higher compliance costs. A unit’s suboptimal choices not only increases a unit’s compliance costs, but should also increase compliance costs for the industry as a whole.

As has been show in several examples, high sulfur coal contracts for a large fraction (50-100%) of coal use can greatly reduce a unit’s “indifference price” to installing a scrubber. Some units under Phase I initially appear to have installed a scrubber when it was not a unit’s optimal compliance option, increasing a unit’s compliance costs. Additional scrubber installations should have resulted in greater emissions reduction, which should simultaneously lower demand and increase supply of allowances as a unit switches from a net demander to a net seller. In doing so, the equilibrium allowance market price should be driven lower, which may explain the lower than expected allowance prices realized during Phase I. Even though the allowance market price was lower than expected, the inefficient unit compliance choices resulted in higher than expected total industry compliance costs.

Under future CAIR regulation, a unit’s compliance options may be restricted by low sulfur coal contracts agreed upon during the 1990s to meet Title IV emissions requirements. A unit may find installing a scrubber and using high sulfur coal to be it best compliance option. However, low sulfur coal contracts may lead a unit to choose a suboptimal compliance choice, such as switching fuels or installing a scrubber while using
low sulfur coal. Suboptimal compliance decisions will lead to higher compliance costs at
the unit-level and may lead to higher total industry compliance costs.

As has been show in several examples, low sulfur coal contracts for a large fraction
(50-100%) of coal use can greatly increase a unit’s “indifference price” to installing a
scrubber. Some units under CAIR may not install a scrubber when it is optimal for them
to do so, increasing a unit’s compliance costs. Fewer scrubber installations would result
in greater emissions, which should simultaneously increase demand and decrease supply
of allowances as a unit would be a net demander instead of a net seller, and the allowance
market price should be driven higher than would be expected. In this case, a higher than
expected allowance market price would occur with higher than expected total industry
compliance costs.

2.8 Conclusions

This paper analytically derives the impacts that long-term fuel contract constraints
may have on a generating unit’s compliance choices and compliance costs in meeting SO$_2$
emissions restrictions. There are five important results from this analysis.

First, given the scrubber choice, it is easy to determine how a coal contract will
impact a unit’s excess demand for allowances. A high sulfur coal contract will weakly
increase a unit’s excess demand while a low sulfur coal contract will weakly decrease a
unit’s excess demand.

Second, some coal contracts may actually decrease a unit’s total costs relative to
using only spot market coal while increasing a unit’s compliance costs if a coal contract
allows a unit to lock in a lower price for a given type of coal. The coal contract will
restrict compliance choices, which may result in higher compliance costs. If the fuel cost
savings is greater than the increase in a unit’s compliance costs, then the coal contract
lowers a unit’s total costs. Since a unit only cares about its total costs, a unit’s compliance
decisions do not necessarily minimize a unit’s compliance costs.
Third, under certain conditions a unit’s compliance costs will increase when a coal contract results in a suboptimal combination of spot market coal use, allowance purchases, and scrubber installation. A suboptimal combination may result from two situations: (1) a coal contract alters a unit’s compliance choice or (2) the compliance choice does not change, but the coal under contract has a higher sulfur to heat content ratio than the same type of coal available in the spot market, which increases a unit’s allowance purchases.

Fourth, coal contract constraints change the allowance price at which a unit will prefer to install a scrubber. In the case of Phase I, a high sulfur coal contract may increase a unit’s “indifference price”, which creates a greater incentive for a unit to scrub and sell its extra allowances. This result may explain why some scrubbers were installed at sub-optimal units while the allowance market price was much lower than expected during Phase I. The opposite may occur under CAIR, where a low sulfur coal contract may increase a unit’s “indifference price” and lower the incentive for a unit to install a scrubber even if it would be the optimal compliance choice. In either case, a suboptimal compliance choice will be made and a unit’s compliance costs will weakly increase.

Fifth, there is certainty how a coal contract will impact a unit’s excess demand for allowances even when the scrubber choice is considered for most allowance price ranges. However, due to the discrete scrubber choice and the change in the “indifference price” due to a coal contract, it is uncertain how a coal contract will alter a unit’s excess demand if the allowance market price falls in one particular price range. A high sulfur coal contract will shift excess demand as derived in Proposition 2 except if the allowance market price falls in the price range \((P_A^S - \epsilon, P_A^S)\) and \(\frac{S_{ih}}{H_{ih}} > \frac{S_{ih}^h}{H_{ih}}\). If the allowance market price falls in this range, there are two countering effects on excess demand, the decrease in excess demand resulting from the scrubber installation and the increase in excess demand from the higher sulfur content of high sulfur contract coal relative to high sulfur spot market coal. A low sulfur coal contract will shift excess demand as derived in Proposition

111
3 except if the allowance market price falls in the price range \( (P_A^S, P_A^S - \epsilon) \) and \( \frac{S_k}{H_k} < \frac{S_l}{H_l} \).

If the allowance market price falls in this range, there are two countering effects on excess demand, the increase in excess demand resulting from no scrubber installation and the decrease in excess demand from the lower sulfur content of low sulfur contract coal relative to low sulfur spot market coal.
### Table 2-1. Phase I Compliance Cost Estimates

<table>
<thead>
<tr>
<th>Source</th>
<th>MCA$_i$/ton</th>
<th>Pred. Costs</th>
<th>Least-Cost</th>
<th>Actual Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>ICF (1989, 1990)</td>
<td>$199-$226</td>
<td>$450-860 million</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>EPRI (1993, 1995)</td>
<td>$879-$1238</td>
<td>$900-1,340 million</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>GAO (1994)</td>
<td>$299</td>
<td>$1,170 million</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Winebrake, et al. (1995)</td>
<td>$143</td>
<td>$502 million</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Pre-Policy Estimates</td>
<td>$143-$1238</td>
<td>$450-$1340 million</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Ellerman et al. (1997)</td>
<td>$200-300</td>
<td>N/A</td>
<td>N/A</td>
<td>$730 million</td>
</tr>
<tr>
<td>Sotkiewicz and Holt (2005)</td>
<td>$150-$180</td>
<td>N/A</td>
<td>$423-$553 million</td>
<td>$990 million</td>
</tr>
<tr>
<td>Carlson et al. (2000)</td>
<td>$71</td>
<td>N/A</td>
<td>$571 million</td>
<td>$910 million</td>
</tr>
<tr>
<td>Post-Policy Estimates</td>
<td>$71-$800</td>
<td>N/A</td>
<td>$423-$571 million</td>
<td>$730-$990 million</td>
</tr>
</tbody>
</table>

Sources: Bohi and Burtraw (1997); Carlson et al. (2000); Sotkiewicz and Holt (2005); Smith and Ellerman (1998)
### Table 2-2. High Sulfur Coal Contract: Assumptions

<table>
<thead>
<tr>
<th>Coal Type</th>
<th>Price/mmBtu</th>
<th>$H_{sf}^s$ Price/Ton</th>
<th>$S_{sf}^s$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_{ih}^s$</td>
<td>$1.60</td>
<td>24</td>
<td>$38.40</td>
</tr>
<tr>
<td>$C_{ih}^s$</td>
<td>$1.30</td>
<td>24</td>
<td>$31.20</td>
</tr>
<tr>
<td>$C_{ih}^c$ (Ex. 1)</td>
<td>$1.50</td>
<td>24</td>
<td>$36.00</td>
</tr>
<tr>
<td>$C_{ih}^c$ (Ex. 2)</td>
<td>$1.20</td>
<td>24</td>
<td>$28.80</td>
</tr>
</tbody>
</table>

$P_A$ $300.00$

$A_c^e$ 20,000 tons

$D_i$ 24,000,000 mmBtu

### Table 2-3. High Sulfur Coal Contract: Results

<table>
<thead>
<tr>
<th>Costs</th>
<th>Compliance Costs (Ex. 1)</th>
<th>Total Costs (Ex. 1)</th>
<th>Compliance Costs (Ex. 2)</th>
<th>Total Costs (Ex. 2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unconstrained</td>
<td>$4.62 million</td>
<td>$35.82 million</td>
<td>$4.62 million</td>
<td>$35.82 million</td>
</tr>
<tr>
<td>Constrained</td>
<td>$5.01 million</td>
<td>$38.61 million</td>
<td>$5.01 million</td>
<td>$35.01 million</td>
</tr>
<tr>
<td>Change</td>
<td>$390,000</td>
<td>$2.79 million</td>
<td>$390,000</td>
<td>-$810,000</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Allowance Use (Tons)</th>
<th>$MCA_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum</td>
<td>11,400 tons</td>
</tr>
<tr>
<td>Maximum</td>
<td>38,000 tons</td>
</tr>
<tr>
<td>Constrained Min.</td>
<td>24,700 tons</td>
</tr>
</tbody>
</table>

### Table 2-4. Low Sulfur Coal Contract Examples: Assumptions

<table>
<thead>
<tr>
<th>Coal Type</th>
<th>Price/mmBtu</th>
<th>$H_{sf}^g$ Price/Ton</th>
<th>$S_{sf}^g$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_{ih}^g$</td>
<td>$1.60</td>
<td>24</td>
<td>$38.40</td>
</tr>
<tr>
<td>$C_{ih}^g$</td>
<td>$1.30</td>
<td>24</td>
<td>$31.20</td>
</tr>
<tr>
<td>$C_{ih}^c$ (Ex. 1)</td>
<td>$1.80</td>
<td>24</td>
<td>$43.20</td>
</tr>
<tr>
<td>$C_{ih}^c$ (Ex. 2)</td>
<td>$1.50</td>
<td>24</td>
<td>$36.00</td>
</tr>
</tbody>
</table>

$P_A$ $200.00$

$A_c^e$ 20,000 tons

$D_i$ 24,000,000 mmBtu
<table>
<thead>
<tr>
<th>Costs</th>
<th>Compliance Costs (Ex. 1)</th>
<th>Total Costs (Ex. 1)</th>
<th>Compliance Costs (Ex. 2)</th>
<th>Total Costs (Ex. 2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unconstrained</td>
<td>$3.6 million</td>
<td>$34.8 million</td>
<td>$3.6 million</td>
<td>$34.8 million</td>
</tr>
<tr>
<td>Constrained</td>
<td>$4.54 million</td>
<td>$38.14 million</td>
<td>$4.54 million</td>
<td>$34.54 million</td>
</tr>
<tr>
<td>Change</td>
<td>$940,000</td>
<td>$3.34 million</td>
<td>$940,000</td>
<td>-$260,000</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Allowance Use (Tons)</th>
<th>$MCA_i^{s,s}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum</td>
<td>11,400 tons</td>
</tr>
<tr>
<td>Maximum</td>
<td>38,000 tons</td>
</tr>
<tr>
<td>Constrained Max.</td>
<td>24,700 tons</td>
</tr>
</tbody>
</table>
Table 2-6. Example Epsilon Magnitude: Case 1

<table>
<thead>
<tr>
<th>Scrubber Characteristics</th>
<th>Generating Unit Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capital Cost $260/kW</td>
<td>Capacity 365.3 MW</td>
</tr>
<tr>
<td>O and M Cost 2 mills/kWh</td>
<td>Heat Rate 10,000 Btu/kWh</td>
</tr>
<tr>
<td>$P_{iz}$ $15,886,295</td>
<td>Cap. Factor 75%</td>
</tr>
<tr>
<td>$r_i$ 95%</td>
<td>$\overline{C}_{th}^c$ 50%, 75% of Coal Use</td>
</tr>
<tr>
<td>$P_A$ $250.00$</td>
<td>$D_i$ 24,000,000 mmBtu</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Characteristics</th>
<th>Value</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low Sulfur Coal (Spot)</td>
<td>Price</td>
<td>$1.50/mmBtu</td>
<td>50% Contract</td>
</tr>
<tr>
<td>Low Sulfur Coal (Spot)</td>
<td>Sulfur Content</td>
<td>0.65%</td>
<td>$P_A^S = 1,592.61$</td>
</tr>
<tr>
<td>Low Sulfur Coal (Spot)</td>
<td>Heat Content</td>
<td>24 mmBtu/ton</td>
<td>$P_A^S - \epsilon = 382.00$</td>
</tr>
<tr>
<td>High Sulfur Coal (Spot)</td>
<td>Price</td>
<td>$1.30/mmBtu</td>
<td>75% Contract</td>
</tr>
<tr>
<td>High Sulfur Coal (Spot)</td>
<td>Sulfur Content</td>
<td>2.5%</td>
<td>$P_A^S = 1,592.61$</td>
</tr>
<tr>
<td>High Sulfur Coal (Spot)</td>
<td>Heat Content</td>
<td>24 mmBtu/ton</td>
<td>$P_A^S - \epsilon = 242.79$</td>
</tr>
<tr>
<td>High Sulfur Coal (Contract)</td>
<td>Price</td>
<td>$1.50/mmBtu</td>
<td>$P_A^S = 1,592.61$</td>
</tr>
<tr>
<td>High Sulfur Coal (Contract)</td>
<td>Sulfur Content</td>
<td>4.0%</td>
<td>$P_A^S - \epsilon = 242.79$</td>
</tr>
</tbody>
</table>
Table 2-7. Example Epsilon Magnitude: Case 2

<table>
<thead>
<tr>
<th>Scrubber Characteristics</th>
<th>Generating Unit Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capital Cost</td>
<td>Capacity</td>
</tr>
<tr>
<td>$260/kW</td>
<td>365.3 MW</td>
</tr>
<tr>
<td>O and M Cost</td>
<td>Heat Rate</td>
</tr>
<tr>
<td>2 mills/kWh</td>
<td>10,000 Btu/kWh</td>
</tr>
<tr>
<td>$P_{iz}$</td>
<td>Cap. Factor</td>
</tr>
<tr>
<td>$15,886,295</td>
<td>75%</td>
</tr>
<tr>
<td>$r_i$</td>
<td>$\bar{C}_{th}^\epsilon$</td>
</tr>
<tr>
<td>95%</td>
<td>50% of Coal Use</td>
</tr>
<tr>
<td>$P_A$</td>
<td>$D_i$</td>
</tr>
<tr>
<td>$250.00$</td>
<td>24,000,000 mmBtu</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Characteristics</th>
<th>Values</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low Sulfur Coal (Spot)</td>
<td>Price</td>
<td>$2.79/mmBtu</td>
<td>BL England</td>
</tr>
<tr>
<td></td>
<td>Heat Content</td>
<td>24 mmBtu/ton</td>
<td>50% Contract</td>
</tr>
<tr>
<td></td>
<td>Sulfur Content</td>
<td>0.5%</td>
<td>$P_A^S = 460.80$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$\epsilon = 44.66$</td>
</tr>
<tr>
<td>High Sulfur Spot Coal (Spot)</td>
<td>Price</td>
<td>$1.52/mmBtu</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Heat Content</td>
<td>24 mmBtu/ton</td>
<td>$P_A - \epsilon = 416.14$</td>
</tr>
<tr>
<td></td>
<td>Sulfur Content</td>
<td>1.91%</td>
<td>Pct. ↓ $P_A^S = 10%$</td>
</tr>
<tr>
<td>High Sulfur Coal (Contract)</td>
<td>Price</td>
<td>$1.72/mmBtu</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Heat Content</td>
<td>24 mmBtu/ton</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sulfur Content</td>
<td>2.32%</td>
<td></td>
</tr>
</tbody>
</table>
## Table 2-8. Example Epsilon Magnitude

<table>
<thead>
<tr>
<th>Scrubber Characteristics</th>
<th>Gen. Unit Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Capital Cost</strong> $141.34/kW</td>
<td><strong>Capacity</strong> 365.3 MW</td>
</tr>
<tr>
<td><strong>O and M Cost</strong> 1.23 mills/kWh</td>
<td><strong>Heat Rate</strong> 10,000 Btu/kWh</td>
</tr>
<tr>
<td>$9,016,616.85</td>
<td><strong>Cap. Factor</strong> 75%</td>
</tr>
<tr>
<td>$9,016,616.85</td>
<td><strong>$i_ih</strong> 50% of Coal Use</td>
</tr>
<tr>
<td><strong>$r_i</strong> 95%</td>
<td><strong>$Di</strong> 24,000,000 mmBtu</td>
</tr>
<tr>
<td>**$PA$$ = $700.00, $600.00</td>
<td><strong>Results</strong></td>
</tr>
</tbody>
</table>

**Parameters**

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Values</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Low Sulfur Coal</strong> (Alabama)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Price</td>
<td>$1.50/mmBtu</td>
<td>Case 1 (Alabama)</td>
</tr>
<tr>
<td>Heat Content</td>
<td>24 mmBtu/ton</td>
<td>$P_A^S = 731.46$</td>
</tr>
<tr>
<td>Sulfur Content</td>
<td>0.7%</td>
<td>$P_A - \epsilon = 773.46$</td>
</tr>
</tbody>
</table>

| **High Sulfur Spot Coal** (Alabama) | | |
| Price | $1.10/mmBtu | Case 2 (CAIR) |
| Heat Content | 24 mmBtu/ton | $P_A^S = 520.35$ |
| Sulfur Content | 1.6% | $P_A - \epsilon = 873.34$ |

| **High Sulfur Spot Coal** (CAIR Example) | | |
| Price | $2.00/mmBtu | Case 2 (CAIR) |
| Heat Content | 25 mmBtu/ton | $P_A^S = 520.35$ |
| Sulfur Content | 1.0% | $P_A - \epsilon = 873.34$ |

| **Low Sulfur Coal** (CAIR Example) | | |
| Price | $2.20/mmBtu | Case 3 (Florida) |
| Heat Content | 25 mmBtu/ton | $P_A^S = 565.60$ |
| Sulfur Content | 0.6% | $P_A - \epsilon = 642.42$ |

| **High Sulfur Spot Coal** (Florida) | | |
| Price | $2.30/mmBtu | Case 3 (Florida) |
| Heat Content | 24 mmBtu/ton | $P_A^S = 565.60$ |
| Sulfur Content | 1.4% | $P_A - \epsilon = 642.42$ |

| **Low Sulfur Coal** (Florida) | | |
| Price | $3.50/mmBtu | | |
| Heat Content | 25 mmBtu/ton | | |
| Sulfur Content | 0.7% | | |
Figure 2-1. The SO$_2$ Allowance Price. Data was given to me by Dallas Burtraw of Resources for the Future

Figure 2-2. Excess Demand Correspondence and Compliance Cost Savings from Fuel Switching Over Allowance Purchasing
Figure 2-3. High Sulfur Contract: Shift in Minimum Excess Demand

Figure 2-4. No Contract: Compliance Costs

Figure 2-5. High Sulfur Contract: Compliance and Total Costs
Figure 2-6. High Sulfur Contract: Relative Savings from Contract Coal

Figure 2-7. Cost Savings from Using Allowances Over Fuel Switching

Figure 2-8. Low Sulfur Contract
Figure 2-9. No Contract: Compliance Costs

Figure 2-10. Low Sulfur Coal Contract: $MCA_i^{s,c}$

Figure 2-11. Low Sulfur Coal Contract: $MCA_i^{s,c}$
Figure 2-12. Compliance Costs: $P_A = MCA^{s,s}$

Figure 2-13. High Sulfur Coal Contract

Figure 2-14. Low Sulfur Coal Contract
Figure 2-15. Excess Demand Correspondence: $MCA_{i}^{e,s} < P_{A}^{S}$

Figure 2-16. Excess Demand Correspondence: $MCA_{i}^{e,s} \geq P_{A}^{S}$
Figure 2-17. Impact of a High Sulfur Coal Contract: $MCA_i^{s,s} < P_A^S$

Figure 2-18. Impact of a High Sulfur Coal Contract: $MCA_i^{s,s} > P_A^S$

Figure 2-19. Impact of a Low Sulfur Coal Contract: $MCA_i^{s,s} > P_A^S$
Figure 2-20. Impact of a low sulfur Coal Contract: $MCA_i^{NS} < P_A^S$
CHAPTER 3
THE EFFECT OF FUEL CONTRACTING CONSTRAINTS ON SO₂ TRADING PROGRAM COMPLIANCE: EMPIRICAL EVIDENCE

3.1 Introduction

The U.S. SO₂ Trading Program created by Title IV of the 1990 Clean Air Act Amendment led to lower compliance costs than what would have occurred under a Command-and-Control approach. However, all compliance cost savings were not realized in the early years of the program. There have been several conjectures as to why the hypothetical outcome was not obtained, including short-run rigidities from fuel contracts. Chapter 2 shows how fuel contracts could alter a generating unit’s compliance decision in the U.S. SO₂ Trading Program, but ignores any aggregate allowance market and industry-wide compliance cost impacts. This paper expands on Chapter 2 by looking at the allowance market equilibrium impacts and total industry compliance costs from fuel contracts through analytics and empirical modeling.

Given the scrubber choice, an allowance market equilibrium will exist. Allowing for the scrubber choice makes it impossible to guarantee an equilibrium, but one still may exist. Binding fuel contracts may lead to altered unit-level excess demands and, in so doing, the allowance market price \( P_A \). Meanwhile, binding contracts can alter compliance decisions and increase total industry compliance costs.

This paper uses generating unit-level simulations to replicate results from previous studies and show that short-run fuel contracts appear to explain a large portion of the previously unexplained excess compliance costs found in previous simulations. Simulating the least-cost compliance choices without including fuel contract constraints results in minimum annual industry compliance costs of $288.3 million, which varies greatly from the actual compliance costs of $1.30 billion found in these simulations. Once fuel contract constraints are introduced into the simulation, the minimum annual industry compliance costs become $1.01 billion. Based on these results, fuel contract constraints explain $651.1 million, or 64% of the excess compliance costs realized in the program for 1996.
Also, this paper considers a more appropriate level for compliance decisions. The literature has only considered compliance costs at the generating unit level. However, actual compliance decisions would be made at the plant level because of the economic relations and the physical proximity between generating units. Coal is delivered at the plant level, where multiple generating units may be located. Since a plant is only concerned about minimizing its total costs at the plant, the minimization at a particular generating unit is not necessary for a plant to make optimal choices. This paper analytically analyzes the plant level decision-making process to show why it is appropriate to consider decisions as the plant level instead of the generating unit level, the interaction of choices for economically related generating units, and how cost-minimization at the plant level may deviate from cost-minimization at the generating unit level.

The paper will be structured in the following manner: Section 2 will look at the conditions for an allowance market equilibrium while Section 3 will look at the comparative statics of the allowance market. Section 4 will look at compliance costs, both for an individual generating unit and the entire industry. Section 5 and Section 6 will explain the data used in the generating unit level simulations and the results from the actual simulations, respectively. Section 7 will analyze the plant level decision making process, how it differs from the generating unit level model, and what additional information the model will add to the literature.

### 3.2 Review of Generating Unit Model

#### 3.2.1 Generating Unit Problem

\[
\min_{z_i,A_i,C_{ih}^c,C_{il}^c} z_i P_{iz} + P_{AA} A_i^s + P_i^c C_{ih}^c + P_i^s C_{il}^c + P_{ih} C_{ih}^s + P_{il} C_{il}^s
\]

subject to...

\[ A_i^s + A_i \geq (1 - z_i T_i)(m)(C_{ih}^s S_{ih}^s + C_{ih}^c S_{ih}^c + C_{il}^s S_{il}^s + C_{il}^c S_{il}^c) \]

\[ (C_{ih}^s H_{ih}^s + C_{ih}^c H_{ih}^c + C_{il}^s H_{il}^s + C_{il}^c H_{il}^c) \geq D_i \]

\[ C_{ih}^c = \overline{C}_{ih}^c \]

\[ \lambda_i \]

\[ \mu_i \]
\[ C_{\text{il}}^c = \text{C}_{\text{il}}^c \quad \mu_{\text{il}} \quad (3-5) \]
\[ C_{\text{ih}}^s, C_{\text{il}}^s \geq 0 \quad (3-6) \]
\[ z_i \in \{0, 1\} \quad (3-7) \]

Equation (3–1) represents the unit’s cost function. These costs include the cost of scrubber installation \((z_i P_{iz})\), net costs of allowance purchases \((P_A A_i)\), and costs of coal purchases \((P_{ih} C_{ih}^s + P_{il} C_{il}^s + P_{ih} C_{ih}^c + P_{il} C_{il}^c)\). The emissions constraint is shown in (3–2), where the number of allowances held \((A_i^e + A_i)\) must be as large as the amount of total emissions by the generating unit \([(1 - z_i r_i)(m)(C_{ih}^s S_{ih}^s + C_{ih}^c S_{ih}^c + C_{il}^s S_{il}^s + C_{il}^c S_{il}^c)]\). Total emissions is a function of the amount of each coal type used as well as the emissions reduction due to a scrubber, if one is installed. The Lagrange multiplier on the emissions constraint is represented by \(\lambda_{i1}\). The demand constraint requires that the amount of heat input to generate electricity \((C_{ih}^s H_{ih}^s + C_{ih}^c H_{ih}^c + C_{il}^s H_{il}^s + C_{il}^c H_{il}^c)\) must cover the consumer demand \((D_i)\) for electricity expressed as heat input, which is seen in (3–3). The Lagrange multiplier on the demand constraint is represented by \(\lambda_{i2}\). Coal contract constraints require the unit to use a specific amount of each contract coal type, \(\text{C}_{\text{ih}}^c\) for high sulfur coal in (3–4) and \(\text{C}_{\text{il}}^c\) for low sulfur coal in (3–5). A unit will use exactly the contracted amount because (1) if the contract coal is more expensive than spot market coal, then a unit will not want to use any more contract coal than is necessary and (2) if contract coal is cheaper than spot market coal, the coal producer would prefer to sell any additional non-contracted coal through the spot market. The Lagrange multiplier for each contract constraint on each coal type is represented by \(\mu_{ih}\) for high sulfur contract coal and \(\mu_{il}\) for low sulfur contract coal.

### 3.2.2 Optimal Compliance Choices

The following is a summary of a generating unit’s compliance choices derived in Chapter 2 both with and without fuel contracts.
Given the scrubber choice, a generating unit that does not face any coal contract constraints will make its optimal choices based on the relationship of the allowance price \( P_A \) and the marginal cost of abatement from switching fuels from high sulfur spot market coal to low sulfur spot market coal \( MCA_{i,s}^{s,s} \). If \( P_A > MCA_{i,s}^{s,s} \), then it is cheaper to meet the emissions constraint by decreasing emissions by switching fuels than purchasing allowances. A unit will use all low sulfur coal and purchase the minimum amount of allowances, which will result in the following compliance choices:

\[
C_{ih}^s = 0, \quad C_{il}^s = C_{il}^{s,MAX} = D_i, \quad \text{and} \quad A_i = A_i^{MIN}.
\]

If \( P_A < MCA_{i,s}^{s,s} \), then it is cheaper to meet the emissions constraint by purchasing allowances than decreasing emissions by switching fuels. A unit will use all high sulfur coal and purchase the maximum amount of allowances, which will result in the following compliance choices:

\[
C_{ih}^s = C_{ih}^{s,MAX} = D_i, \quad C_{il}^s = 0, \quad \text{and} \quad A_i = A_i^{MAX}.
\]

Introducing a high sulfur coal contract constraint will restrict spot market coal use by \( C^c_{ih} \) and will alter excess demand \( (A_i) \). The maximum amount of high sulfur spot market coal use decreases from \( D_i = C_{ih}^{s,MAX} \) to \( D_i - C^c_{ih} = \hat{C}_{ih}^{s,MAX} \). The maximum amount of low sulfur spot market coal decreases from \( D_i = C_{il}^{s,MAX} \) to \( D_i - C^c_{il} = \hat{C}_{il}^{s,MAX} \).

If \( P_A > MCA_i^{s,s} \), a unit will use its contract constrained maximum amount of low sulfur spot market coal \( (\hat{C}_{ih}^{s,MAX}) \) and excess demand will increase from \( A_i^{MIN} \) to \( \hat{A}_i^{MIN} \). If \( P_A < MCA_i^{s,s} \), a unit will use its contract constrained maximum amount of high sulfur spot market coal \( (\hat{C}_{il}^{s,MAX}) \) and excess demand will shift from \( A_i^{MAX} \) to \( \hat{A}_i^{MAX} \). If \( \frac{S_i^s}{H_i^s} \leq \frac{S_i^h}{H_i^h} \), then \( A_i^{MAX} \leq \hat{A}_i^{MAX} \). If \( \frac{S_i^s}{H_i^s} \geq \frac{S_i^h}{H_i^h} \), then \( A_i^{MAX} \geq \hat{A}_i^{MAX} \).

Introducing a low sulfur coal contract constraint will restrict spot market coal use by \( C^c_{il} \) and will alter excess demand \( (A_i) \). The maximum amount of high sulfur spot market coal use decreases from \( D_i = C_{ih}^{s,MAX} \) to \( D_i - C^c_{il} = \hat{C}_{il}^{s,MAX} \). The maximum amount of low sulfur spot market coal decreases from \( D_i = C_{il}^{s,MAX} \) to \( D_i - C^c_{il} = \hat{C}_{il}^{s,MAX} \).

If \( P_A > MCA_i^{s,s} \), a unit will use its contract constrained maximum amount of low sulfur spot market coal \( (\hat{C}_{ih}^{s,MAX}) \) and excess demand will shift from \( A_i^{MIN} \) to \( \hat{A}_i^{MIN} \). If \( \frac{S_i^s}{H_i^s} \leq \frac{S_i^h}{H_i^h} \), then \( A_i^{MIN} \leq \hat{A}_i^{MIN} \). If \( \frac{S_i^s}{H_i^s} \geq \frac{S_i^h}{H_i^h} \), then \( A_i^{MIN} \geq \hat{A}_i^{MIN} \).
then $A^\text{MIN}_i \leq \widehat{A}^\text{MIN}_i$. If $\frac{S^s_i}{H^s_i} \geq \frac{S^c_i}{H^c_i}$, then $A^\text{MIN}_i \geq \widehat{A}^\text{MIN}_i$. If $P_A < MCA^s_i$; a unit will use its contract constrained maximum amount of high sulfur coal ($\widehat{C}^\text{MAX}_{ih}$) and excess demand will decrease from $A^\text{MAX}_i$ to $\widehat{A}^\text{MAX}_i$.

Allowing the scrubber choice to be endogenous results in more complex impacts of coal contracts on compliance decisions. A generating unit that does not face any coal contract constraints will make its optimal choices based on two conditions: (1) the relationship of $P_A$ relative to the allowance price at which a unit is indifferent to installing a scrubber ($P^s_A$) and (2) the relationship of $P_A$ relative to $MCA^s_i$ given the scrubber choice.

If $P^s_A > P_A$, a unit will not install a scrubber because total costs to the generating unit will be lower without installing a scrubber. The resulting coal use and excess demand will be the same as described above: $C^s_{ih} = D_i$, $C^s_{il} = 0$, and $A_i = A^\text{MAX}_i$ if $P_A < MCA^s_i$ and $C^s_{ih} = 0$, $C^s_{il} = D_i$, and $A_i = A^\text{MIN}_i$ if $P_A > MCA^s_i$ where $MCA^s_i$ is the marginal cost of abatement from switching fuels without a scrubber.

If $P^s_A < P_A$, a unit will install a scrubber because total costs will be lower with a scrubber installed. As explained in Chapter 2 the marginal cost of abatement with a scrubber ($M\tilde{C}A^s_i$) will be much higher than the marginal cost of abatement without a scrubber ($MCA^s_i$). The resulting coal use and excess demand will now be $C^s_{ih} = D_i$, $C^s_{il} = 0$, and $A_i = A^\text{MAX}_i$ if $P_A < M\tilde{C}A^s_i$ and $C^s_{ih} = 0$, $C^s_{il} = D_i$, and $A_i = A^\text{MIN}_i$ if $P_A > M\tilde{C}A^s_i$.

The result is a combination of the two excess demand correspondences where at some allowance price ($P^s_A$) where a scrubber will be installed there is a large non-continuous decrease in a unit’s excess demand.

Introducing a high sulfur coal contract constraint will have the same direct impacts as when scrubbers are given. Coal use will be restricted by $\overline{C}^s_{ih}$. The excess demand correspondence will be impacted in the same manner except there will be four shifts instead of two. Minimum excess demand with a scrubber ($A^\text{MIN}_i$) and without a scrubber
(A_i^{MIN}) will increase to \(\hat{A}_i^{SMIN}\) and \(\hat{A}_i^{MIN}\), respectively. Maximum excess demand with a scrubber (A_i^{SMAX}) and without a scrubber (A_i^{MAX}) will shift in the same direction, which depends on the relationship of \(\frac{S_i^h}{H_i^h}\) to \(\frac{S_i^c}{H_i^c}\). A high sulfur coal contract creates a greater incentive to install a scrubber because of the higher minimum excess demand, and decreases the allowance price at which a unit will install a scrubber from \(P_A^S\) to \(P_A^S - \epsilon\). For this price range, a unit will install a scrubber where it would not have without the high sulfur coal contract constraint.

Introducing a low sulfur coal contract constraint will have the same direct impacts as when scrubbers are given. Coal use will be restricted by \(\mathcal{U}_d\). The excess demand correspondence will be impacted in the same manner except there will be four shifts instead of two. Minimum excess demand with a scrubber (A_i^{SMIN}) and without a scrubber (A_i^{MIN}) will shift in the same direction, which depends on the relationship of \(\frac{S_i^h}{H_i^h}\) to \(\frac{S_i^c}{H_i^c}\). Maximum excess demand with a scrubber (A_i^{SMAX}) and without a scrubber (A_i^{MAX}) will decrease to \(\hat{A}_i^{SMAX}\) and \(\hat{A}_i^{MAX}\), respectively. A low sulfur coal contract decreases the incentive to install a scrubber because of the lower maximum excess demand, and increases the allowance price at which a unit will install a scrubber from \(P_A^S\) to \(P_A^S + \epsilon\). For this price range, a unit will no longer install a scrubber where it would have without the low sulfur coal contract constraint.

In summary, coal contracts will restrict a unit’s coal use options, which may alter a unit’s compliance choices and excess demand for allowances. Less freedom in compliance decisions may result in an increase in a unit’s compliance costs.

### 3.3 Allowance Market Equilibrium

An allowance market equilibrium will exist under certain conditions. First, assume that there is perfect information and that all generating unit’s are price takers in the allowance market. The definition of an equilibrium for the allowance market is as follows:

**Definition 5.8.1**: An equilibrium for the allowance market is a price \(P_A^* \geq 0\), allowance excess demands \((A_i^*)\), spot market coal fuel purchases \((C_{ih}^s, C_{il}^s)\), and scrubber
installation choice \( (z_i^*) \) such that: (1) For each \( i \in \{1, \ldots, n\} \), \( A_i^*, z_i^*, C_{ih}^s, C_{il}^{cs} \) solve...

\[
\begin{align*}
\min_{z_i, A_i, C_{ih}^c, C_{il}^c} & \quad z_i P_{iz} + P_{i}^s A_i + P_{ih}^c C_{ih}^c + P_{il}^c C_{il}^c + P_{ih}^s C_{ih}^s + P_{il}^s C_{il}^s \\
\text{subject to} & \quad A_i + A_i \geq (1 - z_i r_i) (m) (C_{ih}^s S_{ih}^s + C_{il}^c S_{il}^c + C_{ih}^s S_{ih}^c + C_{il}^c S_{il}^c) \\
& \quad (C_{ih}^c H_{ih}^c + C_{il}^c H_{il}^c + C_{ih}^s H_{ih}^s + C_{il}^s H_{il}^s) \geq D_i \\
& \quad C_{ih}^c \geq C_{ih} \geq 0 \\
& \quad C_{il}^c \geq C_{il}^c \geq 0 \\
& \quad z_i \in \{0, 1\} \\
& \quad A_i \text{ is Unrestricted}
\end{align*}
\]  

(3–8)  

(3–9)  

(3–10)  

(3–11)  

(3–12)  

(3–13)  

(3–14)  

(3–15)  

(2) The allowance market clears. At \( P_A^* \),

\[
\sum_{i=1}^{n} A_i \leq 0 \quad \text{and} \quad P_A^* \sum_{i=1}^{n} A_i = 0
\]  

(3–16)  

**Theorem 5.1**: Assuming the scrubber choice \( (z_i^*) \) as given, an equilibrium exists for the allowance market.

From Kakutani’s Fixed Point Theorem, a fixed point exists if the market excess demand correspondence upper semi-continuous, compact-valued, and convex-valued. Each generating unit’s excess demand correspondences are upper semi-continuous, compact-valued, and convex-valued, which implies that the market excess demand is also upper semi-continuous, compact-valued, and convex-valued. Given these conditions there is a fixed point, and therefore, an equilibrium exists. Note that there may be multiple equilibria, but there is at least one equilibrium. The Proof of Theorem 1 is in Appendix B.

The existence of an allowance market equilibrium is no longer guaranteed once the discrete scrubber choice is introduced into the model. The non-convex nature of the scrubber decision variable makes it impossible to guarantee that an equilibrium exists because the excess demand is no longer convex for the range \( (A_i^{S\text{MAX}}, A_i^{M\text{IN}}) \). In such
a case, there will either be positive or negative market excess demand. In either case, it could be considered a “quasi-equilibrium” because it can be assumed that an allowance broker will sell any excess demand or buy any excess supply of allowances.

3.4 Comparative Statics: Effects on the Allowance Market

3.4.1 Comparative Statics: Effect of Relative Fuel Cost on the Allowance Market

Since a generating unit’s excess demand for allowances relies on the relative costs of purchasing allowances ($P_A$) compared to reducing emissions through switching from high sulfur to low sulfur coal ($MCA_{i,s}^{s,s}$). If $P_A > MCA_{i,s}^{s,s}$, then it is cheaper to switch to low sulfur coal. If $P_A < MCA_{i,s}^{s,s}$, then it is cheaper to purchase allowances. Therefore, changing the parameters of the marginal cost of abatement may alter the excess demand and, in turn, impact the allowance price.

**Proposition 1:** Assuming the scrubber choice, a higher fuel price differential for low sulfur spot market coal relative to high sulfur spot market coal will weakly increase $P_A$.

**Proof of Proposition 1:** From Chapter 2, the marginal cost of abatement is derived as

$$MCA_{i,s}^{s,s} = \left(\frac{P_{si} - P_{si}}{H_{si}} - \frac{P_{si} - P_{si}}{H_{si}}\right) \left(\frac{S_{si} - S_{si}}{H_{si} - H_{si}}\right) \left(1 - z_r(m)\right). \quad (3–17)$$

Consider the impact of an increase in the price of low sulfur spot market coal on the $MCA_{i,s}^{s,s}$. An increase in the price difference between fuels per unit of heat from $(P_{si} - P_{si})$ to $(P_{si} - P_{si})$ where $P_{si} < P_{si}$ increases the numerator of (3–17) and results in an increase in the marginal cost of abatement from $MCA_{i,s}^{s,s}$ to $MCA_{i,s}^{s,s} + \delta$ where

$$\delta = \left(\frac{P_{si} - P_{si}}{H_{si} - H_{si}}\right) \left(\frac{S_{si} - S_{si}}{H_{si} - H_{si}}\right) \left(1 - z_r(m)\right).$$

A higher $MCA_{i,s}^{s,s}$ makes the relative cost to the generating unit purchasing allowances lower, and will lead to a weak increase in a unit’s excess demand. Excess demand will increase if $MCA_{i,s}^{s,s} < P_A$ and $MCA_{i,s}^{s,s} + \delta > P_A$ and not change if $MCA_{i,s}^{s,s} + \delta < P_A$ or $MCA_{i,s}^{s,s} > P_A$. Greater excess demand in the allowance market results in an increase in the total allowance market demand and possibly a decrease in allowance market supply, both of which will weakly increase $P_A$. 

134
3.4.2 Comparative Statics: Effect of Coal Contracts on the Allowance Market Given the Scrubber Choice

Assuming the scrubber choice as given, each binding coal contract will have an unambiguous impact on the allowance price. A binding high sulfur coal contract weakly increases the allowance price, ceteris paribus. A binding low sulfur coal contract weakly decreases the allowance price in the market, ceteris paribus.

3.4.2.1 Impact of high sulfur coal contract on allowance market

A generating unit’s excess demand for allowances may be altered by a binding high sulfur coal contract constraint. From Chapter 2, a binding high sulfur coal contract will result in more high sulfur coal use than would be optimal for a generating unit and increase a generating unit’s excess demand. An increase in a generating unit’s excess demand may increase the allowance market price.

**Proposition 2:** Assuming the scrubber choice as given and \( \frac{S_{ih}}{H_{ih}} = \frac{S_{ih}}{H_{ih}} \), a high sulfur contract results in a weakly higher allowance price.

**Proof of Proposition 2:** As has already been shown in Chapter 2, given the scrubber choice and \( \frac{S_{ih}}{H_{ih}} = \frac{S_{ih}}{H_{ih}} \), a high sulfur contract results in a weak increase in a generating unit’s excess demand.

If \( P_A < MCA_{i,s} \), a generating unit prefers to use high sulfur coal, create its maximum possible emissions, and have an excess demand of \( A_{i,MAX} \). Assuming the same relative sulfur content for spot and contract coal, a high sulfur coal contract will not change total emissions or excess demand (\( \hat{A}_{i,MAX} = A_{i,MAX} \)) and \( P_A \) remains unchanged.

If \( P_A > MCA_{i,s} \), a generating unit prefers to switch fuels from high to low sulfur coal, create its minimum possible emissions, and have an excess demand of \( A_{i,MIN} \). However, the high sulfur coal contract would force greater than the minimum amount of emissions and weakly increase excess demand to \( \hat{A}_{i,MIN} \). A higher excess demand will lead to a decrease in the allowance market supply or both a decrease in allowance market supply and an increase in the allowance market demand. In both cases \( P_A \) weakly increases.
3.4.2.2 Impact of low sulfur coal contract on allowance market

A generating unit’s excess demand for allowances may be altered by a binding low sulfur coal contract constraint. From Chapter 2, a binding low sulfur coal contract will result in more low sulfur coal use than would be optimal for a generating unit and decrease a generating unit’s excess demand. A decrease in a generating unit’s excess demand may decrease the allowance market price.

**Proposition 3:** Assuming the scrubber choice as given and \( \frac{S^*_i}{R^*_i} = \frac{S^c_i}{R^c_i} \), a low sulfur contract results in a weakly lower allowance price.

**Proof of Proposition 3:** As has already been shown in Chapter 2, given the scrubber choice and \( \frac{S^*_i}{R^*_i} = \frac{S^c_i}{R^c_i} \), a low sulfur contract results in a weak decrease in a generating unit’s excess demand.

If \( P_A > MCA^{s,s}_i \), a generating unit prefers to switch fuels from high to low sulfur coal, create its minimum possible emissions, and have an excess demand of \( A^{MIN}_i \). Assuming the same relative sulfur content for spot and contract coal, a low sulfur coal contract will not change total emissions or excess demand (\( \hat{A}^{MIN}_i = A^{MIN}_i \)) and \( P_A \) remains unchanged.

If \( P_A < MCA^{s,s}_i \), a generating unit prefers to use high sulfur coal, create its maximum possible emissions, and have an excess demand of \( A^{MAX}_i \). However, the low sulfur coal contract would force less than the maximum amount of emissions and weakly decrease excess demand to \( \hat{A}^{MAX}_i \). A lower excess demand will lead to an increase in the allowance market supply or both an increase in allowance market supply and a decrease in the allowance market demand. In both cases \( P_A \) weakly decreases.

3.4.3 Comparative Statics: Effect of Coal Contracts on the Allowance Market with Endogenous Scrubber Choice

Previously when the scrubber choice was taken as given, the impact of coal contracts on the allowance price was unambiguously non-negative or non-positive. High sulfur contracts may only lead to an increase in the allowance price while low sulfur contracts
may lead to only a decrease in the allowance price. However, taking into account the scrubber choice causes the sign of the impact on the allowance price to become ambiguous.

When you consider the scrubber choice in the decision-making process, it is uncertain how a coal contract will affect the allowance market because the contract may increase or decrease excess demand depending on the allowance price ranges derived in Chapter 2. Although it is certain that if the coal contract binds, then there will be a shift to a sub-optimal excess demand for three different allowance price ranges.

### 3.4.3.1 High sulfur coal contract binds

Each of the three price ranges derived in Chapter 2 must be discussed to understand how a high sulfur coal contract will effect the allowance market, both in terms of the allowance market supply, allowance market demand, and the allowance price. Assume

\[
\frac{S^s_{ih}}{H^s_{ih}} = \frac{S^c_{ih}}{H^c_{ih}}.
\]

If a generating unit has a high sulfur coal contract, the unit’s excess demand increases for two allowance price ranges: \((P_A > M\tilde{C}A_i^{s,s})\) and \((P_A^S - \epsilon > P_A > MCA_i^{s,s})\).

The increase in excess demand will be from \(A_i^{SMIN} \) to \(\hat{A}_i^{MIN}\) when \((P_A > M\tilde{C}A_i^{s,s})\).

The increase in excess demand will be from \(A_i^{MIN}\) to \(\hat{A}_i^{MIN}\) or \(A_i^{MIN}\) to \(A_i^{MAX}\) when \((P_A^S - \epsilon > P_A > MCA_i^{s,s})\), depending on the relationship between \((P_A^S - \epsilon)\) and \(MCA_i^{s,s}\).

It will be the latter in the special case where the generating unit always prefers to use high sulfur coal.

When the market allowance price is in these two ranges that result in an increase in a generating unit’s excess demand, there will be either an increase in the market demand for allowances, or both an increase in market demand and a decrease in market supply for allowances. In both situations, the allowance price will be driven higher.

The third price range that has a shift in the excess demand is \((P_A^S - \epsilon, P_A^S)\). A generating unit decreases its excess demand from \(A_i^{MIN}\) to \(A_i^{SMAX}\), which is a result of a unit installing a scrubber for a price range for which it initially would not install a scrubber.
When the market allowance price is in this range that results in a decrease in a
generating unit’s excess demand, there will be either an decrease in the market demand
for allowances, or both an decrease in market demand and a increase in market supply for
allowances. In both situations, the allowance price will be driven lower.

### 3.4.3.2 Low sulfur coal contract binds

Each of the three price ranges derived in Chapter 2 must be discussed to understand
how a low sulfur coal contract will effect the allowance market, both in terms of the
allowance market supply, allowance market demand, and the allowance price. Assume
\[
\frac{s_i^a}{\bar{h}_i} = \frac{s_i^c}{\bar{h}_i}.
\]

If a generating unit has a low sulfur coal contract, the unit’s excess demand decreases
for two allowance price ranges: \( (M \tilde{C} A_i^{s,s} > P^A > P^S + \epsilon) \) and \( (\min\{P^S, MCA_i^{s,s}\} > P^A) \). The decrease in excess demand will be from \( A_i^{SMAX} \) to \( \tilde{A}_i^{MAX} \) when \( (M \tilde{C} A_i^{s,s} > P^A > P^S + \epsilon) \). The decrease in excess demand will be from \( A_i^{MAX} \) to \( \tilde{A}_i^{MAX} \) when
\( (\min\{P^S, MCA_i^{s,s}\} > P^A) \).

When the market allowance price is in these ranges that result in a decrease in a
generating unit’s excess demand, there will be either an decrease in the market demand
for allowances, or both an decrease in market demand and a increase in market supply for
allowances. In both situations, \( P^A \) will be driven lower.

The third price range that has a shift in the excess demand is \( (P^S, P^S + \epsilon) \). A
generating unit increases its excess demand from either \( A_i^{SMAX} \) to \( A_i^{MIN} \) or \( A_i^{SMAX} \) to
\( \tilde{A}_i^{MAX} \) depending on the relationship between \( (P^S + \epsilon) \) and \( MCA_i^{s,s} \). This increase is
a result of a unit not installing a scrubber for a price range for it initially would have
installed a scrubber.

When the market allowance price is in this range that results in an increase in a
generating unit’s excess demand, there will be either an increase in the market demand
for allowances, or both an increase in market demand and a decrease in market supply for
allowances. In both situations, \( P^A \) will be driven higher.
3.5 Compliance Costs

Total compliance costs for a generating unit are the *additional costs due to the program*, including costs from switching fuels, the costs from its net allowance position, and scrubber installation costs (seen in (3–18)).

\[
z_i P_{iz} + P^* A_i + \max \left\{ \left( P^s_i C^s_i + P^s_{ih} C^s_{ih} - P_{ih} \hat{C}^{s,MAX}_{ih} \right), 0 \right\}
\]  

(3–18)

Compliance costs may be positive or negative depending on its compliance decisions and its initial allowance allocation. The scrubber installation costs are represented by \( P_{iz} \), and will only attribute to a unit’s compliance costs if a scrubber is installed in response to the program \( (z_i = 1) \). The costs of a unit’s net allowance position is the difference between a generating unit’s initial allowance allocation and its actual emissions multiplied by the allowance price \( (P_A A_i) \). The costs of switching fuels is the larger of two values: (1) total costs of actual coal purchases \( (P^s_{ih} C^s_{ih} + P^s_{il} C^s_{il} + P^c_{ih} C^c_{ih} + P^c_{il} C^c_{il}) \) minus the costs of purchasing only high sulfur spot market coal given any contracted coal \( (P^s_{ih} \hat{C}^{s,MAX}_{ih} + P^c_{ih} \hat{C}^c_{ih} + P^c_{il} \hat{C}^c_{il}) \), or (2) zero. The latter will only occur if it is weakly cheaper for the generating unit to use low sulfur coal without the emissions restrictions \( (P^s_{ih} \geq P^s_{il}) \). It is important to consider that the contracted coal will be used regardless of the program and will have no direct impact on compliance costs. However, a contract could have an indirect impact by altering compliance decisions.

3.5.1 Compliance Costs with Coal Contracts Relative to Compliance Costs from Previous Studies

Previous studies have assumed no restrictions on coal use, which results in a different estimation of compliance costs. The optimal compliance choices in this case will not account for any coal use restrictions. The constant “c” is the minimum costs for a generating unit to meet its electricity demand if emissions and coal use are not restricted.

\[
z_i^* P_{iz} + P^* A_i^* + P^s_{il} C^s_{il} + P^s_{ih} C^s_{ih} - c
\]  

(3–19)
A binding high (low) sulfur coal contract constraint leads to two possible cost inefficiencies, but only one of which increases compliance costs. First, a contract could lead to a generating unit using more than the optimal amount of high (low) sulfur coal and less than the optimal low (high) sulfur coal. In this case, actual compliance decisions are altered and may lead to a sub-optimal coal mix. Second, a contract may force a unit to use some high (low) sulfur coal that is “more expensive” than the high (low) sulfur spot market coal price, which increases total costs while leaving compliance costs unchanged. In previous studies, both of these cost inefficiencies were identified as excess compliance costs because contract restrictions were ignored in the baseline costs without the program (c).

\[(\tilde{z}_i P_{iz} + P^*_i A_i + P^*_i C^s_{il} + P^*_i C^s_{ih} + P^*_i C^s_{il} - c) \geq (z^*_i P_{iz} + P^*_i A_i + P^*_i C^s_{il} + P^*_i C^s_{ih} - c)\]

(3–20)

The minimum compliance cost choices with no contract constraint for previous studies are denoted by “∗” while the contract constrained minimum compliance cost choices are denoted by “∧” in (3–20). The assumed “c” is the total costs of meeting demand assuming no contract constraint or emissions constraint. The cost difference between these two sets of choices will be the combination of changes in compliance decisions and fuel costs. Some of these “excess compliance costs” may not be compliance costs, which makes the derived compliance costs too high. So it is important to include the contract constrained coal use in the baseline “c” to get the appropriate compliance costs. Assuming that contracted coal is at least as expensive as spot market coal, the compliance costs will be greater for the contract constrained case as shown in (3–20) and as expressed in (3–21).

\[
P_{iz}(\tilde{z}_i - z^*_i) + P^*_i (A_i - A^*_i) + P^*_i (C^s_{il} - C^s_{il}) + P^*_i (C^s_{ih} - P^*_i C^s_{ih} - c) \geq 0 \quad (3–21)
\]

Consider a simple example where high sulfur contract coal is more expensive than high sulfur spot market coal, low sulfur coal is preferred over high sulfur coal, and no scrubber would be installed if a generating unit had total freedom in its coal use choices. Now compare a generating unit’s compliance costs to the compliance costs a unit would
face with a high sulfur coal contract for 100% of its coal use. The change in compliance costs seen in (3–22) include the additional costs from an increase in allowance purchases and a decrease in coal costs from using cheaper, but dirtier fuel.

\[
P_A^*(A_i^{MAX} - A_i^{MIN}) - P_{il}C_{il}^{s,MAX} + P_{ih}C_{ih}^c > 0 \tag{3–22}
\]

Since the contract coal would have to be used regardless of enactment of the program, the additional costs for high sulfur contract coal use instead of high sulfur spot market coal \((P_{ih}C_{ih}^{c,MAX} - P_{ih}C_{ih}^{s,MAX})\) should not be included in compliance costs. However, previous studies would recognize these fuel costs as compliance costs based on the assumed cost minimization without contract constraints.

\[
\hat{z}_i P_{iz} + P_A^* \hat{A}_i + P_{il} \hat{C}_{il}^s + P_{ih} \hat{C}_{ih}^s + P_{il}C_{il}^c + P_{il}C_{il}^c - \hat{c} \tag{3–23}
\]

The appropriate unit-level compliance costs will take the form shown in (3–23) where the baseline total costs will take the value “\(\hat{c}\)”, which represents the costs of meeting electricity demand given the coal contract constraint. These costs “\(\hat{c}\)” will be different than “\(c\)” because the spot market coal use will be altered if the contracted coal differs relative the spot market coal it replaces in production.

\[
P_{il} \hat{C}_{il}^s + P_{ih} \hat{C}_{ih}^s + P_{il}C_{il}^c + P_{il}C_{il}^c \neq P_{il}C_{il}^s + P_{ih}C_{ih}^s \tag{3–24}
\]

### 3.5.2 Total Industry Compliance Cost

The total compliance costs to the industry are the sum of the combined scrubber installation costs and fuel switching costs for all affected generating units. The total industry costs from net allowance purchases are zero because each allowance sold by one generating unit at \(P_A^*\) is purchased by another generating unit at \(P_A^*\). Assuming that high sulfur coal is cheaper than low sulfur coal, then the total industry compliance costs are (3–25).

\[
\sum_{i=1}^{n} \left[ z_i P_{iz} + \max\{(P_{il}C_{il}^s + P_{ih}C_{ih}^s - P_{ih}C_{ih}^{s,MAX}), 0\}\right] \tag{3–25}
\]
The minimum unconstrained total industry compliance costs to the industry is derived from the following problem. Each generating unit chooses its optimal $A_i^*, C^s_{ih} \geq 0, C^s_{il} \geq 0, z_i^* \in \{0, 1\}$ based on the market equilibrium allowance price, $P^*_A$. The total compliance costs as shown in the objective function in (3–26) are the sum of the compliance costs for each generating unit. Similar to the generating unit’s problem in Chapter 2, there are two constraints that must be met. First, the sum of allowance allocations must cover the sum of emissions that are emitted by all affected generating units. Second, each generating unit must produce enough electricity to cover its electricity demand requirement.

\[
\min_{z_i, A_i, C^s_{ih}, C^s_{il}} \sum_{i=1}^n z_i P_{iz} + \max\{(P^s C^s_{il} + P^s C^s_{ih} - P^s C^s_{ih}^{MAX}), 0\} \tag{3–26}
\]

\[
s.t. \sum_{i=1}^n (1 - z_i r_i)(C^s_{il} S^s_{il} + C^s_{ih} S^s_{ih})(m) \leq \sum_{i=1}^n A_i^s
\]

\[
(C^s_{il} H^s_{il} + C^s_{ih} H^s_{ih}) \geq D_i \quad \forall i \in \{1, ..., n\}
\]

\[
z_i \in \{0, 1\} \quad \forall i \in \{1, ..., n\}
\]

If all generating units’ cost-minimizing decisions result in an equilibrium in the allowance market, then total industry compliance costs are minimized. We can prove this by showing the first-order conditions for the minimized total industry compliance costs match up with the first-order conditions from the generating unit’s problem in Chapter 2, and the optimal choices will be the same for both problems.

Solve for the first-order conditions given $z_i$. For high sulfur coal:

\[
P_{ih} + \lambda_{i1}(1 - z_i r_i)(m)(S^s_{ih}) - \lambda_{i2} H^s_{ih} \geq 0, = 0 \text{ if } C_{ih} > 0 \tag{3–27}
\]

For low sulfur coal:

\[
P_{il} + \lambda_{i1}(1 - z_i r_i)(m)(S^s_{il}) - \lambda_{i2} H^s_{il} \geq 0, = 0 \text{ if } C_{il} > 0 \tag{3–28}
\]
The first-order conditions are identical to those of the individual generating unit in Chapter 2 when neither coal contract constraints bind. So a generating unit’s cost minimizing choices of \( C_{s_i}^*, C_{s_{il}}^* \) at \( P_A^* \) for each generating unit also minimize total industry compliance costs at \( P_A^* \).

These first-order conditions can be used to solve for \( \lambda_i \), the allowance shadow price, which is also the same as for the generating unit problem. Since the compliance choices that minimize the costs for all generating units result in the equilibrium \( P_A^* \), the allowance choices also minimize the total industry costs.

\[
\lambda_i = MA_i^{s,s} = \frac{P_{il}^s - P_{ih}^s}{(1 - z_ir_i)(m)(S_{il}^s - S_{ih}^s)} \quad (3-29)
\]

The same approach can be used under the industry-wide compliance cost problem with coal contract constraints to show that contract constrained minimum total industry compliance cost will differ from the unconstrained costs.

\[
\min_{z_i,A_i,C_{il},C_{ih}} \sum_{i=1}^{n} [z_i P_{iz} + \max\{(P_{il}^s \widehat{C}_{il}^s + P_{ih}^s \widehat{C}_{ih}^s - P_{il}^s \widehat{C}_{il}^{MAX}, 0]\} \quad (3-30)
\]

s.t. \[
\sum_{i=1}^{n} (1 - z_ir_i)(\widehat{C}_{il}^s S_{il}^s + \widehat{C}_{ih}^s S_{ih}^s + \widehat{C}_{il}^c H_{il}^c + \widehat{C}_{ih}^c H_{ih}^c)(m) \leq \sum_{i=1}^{n} A_i^c \]

\[
(\widehat{C}_{il}^c H_{il}^s + \widehat{C}_{ih}^c H_{ih}^s + \widehat{C}_{il}^c H_{il}^c + \widehat{C}_{ih}^c H_{ih}^c) \geq D_i \quad \forall i \in \{1, ..., n\}
\]

\[
\widehat{C}_{il}^c, \widehat{C}_{ih}^c \geq 0 \quad \forall i \in \{1, ..., n\}
\]

\[
z_i \in \{0, 1\} \quad \forall i \in \{1, ..., n\}
\]

The first-order conditions. For high sulfur spot market coal...

\[
P_{ih}^s + \lambda_i (1 - z_ir_i)(m) S_{ih}^s - \lambda_i z H_{ih}^s \geq 0, = 0 \text{ if } C_{ih}^s > 0 \quad (3-31)
\]

For low sulfur spot market coal...

\[
P_{il}^s + \lambda_i (1 - z_ir_i)(m) S_{il}^s - \lambda_i z H_{il}^s \geq 0, = 0 \text{ if } C_{il}^s > 0 \quad (3-32)
\]
The first-order conditions are identical to those of the individual generating unit in Chapter 2.

\[
\lambda_{i1} = \frac{P^{s\text{il}}}{H^{s\text{il}}_{th}} - \frac{P^{s\text{ih}}}{H^{s\text{ih}}_{th}} \frac{(1 - z_i r_i)(m)\left(S^{s\text{ih}}_{s\text{ih}} - S^{s\text{il}}_{s\text{il}}\right)}{(1 - z_i r_i)(m)\left(S^{s\text{ih}}_{s\text{ih}} - S^{s\text{il}}_{s\text{il}}\right)}
\] (3–33)

These first-order conditions can be used to solve for \(\lambda_{i1}\), the allowance shadow price, which is also the same as for the individual generating unit problem. If a generating unit uses high sulfur coal, \(P_A \leq MCA_i^{s,s}\). If a generating unit uses low sulfur coal, \(P_A \geq MCA_i^{s,s}\). If a generating unit uses both high and low sulfur coal, \(P_A = MCA_i^{s,s}\).

So a generating unit’s cost minimizing choices of \(z_i^*, C_{ih}^{s*}, C_{il}^{s*}, A_i^{s*}\) for each generating unit also minimize total industry compliance costs. If the contract constrained compliance choices that minimize the costs for a generating unit results in an equilibrium \(P_A^*\), the choices also minimize the contract constrained total industry costs. Note that the optimal parameter combination for the contract constrained case will not be the same as under the unconstrained case.

It has already been shown that any binding contract constraint for an individual generating unit will result in a sub-optimal combination of coal use, which will weakly increase compliance costs for the contract constrained generating unit. Any sub-optimal choices made by one generating unit will weakly increase the costs for the entire industry.

### 3.5.3 Impact of Allowance Allocation on Compliance Costs Given Scrubber the Choice

There are several studies that have considered the impact of the allowance allocation distribution on cost efficiencies of allowance trading systems. Montgomery (1972) showed that the allowance allocation distribution does not affect compliance costs, but it does not consider the possible effects of contract constraints or PUC regulation. Stavins (1995) has shown that transaction costs in allowance trading markets with continuous marginal abatement costs can cause the initial allowance allocation distribution to matter for efficiency. Montero (1997) extends Stavins (1995) by introducing non-continuous marginal
abatement costs through discrete technology choices and introducing uncertainty into
the Stavins’ model. Montero finds that in an allowance trading system with transaction
costs, non-continuous marginal abatement costs resulting from discrete technology choices
can cause the initial allocation of allowances to matter for efficiency, even with constant
marginal costs of abatement and certainty.

The importance of the allowance allocation in these previous studies relies on the
existence of transaction costs. However, this model has assumed no allowance transaction
costs, which allows it to show that even with coal contract constraints the allowance
allocation distribution will not impact a generating unit’s compliance choices or the total
industry compliance costs.\footnote{\textit{\textsuperscript{1}}} 

Consider the first-order conditions for both high sulfur and low sulfur coal, which are
independent of a generating unit’s allowance allocation. The type of coal a unit will use
will not depend on $A_i^e$.

\begin{equation}
    P_{ih} + \lambda_{i1}(1 - z_ir_i)(m)(S_{ih}^s) - \lambda_{i2}H_{ih}^s \geq 0 \quad (3-34)
\end{equation}

\begin{equation}
    P_{il} + \lambda_{i1}(1 - z_ir_i)(m)(S_{il}^s) - \lambda_{i2}H_{il}^s \geq 0 \quad (3-35)
\end{equation}

The choice between switching fuels or purchasing allowances is based solely on a
generating unit’s relative marginal cost of purchasing the next allowance compared to the
effective marginal cost of abating the next unit of emissions. As can be seen, $A_i^e$ has no
impact on a generating unit’s compliance decisions. A generating unit will use allowances

\footnote{\textit{\textsuperscript{1}} It is assumed that generating units are unable to break their contracts. Generating
units could realistically break their contracts at a very high price and create the additional
freedom in its compliance choices. In such a case, contract constraints would result in very
high transaction costs for trading those additional allowances.}
when \( P_A^* < MCA_i^{s,s} \) and switch fuels when \( P_A^* > MCA_i^{s,s} \).

\[
P_A^* \geq MCA_i^{s,s} = \frac{P_{il} - P_{ih}}{H_{ih} - H_{il}} \frac{S_{ih} - S_{il}}{(1 - z_i r_i)(m)(S_{ih} H_{ih} - S_{il} H_{il})}
\]  

(3–36)

### 3.5.4 Impact of Allowance Allocation with Endogenous Scrubber Choice

Consider the expression for the allowance price at which a generating unit is indifferent to installing a scrubber \( (P_A^S) \), which has already been derived in Chapter 2.

\[
P_{iz} + P_{ih}(\tilde{C}_{ih} - \tilde{C}_{ih}) + P_{id}(\tilde{C}_{id} - \tilde{C}_{id}) \leq P_A^S
\]

(3–37)

It is possible to fill in for \( A_i = (E_i - A_i^e) \) since excess demand is the difference between actual emissions and initial allowance allocation to see how \( A_i^e \) will impact \( P_A^S \). In the denominator, \( A_i^e \) and \(-A_i^e\) cancel out, leaving an expression for \( P_A^S \) that is unaffected by \( A_i^e \). So a generating unit’s scrubber choice will be made independent of \( A_i^e \).

\[
\Rightarrow \frac{P_{iz} + P_{ih}(\tilde{C}_{ih} - \tilde{C}_{ih}) + P_{id}(\tilde{C}_{id} - \tilde{C}_{id})}{(E_i + A_i^e - E_i - A_i^e)} \leq P_A^S
\]

Now consider the compliance choices made after the scrubber installation decision. It was shown in Chapter 2 that a generating unit’s compliance choices are based on the relationship between the \( P_A^* \) and \( MCA_i^{s,s} \) or \( M\tilde{CA}_i^{s,s} \), depending on the unit’s scrubber choice, for a particular unit of coal. Similar to what was shown above, a generating unit’s \( M\tilde{CA}_i^{s,s} \) and \( MCA_i^{s,s} \) for a given unit of coal are not affected by \( A_i^e \) because allowances are not a parameter in the marginal cost of abatement.

\[
M\tilde{CA}_i^{s,s} = \frac{P_{il} - P_{ih}}{H_{il} - H_{ih}} \frac{S_{ih} - S_{il}}{(1 - z_i r_i)(m)(S_{ih} H_{ih} - S_{il} H_{il})}
\]

\[
MCA_i^{s,s} = \frac{P_{il} - P_{ih}}{(m)(S_{ih} H_{ih} - S_{il} H_{il})}
\]
3.6 Simulation Model

3.6.1 Introduction

It has been shown analytically that contracts may alter compliance choices by altering coal use and scrubber installation and lead to greater compliance costs. These results may be able to explain a large portion of the excess compliance costs found in previous studies. This section will show how much of these excess compliance costs can be explained by contract constraints.

The first portion of this section will look at the data used to parameterize the simulation model, which includes a description of where the data was obtained, the techniques used to create the parameters, and some issues regarding the data. The second portion will look at the model design and approach. The last portion will summarize the simulation results in terms of the total industry, individual states, and individual generating units.

3.6.2 Data

All data used in the simulation, with an exception for the coal contract data, were obtained from Dr. Paul Sotkiewicz. Using the same data allows for direct result comparisons to determine the coal contract impacts. Dr. Sotkiewicz originally hand-collected the the data from the EIA’s “Cost and Quality of Fuels 1996,” the EIA’s “Electric Power Annual 1997,” and the EPA’s “1996 Compliance Report.”

Up to this point all generating units are assumed to be coal-fired units because it is the primary fuel options for electricity generation in the U.S. However, there are 24 units of the 431 units that used fuel oil or natural gas for electricity generation. The treatment of these units is described in Section 6.2.1.

3.6.2.1 Fuel data

Fuel data on heat content, sulfur content, and delivered price were obtained from the EIA’s “Cost and Quality of Fuels 1996”, which compiled information from FERC Form 423. The coal contract data was gathered directly from the FERC Form 423 database for
1996, which describes the characteristics of all fuel delivered to utility plants. Information on the heat content, sulfur content, purchasing agreement, and delivered price for each shipment are available, which can differ greatly from utility to utility and delivery to delivery for each plant depending on location.

The heat content of delivered coal is in Btus of heat per ton of coal, barrel of oil, or 1,000 cubic feet of natural gas. All fuel parameters are converted in terms of a heat content baseline to allow for comparisons across units.

The purchasing agreement is labeled as two possible parameters: (1) spot market and (2) contract purchases. An agreement is considered a spot market purchase if the agreement is for less than 2 years. Purchasing agreements of two years or greater are considered to be under contract. The amount of fuel under contract is in tons, barrels, or 1,000 cubic feet depending on the fuel. The data is manipulated into total heat content by multiplying the heat content per unit of fuel by the amount of fuel delivered.

Since coal deliveries are made at the plant level, the size of the contract constraint is not easily derived for each generating unit. The parameter for the amount of contract coal for each generating unit was derived in the following manner. First, any unit at a given plant that actually installed a scrubber is allocated as much high sulfur contract coal as possible while receiving as little low sulfur contract coal as possible. The reasoning for this is that a unit with a scrubber will have a larger marginal cost of abatement from switching fuels ($MCA_{i,s} < M\tilde{C}A_{i,s}$). Second, any remainder is spread out evenly throughout the remaining generating units without installed scrubbers. Third, if the equal distribution results in too much coal for a unit to use in production, the excess coal will be shifted to a unit that requires a greater total heat input. Fourth, if a plant’s coal contracts result in more heat input than was actually required in production, coal use is capped at the heat input needed to meet demand. Any remaining coal is considered to be remain stored for future use.
Consider the following example for a plant with three generating units each requiring 200,000 mmBtu of heat input to cover their electricity demand and one unit has a scrubber. Contracts account for 100% of coal purchasing agreements where there are contracts for 300,000 mmBtu for both high sulfur contract coal and low sulfur contract coal. Based on the distribution approach described above, Unit 1 will use as much of the high sulfur coal as possible (200,000 mmBtu) and the remaining high sulfur coal will be distributed equally among the remaining two units (50,000 mmBtu each for Unit 2 and Unit 3). The low sulfur coal will be distributed to Unit 2 and Unit 3 equally because neither has a scrubber installed (150,000 mmBtu each). Since contracts account for 100% of coal use, there is no need to purchase any coal on the spot market. If there had been any excess coal, such as an extra 10,000 mmBtu of low sulfur contract coal, it would not change the allocation in Table 3-1 and would be considered coal stored at the plant for use the following year.

Sulfur content is the percentage of each ton of coal, barrel of oil, or 1,000 cubic feet of natural gas that is sulfur. The data must be manipulated to create the desired variable, which is pounds of sulfur dioxide per million Btus of heat. Phase I of Title IV distributes allowance allocations based on 2.5 pounds of SO$_2$ per million Btus of heat. So fuel is considered “high sulfur” if contains greater then 2.5 lbs. of SO$_2$ per mmBtu and “low sulfur” if it contains less than 2.5 lbs. of SO$_2$ per mmBtu. Any coal use that has a higher (lower) sulfur content will increase (decrease) emissions above (below) its allocation allows.$^2$

Getting the data in terms of pounds of sulfur dioxide per million Btus of heat requires an emissions factor, which is the amount of sulfur dioxide emissions that will result from a unit of sulfur. Emissions factors were found in the EIA’s “Electric Power Annual 1997”. By taking the sulfur content multiplied by the emissions factor divided by the millions of

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$^2$ Coal sulfur content can vary significantly within each category (high or low sulfur).
Btu per unit (ton, 1,000 barrels, or million cubic feet), it results in a parameter in pounds of sulfur dioxide per million Btu (lbs. SO$_2$/mmBtu).

Although nearly all generating units affected by Phase I were coal-fired units, 24 units use fuel oil or natural gas for electricity generation. For these units, fuel oil is designated as high sulfur fuel option while natural gas is designated as the lower sulfur fuel option for non-coal fired units.

The delivered price is the cents per ton, barrel, or 1,000 cubic feet paid at the time of delivery. The price includes the purchasing of the fuel and the transportation costs of shipment. The price is converted to the price of fuel in cents per million Btus. A separate delivered price is required for both high sulfur and low sulfur fuel, which is a weighted average of all deliveries of each category of coal. So the high (low) sulfur price used in the simulations is the weighted average delivered price for all high (low) sulfur coal deliveries. The parameter used in the simulations is actually dollars per mmBtu, or cents/mmBtu divided by 100.

Another issue is that not all generating units purchased both high sulfur and low sulfur fuel. Proxies were required to determine the fuel characteristics facing each unit, and were first taken from other generating units that were owned by the same company where available. If a unit did not have another unit under the same company, a proxy was taken from the geographically closest plant because shipping costs are an important factor in determining the delivered price. Regional variation in prices will be much smaller variation in prices across the U.S.

3.6.2.2 Allowance, actual emissions, and demand data

Data for allowance allocation, actual emissions, and electricity demand was found in the EPA’s “1996 Compliance Report”. Electricity demand is measured in terms of the heat input instead of actual megawatt-hours of electricity. For a given unit, there is a given amount of heat input required to produce one unit of electricity. This linear nature of electricity production per unit of heat input allows for this simple conversion. For
example, if it requires 1 mmBtu to create 1 MWh of electricity, a unit facing a demand of 100 MWh would require 100 mmBtu of heat input. Allowance allocations and actual emissions can be used directly without any manipulation. Actual emissions are used as the initial allowance allocation allowance banking caused the amount of allowances used during 1996 be less than the total amount of allocated allowances.

3.6.2.3 Technical generator and scrubber data

Generator nameplate capacity and heat rate data was found in the EIA’s “Annual Generator Data 1996”. The heat rate is the amount of heat required to produce one kilowatt-hour of electricity. Heat rate data unavailable in the 1996 report were gathered from “Annual Generator Data 1992-1995”.

Scrubber cost data was found in the EIA’s “Electric Power Annual 1997”. The data was the historical scrubber cost data, including state-by-state average installed costs per kilowatt of capacity, average operation and maintenance costs in terms of mills per kilowatt-hour, megawatts of capacity for units with scrubbers installed, and sulfur removal efficiency.3

The scrubber installation choice is multi-year decision. However, the simulation model is a one-year model, which makes it necessary to annualize the costs of installing and operating a scrubber. Scrubber installation costs will differ depending on the scrubber technology and the size of the generating unit. Total scrubber costs are the discounted annualized cost of scrubber installation and the operation and maintenance costs for the

3 Engineering-based estimates for scrubber installation and operation costs are an alternative to historical-based estimates.
given electricity production. The chosen discount rate of ten percent and a twenty year lifespan for capital equipment are the same as in Sotkiewicz and Holt (2005).

3.6.3 Simulation Model Design

The simulation requires a mixed integer linear program because of the discrete scrubber choice. The simulation model is coded in Matlab and the linear program is solved using the open source LP Solve mixed integer linear programming solver. If the scrubber choice is taken as given, the simulation becomes a simple linear programming model, which guarantees an equilibrium.

An endogenous scrubber choice creates a non-convexity that may not result in an allowance market equilibrium. In such a case, there will be either a positive or a negative excess demand for allowances and an allowance price at which a generating unit is indifferent to installing a scrubber. This could be considered a “quasi-equilibrium” where the excess demand is either bought from or sold to an allowance broker at the “quasi-equilibrium” allowance price. The technical explanation of the bisection iterative process used to converge to an equilibrium allowance price is described in detail in Appendix B.

3.6.4 Simulation Results

Seven different generating unit level simulations were run to determine compliance costs under several sets of conditions depending on the assumptions on the emissions constraint, contract constraint, and scrubber choice. These simulations are used to derive the impacts on not only the industry, but also on individual states and generating units.

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4 To annualize capital costs, the following equation is used to determine the present value of the costs: \( \frac{\rho(1+\rho)^t}{(1+\rho)^t-1} \) where \( \rho \) is the discount rate and “t” is the number of years the lifetime of the equipment.

5 The use of historical scrubber cost data will result in different results than engineering cost estimates because the historical costs for scrubbers in 1996 dollars are cheaper than engineering estimates for 316 out of 431 units.
3.6.4.1 Total industry costs and allowance market results

The simulation results are used to analyze three key issues: (1) replication of results from previous studies, (2) the impact contract constraints have on the results from previous studies, and (3) the “true” compliance costs resulting from the Title IV program. Simulations 1, 3, and 4 recreate the results from previous studies while Simulations 2, 5, and 6 introduce the contract constraints to the model. Simulation 7 derives industry costs based on actual compliance choices.

First, consider the ability of the simulation models to recreate the results from previous studies. Simulation 1 recreates the unconstrained cost-minimization results from Sotkiewicz (2003) and Sotkiewicz and Holt (2005). There were 17 scrubbers that were installed as a result of the New Source Performance Standards (NSPS) and were unrelated to Title IV. Assuming these scrubbers as given, the total costs to the industry of meeting electricity demand were $7.69 billion. These costs will be used as the baseline total industry costs to determine total industry compliance costs comparable to previous studies.

Simulation 3 recreates the emissions constrained results from Sotkiewicz and Holt (2005) assuming the 46 scrubbers that were installed in 1996 as given. The simulation results in an allowance price of $149.64, which exactly replicates the allowance price found by Sotkiewicz (2003) and Sotkiewicz and Holt (2005). Total industry costs are $8.23 billion where 29 scrubbers were actually installed in response to Title IV. The difference between Simulation 3 and Simulation 1 is the total industry compliance costs of meeting the emissions constraint, which is $541 million and similar to the results found in previous
Carlson et al. (2000) and Sotkiewicz and Holt (2005) found the least cost outcome to be $571 million and $527 million, respectively.  

Simulation 4 recreates the emissions constrained results from Sotkiewicz (2003) that allows a generating unit’s scrubber choice to be endogenous. The model assumes the 17 scrubbers installed to meet the NSPS, but allows generating units to make the scrubber installation choice. The simulation results in an allowance price of $155.58. Total industry costs are $7.97 billion, where 27 scrubbers were installed in response to Title IV (42 scrubbers total). Allowing generating units to make their scrubber installation choice results in two fewer installed scrubbers, which may explain the slightly higher $P_A^*$ because fewer scrubbers will decrease supply and increase demand for allowances. The difference between Simulation 4 and Simulation 1 is the total industry compliance costs of meeting the emissions constraint, which is lower than the costs found in Simulation 3 at $288 million. The results are comparable to the $340 million found in Sotkiewicz (2003). As expected, freedom in the scrubber choice improves efficiency and lowers total industry compliance costs by $252 million, or 47% lower than in Simulation 3.

The allowance market does not clear in Simulation 4 because generating units are allowed to make their scrubber choice. The discrete nature of scrubber installation leads to a non-negative excess demand. However, the excess supply of 53,576 allowances in Simulation 4 account for less than 1% of the 5+ million allowance market and could be assumed to be banked for future use or sold to an allowance broker, which could be considered a quasi-equilibrium.

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6 The value slightly differs relative to the results from Sotkiewicz (2003) and Sotkiewicz and Holt (2005) because the scrubber cost estimates in this study have higher estimated variable operating costs.

7 Burtraw et al. (2005) and Sotkiewicz and Holt (2005)
Second, consider how fuel contract constraints will impact the total industry compliance costs. Simulation 5 introduces fuel contract constraints to the emissions constrained model assuming the 46 scrubbers installed as in Simulation 3. The simulation results in a higher allowance price of $206.70, which could be the result of a greater demand for allowances due to more high sulfur coal use resulting from high sulfur coal contracts. Total industry costs are $8.76 billion, where 29 scrubbers were installed in response to Title IV. Assuming these scrubber choices, the minimum compliance costs relative to the unconstrained model in Simulation 1 are $1.07 billion, or $531 million (98%) higher than if contracts are not taken into consideration.

Simulation 6 introduces fuel contract constraints to the emissions constrained model while allowing generating units to make their scrubber choice. The simulation results in an allowance price of $210.74. Total industry costs are $8.63 billion where 44 scrubbers are installed in response to Title IV. The minimum compliance costs when compared to Simulation 1 are $939 million, or $651 million higher than if contracts are not taken into consideration. The minimum compliance costs are close to the actual cost found in Sotkiewicz and Holt (2005) at $990 million and Carlson et al. (2000) at $910 million.

Allowing generating units to choose whether to install a scrubber allows the industry to lower its total costs by $132 million. As would be expected, introducing the contract constraint results in more scrubber installations due to Title IV from 27 to 44 because high-sulfur fuel contracts increase the incentive for a constrained generating unit to install a scrubber. As in Simulation 4, the allowance market does not clear due to the discrete, endogenous scrubber choice. However, the excess demand of 7,797 allowances account for less than 0.2% of the 5+ million allowance market, and could be assumed to be bought from an allowance broker.

The actual total industry compliance costs are found in Simulation 7. By using the actual emissions and electricity production for each unit, it is possible to determine each unit’s actual coal mix. These actual decisions resulted in an allowance price range
of $69.33-$95.38 during 1996, total industry costs of $8.98 billion, and total industry compliance costs of $1.30 billion relative to Simulation 1. If the contract constraints are excluded from the model and the actual costs are compared to Simulation 3 and Simulation 4, the excess compliance costs are $757 million and $1.01 billion, respectively. However, including the contract constraint into the model results in excess compliance costs of $226 million and $358 million. Contract constraints explain $531 million and $651 million of excess compliance costs, respectively.

Third, the “true” compliance costs will differ from these estimates because the appropriate baseline was not used. As shown analytically in Section 4, comparing Simulation 5 and Simulation 6 to Simulation 1 is not the most appropriate measure of compliance costs. The contract constraints should be included in both the baseline simulation and the policy-restricted simulation. Simulation 2 runs the same model as in Simulation 1 except that it includes contract constraints and results in total industry costs of $8.27 billion. The difference between total industry costs in Simulation 1 and Simulation 2 are the additional costs due to contract constraints, which are $582 million. These additional costs would have resulted with or without the SO\textsubscript{2} Trading Program and should not be considered compliance costs. This is a key result because these costs were labeled compliance costs by previous studies even though these costs are a result of generating units locking in prices to protect from the uncertainty of higher coal prices in the future.

By comparing results in Simulation 5 to Simulation 2, the minimum compliance costs considering contracts and given the scrubber choice are found to be $490.1 million. “True” minimum compliance costs are much lower ($610 million lower) once this additional constraint is included in the model. In Simulation 6, the “true” minimum compliance costs are $357.8 million, or $581.6 million less than if contracts are excluded from the model. These are similar to the least-cost results found by Sotkiewicz (2003) at $340-$527 million, Sotkiewicz and Holt (2005) at $423-$553 million, and Carlson et al. (2000) at $571 million.
Although actual industry compliance costs are higher than the least-cost results at $716 million, these compliance costs are lower than the compliance costs found in Sotkiewicz (2003) and Sotkiewicz and Holt (2005) at $990 million and Carlson et al. (2000) at $910 million. Contract constraints appear to explain some of the excess compliance costs found in previous studies, which implies that generating units’ decisions were more cost-effective than previously stated in the literature.

3.6.4.2 Industry and generating unit coal use

By comparing coal use in Simulation 5 to that in Simulation 3, the impact of contract constraints assuming scrubbers as given can be derived. Simulation 3 uses a total of 2,607,025,040 mmBtu of high sulfur coal (40.7%) and 3,794,557,150 mmBtu of low sulfur coal (59.3%). Simulation 5 uses a total of 2,041,933,640 mmBtu of high sulfur coal (31.9%) and 4,359,648,550 mmBtu of low sulfur coal (68.1%). Introducing contract constraints into the model results in a 8.8% decrease in high sulfur coal relative to Simulation 3. Contract constraints results in less high sulfur coal than would have otherwise been preferred. Contract constraints led to 16 units (3.7% of affected units) using a suboptimal coal combination. 15 of the 16 units had 100% of its coal use altered. Only 2 of these units had an increase in high sulfur coal.

Simulation 4 uses a total of 2,651,410,732 mmBtu of high sulfur coal (41.4%) and 3,750,168,009 mmBtu of low sulfur coal (58.6%). Simulation 6 uses a total of 2,614,773,732 mmBtu of high sulfur coal (40.8%) and 3,786,804,109 mmBtu of low sulfur coal (59.2%). Including contract constraints into the model results in a 0.6% decrease in high sulfur coal relative to Simulation 4. Overall coal use does not appear to have been significantly altered. However, this does not tell the whole story. Contract constraints led to 27 units (6.3% of affected units) using a suboptimal coal combination. 5 of the 27 units had a change of at least 98% of coal use and 15 of the 27 had at least a 50% change in coal use. 14 of the 27 units had an increase in high sulfur coal use while 13 units had an decrease of high sulfur coal use. The concern with the contracts is not necessarily that the entire
industry choices are shifted, but that individual generating units are not able to make their cost-minimizing choices.

3.6.4.3 Generating unit scrubber installation choices

There are three issues to consider regarding generating units’ scrubber choices: (1) impacts from the endogenous scrubber choice without contract constraints, (2) impacts from the endogenous scrubber choice with contract constraints, and (3) impact of contract constraints on scrubber choices. First, comparing scrubber installations in Simulation 4 to Simulation 3 will show how scrubber decisions would be altered if the scrubber decision is made endogenous and contract constraints are excluded from the model. Allowing the scrubber choice to be endogenous results in 48 generating units altering their scrubber choice, including 25 scrubbers to be removed and 23 to be added for a total of 2 fewer installed scrubbers. 21 generating units maintain the same scrubber choices, but 17 of those were installed for NSPS. So only 4 scrubber choices remained the same.

Second, comparing scrubber installations in Simulation 6 to Simulation 5 will show how scrubber decisions would be altered if the scrubber decision is made endogenous and contract constraints are included in the model. Allowing the scrubber choice to be endogenous results in 53 generating units altering their scrubber choice, including 19 scrubbers to be removed and 34 to be added for a total of 15 more installed scrubbers. 27 generating units maintain the same scrubber choices, but 17 of those were installed for NSPS. So 10 scrubber installations remained the same.

Finally, it is important to consider the impacts contract constraints have on a unit’s endogenous scrubber installation decision, which can be determined by comparing Simulation 6 to Simulation 4. 33 scrubber choices are altered as a result of contract constraints, including 25 units that will now install a scrubber and 8 units that no longer install a scrubber. Of the 25 units that chose to install a scrubber, 20 of them had a high sulfur coal contract. Of the 8 units that chose to not install a scrubber, all 8 of them had a low sulfur coal contract. So 28 of 33 scrubber choices appear to have been directly
impacts by contract constraints. As can be seen in Table 3-4, contract constraints increase scrubber installations in Ohio, Alabama, Florida, Indiana, Mississippi, and Missouri and decrease scrubber installations in West Virginia, New York, Pennsylvania, Wisconsin, Georgia, Kentucky, and New Jersey.

An unexpected result in Simulation 6 is that scrubber installations actually increase relative to Simulation 5. These are likely a result of the assumed scrubber cost estimates because the historical scrubber cost data used in the simulations is lower than the engineering cost estimates. Scrubbers appear cheaper to install than the engineering estimates state. Of the 404 generating units with at least a 90% removal rate, 31 historical capital cost estimates are higher, 84 are the same, and 289 are lower than the estimated engineering capital costs. The higher cost estimates are not much higher than the engineering costs with a difference of $11/kW. However, the historical capital cost estimates that are lower than the engineering capital cost estimates range from $50/kW to $216/kW higher, which could have some significant impacts on scrubber installation choices. For example, historical capital cost estimates for generating units in Missouri are assumed to be $50/kW while the engineering cost estimates are assumed to be $266/kW, or a 432% difference.

As can be seen in Table 3-5, there is a significant difference in scrubber installations. The use of engineering cost estimates for scrubber installation results in a decrease in scrubber installations from 44 to 25 in Simulation 4 and from 61 to 38 in Simulation 6 because of the higher costs involved. Notice that introducing contract constraints results in additional scrubber installations from 25 to 38, which is close to the actual installations of 46 scrubbers. Compliance cost interpretations remain similar to simulations using

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8 27 of the generating units are not directly comparable because historical data (50% removal rate) assumes a different scrubber technology than the engineering data (90% removal rate).
historical scrubber cost estimate data, with compliance costs slightly higher for all simulations.

3.6.4.4 Impact of allowance allocation on the allowance market and compliance costs

The impacts of altering the initial allowance allocation are as would be expected. Fewer available allowances forces the industry to produce fewer emissions, which will result in a higher allowance price, more scrubber installations, and higher total industry compliance costs. A decrease in the initial allowance allocation by 10% leads to an increase in the number of installed scrubbers by 17 in Simulation 4 and 12 in Simulation 6, an increase in the equilibrium allowance price of 33.85 in Simulation 4 and $11.48 in Simulation 6, and an increase in the total industry compliance costs increase by $93.6 million (32%) in Simulation 4 and $118.8 million (33%) in Simulation 6.\(^9\) Contract constraints restrict compliance options, which will lead to fewer compliance choice changes, which leads to less of an impact on both scrubber installations and the allowance market. However, restricting compliance options also leads to the higher compliance costs to meet the additional emissions reduction.

3.6.4.5 Summary of simulation results

Contract constraints appear to explain a large portion of the “excess” compliance costs found in the previous studies. Much of these excess costs would have occurred with or without the program due to the contract restrictions, and therefore are not actually compliance costs. These results find that firms’ compliance choices appear to be more cost-effective than previously thought because previous work has ignored a key restriction on a generating unit’s freedom in compliance options.

\(^9\) The results are not reliant on how the 10% reduction in initial allowance allocation occurs because the distribution of the allocation will not alter compliance decisions.
The “true” compliance costs to the industry appear to be lower relative to the previous compliance cost estimates. Actual compliance decisions resulted in total industry compliance costs that were higher than the least cost choices given the contract constraints ($226 million compared to Simulation 5 and $358 million compared to Simulation 6).

### 3.7 Plant Level Decision-Making Process

#### 3.7.1 Introduction

The generating unit model in Chapter 2 does not account for the fact that two or more generating units are often owned and operated by one firm at the same plant. A plant’s decision-making process may not minimize costs for each generating unit because a plant’s concern is based on the combined costs of all generating units under its operational control. This model derives the plant level problem, which allows us to analyze differences in high versus low sulfur coal, spot versus contract coal, allowance excess demand, scrubber installation, and the positioning of contract coal use based on the different generating unit characteristics at a particular plant.

A plant level decision-making model is more realistic than a generating unit level model to determine compliance decisions because coal deliveries are made at the plant level where there are often multiple generating units. All generating units at that plant facing the same coal use options, including sulfur contents, heat contents, and delivered prices for both spot market and contract coal. The contract constraints become more complex in this model where the sum of contract coal use for all generating units at a plant must cover the contract requirement, \( \sum_{i=1}^{n} C_{ij}^c \geq C_f^c \; \forall \; i \in \{1, 2, ..., n\} \). A plant with multiple units has greater degrees of freedom in it’s choices as to what fuel types to purchase, in what quantities, and at which unit to burn the fuel based on their emissions, demand, and coal contract constraints. The improved freedom in choice variables should lead to lower compliance costs.
Some anecdotal evidence of these cost savings is seen in a comparison of the 46 generating units that had scrubbers installed in 1996. Of those units, 37 units are each located at a plant that did not operate a generating unit that did not have a scrubber installed. The remaining 9 generating units were each located at a plant that operated at least one other generating unit that did not install a scrubber. By comparing the average excess compliance costs (in percentage terms), it is possible to see how having at least one additional generating unit at a plant improves its abilities to lower compliance costs. For the generating units located at a plant without an additional generating unit without a scrubber had average excess compliance costs of 6.8% above the unit’s minimum compliance costs. Generating units at a plant with at least one additional generating unit that did not install a scrubber had average excess compliance costs of 2.8% above the unit’s minimum compliance costs.

Three additional factors will be of great importance at the plant level. First, plants are able to trade allowances between generating units as needed to cover emissions at no additional costs. The literature has stated that trading allowances between its units at the same plant has been a common occurrence, which supports the use of a model that considers decisions at the plant level instead of the generating unit level. Second, another aspect to consider is the choice to install a scrubber, which is based on the characteristics of all the units at a plant, not just the unit at which the scrubber may be installed. Third, a plant’s decisions become more complex if it has one or more “unaffected” units.

A plant may have one or more generating units at its location that are not affected by Phase I and does not have to meet any emissions requirements. Owning a non-affected

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10 Montero (1996)
unit allows greater freedom in coal use and may greatly alter a plant’s preferred 
compliance options.\textsuperscript{11}

Plants must consider the total combined costs over all generating units, which 
may lead to plant level decisions that are contrary to a specific generating unit’s 

cost-minimizing choice. A plant may be able to lower total costs by increasing the costs at 
one generating unit to save money at other units.

\textbf{3.7.2 Plant-Level Problem}

A plant solves the following problem. The subscript “$i$” represents a specific 
generating unit for each operating plant while “$n$” represents the number of generating 
units owned by the plant.

\begin{equation}
\text{min} \quad \sum_{i=1}^{n} z_i P_{iz} + P_{A_i} + P_{h} C_{ih} + P_{l} C_{il} + P_{h} C_{ch} + P_{l} C_{cl}
\end{equation}

\text{subject to...} \quad A_i^e + A_i \geq (1 - z_ir_i)(m)\left[C_{ih}^s S_{ih}^s + C_{ih}^c S_{ih}^c + C_{il}^s S_{il}^s + C_{il}^c S_{il}^c\right] \lambda_i \quad \lambda_{i1}

\begin{equation}
(C_{ih}^s H_{ih}^s + C_{ih}^c H_{ih}^c + C_{il}^s H_{il}^s + C_{il}^c H_{il}^c) \geq D_i \quad \lambda_{i2}
\end{equation}

\begin{equation}
\sum_{i=1}^{n} C_{ih}^s \geq \bar{C}_{h}^s \mu_h \quad \lambda_{i1}
\end{equation}

\begin{equation}
\sum_{i=1}^{n} C_{il}^c \geq \bar{C}_{il}^c \mu_l \quad \lambda_{i2}
\end{equation}

\begin{equation}
z_i \in \{0, 1\} \quad \lambda_{i1}
\end{equation}

\begin{equation}
C_{ih}^s, C_{il}^c \geq 0 \quad \lambda_{i2}
\end{equation}

\begin{equation}
i \in \{1, ..., n\}
\end{equation}

The Lagrange multiplier on a generating unit’s emissions constraint is represented by $\lambda_{i1}$.
The Lagrange multiplier on a generating unit’s demand constraint is represented by $\lambda_{i2}$.
Coal contract constraints require a plant to use a minimum amount of each contract coal

\textsuperscript{11} Due to the design of the policy with “compensation” provision, a plant can shift 
coal use, but not electricity production to a non-affected unit without the unit being 
incorporated into the program.
type, $C_h^c$ for high sulfur coal and $C_l^c$ for low sulfur coal. The amount of contract coal at a generating unit is a choice variable because a plant is able to choose which generating unit to use its allotted contract coal. The Lagrange multiplier of each contract coal type is represented by $\mu_h$ for high sulfur coal and $\mu_l$ for low sulfur coal.

### 3.7.3 First-Order Conditions

The partial derivative with respect to $A_i$ yields the impact of a one unit change in its net allowance position on the unit’s total costs.

$$P_A - \lambda_1 = 0$$ (3–46)

Since $A_i$ can be either positive or negative based on the net allowance position, (3–46) will hold with equality. The additional cost to the firm of emitting one more ton of emissions is equivalent to the allowance price, $\lambda_1 = P_A$, which is the same result as from the previous models.

The partial derivative with respect to $C_{ih}^s$ represents the impact a one unit change in high sulfur spot market coal has on the unit’s total costs.

$$P_h^s + \lambda_{i1} (1 - z_i r_i) (m) (S_h^s) - \lambda_2 H_h^s \geq 0, = 0 \text{ if } C_{ih}^s > 0$$ (3–47)

If the generating unit uses some amount of high sulfur spot market coal ($C_{ih}^s > 0$), then (3–47) holds with equality.

The partial derivative with respect to $C_{il}^s$ represents the impact a one unit change in low sulfur spot market coal has on the unit’s total costs.

$$P_l^s + \lambda_{i1} (1 - z_i r_i) (m) (S_l^s) - \lambda_2 H_l^s \geq 0, = 0 \text{ if } C_{il}^s > 0$$ (3–48)

Similar to high sulfur spot market coal, if the generating unit uses some low sulfur spot market coal ($C_{il}^s > 0$), then (3–48) holds with equality.
The partial derivative with respect to $C_{ih}^c$ represents the impact a one unit change in high sulfur contract coal has on the unit’s total costs.

$$P_h^c + \lambda_{1h}(1 - z_{hr_i})(m)(S_{h}^c) - \lambda_{2h}H_{h}^c - \mu_h \geq 0, = 0 \text{ if } C_{ih}^c > 0 \quad (3–49)$$

Unlike with high sulfur spot market coal, high sulfur contract coal will be impacted by the high sulfur coal contract constraint ($\mu_h$). If the generating unit uses some amount of high sulfur contract coal ($C_{ih}^c > 0$), then (3–49) holds with equality.

The partial derivative with respect to $C_{il}^c$ represents the impact a one unit change in low sulfur contract coal has on the unit’s total costs.

$$P_l^c + \lambda_{1l}(1 - z_{lr_i})(m)(S_{l}^c) - \lambda_{2l}H_{l}^c - \mu_l \geq 0, = 0 \text{ if } C_{il}^c > 0 \quad (3–50)$$

Unlike with low sulfur spot market coal, low sulfur contract coal will be impacted by the low sulfur coal contract constraint ($\mu_l$). Similar to high sulfur contract coal, if the generating unit uses some low sulfur contract coal ($C_{il}^c > 0$), then (3–50) holds with equality.

### 3.7.4 Characterizing a Unit’s Spot Market Fuel Choices

A plant’s choice of fuel type for a given generating unit is not only based on the plant’s marginal cost of abatement relative to the allowance price, but also the plant’s scrubber installation choice for each individual unit. For this section, we assume that the scrubber choice is given and focus solely on a generating unit’s marginal cost of abatement and the allowance price, excluding the use of contract coal. The interaction of choices for the use of contract coal, the consideration of multiple generating units, and scrubber choice will be discussed later. As in previous models, three cases must be considered: a generating unit uses both high and low sulfur spot market coal, only high sulfur spot market coal, and only low sulfur spot market coal.
3.7.4.1 Case 1: Necessary conditions for using both high sulfur and low sulfur spot market coal

Assume that demand for each generating unit is given and a generating unit chooses to use both high sulfur and low sulfur spot market coal ($C^s_{ih} > 0$ and $C^s_{il} > 0$), which implies that both (3–47) and (3–48) hold with equality. The additional costs to the generating unit of using one more unit of low sulfur spot market coal is equal to the additional costs of using one more unit of high sulfur spot market coal.

$$P^s_h + \lambda_{i1}(1 - z_ir_i)(m)(S^s_h) - \lambda_{i2}H^s_h = P^s_l + \lambda_{i1}(1 - z_ir_i)(m)(S^s_l) - \lambda_{i2}H^s_l \quad (3–51)$$

Since both (3–47) and (3–48) hold with equality, it is possible to find an expression for ($\lambda_{i2}$) in each equation and set the two expressions equal to each other and derive the allowance shadow price ($\lambda_{i1}$) in (3–52).

$$\Rightarrow P_A = \lambda_{i1} = \text{MCA}^{s,s}_i = \frac{P^s_h - P^s_l}{(1 - z_ir_i)(m)(\frac{S^s_h}{H^s_h} - \frac{S^s_l}{H^s_l})} \quad (3–52)$$

As discussed earlier, the allowance shadow price ($\lambda_{i1}$) is an expression for a generating unit’s Marginal Cost of Abatement from Switching from high sulfur spot market to low sulfur spot market coal ($\text{MCA}^{s,s}_i$). From (3–46), we also know that the actual allowance price equals the allowance shadow price ($P_A = \lambda_{i1}$). As can be seen in (3–52), the allowance price ($P_A$) equals to the marginal cost of abatement ($\text{MCA}^{s,s}_i$), which is the increase in coal costs from switching from high sulfur spot to low sulfur spot market coal per unit of reduced emissions.

The marginal costs of abatement may or may not differ across generating units. If a plant does not install any scrubbers, then $\text{MCA}^{s,s}_i = \text{MCA}^{s,s}_j \forall \{i, j\}$ for all generating units and the plant’s choices will be identical to the generating units’ decisions in Section 5. This can be seen in (3–52) where the only way that the marginal costs of abatement can differ across generating units is through the scrubber choice and a scrubber’s emissions capture rate. If all generating units at a given plant both install a scrubber where $r_i = r_j$,
then $MCA_i^{s,s} = MCA_j^{s,s}$. Once again the plants’ choices will be identical to the generating units’ choices made in Section 5.

Marginal costs of abatement will only differ across generating units at a plant if (1) a plant installs a scrubber at some but not all of its generating units, or (2) a plant installs a scrubber at all its generating units but the scrubbers have different capture rates ($r_i \neq r_j \exists\{i,j\}$). We will introduce the scrubber choice, and derive its impact on a plant’s choices later.

3.7.4.2 Case 2: Necessary conditions for only high sulfur spot market coal use

If a generating unit chooses to use only high sulfur spot market coal ($C_h^s > 0$), then (3–47) holds with equality and (3–48) holds with weak inequality resulting in (3–53).

$$P_h^s + \lambda_{11}(1 - z_i r_i)(m)(S_h^s) - \lambda_{12}H_h^s \leq P_l^s + \lambda_{11}(1 - z_i r_i)(m)(S_l^s) - \lambda_{12}H_l^s$$ (3–53)

Equation (3–53) states that additional costs to the generating unit of using one more unit of high sulfur spot market coal is weakly less than or equal to the additional costs of using one more unit of low sulfur spot market coal inclusive of emissions and demand requirements.

Following Section 6.4.1 we can derive the relation of $P_A$ to $MCA_i^{s,s}$. By comparing these two expressions and solving for $\lambda_{12}$, you get an inequality comparing $\lambda_{11} = P_A$ and $MCA_i^{s,s}$. Since the generating unit uses high sulfur spot market coal, the allowance price is weakly less than the marginal cost of abatement ($P_A \leq MCA_i^{s,s}$) as shown in (3–54).

$$\Rightarrow P_A \leq MCA_i^{s,s} = \frac{P_l^s - P_h^s}{(1 - z_i r_i)(m)(S_l^s/H_l^s - S_h^s/H_h^s)}$$ (3–54)

3.7.4.3 Case 3: Necessary conditions for only low sulfur spot market coal use

Similarly to the above case, if a generating unit chooses to use only low sulfur spot market coal ($C_l^s > 0$), then (3–47) holds with equality and (3–48) hold with weak inequality resulting in (3–55). The additional costs to the generating unit of using one
more unit of low sulfur spot market coal is weakly less than or equal to the additional costs of using one more unit of high sulfur spot market coal inclusive of emissions and demand requirements.

\[ P^*_h + \lambda_1 (1 - z_i r_i)(m)(S^*_h) - \lambda_2 H^*_h \geq P^*_l + \lambda_1 (1 - z_i r_i)(m)(S^*_l) - \lambda_2 H^*_l \]  

(3–55)

Once again we can derive the relation of \( P_A \) to \( MCA^s,i \). By comparing these two expressions and solving for \( \lambda_{i2} \), you get an inequality comparing \( \lambda_{i1} = P_A \) and \( MCA^s,i \). Since the generating unit uses low sulfur spot market coal, the allowance price is weakly greater than the marginal cost of abatement (\( P_A \geq MCA^s,i \)) as shown in (3–56).

\[ \Rightarrow P_A \geq MCA^s,i = \frac{P^*_l - P^*_h}{(1 - z_i r_i)(m)(\frac{S^*_l}{H^*_l} - \frac{S^*_h}{H^*_h})} \]  

(3–56)

### 3.7.5 Excess Demand Correspondence

When only considering the use of spot market coal (no contract constraints), a unit’s excess demand correspondence will look nearly identical to the correspondence in Chapter 2. The minimum and maximum excess demand for allowances can be derived for each of the three cases described above in the same manner as in Chapter 2.

First, if a generating unit faces \( P_A < MCA^s,i \) it will use the maximum amount of high sulfur spot market coal. The maximum amount of high sulfur spot market coal is expressed in (3–57).

\[ C^s,MAX_{ih} = \frac{D_i}{H^*_h} \]  

(3–57)

Replacing \( C^s_{ih} \) in (3–41) with the expression in (3–57) for \( C^s,MAX_{ih} \) gives an expression for the maximum allowance excess demand in (3–58). A generating unit’s maximum excess demand must cover the difference between its initial allowance allocation (\( A^e_i \)) and the amount of allowances needed to cover the unit’s maximum actual emissions \([E^MAX_i = (1 - z_i r_i)(m)(S^*_h)(\frac{D_i}{H^*_h})]\).

\[ A^MAX_i = E^MAX_i - A^e_i \]  

(3–58)
If a generating unit faces $P_A > MCA_i^{s,s}$, it will use the maximum amount of low sulfur spot market coal, which can be found from (3–41). Assuming only low sulfur spot market coal use to meet demand, the maximum amount of low sulfur coal is expressed in (3–59).

$$\overline{C}_{i}^{s} = \frac{D_i}{H_{i}}$$ (3–59)

Replacing $C_{i}^{s}$ in (3–41) with the expression in (3–59) for $C_{i}^{s,\text{MAX}}$ gives an expression for the minimum allowance excess demand in (3–60). A generating unit’s minimum excess demand must cover the difference between its initial allowance allocation ($A_i^e$) and the amount of allowances needed to cover the unit’s minimum actual emissions

$$E_{i}^{\text{MIN}} = (1 - z_i r_i)(m)(S_{i}^{a})(\frac{D_i}{H_{i}}).$$

If a unit’s initial allocation can cover its minimum possible emissions, then it will have a negative net allowance position and be a net buyer seller of allowances.

$$A_{i}^{\text{MIN}} = E_{i}^{\text{MIN}} - A_{i}^{e}$$ (3–60)

If $P_A = MCA_i^{s,s}$, a generating unit may use any combination of high sulfur spot market coal and low sulfur spot market coal and lead to any level of excess demand in the range ($E_{i}^{\text{MIN}} - A_{i}^{e}, E_{i}^{\text{MAX}} - A_{i}^{e}$). The allowance excess demand can be represented by

$$A_i = (\rho E_i^{\text{MAX}} - (1 - \rho) E_i^{\text{MIN}} - A_i^e)$$ where the constant $\rho \in [0, 1]$. A unit that is indifferent between fuel switching and allowances purchasing could be either a net buyer or a net seller.

Combining the excess demands for each of the three cases creates the excess demand correspondence shown below.

$$A_i = \begin{cases} 
A_i^{\text{MAX}} & \text{if } P_A > MCA_i^{s,s} \\
\rho A_i^{\text{MAX}} - (1 - \rho) A_i^{\text{MIN}} & \text{if } P_A = MCA_i^{s,s} \forall \rho \in [0, 1] \\
A_i^{\text{MIN}} & \text{if } P_A < MCA_i^{s,s}
\end{cases}$$

A generating unit’s excess demand correspondence can be seen graphically in Chapter 2. High sulfur coal use corresponds to the right-hand vertical line where $P_A < MCA_i^{s,s}$. Low
sulfur coal use corresponds to the left-hand vertical line where $P_A > MCA_i^{s,s}$. The case where a generating unit uses some combination of low sulfur coal and high sulfur coal is represented by the horizontal line at which $P_A = MCA_i^{s,s}$.

3.7.6 Characterizing a Generating Unit’s Contract Fuel Choices

Unlike in the generating unit-level model, contracted coal is not treated the same as spot market coal. It is not possible to simply require a certain amount of high or low sulfur contract coal use because the use of contract coal is a choice variable at the generating unit level.

The use of contract coal will be based on the relative marginal costs of using contract coal at each generating unit operated by a plant. A plant will choose to use contract coal at the generating unit that will result in the lowest increase in the plant’s total costs. To make these cost comparisons, it is necessary to derive the marginal costs of abatement for the given combination of spot and contract coal and compare them across generating units. Initially we will ignore a plant’s scrubber choice for each generating unit and a plant makes the same choice for all its generating units ($z_i = z_j = 0$, or $z_i = z_j = 1$ and $r_i = r_j$). Under these conditions, the marginal costs of abatement are identical across all generating units, and it does not matter at which of these generating units the contract coal is used. This will be shown separately for both a high sulfur and low sulfur coal contract because the use of high sulfur contract coal is independent of low sulfur contract coal and visa versa.

3.7.6.1 Case 1: Necessary conditions for high sulfur contract coal use at Generating Unit “i”

We first consider a plant with a high sulfur coal contract. We can derive the marginal cost of abatement of switching fuels from high sulfur contract coal to low sulfur spot market coal in (3–61). The marginal cost of abatement from switching from high sulfur contract coal to low sulfur spot market coal ($MCA_i^{c,s}$) will be the same for all generating units that make the same scrubber installation choice ($z_i$), including the same scrubber
technology with the same capture rate ($r_i$).

\[ P_h^c + \lambda_i (1 - z_i r_i)(m)(S_h^c) + \lambda_i H_h^c - \mu_h = P_i^s + \lambda_i (1 - z_i r_i)(m)(S_i^s) + \lambda_i H_i^s \]

\Rightarrow \lambda_i = \text{MCA}_{c,s}^i + \frac{\mu_h}{H_h} \frac{S_h^s}{S_i^s} - \frac{S_i^r}{H_i^c} \quad (3–61)

All units at which a plant does not install a scrubber have the same marginal cost of abatement of switching from high sulfur contract coal to low sulfur spot market coal ($\text{MCA}_{c,s}^i = \text{MCA}_{c,s}^j$). Also all units at a plant that install a scrubber with the same capture rate will have identical $\text{MCA}_{c,s}^i$.

### 3.7.6.2 Case 2: Necessary conditions for low sulfur contract coal use at generating unit “i”

Second, derive the marginal cost of abatement of switching fuels from high sulfur spot market coal to low sulfur contract coal in (3–62). The $\text{MCA}_{s,c}^i$ will be the same for all generating units that make the same scrubber installation choice, including the same scrubber technology with the same capture rate.

\[ P_h^s + \lambda_i (1 - z_i r_i)(m)(S_h^s) + \lambda_i H_h^s = P_i^c + \lambda_i (1 - z_i r_i)(m)(S_i^c) + \lambda_i H_i^c - \mu_i \]

\Rightarrow \lambda_i = \text{MCA}_{s,c}^i - \frac{\mu_i}{H_i} \frac{S_h^s}{H_i^c} - \frac{S_i^r}{H_i^c} \quad (3–62)

All units at which a plant does not install a scrubber have the same marginal cost of abatement of switching from high sulfur spot market coal to low sulfur contract coal ($\text{MCA}_{s,c}^i = \text{MCA}_{s,c}^j$). Also all units at a plant that install a scrubber with the same capture rate will have identical $\text{MCA}_{s,c}^i$.

### 3.7.7 “Non-Affected” Generating Units at an “Affected” Plant

So far it has been assumed that all generating units operated by a plant are all “affected” units, meaning that all units face an emissions compliance constraint as a result of Phase I. However, there are 27 plants (out of 160 total plants) that have both “affected”
and “non-affected” units.\textsuperscript{12} Now we will introduce generating units that are not “Phase I affected” into a plant’s decision-making process.

The emissions constraint does not bind ($\lambda_{i1} = 0$) for these units, which means that “non-affected” generating units will prefer to use the coal type with the lowest delivered price. For most plants this will be high sulfur coal, particularly those located in the Eastern U.S.

3.7.7.1 Characterization of “non-affected” generating units at an “affected” plant

The first-order conditions from Section 7.3 will no longer be dependent on the emissions for a non-affected unit because the emissions constraint will never bind ($\lambda_{i1} = 0$), as can be seen in (3–63) and (3–64).

\[
\begin{align*}
\frac{\partial L}{\partial C^s_{ih}} &= P^s_h - \lambda_{i2} H^s_h \geq 0, = 0 \text{ if } C^s_{ih} > 0 \quad (3–63) \\
\frac{\partial L}{\partial C^s_{il}} &= P^s_l - \lambda_{i2} H^s_l \geq 0, = 0 \text{ if } C^s_{il} > 0 \quad (3–64)
\end{align*}
\]

Assuming that a generating unit uses both high and low sulfur spot market coal, we use (3–63) and (3–64) to derive (3–65). If a generating unit uses both high and low sulfur spot market coal, then the price per unit of heat input is equal for both coal types. A plant will no longer make it’s generating unit level fuel choices based on its marginal cost of abatement because it no longer is concerned about abating emissions.

\[
\frac{P^s_h}{H^s_h} = \frac{P^s_l}{H^s_l} \quad (3–65)
\]

By using the first-order conditions, we can determine when a generating unit will only use one type of spot market coal. If a generating unit uses only high sulfur spot market

\textsuperscript{12} Source: www.eia.doe.gov, “Existing Generating Units in the United States by State, Company and Plant, 2003” database.
coal, then (3–63) holds with equality and (3–64) remains weakly greater than zero and low sulfur coal is weakly more expensive \((\frac{P_s}{H_s} \leq \frac{P_s}{H_l})\). If a generating unit uses only low sulfur spot market coal, then (3–64) holds with equality and (3–63) remains weakly greater than zero and high sulfur spot market coal is more expensive \((\frac{P_s}{H_s} \geq \frac{P_s}{H_l})\).

### 3.7.7.2 “Non-affected” generating units and high sulfur coal contracts

Now consider how these non-affected units will impact a plant’s coal use choices for its generating units. This is one issue that will only impact plants under Phase I because only the dirtiest units are affected while under Phase II and CAIR all generating units in the U.S. are affected units. There is only a concern with Phase I where most units preferred to switch from high to low sulfur coal. So assume a plant faces a high sulfur coal contract.

First, assume that two generating units (Unit “i” and Unit “j”) are both affected units. A plant will be indifferent to using high sulfur contract coal at either unit when the first-order conditions for using high sulfur contract coal are equal across generating units.

\[
P_h^c + \lambda_i(1 - z_i)(m)(S_h^c) - \lambda_1H_h^c - \mu_h = P_h^c + \lambda_j(1 - z_j)(m)(S_h^c) - \lambda_2H_h^c - \mu_h
\]

\[
\Rightarrow \lambda_i(1 - z_i)(m)(S_h^c) - \lambda_1H_h^c = \lambda_j(1 - z_j)(m)(S_h^c) - \lambda_2H_h^c
\]

(3–66)

Now assume that Unit “i” is an affected unit and its emissions constraint binds \((\lambda_i > 0)\) while Unit “j” is not affected and the emissions constraint will not bind \((\lambda_j = 0)\). Under this condition, the additional costs of using high sulfur contract coal at an affected unit is greater than at a non-affected unit.

\[
P_h^c + \lambda_i(1 - z_i)(m)(S_h^c) - \lambda_1H_h^c - \mu_h > P_h^c - \lambda_2H_h^c - \mu_h
\]

\[
\Rightarrow \lambda_i(1 - z_i)(m)(S_h^c) - \lambda_1H_h^c > -\lambda_2H_h^c
\]

\[
\Rightarrow \lambda_i(1 - z_i)(m)(S_h^c) > 0
\]

(3–67)
Consider a simple example where a plant operates two generating units, one that is affected (Unit “i”) and another that is not affected (Unit “j”) by Phase I of Title IV. Assume $\frac{P_{s \text{h}}}{H_{s \text{h}}} < \frac{P_{s \text{l}}}{H_{s \text{l}}}$, which is normally the case under Phase I. Furthermore, the plant prefers to switch from high sulfur coal to low sulfur coal to meet its emissions requirement for Unit i because $P_A > MCA_{i,s}$. But the plant also has a high sulfur coal contract for a small amount of high sulfur coal ($\bar{C}_{\text{h}} < \frac{P_A}{H_{s \text{h}}}$) that has identical characteristics to high sulfur spot market coal. The plant must choose at which generating unit to use the high sulfur contract coal. Since plant prefers to use low sulfur coal to lower its emissions at Unit “i” and prefers to use high sulfur coal at Unit “j” to minimize its coal costs, then the plant’s contract will not bind and will not increase a plant’s total costs. Alternatively, if Unit “j” was an affected unit and $P_A > MCA_{j,s}$, a high sulfur contract would bind and result in higher total costs for the plant. A non-affected unit will weakly decrease a plant’s total costs relative to if the unit WAS affected. High sulfur coal can be shifted to the unaffected unit to relax the emissions constraint.

3.7.8 Scrubber Installation Choice

Up to this point, we have assumed a plant’s scrubber choice for a generating unit as given. Now consider a plant’s scrubber installation choice for a given generating unit. A plant chooses to use contract coal in different generating units depending on whether it has installed a scrubber at the particular generating unit. The choice is based on the scrubber choices because it is the only variable that can change the marginal cost of abatement across a plant’s generating units.

3.7.8.1 Marginal cost of abatement with and without a scrubber

Finding the allowance price at which a generating unit will install a scrubber is not as simple as in the generating unit model because a plant must take into account the costs of

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13 Over 86% of generating units had higher delivered prices for low sulfur coal than high sulfur coal on the spot market.
all units when choosing to install a scrubber. The marginal cost of abatement for all coal
types has already been derived. Now the $MCA_i$ for each coal combination both with and
without a scrubber can be derived. The only way the marginal cost of abatement can vary
across generating units is through the scrubber choice ($z_i$ and $r_i$).

First, consider the marginal cost of abatement of switching from high sulfur spot
market coal to low sulfur spot market coal ($MCA_i^{s,s}$) with a scrubber in (3–68), and
compare it to the marginal cost of abatement without a scrubber in (3–69). As in Chapter
2, a scrubber decreases the savings from switching spot market fuels because a scrubber
causes the emissions reduction to be smaller than without a scrubber.

$$\lambda_{i1} = MCA_i^{s,s} = \frac{P_s^h - P_s^l}{(1 - r_i)(m)(\frac{S_s^h}{H_s^h} - \frac{S_s^l}{H_s^l})}$$  \hspace{1cm} (3–68)

$$\lambda_{i1} = MCA_i^{s,s} = \frac{P_s^l - P_s^h}{(m)(\frac{S_s^l}{H_s^l} - \frac{S_s^h}{H_s^h})}$$ \hspace{1cm} (3–69)

Second, consider the marginal cost of abatement of switching from high sulfur
contract coal to low sulfur spot market coal ($MCA_i^{c,s}$) with a scrubber in (3–70), and
compare it to the marginal cost of abatement without a scrubber in (3–71). As in the case
of only spot market coal, installing a scrubber decreases the savings from switching fuels.
In the case of a high sulfur contract, it is less costly to a plant to use high sulfur coal at a
particular generating unit if it has a scrubber.

$$\Rightarrow \lambda_{i1} = MCA_i^{c,s} + \frac{\frac{\mu_h}{H_h}}{(1 - r_i)(m)(\frac{S_s^h}{H_h} - \frac{S_s^l}{H_l})}$$  \hspace{1cm} (3–70)

$$\Rightarrow \lambda_{i1} = MCA_i^{c,s} + \frac{\mu_h}{H_h}
\frac{\mu_h}{H_h} + \frac{\frac{\mu_h}{H_h}}{(m)(\frac{S_s^l}{H_l} - \frac{S_s^h}{H_h})}$$ \hspace{1cm} (3–71)

Third, consider the marginal cost of abatement of switching from high sulfur spot
market coal to low sulfur contract coal ($MCA_i^{s,c}$) with a scrubber in (3–72), and compare
it to the marginal cost of abatement without a scrubber in (3–73). As in the two cases
above, installing a scrubber decreases the savings from switching fuels. In the case of a low
sulfur contract, it is more costly to a plant to use low sulfur coal at a particular generating unit if it has a scrubber.

\[ \Rightarrow \lambda_{i1} = \frac{\mu_i}{H_i} \left( \frac{S_k}{H_k} - \frac{S_l}{H_l} \right) \] (3–72)

\[ \Rightarrow \lambda_{i1} = \frac{\mu_i}{H_i} \frac{S_k}{H_k} \left( m \right) \left( \frac{S_k}{H_k} - \frac{S_l}{H_l} \right) \] (3–73)

For each combination of coal types, installing a scrubber decreases the size of the denominator, which increases \( MCA_i \). As in Chapter 2, a scrubber greatly decreases the savings from switching fuels. A higher \( MCA_i \) increases the range of allowance prices at which a plant will prefer to purchase allowances instead of switching fuels by lowering the price at which a generating unit will be indifferent between purchasing allowances and switching from high sulfur to low sulfur coal. Any unit operated by a plant that has a scrubber will have a larger marginal cost of abatement than any unit without a scrubber \( (M\tilde{CA}_i > MCA_j) \).

### 3.7.9 A Plant’s Preferred Order of Scrubber Installation

Given a plant chooses to install a scrubber, it will install the scrubber at the generating unit at which it will get the greatest “bang-for-the-buck”, which will be the generating unit with the lowest average cost of abatement through scrubber installation \((ACA_i)\). A generating unit will have the lowest \( ACA_i \) if the cost of a scrubber per ton of emissions reduction \((ACA_i = \frac{P_{iz}}{mr_i(S_h^cC_h^c + S_h^lC_h^l + S_l^cC_l^c + S_l^lC_l^l)})\) is lower than all other generating units operated by a plant. Give the same coal use ratio (percent of coal use for each coal category), the price per unit of heat or price per unit of reduced emissions only vary based on total demand \((D_i = C_{ih} + C_{ih}^c + C_{il} + C_{ih}^l)\) because “m” and “r_i” are constants. In other words, scrubber installation will be based on the average cost for scrubber installation per unit of demand \((ACA_i = \frac{P_{iz}}{D_i})\).

The decision is based solely on a unit’s \( ACA_i \) because the marginal costs of abatement are equal across generating units with no scrubbers installed at the plant.
Following along the same thought process, if a plant chooses to install a scrubber at two generating units, the scrubbers will be installed at the generating units with the two lowest $ACA_i$. The above condition will only hold for affected generating units. A plant will not install a scrubber at a non-affected generating unit because reducing emissions at a non-affected unit does not relax any emissions constraints.\(^{14}\)

3.7.9.1 At which generating units will a plant install a scrubber?

The order a plant will install scrubbers at its generating units and a plant’s marginal costs of abatement for both with and without a scrubber are known. Now it must be defined when a plant will install a scrubber at a given generating unit by finding the allowance price at which a plant is indifferent to installing a scrubber. This is tough to analytically show because a plant has multiple choices to minimize its total costs through scrubber installation.

Assume that all generating units operated by a plant are affected by Phase I, each unit uses its cost minimizing combination of coal and allowances based on its scrubber choice, and the units are sorted by $ACA_i$ from smallest to largest ($ACA_1 < ACA_2 < ... < ACA_{n-1} < ACA_n$). A plant’s scrubber choices will be based on the relative total costs of each possible combination of scrubber installation. A plant will not install a scrubber at any generating units if its total costs are lower with no scrubbers installed than installing a scrubber at the generating unit with the lowest $ACA_i$ ($C(z_1 = 0, z_2 = 0, ..., z_n = 0) < C(z_1 = 1, z_2 = 0, ..., z_n = 0)$) where $C(\bullet)$ is the total costs for a given scrubber choices and optimal coal and allowance choices. We already know that any other combination of scrubber installation must result in higher costs.

\(^{14}\) Some plants voluntary enrolled units into Phase I, which are labeled as substitution units or compensation units. Although these units were not initially affected, they were enrolled into the program and face the same types of requirements as the original units. For this reason, they are considered affected units.
If total costs are lower with a scrubber installed at the generating unit with the lowest \( ACA_i \) than without a scrubber at any units \( (C(z_1 = 1, z_2 = 0, ..., z_n = 0) < C(z_1 = 0, z_2 = 0, ..., z_n = 0)) \) and lower than with a scrubber installed at the two generating units with the lowest \( ACA_i \) \( (C(z_1 = 1, z_2 = 0, ..., z_n = 0) < C(z_1 = 1, z_2 = 1, z_3 = 0, ..., z_n = 0)) \), then a scrubber is installed only at the generating unit with the lowest \( ACA_i \).

Generalizing this condition, a plant’s decision to install a scrubber at generating unit “m”. A plant will install “m” scrubbers at the “m” largest generating units if

\[
(C(z_1 = 1, z_2 = 1, ..., z_m = 1, z_{m+1} = 0, ..., z_n = 0) < C(z_1 = 1, z_2 = 1, ..., z_{m-1} = 1, z_m = 0, ..., z_n = 0)) \quad \text{and} \quad (C(z_1 = 1, z_2 = 1, ..., z_m = 1, z_{m+1} = 0, ..., z_n = 0) < C(z_1 = 1, z_2 = 1, ..., z_{m+1} = 1, z_{m+2} = 0, ..., z_n = 0)).
\]

3.7.9.2 At what allowance price will a plant install a scrubber at a given generating unit?

Finding the allowance price at which a plant is indifferent to installing a scrubber at a given generating unit is the allowance price at which the total costs to the plant are the same both with and without the scrubber \( (P_{\hat{X}}) \). Solving for this value for the plant’s scrubber choice for each generating unit requires an assumption on the scrubber choices of all other generating units. Luckily, the scrubber installation choices have already been ordered above.

At first glance, it appears difficult to derive \( P_{\hat{X}} \) because a plant compares its total costs over all of its generating units, and a plant must choose whether to install a scrubber at each unit. However, it has been shown that a plant will base its scrubber installation on a single factor, relative \( ACA_i \). There are several requirements for a plant to install a scrubber at a given affected generating unit “i”: (1) a plant installs a scrubber at all affected generating units with a lower \( ACA_i \) than unit “i”, (2) it is cheaper for a plant to install a scrubber than to not install a scrubber at unit “i”. This requires a simple comparison between the costs of installing a scrubber versus not installing a scrubber. Let “\( \tilde{X} \)” represent the parameters without a scrubber installed, and “\( \hat{X} \)” represent the
generating unit(s) a plant will use contracted coal, which can be derived from the
3.7.9.3 Scrubber installation and high sulfur coal contracts

A special case exists for (3–74) in which the generating unit is a non-affected unit, which
results in $P_A \to \infty$ because the unit does not have to cover its emissions with allowances
and gains nothing from installing a scrubber. An indifference price of infinity implies that
a scrubber will never be installed at Unit “i” if it an unaffected unit.

$$
\Rightarrow P_A^s = \frac{P_{iz} + P_h(C_{ih} - \hat{C}_{ih}) + P_l(C_{il} - \hat{C}_{il})}{(A_i - A_i)} = \frac{P_{iz} + P_h(C_{ih} - \hat{C}_{ih}) + P_l(C_{il} - \hat{C}_{il})}{0} = \infty
$$

3.7.9.3 Scrubber installation and high sulfur coal contracts

So far we have ignored any coal contract constraints. We must determine at which
generating unit(s) a plant will use contracted coal, which can be derived from the

$$
\sum_{j=1}^{i-1} \left( P_{ij} + P_A\tilde{A}_j + P_h\tilde{C}_{jh} + P_i\tilde{C}_{jl} + P_h\tilde{C}_{ih} + P_l\tilde{C}_{il} \right)
+ P_{iz} + P_A\tilde{A}_i + P_h\tilde{C}_{ih} + P_i\tilde{C}_{il} + P_h\tilde{C}_{ih} + P_l\tilde{C}_{il}
+ \sum_{k=i+1}^{n} \left( P_A\tilde{A}_k + P_h\tilde{C}_{kh} + P_i\tilde{C}_{kl} + P_h\tilde{C}_{ih} + P_l\tilde{C}_{il} \right)
= \sum_{j=1}^{i-1} \left( P_{ij} + P_A\tilde{A}_j + P_h\tilde{C}_{jh} + P_i\tilde{C}_{jl} + P_h\tilde{C}_{ih} + P_l\tilde{C}_{il} \right)
+ P_A\tilde{A}_i + P_h\tilde{C}_{ih} + P_i\tilde{C}_{il} + P_h\tilde{C}_{ih} + P_l\tilde{C}_{il}
+ \sum_{k=i+1}^{n} \left( P_A\tilde{A}_k + P_h\tilde{C}_{kh} + P_i\tilde{C}_{kl} + P_h\tilde{C}_{ih} + P_l\tilde{C}_{il} \right)
\Rightarrow P_{iz} + P_A\tilde{A}_i + P_h\tilde{C}_{ih} + P_i\tilde{C}_{il} + P_h\tilde{C}_{ih} + P_l\tilde{C}_{il}
= P_A\tilde{A}_i + P_h\tilde{C}_{ih} + P_i\tilde{C}_{il} + P_h\tilde{C}_{ih} + P_l\tilde{C}_{il} \tag{3–74}
$$

Assuming no contract coal, we can derive the allowance price at which a plant is
indifferent to installing a scrubber for a given generating unit in (3–75).

$$
 \Rightarrow P_A^s = \frac{P_{iz} + P_h(C_{ih} - \hat{C}_{ih}) + P_l(C_{il} - \hat{C}_{il})}{(A_i - A_i)} \tag{3–75}
$$

A special case exists for (3–75) in which the generating unit is a non-affected unit, which
results in $P_A \to \infty$ because the unit does not have to cover its emissions with allowances
and gains nothing from installing a scrubber. An indifference price of infinity implies that
a scrubber will never be installed at Unit “i” if it an unaffected unit.

$$
\Rightarrow P_A^s = \frac{P_{iz} + P_h(C_{ih} - \hat{C}_{ih}) + P_l(C_{il} - \hat{C}_{il})}{(A_i - A_i)} = \frac{P_{iz} + P_h(C_{ih} - \hat{C}_{ih}) + P_l(C_{il} - \hat{C}_{il})}{0} = \infty
$$

3.7.9.3 Scrubber installation and high sulfur coal contracts

So far we have ignored any coal contract constraints. We must determine at which
generating unit(s) a plant will use contracted coal, which can be derived from the
following three conditions: (1) given a plant installs no scrubbers, a plant is indifferent to using contracted coal at any generating unit because each unit has the same \( MCA_i \), (2) the marginal costs of using high sulfur contract coal at a generating unit with a scrubber are lower than using high sulfur contract coal a generating unit without a scrubber, and (3) any generating unit with a scrubber will have a lower \( ACA_i \) than a generating unit without a scrubber. We can simplify a plant’s contract coal use choices from these three conditions by using any high sulfur contract coal at the generating unit with the lowest \( ACA_i \), which is also the generating unit at which a plant will first install a scrubber. By doing so, we can determine at which generating unit to use high sulfur contract coal before the scrubber choice is actually made by the plant. If all high sulfur contract coal will not cover the entire heat input needed to meet demand at the generating unit with the lowest \( ACA_i \) (\( H_{ih}^{s}C_{ih}^{s,MAX} > H_{ih}^{c}C_{ih}^{c} \)), then all high sulfur coal will be used at that unit. If there is more high sulfur contract coal than can be used at the generating unit with the lowest \( ACA_i \) (\( H_{ih}^{s}C_{ih}^{s,MAX} < H_{ih}^{c}C_{ih}^{c} \)), then the remainder will be used at the unit with the second lowest \( ACA_i \). The same process will be used if there remains any additional contract coal after meeting the heat input demand for the generating unit with the second lowest \( ACA_i \).

A plant with a binding high sulfur coal contract has a greater incentive to install a scrubber at each of its generating units because it must use some high sulfur coal, even if it would prefer to use low sulfur coal at all generating units. A high sulfur coal contract decreases the indifference price at which a unit will install a scrubber from \( P_A \) to \( (P_A - \epsilon) \) for each generating unit. The incentive may not be large enough to result in a scrubber installation at its generating unit with the lowest \( ACA_i \). In such a case, a plant is indifferent to using high sulfur contract coal at any of its generating units because all units have the same \( MCA_i^{c,s} \).

A binding high sulfur coal contract results in a decrease in \( P_A^s \).

At \( P_A^s \) where...

\[
P_{iz} + P_{A} \tilde{A}_i + P_{h} \tilde{C}_{ih}^{s} + P_{l} \tilde{C}_{il}^{s} = P_{A} \tilde{A}_i + P_{h} \tilde{C}_{ih}^{c} + P_{l} \tilde{C}_{il}^{c} \]  

(3–77)
If high sulfur contract coal is at least as expensive as high sulfur spot market coal, we know that...

\[
P_{iz} + P_{A\tilde{A}_i} + P_{h\tilde{C}_{ih}} + P_{i\tilde{C}_{il}} + P_{h\tilde{C}_{ih}} < P_{A\hat{A}_i} + P_{h\hat{C}_{ih}} + P_{i\hat{C}_{il}} + P_{h\hat{C}_{ih}} \quad (3-78)
\]

This is the same result as in Chapter 2 where a high sulfur coal contract results in an inefficient coal use combination of high and low sulfur coal. The indifference price at which a plant will install a scrubber at a given generating unit will weakly decrease when a plant chooses to use high sulfur contract coal at that unit.

3.7.9.4 Scrubber installation and low sulfur coal contracts

It can be determined at which generating unit(s) a plant will use low sulfur contracted coal from the following three conditions: (1) given a plant installs no scrubbers, a plant is indifferent to using contracted coal at any generating unit because each unit has the same $MCA_i$, (2) the marginal costs of using low sulfur contract coal at a generating unit with a scrubber are higher than using low sulfur contract coal a generating unit without a scrubber, and (3) any generating unit with a scrubber will have a lower $ACA_i$ than a generating unit without a scrubber. We can simplify a plant’s contract coal use choices from these three conditions by using any low sulfur contract coal at the generating unit with the highest $ACA_i$, which is also the generating unit at which will be the last that a plant will install a scrubber. By doing so, we can determine at which generating unit to use low sulfur contract coal before the scrubber choice is actually made by the plant. If all low sulfur contract coal will not cover the entire heat input needed to meet demand at the generating unit with the highest $ACA_i$ ($H_{il}^{s}C_{il}^{s,MAX} > H_{il}^{c}C_{il}^{c}$), then all low sulfur coal will be used at that unit. If there is more low sulfur contract coal than can be used at the generating unit with the highest $ACA_i$ ($H_{il}^{s}C_{il}^{s,MAX} < H_{il}^{c}C_{il}^{c}$), then the remainder will be used at the unit with the second highest $ACA_i$. The same process will be used if there remains any additional contract coal after meeting the heat input demand for the generating unit with the second highest $ACA_i$. 

181
A plant with a binding low sulfur coal contract has a smaller incentive to install a scrubber at each of its generating units because it must use some low sulfur coal, even if it would prefer to use high sulfur coal at all generating units. A low sulfur coal contract increases the indifference price at which a unit will install a scrubber from $P_A$ to $(P_A + \epsilon)$ for each generating unit. A plant is indifferent to using low sulfur contract coal at any of its generating units if no scrubbers are installed because all units have the same $MCA_A^{*,c}$.

A binding low sulfur coal contract results in an increase in $P_A^S$.

At $P_A^S$ where...

$$P_{iz} + P_A\tilde{A}_i + P_h^s\tilde{C}_{ih}^s + P_{l}^s\tilde{C}_{il}^s = P_A\tilde{A}_i + P_h^s\tilde{C}_{ih}^s + P_{l}^s\tilde{C}_{il}^s$$  (3–79)

If low sulfur contract coal is at least as expensive as low sulfur spot market coal, we know that...

$$P_{iz} + P_A\tilde{A}_i + P_h^s\tilde{C}_{ih}^s + P_{l}^s\tilde{C}_{il}^s + P_{l}^c\tilde{C}_{il}^c > P_A\tilde{A}_i + P_h^s\tilde{C}_{ih}^s + P_{l}^s\tilde{C}_{il}^s + P_{l}^c\tilde{C}_{il}^c$$  (3–80)

This is the same result as in Chapter 2. A low sulfur coal contract results in an inefficient coal use combination of high and low sulfur coal. The indifference price at which a plant will install a scrubber at a given generating unit will weakly increase when a plant chooses to use low sulfur contract coal at that unit.

3.7.10 Scrubber Installation Example: Plant with Two Affected Generating Units

For a simple example, consider the scrubber installation choices for a plant with only two generating units. Assume that a plant will install a scrubber at Unit 1 before it will install a scrubber at Unit 2 because $(ACA_1 < ACA_2)$. There are three cases that may result, each of which is described below with their own indifferent price for installing a scrubber.
3.7.10.1 Case 1: Install no scrubbers

In the case of a plant choosing not to install any scrubbers, two conditions must hold. First, the total costs of not installing any scrubbers must be less than installing a scrubber at the generating unit with the lowest $ACA_1$.

$$P_A \tilde{A}_1 + P_h \tilde{C}^{s}_{1h} + P_l \tilde{C}^{s}_{1l} + P_h \tilde{C}^{c}_{1h} + P_l \tilde{C}^{c}_{1l} + P_A \tilde{A}_2 + P_h \tilde{C}^{s}_{2h} + P_l \tilde{C}^{s}_{2l} + P_h \tilde{C}^{c}_{2h} + P_l \tilde{C}^{c}_{2l} < P_{1z} + P_A \tilde{A}_1 + P_h \tilde{C}^{s}_{1h} + P_l \tilde{C}^{s}_{1l} + P_h \tilde{C}^{c}_{1h} + P_l \tilde{C}^{c}_{1l} + P_A \tilde{A}_2 + P_h \tilde{C}^{s}_{2h} + P_l \tilde{C}^{s}_{2l} + P_h \tilde{C}^{c}_{2h} + P_l \tilde{C}^{c}_{2l}$$

From this equation, we can solve for $P_A^S$ for this condition to hold in (3–81). The amount of contract coal is the same no matter the scrubber choice at each generating unit made by a plant.

$$P_A^S < \frac{P_{1z} + P_h (\tilde{C}^{s}_{1h} - \tilde{C}^{s}_{1l}) + P_l (\tilde{C}^{s}_{1l} - \tilde{C}^{s}_{1l})}{(\tilde{A}_1 - \tilde{A}_1)}$$ (3–81)

Second, the total costs to the plant of not installing any scrubbers must be less than the total costs of installing scrubbers at both generating units.

$$P_A \tilde{A}_1 + P_h \tilde{C}^{s}_{1h} + P_l \tilde{C}^{s}_{1l} + P_h \tilde{C}^{c}_{1h} + P_l \tilde{C}^{c}_{1l} + P_A \tilde{A}_2 + P_h \tilde{C}^{s}_{2h} + P_l \tilde{C}^{s}_{2l} + P_h \tilde{C}^{c}_{2h} + P_l \tilde{C}^{c}_{2l} < P_{1z} + P_A \tilde{A}_1 + P_h \tilde{C}^{s}_{1h} + P_l \tilde{C}^{s}_{1l} + P_h \tilde{C}^{c}_{1h} + P_l \tilde{C}^{c}_{1l} + P_{2z} + P_A \tilde{A}_2 + P_h \tilde{C}^{s}_{2h} + P_l \tilde{C}^{s}_{2l} + P_h \tilde{C}^{c}_{2h} + P_l \tilde{C}^{c}_{2l}$$

From this equation, we can solve for $P_A^S$ for this condition to hold in (3–82).

$$P_A^S < \frac{P_{1z} + P_h [(\tilde{C}^{s}_{1h} - \tilde{C}^{s}_{1l}} + (\tilde{C}^{s}_{2h} - \tilde{C}^{s}_{2l})] + P_{2z} + P_l [(\tilde{C}^{s}_{1l} - \tilde{C}^{s}_{1l}) + (\tilde{C}^{s}_{2l} - \tilde{C}^{s}_{2l})]}{(A_1 - \tilde{A}_1) + (\tilde{A}_2 - \tilde{A}_2)}$$ (3–82)

The minimum of the two $P_A^S$ will be the allowance price at which a plant is indifferent to installing a scrubber and not installing any scrubbers. Notice that the allowance price
for installing one scrubber will be weakly less than the allowance at which a plant would install scrubbers at both its generating units.

3.7.10.2 Case 2: Install one scrubber

We know that a plant will install a scrubber at the generating unit with the lowest $ACA_i$, which in this case is assumed to be Unit 1. For a plant to install one scrubber, two conditions must hold. First, the total costs of installing one generating unit must be lower than the total costs of installing no scrubbers.

\[
P_{1z} + P_A \tilde{A}_1 + P_h^s \tilde{C}_{1h}^s + P_i^s \tilde{C}_{1i}^s + P_c^c \tilde{C}_{1h}^c + P_c^c \tilde{C}_{1i}^c + P_A \tilde{A}_2 + P_h^s \tilde{C}_{2h}^s + P_i^s \tilde{C}_{2i}^s + P_c^c \tilde{C}_{2h}^c + P_c^c \tilde{C}_{2i}^c < P_A \tilde{A}_1 + P_h^s \tilde{C}_{1h}^s + P_i^s \tilde{C}_{1i}^s + P_c^c \tilde{C}_{1h}^c + P_c^c \tilde{C}_{1i}^c + P_A \tilde{A}_2 + P_h^s \tilde{C}_{2h}^s + P_i^s \tilde{C}_{2i}^s + P_c^c \tilde{C}_{2h}^c + P_c^c \tilde{C}_{2i}^c
\]

From this equation, we can solve for $P_A^S$ for this condition to hold in (3–83).

\[
\frac{P_{1z} + P_h^s(\tilde{C}_{1h}^s - \tilde{C}_{1h}^s) + P_i^s(\tilde{C}_{1i}^s - \tilde{C}_{1i}^s)}{\tilde{A}_1 - \tilde{A}_1} < P_A^S
\] (3–83)

Second, the total costs of installing one generating unit must be lower than the total costs of installing two scrubbers.

\[
P_{1z} + P_A \tilde{A}_1 + P_h^s \tilde{C}_{1h}^s + P_i^s \tilde{C}_{1i}^s + P_c^c \tilde{C}_{1h}^c + P_c^c \tilde{C}_{1i}^c + P_A \tilde{A}_2 + P_h^s \tilde{C}_{2h}^s + P_i^s \tilde{C}_{2i}^s + P_c^c \tilde{C}_{2h}^c + P_c^c \tilde{C}_{2i}^c < P_{1z} + P_A \tilde{A}_1 + P_h^s \tilde{C}_{1h}^s + P_i^s \tilde{C}_{1i}^s + P_h^c \tilde{C}_{1h}^c + P_i^s \tilde{C}_{1i}^c + P_i^s \tilde{C}_{2i}^s + P_h^c \tilde{C}_{2h}^c + P_i^s \tilde{C}_{2i}^s
\]

From this equation, we can solve for $P_A^S$ for this condition to hold in (3–84).

\[
\frac{P_{2z} + P_h^s(\tilde{C}_{2h}^s - \tilde{C}_{2h}^s) + P_i^s(\tilde{C}_{2i}^s - \tilde{C}_{2i}^s)}{(\tilde{A}_2 - \tilde{A}_2)} > P_A^S
\] (3–84)

The allowance price must be between these two indifference prices, which results in $P_A^S < P_A$ for Unit 1 and $P_A^S > P_A$ for Unit 2.
3.7.10.3 Case 3: Install two scrubbers

For a plant to install a scrubber at both generating units, two conditions must hold. First, the total costs of installing two generating units must be lower than the total costs of installing one scrubber.

\[
P_{1z} + P_A \tilde{A}_1 + P_s \tilde{C}_{1h} + P_s \tilde{C}_{1l} + P_c \tilde{C}_{1h} + P_c \tilde{C}_{1l} + P_{2z} \\
+ P_A \tilde{A}_2 + P_s \tilde{C}_{2h} + P_s \tilde{C}_{2l} + P_c \tilde{C}_{2h} + P_c \tilde{C}_{2l} \\
< P_{1z} + P_A \tilde{A}_1 + P_s \tilde{C}_{1h} + P_s \tilde{C}_{1l} + P_c \tilde{C}_{1h} + P_c \tilde{C}_{1l} \\
+ P_A \tilde{A}_2 + P_s \tilde{C}_{2h} + P_s \tilde{C}_{2l} + P_c \tilde{C}_{2h} + P_c \tilde{C}_{2l}
\]

From this equation, we can solve for \( P_A^S \) for this condition to hold in (3–85).

\[
\frac{P_{2z} + P_h^s(\tilde{C}_{2h} - \tilde{C}_{2l}) + P_l^s(\tilde{C}_{2l} - \tilde{C}_{2l})}{(\tilde{A}_2 - \tilde{A}_2)} < P_A^S 
\]

Second, the total costs of installing a scrubber at both generating units must be lower than the total costs of installing no scrubbers.

\[
P_{1z} + P_A \tilde{A}_1 + P_s \tilde{C}_{1h} + P_s \tilde{C}_{1l} + P_c \tilde{C}_{1h} + P_c \tilde{C}_{1l} + P_{2z} \\
+ P_A \tilde{A}_2 + P_s \tilde{C}_{2h} + P_s \tilde{C}_{2l} + P_c \tilde{C}_{2h} + P_c \tilde{C}_{2l} \\
< P_A \tilde{A}_1 + P_s \tilde{C}_{1h} + P_s \tilde{C}_{1l} + P_c \tilde{C}_{1h} + P_c \tilde{C}_{1l} \\
+ P_A \tilde{A}_2 + P_s \tilde{C}_{2h} + P_s \tilde{C}_{2l} + P_c \tilde{C}_{2h} + P_c \tilde{C}_{2l}
\]

From this equation, we can solve for \( P_A^S \) for this condition to hold in (3–86).

\[
\frac{P_{1z} + P_h^s(\tilde{C}_{1h} - \tilde{C}_{1h}) + P_l^s(\tilde{C}_{1l} - \tilde{C}_{1l}) + P_{2z} + P_h^s(\tilde{C}_{2h} - \tilde{C}_{2h}) + P_l^s(\tilde{C}_{2l} - \tilde{C}_{2l})}{(\tilde{A}_2 - \tilde{A}_2)} < P_A^S \]

The allowance price must be greater than both of these two indifference prices for two scrubbers to be installed.
We can monotonically order these indifference prices at which a plant will be indifferent to installing a scrubber in each of the above cases. A simple mathematical example using data based on data from the Colbert generating units can be used to show the monotonic nature of these indifference prices in Table 3-7.

A plant with no contract coal will prefer to install no scrubbers if the allowance price is below $194.48. An allowance price between $194.48 and $230.89 will lead a plant to install a scrubber at Unit 1, but not at Unit 2. A plant will install scrubbers at both units if the allowance price is greater than $230.89.

Now consider the plant has a high sulfur coal contract for 28.92% of coal use (13,855,269 mmBtu), which will alter the indifference at which a plant will install a scrubber at Unit 1. We have already shown that high sulfur contract coal will be used at the generating unit with the lowest $ACA_i$, which is Unit 1. The required use of high sulfur coal will lower the allowance indifferent price to installing a scrubber at Unit 1 to $140.69. There will be no change in the indifference price to installing a scrubber at Unit 2 because the high sulfur coal contract does not bind for that generating unit.

Now consider the plant has a high sulfur coal contract for all of its coal use in both generating units (47,913,973 mmBtu). The indifference prices for both generating units will both decrease as a result. The allowance price at which the plant will install a scrubber at Unit 1 will again be $140.49. The indifference price for Unit 2 will decrease to $153.61. A high sulfur coal contract for all of a generating unit’s coal requirements results in large reductions of the allowance price at which a plant will be indifferent to installing a scrubber for both Unit 1 ($54 or 28%) and Unit 2 ($77 or 33%).

### 3.7.11 Scrubber Installation Example: Plant with One Affected and One Non-Affected Generating Units

The $P^S_A$ for the non-affected unit (Unit 2) will be infinity because there is no price at which a plant would want to install a scrubber at a non-affected unit. The non-affected
unit will not buy or sell any allowances either since it has no emissions constraint. The only possible choice is to install a scrubber at the affected unit (Unit 1).

**Case 1: Install No Scrubber**

The total costs of not installing a scrubber must be lower than the total costs of installing a scrubber at the affected unit.

\[ P_A \hat{A}_1 + P_h \tilde{C}_{1h} + P_i \tilde{C}_{1l} + P_c \tilde{C}_{c1} + P_h \tilde{C}_{2h} + P_i \tilde{C}_{2l} + P_c \tilde{C}_{c2} < P_{1z} + P_A \tilde{A}_1 + P_h \tilde{C}_{1h} + P_i \tilde{C}_{1l} + P_c \tilde{C}_{c1} + P_h \tilde{C}_{2h} + P_i \tilde{C}_{2l} + P_c \tilde{C}_{c2} \]

From this equation, we can solve for \( P_A^S \) for this condition to hold in (3-87).

\[ P_A^S < \frac{P_{1z} + P_h (\tilde{C}_{1h} - \hat{C}_{1h}) + P_i (\tilde{C}_{1l} - \hat{C}_{1l})}{(\hat{A}_1 - \tilde{A}_1)} \]  \( (3-87) \)

**Case 2: Install One Scrubber**

The total costs of installing a scrubber must be lower than the total costs of not installing a scrubber at the affected unit.

\[ P_{1z} + P_A \tilde{A}_1 + P_h \tilde{C}_{1h} + P_i \tilde{C}_{1l} + P_c \tilde{C}_{c1} + P_h \tilde{C}_{2h} + P_i \tilde{C}_{2l} + P_c \tilde{C}_{c2} < P_{1z} + P_A \tilde{A}_1 + P_h \tilde{C}_{1h} + P_i \tilde{C}_{1l} + P_c \tilde{C}_{c1} + P_h \tilde{C}_{2h} + P_i \tilde{C}_{2l} + P_c \tilde{C}_{c2} \]

From this equation, we can solve for \( P_A^S \) for this condition to hold in (3-88).

\[ P_A^S > \frac{P_{1z} + P_h (\tilde{C}_{1h} - \hat{C}_{1h}) + P_i (\tilde{C}_{1l} - \hat{C}_{1l})}{(\hat{A}_1 - \tilde{A}_1)} \]  \( (3-88) \)

### 3.7.12 Summary of Plant Level Results

A plant’s decision-making process may not minimize costs for each generating unit because a plant’s concern is based on the combined costs of all generating units under its operational control. The choice to install a scrubber is based on the characteristics of all the units at a plant, not just the unit at which the scrubber may be installed. Once the
order of preferred scrubber installations is determined based on the $ACA_i$, a plant is able to make its cost minimizing fuel choices.

A plant level model is more realistic than a generating unit level model because coal deliveries are made at the plant level where there are often multiple generating units. Operating multiple units allows a plant to relax its contract constraint because there are additional degrees of freedom in fuel use depending on each unit’s emissions, demand, and coal contract constraints. Also, plants are able to trade allowances between generating units as needed to cover emissions at no additional cost. A plant may also have one or more “non-affected” generating units, which face no emissions constraint. Any high sulfur contract coal can be used at these non-affect units without any negative financial repercussions due to the policy. These factors can lead to plant-level choices that do not minimize each generating unit’s total costs.

3.8 CONCLUSIONS

The U.S. SO$_2$ Trading Program led to lower compliance costs than what would have occurred under a command-and-control approach. However, all compliance cost savings were not realized in part due to short-run fuel contract rigidities, particularly during the first years of the program. This paper considers the allowance market equilibrium impacts and total industry compliance costs from fuel contracts both through analytics and empirical modeling.

An allowance market equilibrium will exist only if the discrete scrubber choice is given. Allowing for an endogenous scrubber choice makes it impossible to guarantee an equilibrium, although one may still may exist. Binding fuel contracts may alter a unit’s compliance decisions and excess demand. Altering compliance decisions could lead to both an altered allowance market price and an increase total industry compliance costs.

Generating unit-level simulations were able to effectively replicate the results from previous studies and show that fuel contracts can explain a portion of the previously unexplained excess compliance costs. Simulating the least-cost compliance choices without
including fuel contract constraints results in minimum annual industry compliance costs of $288.3 million, which varies greatly from the actual compliance costs of $1.30 billion found in these simulations. Once fuel contract constraints are introduced into the simulation, the minimum annual industry compliance costs become $939 million-$1.07 billion. Based on these results, fuel contract constraints appear to explain $651.1 million, or 65% of the excess compliance costs realized in the program for 1996. These impacts should slowly decrease over time as firms adjust to the policy environment and binding contracts expire. However, the impacts on compliance costs should linger for years due to the long length of coal contract agreements. Also, contracts appear to remain prevalent in coal purchasing agreements and could lead to some issues resulting from further SO\textsubscript{2} emissions restrictions.

A plant’s decision-making process may not minimize costs for each generating unit because a plant’s concern is based on the combined costs of all generating units under its operational control. The choice to install a scrubber is based on the characteristics of all the units at a plant, not just the unit at which the scrubber may be installed. Once the order of preferred scrubber installations is determined based on the \textit{ACA}_i, a plant is able to make its cost minimizing fuel choices.

A plant level model is more realistic than a generating unit level model because coal deliveries are made at the plant level where there are often multiple generating units. Operating multiple units allows a plant to relax its contract constraint because there are additional degrees of freedom in fuel use depending on each unit’s emissions, demand, and coal contract constraints. Also, plants are able to trade allowances between generating units as needed to cover emissions at no additional cost. A plant may also have one or more “non-affected” generating units, which face no emissions constraint. Any high sulfur contract coal can be used at these non-affect units without any negative financial repercussions due to the policy. These factors can lead to plant-level choices that do not minimize each generating unit’s total costs.
### Table 3-1. Example: Contract Coal Distribution

<table>
<thead>
<tr>
<th>Plant-Level Constraint</th>
<th>Total mmBtu</th>
<th>Unit</th>
<th>Demand</th>
<th>Scrubber</th>
</tr>
</thead>
<tbody>
<tr>
<td>High Sulfur Contract</td>
<td>300,000</td>
<td>1</td>
<td>200,000</td>
<td>Yes</td>
</tr>
<tr>
<td>Low Sulfur Contract</td>
<td>300,000</td>
<td>2</td>
<td>200,000</td>
<td>No</td>
</tr>
<tr>
<td>Demand</td>
<td>600,000</td>
<td>3</td>
<td>200,000</td>
<td>No</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Coal Dist’n by Unit</th>
<th>High Sulfur Coal</th>
<th>Low Sulfur Coal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit 1</td>
<td>200,000</td>
<td>0</td>
</tr>
<tr>
<td>Unit 2</td>
<td>50,000</td>
<td>150,000</td>
</tr>
<tr>
<td>Unit 3</td>
<td>50,000</td>
<td>150,000</td>
</tr>
</tbody>
</table>

### Table 3-2. Sulfur Conversion by Fuel Type

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Emissions Conversion Factor</th>
<th>Baseline</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bituminous</td>
<td>(38 * Sulfur Content)/(mmBtu per ton)</td>
<td>= lbs. SO$_2$/mmBtu</td>
</tr>
<tr>
<td>Sub-bituminous</td>
<td>(35 * Sulfur Content)/(mmBtu per ton)</td>
<td>= lbs. SO$_2$/mmBtu</td>
</tr>
<tr>
<td>Anthracite</td>
<td>(39 * Sulfur Content)/(mmBtu per ton)</td>
<td>= lbs. SO$_2$/mmBtu</td>
</tr>
<tr>
<td>Lignite</td>
<td>(30 * Sulfur Content)/(mmBtu per ton)</td>
<td>= lbs. SO$_2$/mmBtu</td>
</tr>
<tr>
<td>Fuel Oil #2</td>
<td>(144 * Sulfur Content)/(mmBtu per 1,000 bbl.)</td>
<td>= lbs. SO$_2$/mmBtu</td>
</tr>
<tr>
<td>Fuel Oil #6</td>
<td>(162 * Sulfur Content)/(mmBtu per 1,000 bbl.)</td>
<td>= lbs. SO$_2$/mmBtu</td>
</tr>
<tr>
<td>Natural Gas</td>
<td>(0.60 lbs. SO$_2$/mmCF)/(mmBtu per mmCF)</td>
<td>= lbs. SO$_2$/mmBtu</td>
</tr>
</tbody>
</table>
Table 3-3. Simulation Results

<table>
<thead>
<tr>
<th>Sim.</th>
<th>Emissions Constraint</th>
<th>Contract Constraint</th>
<th>Scrubber Choice</th>
<th>Scrubbers Installed</th>
<th>$P_A$</th>
<th>$A_i$</th>
<th>Total Costs</th>
<th>Compl. Costs vs. (Sim. 1)</th>
<th>Comp. Costs vs. (Sim. 2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1)</td>
<td>NO</td>
<td>NO</td>
<td>Given</td>
<td>17</td>
<td>NA</td>
<td>NA</td>
<td>$7,685,800,000</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>(2)</td>
<td>NO</td>
<td>YES</td>
<td>Given</td>
<td>17</td>
<td>NA</td>
<td>NA</td>
<td>$8,267,400,000</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>(3)</td>
<td>YES</td>
<td>NO</td>
<td>Given</td>
<td>46</td>
<td>$149.64$</td>
<td>0</td>
<td>$8,226,500,000</td>
<td>$540,700,000</td>
<td>NA</td>
</tr>
<tr>
<td>(4)</td>
<td>YES</td>
<td>NO</td>
<td>Chosen</td>
<td>44</td>
<td>$155.58$</td>
<td>-53,576</td>
<td>$7,974,100,000</td>
<td>$288,300,000</td>
<td>NA</td>
</tr>
<tr>
<td>(5)</td>
<td>YES</td>
<td>YES</td>
<td>Given</td>
<td>46</td>
<td>$206.70$</td>
<td>0</td>
<td>$8,757,500,000</td>
<td>$1,071,700,000</td>
<td>$490,100,000</td>
</tr>
<tr>
<td>(6)</td>
<td>YES</td>
<td>YES</td>
<td>Chosen</td>
<td>61</td>
<td>$210.74$</td>
<td>7,797</td>
<td>$8,625,200,000</td>
<td>$939,400,000</td>
<td>$357,800,000</td>
</tr>
<tr>
<td>(7)</td>
<td>-</td>
<td>-</td>
<td>Actual</td>
<td>46</td>
<td>NA</td>
<td>NA</td>
<td>$8,983,500,000</td>
<td>$1,297,700,000</td>
<td>$716,100,000</td>
</tr>
</tbody>
</table>
### Table 3-4. Impact of Contract Constraint on Scrubber Choice

<table>
<thead>
<tr>
<th>State</th>
<th>Decrease</th>
<th>State</th>
<th>Increase</th>
</tr>
</thead>
<tbody>
<tr>
<td>WV</td>
<td>-4</td>
<td>MO</td>
<td>2</td>
</tr>
<tr>
<td>NY</td>
<td>-2</td>
<td>MS</td>
<td>2</td>
</tr>
<tr>
<td>PA</td>
<td>-2</td>
<td>IN</td>
<td>3</td>
</tr>
<tr>
<td>WI</td>
<td>-2</td>
<td>FL</td>
<td>4</td>
</tr>
<tr>
<td>GA</td>
<td>-1</td>
<td>AL</td>
<td>7</td>
</tr>
<tr>
<td>KY</td>
<td>-1</td>
<td>OH</td>
<td>10</td>
</tr>
<tr>
<td>NJ</td>
<td>-1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Table 3-5. Simulations with Engineering Data

<table>
<thead>
<tr>
<th>Sim.</th>
<th>$A_i$</th>
<th>$P_A$</th>
<th>Scrubbers Installed</th>
<th>Industry Costs (vs. 1)</th>
<th>Comp. Costs (vs. 1)</th>
<th>Comp. Costs (vs. 2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>NA</td>
<td>NA</td>
<td>17</td>
<td>$7,685,800,000</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>2</td>
<td>NA</td>
<td>NA</td>
<td>17</td>
<td>$8,267,400,000</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>$149.64</td>
<td>46</td>
<td>$8,239,000,000</td>
<td>$553,200,000</td>
<td>NA</td>
</tr>
<tr>
<td>4</td>
<td>1,972</td>
<td>$214.83</td>
<td>25</td>
<td>$8,010,200,000</td>
<td>$324,400,000</td>
<td>NA</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>$207.60</td>
<td>46</td>
<td>$8,770,900,000</td>
<td>$1,085,100,000</td>
<td>$503,500,000</td>
</tr>
<tr>
<td>6</td>
<td>2,611</td>
<td>$238.55</td>
<td>38</td>
<td>$8,686,300,000</td>
<td>$1,000,500,000</td>
<td>$418,900,000</td>
</tr>
<tr>
<td>7</td>
<td>NA</td>
<td>NA</td>
<td>46</td>
<td>$8,995,600,000</td>
<td>$1,309,800,000</td>
<td>$728,200,000</td>
</tr>
</tbody>
</table>

### Table 3-6. Impacts of a Reduction in the Allowance Allocation of 10%

<table>
<thead>
<tr>
<th>Simulation</th>
<th>Initial Allocation</th>
<th>Allocation Minus 10%</th>
<th>Increase</th>
</tr>
</thead>
<tbody>
<tr>
<td>Industry Compliance Costs</td>
<td>$288,300,000</td>
<td>$381,900,000</td>
<td>$93,600,000</td>
</tr>
<tr>
<td>Scrubbers Installed</td>
<td>44</td>
<td>61</td>
<td>17</td>
</tr>
<tr>
<td>Allowance Price</td>
<td>$155.58</td>
<td>$189.43</td>
<td>$33.85</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Simulation</th>
<th>Initial Allocation</th>
<th>Allocation Minus 10%</th>
<th>Increase</th>
</tr>
</thead>
<tbody>
<tr>
<td>Industry Compliance Costs</td>
<td>$357,800,000</td>
<td>$476,600,000</td>
<td>$118,800,000</td>
</tr>
<tr>
<td>Scrubbers Installed</td>
<td>61</td>
<td>73</td>
<td>12</td>
</tr>
<tr>
<td>Allowance Price</td>
<td>$210.74</td>
<td>$222.22</td>
<td>$11.48</td>
</tr>
</tbody>
</table>

### Table 3-7. Math Example: Two Affected Units

<table>
<thead>
<tr>
<th>Coal Type</th>
<th>Price</th>
<th>Sulfur Content</th>
<th>Heat Content</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low Sulfur Spot</td>
<td>$1.20</td>
<td>0.625%</td>
<td>24 mmBtu</td>
</tr>
<tr>
<td>High Sulfur Spot</td>
<td>$1.10</td>
<td>2.580%</td>
<td>24 mmBtu</td>
</tr>
<tr>
<td>High Sulfur Contract</td>
<td>$1.15</td>
<td>2.580%</td>
<td>24 mmBtu</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Generating Unit</th>
<th>$P_{i1}$</th>
<th>$r_i$</th>
<th>Demand (mmBtu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit 1</td>
<td>$2,719,320</td>
<td>90%</td>
<td>13,855,269</td>
</tr>
<tr>
<td>Unit 2</td>
<td>$7,298,412</td>
<td>90%</td>
<td>34,058,704</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Scrubber Installation</th>
<th>$P_{A}^{S}$: No Contract</th>
<th>$P_{A}^{S}$: Unit 1 Demand</th>
<th>$P_{A}^{S}$: Unit 1 and Unit 2 Demand</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>&lt; $194.48</td>
<td>&lt; $140.69</td>
<td>&lt; $140.69</td>
</tr>
<tr>
<td>Unit 1</td>
<td>($194.48, $230.89)</td>
<td>($140.69, $230.89)</td>
<td>($140.69, $153.61)</td>
</tr>
<tr>
<td>Unit 2</td>
<td>$230.89</td>
<td>$230.89</td>
<td>$153.61</td>
</tr>
</tbody>
</table>
Figure 3-1. Excess Demand Correspondence

Figure 3-2. Impact of High Sulfur Coal Contract
Figure 3-3. Impact of Low Sulfur Coal Contract

Figure 3-4. Excess Demand Correspondence with Scrubber Choice
Figure 3-5. Impacts of High Sulfur Coal Contract

Figure 3-6. Impacts of Low Sulfur Coal Contract
Figure 3-7. Given Scrubber Choice: Shift from High Sulfur Contract

Figure 3-8. Given Scrubber Choice: Shift from Low Sulfur Contract
Figure 3-9. With Scrubber Choice: Shift from High Sulfur Contract
Figure 3-10. With Scrubber Choice: Shift from Low Sulfur Contract
A.1 Impacts on Total Costs and Compliance Costs from a Coal Contract Constraint

First, consider a unit’s total costs without a coal contract constraint. Without the program restrictions on emissions, a unit will simply minimize its costs of meeting electricity demand by using the coal with the lowest price per unit of heat content.

\[ P_{si}^s C_{si}^{st} + P_{si}^s C_{si}^{st} \]  

(A–1)

With the emissions constraint from the program, a unit will minimize its costs of coal use, net allowance purchases, and scrubber installation.

\[ z_i^* P_{iz} + P_{Ai} A_i^* + P_{si}^s (C_{si}^{st} - C_{si}^{s}) + P_{si}^s (C_{si}^{s} - C_{si}^{st}) \]

(A–2)

The difference between (A–1) and (A–2) is the total compliance costs resulting from the program, which includes the change in coal costs, change in the net allowance purchases, and scrubber installation costs.

\[ z_i^* P_{iz} + P_{Ai} A_i^* + P_{si}^s (C_{si}^{st} - C_{si}^{s}) + P_{si}^s (C_{si}^{s} - C_{si}^{st}) \]

(A–3)

Second, consider a unit’s total costs with a coal contract constraint. Without the program restrictions on emissions, a unit will simply minimize its costs of meeting electricity demand by using all the the coal under contract, and cover the remainder of its coal demand with the coal with the lowest price per unit of heat content.

\[ P_{ci}^c C_{ci}^{ct} + P_{ci}^c C_{ci}^{ct} + P_{ci}^s C_{ci}^{st} + P_{ci}^s C_{ci}^{st} \]

(A–4)

With the emissions constraint, a unit will minimize its costs for coal use, net allowance purchases, and scrubber installation given its emissions and coal contract constraint.

\[ \hat{z}_i^* P_{iz} + P_{Ai} A_i^* + P_{ci}^c C_{ci}^{ct} + P_{ci}^c C_{ci}^{ct} + P_{ci}^s C_{ci}^{st} + P_{ci}^s C_{ci}^{st} \]

(A–5)
The difference between (A–4) and (A–5) is the total compliance costs resulting from the program, which includes the change in spot market coal costs, net allowance purchases, and scrubber installation. The costs from contract coal cancel out because contract coal use will be the same both with and without the program.

\[
\tilde{z}_i^* P_{iz} + P^*_A A^*_i + P^s (\hat{C}^s_{ih} - \hat{C}'^s_{ih}) + P^s (\hat{C}^s_{il} - \hat{C}'^s_{il}) \quad (A-6)
\]

The sufficient conditions under which a coal contract constraint will increase or decrease a unit’s compliance costs can be derived from the difference in compliance costs with and without a coal contract \(( (A-6) \text{ minus } (A-3) ) \).

\[
\left[ z_i^* P_{iz} + P^*_A A^*_i + P^s (\hat{C}^s_{ih} - \hat{C}'^s_{ih}) + P^s (\hat{C}^s_{il} - \hat{C}'^s_{il}) \right] \\
- \left[ z_i^* P_{iz} + P^*_A A^*_i + P^s (C^s_{ih} - C'_{ih}) + P^s (C^s_{il} - C'_{il}) \right] \quad (A-7)
\]

For simplicity, assume that the scrubber choice as a given and high sulfur spot market coal is relatively cheaper than low sulfur spot market coal. So without an emissions constraint a unit will prefer to use the cheaper high sulfur coal. Proposition 1 can be proven by considering the change in compliance costs in (A–8) resulting from a coal contract. First consider a high sulfur coal contract to show Proposition 1(i) and Proposition 1(ii) hold.

**Proof of Proposition 1(i):**

If \( P_A > MCA^s_i \), a unit prefers to switch from high to low sulfur coal to meet its emissions requirement because it is the least-cost compliance option. Without a high sulfur coal contract, a unit will use all low sulfur coal \((C^s_{il} = C^s_{il}^{MAX} \text{ and } C^s_{ih} = 0)\) and require the fewest allowances to cover the minimum emissions level \((A_{iMIN})\). With a high sulfur coal contract, a unit will use less low sulfur coal \((\hat{C}^s_{il}^{MAX} < C^s_{il}^{MAX})\), which will
increase the emissions level and require additional allowances ($\hat{A}_i^{MIN} > A_i^{MIN}$).

$$[P_A^s \hat{A}_i^{MIN} + P_{ih}^s (0 - \hat{\bar{C}}_{ih}^{s,MAX}) + P_{il}^s (\hat{\bar{C}}_{il}^{s,MAX} - 0)] - [P_A^s A_i^{MIN} + P_{ih}^s (0 - \bar{C}_{ih}^{s,MAX}) + P_{il}^s (\bar{C}_{il}^{s,MAX} - 0)]$$

(A–8)

The change in compliance costs will be:

$$P_A^s (\hat{A}_i^{MIN} - A_i^{MIN}) + P_{ih}^s (\bar{C}_{ih}^{s,MAX} - \hat{\bar{C}}_{ih}^{s,MAX}) + P_{il}^s (\hat{\bar{C}}_{il}^{s,MAX} - C_{il}^{s,MAX})$$

(A–9)

The first term is positive because $\hat{A}_i^{MIN} - A_i^{MIN}$. The second term is also positive because $C_{ih}^{s,MAX} \geq \hat{\bar{C}}_{ih}^{s,MAX}$. The third term is negative because $\hat{\bar{C}}_{il}^{s,MAX} \leq C_{il}^{s,MAX}$.

Now fill in for coal use:

$$C_{ih}^{s,MAX} = \frac{D_i}{H_{ih}^s} \quad \hat{\bar{C}}_{ih}^{s,MAX} = \frac{D_i - C_{ih} C_{ih}^c}{H_{ih}^s} \quad C_{il}^{s,MAX} = \frac{D_i}{H_{il}^s} \quad \hat{\bar{C}}_{il}^{s,MAX} = \frac{D_i - C_{ih} C_{ih}^c}{H_{il}^s}$$

The change in compliance costs resulting from a high sulfur coal contract is the increase in net allowance purchases minus the cost savings from not switching fuels from the high sulfur contract coal.

$$P_A^s (\hat{A}_i^{MIN} - A_i^{MIN}) + (\frac{P_{ih}^s}{H_{ih}^s} - \frac{P_{il}^s}{H_{il}^s}) \bar{C}_{ih} C_{ih}^c$$

(A–10)

Now fill in for the net allowance position:

$$A_i^{MIN} = \frac{D_i}{H_{il}^s} S_{ih}^s m - A_i^e \quad \hat{A}_i^{MIN} = \frac{D_i - C_{ih} C_{ih}^c}{H_{il}^s} S_{il}^s + C_{ih} S_{ih}^s m - A_i^e$$

$$\Rightarrow m P_A^s (C_{ih}^c S_{ih}^s - \frac{C_{ih} C_{ih}^c}{H_{il}^s} S_{il}^s) + (\frac{P_{ih}^s}{H_{ih}^s} - \frac{P_{il}^s}{H_{il}^s}) \bar{C}_{ih} C_{ih}^c$$

By adding and subtracting $m P_A^s S_{ih}^s$, combining like terms, and dividing through by $m \left( \frac{S_{ih}^s}{H_{ih}^s} - \frac{S_{il}^s}{H_{il}^s} \right)$, the expression can be simplified to:

$$\Rightarrow \bar{C}_{ih} C_{ih}^c \left[ P_A^s \left( \frac{S_{ih}^s}{H_{ih}^s} - \frac{S_{il}^s}{H_{il}^s} \right) + P_A - \frac{P_{il}^s - P_{ih}^s}{m \left( \frac{S_{ih}^s}{H_{ih}^s} - \frac{S_{il}^s}{H_{il}^s} \right)} \right]$$

$$\Rightarrow \bar{C}_{ih} C_{ih}^c \left[ P_A^s \left( \frac{S_{ih}^s}{H_{ih}^s} - \frac{S_{il}^s}{H_{il}^s} \right) + P_A - MCA_i^{s,8} \right]$$

(A–11)
For this case, it is assumed the $P_A^* > MCA_i^{s,s}$. So if $\frac{S_{ih}^c}{H_{ih}^c} > \frac{S_{ih}^s}{H_{ih}^s}$, compliance costs will increase, and the increase will be get larger as the coal contract gets larger. ■

**Proof of Proposition 1(ii):**

If $P_A \leq MCA_i^{s,s}$, a unit prefers to use all high sulfur coal and purchase allowances to meet its emissions requirement because it is the least-cost compliance option. Without a high sulfur coal contract, a unit will use all high sulfur spot market coal ($C_{ih}^{s*} = C_{ih}^{s,MAX}$ and $C_{il}^{s*} = 0$) and require the most allowance use to cover its maximum emissions level ($A_i^{MAX}$). With a high sulfur coal contract, a unit will use less high sulfur spot market coal ($\hat{C}_{ih}^{s,MAX} < C_{ih}^{s,MAX}$). If high sulfur contract coal has a higher sulfur to heat content ratio ($\frac{S_{ih}^c}{H_{ih}^c} > \frac{S_{ih}^s}{H_{ih}^s}$), a unit will generate additional emissions, which will require a unit to purchase more or sell fewer allowances ($\hat{A}_i^{MAX} > A_i^{MAX}$). Now fill in for known values and combine like terms:

$$P_A^*(\hat{A}_i^{MAX} - A_i^{MAX}) = P_A^*C_{ih}^{s,MAX} \left(\frac{S_{ih}^c}{H_{ih}^c} - \frac{S_{ih}^s}{H_{ih}^s}\right)$$

(A–12)

All coal use remains the same, which means the change in compliance costs will be the increase in costs from additional allowances. If $\frac{S_{ih}^c}{H_{ih}^c} > \frac{S_{ih}^s}{H_{ih}^s}$, a unit’s compliance costs will increase. ■

**Proof of Proposition 1(iii):**

If $P_A \geq MCA_i^{s,s}$, a unit prefers to switch to all low sulfur use because it is the least-cost compliance option. Without a low sulfur coal contract, a unit will use all low sulfur spot market coal ($C_{il}^{s*} = C_{il}^{s,MAX}$ and $C_{ih}^{s*} = 0$) and require the least possible allowances to cover its minimum emissions level ($A_i^{MIN}$). With a low sulfur coal contract, a unit will use less low sulfur spot market coal ($\hat{C}_{il}^{s,MAX} < C_{il}^{s,MAX}$). If low sulfur contract coal has a higher sulfur to heat content ratio ($\frac{S_{il}^c}{H_{il}^c} > \frac{S_{il}^s}{H_{il}^s}$), a unit will generate additional emissions, which will require a unit to purchase more or sell fewer allowances ($\hat{A}_i^{MIN} > A_i^{MIN}$). Coal use will remain the same with and without an emissions constraint,
and will cancel out. Fill in for known values and combine like terms:

\[ A_i^{MIN} = \frac{D_i}{H_i^s}S_i^s m - A_i^e \quad \widehat{A}_i^{MIN} = \frac{D_i - C_{iH}^c H_i^c}{H_i^s} S_i^s + C_{iS}^c S_{iM} - A_i^e \]

\[ P_A^s (\widehat{A}_i^{MIN} - A_i^{MIN}) = P_A^s C_{iH}^c H_i^s \left( \frac{S_i^s}{H_i^c} - \frac{S_i^s}{H_i^c} \right) \]  

(A-13)

The change in compliance costs will be the increase in costs from the increase in a unit’s net allowance position. If \( \frac{S_i^s}{H_i^s} > \frac{S_i^s}{H_i^s} \), a unit’s compliance costs will increase. ■

Proof of Proposition 1(iv):

If \( P_A < MCA_i^{s,s} \), a unit prefers to use all high sulfur coal and purchase allowances instead of switching fuels to meet its emissions requirement because it is the least-cost compliance option. Without a low sulfur coal contract, a unit will use all high sulfur coal (\( C_{iH}^{s,MAX} = C_{iH}^{s,MAX} \) and \( C_{iS}^{s,MAX} = 0 \)) and require the largest net allowance position to cover the maximum emissions level (\( A_i^{MAX} \)). With a low sulfur coal contract, a unit will use less high sulfur coal (\( \widehat{C}_{iH}^{s,MAX} < C_{iH}^{s,MAX} \)), which will decrease the emissions level and requires fewer allowances (\( \widehat{A}_i^{MAX} > A_i^{MAX} \)). Since a unit prefers to use high sulfur coal with and without the emissions constraint, coal use will remain the same. Fill in for known values and combine like terms:

\[ P_A^s (\widehat{A}_i^{MIN} - A_i^{MIN}) + P_{ih}^s (C_{iH}^{s,MAX} - \widehat{C}_{iH}^{s,MAX} - \widehat{C}_{iS}^{s,MAX} + C_{iS}^{s,MAX}) = P_A^s (\widehat{A}_i^{MIN} - A_i^{MIN}) \]  

(A-14)

The change in compliance costs is the change in costs from the change in net allowance position. Now fill in for the net allowance position:

\[ A_i^{MAX} = \frac{D_i}{H_i^s}S_i^s m - A_i^e \quad \widehat{A}_i^{MAX} = \frac{D_i - C_{iH}^c H_i^c}{H_i^s} S_i^s + C_{iS}^c S_{iM} - A_i^e \]

\[ \Rightarrow \widehat{C}_{iH}^{s} H_i^c P_A^s m \left( \frac{S_i^s}{H_i^c} - \frac{S_i^s}{H_i^c} \right) < 0 \]  

(A-15)

Since \( \frac{S_i^c}{H_i^c} < \frac{S_i^s}{H_i^s} \), compliance costs will decrease. ■

Another way of looking at the impacts of coal contract constraints on compliance costs is to find the change in total costs for a unit facing an emissions constraint with
and without a coal contract ((A–5)-(A–2)) and split it into two components, the change in compliance costs and the change in fuel costs. For simplicity, assume the conditions in Proposition 1(i) hold.

\[ z_i^* P_{iz} + P_A^s(\hat{A}_i^s - A_i^s) + P_{ih}^c \tilde{C}_{ih}^c + P_{il}^c \tilde{C}_{il}^c + P_s^s(\hat{C}_{il}^{ss} - C_{il}^{ss}) + P_{il}^s(\hat{C}_{il}^{ss} - C_{il}^{ss}) \]  

(A–16)

Assume that a unit faces a high sulfur coal contract, and prefers to switch to low sulfur coal use to meet its emissions requirement instead of purchasing allowances or installing a scrubber.

\[ P_A^s(\hat{A}_i^{MIN} - A_i^{MIN}) + P_{ih}^c \tilde{C}_{ih}^c + P_{il}^s(\hat{C}_{il}^{s,MAX} - C_{il}^{s,MAX}) \]  

(A–17)

To be able to interpret this expression, it is necessary to add and subtract \((P_{ih}^s \tilde{C}_{ih}^c H_{ih}^c H_{ih}^s)\).

\[ \tilde{C}_{ih}^c (P_{ih}^c - P_{ih}^s \frac{H_{ih}^c H_{ih}^s}{H_{ih}^s}) + P_A^s(\hat{A}_i^{MIN} - A_i^{MIN}) + P_{ih}^c \tilde{C}_{ih}^c \frac{H_{ih}^c}{H_{ih}^s} + P_{il}^s(\hat{C}_{il}^{s,MAX} - C_{il}^{s,MAX}) \]  

(A–18)

The first term is the change in high sulfur coal costs from using the contract coal instead of spot market coal. These are not changes in compliance costs because they will occur with or without the program. The remaining terms are the change in compliance costs resulting from the program.

\[ \tilde{C}_{ih}^c (P_{ih}^c - P_{ih}^s \frac{H_{ih}^c}{H_{ih}^s}) + P_A^s(\hat{A}_i^{MIN} - A_i^{MIN}) + (\frac{P_{ih}^s}{H_{ih}^s} - \frac{P_{il}^s}{H_{il}^s}) \tilde{C}_{ih}^c H_{ih}^c \]  

(A–19)

By filling in for the coal use, the last terms give the same expression for the change in compliance costs as in the proof of Proposition 1(i).

\[ \tilde{C}_{ih}^c H_{ih}^c \left[ P_A^s \left( \frac{S_{ih}^c H_{ih}^c}{S_{ih}^c H_{ih}^s} - \frac{S_{ih}^s}{H_{ih}^s} \right) + P_A - MCA_i^{s,s} \right] \]  

(A–20)

A unit’s compliance costs increase if \( \frac{S_{ih}^c}{H_{ih}^c} > \frac{S_{ih}^s}{H_{ih}^s} \).
A.2 Derivation of Cost-Minimizing Input Use to Find $P^s_A$

Assuming no scrubber, the cost-minimizing combination of coal and allowances solves the problem below.

$$\min_{\tilde{A}_i, \tilde{C}_{ih}, \tilde{C}_{il}} (P_{A_i}^{MAX} + P_{s_i}^{C_s,MAX}, P_{A_i}^{MIN} + P_{s_i}^{C_s,MAX})$$  \hspace{1cm} (A–21)

Assuming a scrubber is installed, the cost-minimizing combination of inputs is expressed below.

$$\min_{\tilde{A}_i, \tilde{C}_{ih}, \tilde{C}_{il}} (P_{A_i}^{SMAX} + P_{s_i}^{C_s,MAX}, P_{A_i}^{SMIN} + P_{s_i}^{C_s,MAX})$$  \hspace{1cm} (A–22)

Notice that contract coal use and the cost of installing a scrubber can be ignored because all are constants.
APPENDIX B
MARKET EQUILIBRIUM AND SIMULATION DESIGN

B.1 Conditions for Existence of an Equilibrium

Theorem 5.1: Assuming the scrubber choice \( z_i^* \) as given, a market equilibrium exists.

Proof of Theorem 5.1: To prove that a market equilibrium exists, it is necessary to apply Kakutani’s Fixed Point Theorem.

Kakutani’s Fixed Point Theorem that states: If \( X \) is a non-empty, compact, convex subset of \( \mathbb{R}^m \) and if \( f \) is an upper semi-continuous correspondence from \( X \) into itself such that \( (\forall x \in X) \) the set \( f(x) \) is non-empty and convex, then \( f \) has a fixed point (there is an \( x \in f(x) \)).

Assuming all other parameters as given for all generating unit “i”, a generating units excess demand is a function of the allowance price, \( A_i(P_A) \). Consider a generating unit’s excess demand correspondence from Section 5.

\[
A_i = \begin{cases} 
A_i^{MAX} & \text{if } P_A > MCA_i^{s,s} \\
\rho A_i^{MAX} - (1 - \rho)A_i^{MIN} & \text{if } P_A = MCA_i^{s,s} \forall \rho \in [0, 1] \\
A_i^{MIN} & \text{if } P_A < MCA_i^{s,s}
\end{cases}
\]

To find the market excess demand, you must sum all generating unit excess demands, which gives you \( A_m = \sum_{i=1}^{n} A_i \). It is necessary to show that the market excess demand is compact. The market excess demand is bounded above by the sum of the maximum allowance excess demands for each generating unit \( (\sum_{i=1}^{n} A_i^{MAX}) \) and below by the sum of the minimum allowance excess demands for each generating unit \( (\sum_{i=1}^{n} A_i^{MIN}) \). So the market excess demand lies in a closed interval \([\sum_{i=1}^{n} A_i^{MIN}, \sum_{i=1}^{n} A_i^{MAX}] \equiv X\). X being a closed interval on the real line is non-empty, compact (closed and bounded), and convex (any point on the line connecting any two points in the set is also in the set).

It is necessary to show that the set of prices is compact (closed and bounded). Define the lower bound on price to be zero because it is necessary to have a positive price. Define the upper bound on price to be \( \bar{P}_A = \arg \min \sum_{i=1}^{n} A_i(P_A) \), or the allowance.
price that results in the smallest possible excess demand for a particular generating unit multiplied by two. This ensures a upper bound that will be higher than any possible price. The closed interval for prices is $[0, P_A]$, which is non-empty by design. Since there is an upper bound, a lower bound, and both bounds are included in the set (closed), the set is compact.

Since the set of prices and market excess demands are compact and the market excess demand depends on the allowance price, the market excess demand ($A_m(P_A)$) is a mapping from $[0, P_A]$ into $X$. It is necessary to show that excess demand is non-empty, convex valued at each $P_A \in [0, P_A]$, and upper semi-continuous. It is sufficient to show that each generating unit’s excess demand correspondence is non-empty, convex, and upper semi-continuous because the sum of a finite number of non-empty, convex, upper semi-continuous correspondences is also non-empty, convex, and upper semi-continuous.

A generating units’ excess demand ($A_i(P_A)$) are defined to be mappings from $[0, P_A]$ into $X$, which makes them non-empty by construction. A generating unit’s excess demand correspondence is closed and bounded in the interval $[A_i^{MIN}, A_i^{MAX}]$, which makes it a compact set. The set of excess demands is convex because the average of any two excess demand values is also in the set. For a correspondence to be upper semi-continuous, the convergence excess demand value of any price sequence must also be in the correspondence. Since every possible price sequence converges to a value that is in the excess demand correspondence (see Figure B.2), each unit’s excess demand correspondence is upper semi-continuous.

Now we must define the mapping from $X$ into the set of prices $[0, P_A]$ as $\mu(x)$ where...

$$\mu(x) = \begin{cases} P_A \in [0, P_A] : P_A \ast x = \max_{Q \in [P_A]} Q \ast x & \text{if } x \neq 0 \\ P_A \in [0, P_A] : P_A \ast x = 0 & \text{if otherwise} \end{cases}$$

Since $[0, P_A]$ is non-empty, $\mu(x)$ must be non-empty as well. The mapping is convex valued since for market excess demand equal to zero ($x = 0$), $\mu(x) = [0, P_A]$. If there is a
positive excess demand \((x > 0)\), \(\mu(x) = \overline{P}_A\). If there is a negative excess demand \((x < 0)\), or excess supply, \(\mu(x) = 0\). Since \([0, \overline{P}_A]\) is compact, the graph of \(\mu(x)\) is closed, which implies \(\mu(x)\) is upper semi-continuous.

Now define \(F(x, P_A) = \mu(x) \times A_m(P_A)\). Since \(\mu(x)\) and \(A_m(P_A)\) satisfy all properties needed to apply Kakutani’s Fixed Point Theorem, there exists a fixed point \((x^*, P_A^*)\) such that \(P_A \in [0, \overline{P}_A]\) and \(x^* \in X\) such that \(P_A \in \mu(x^*)\) and \(x^* \in A_m(P_A^*)\).

In English...There is a market excess demand correspondence for which each excess demand value can only result from only one allowance price while each allowance price will result in at least one market excess demand value.

Once the scrubber choice is introduced into the decision-making process, the correspondence becomes more complex, as seen in Figure B.2. An equilibrium may in fact exist, but there is no way to guarantee an equilibrium because the excess demand correspondence is no longer a convex set. The average of the two excess demand values \(A_i^{SMAX}\) and \(A_i^{MIN}\) is not in the excess demand correspondence.

**B.2 Technical Details of Simulation Model Design**

The equilibrium allowance market price is solved by using a bisection iterative process. An upper limit ($1,000) and lower limit ($0) for the allowance price are chosen. The initial allowance price is set to the upper limit and the simulation solves for each generating unit’s cost-minimizing choices. Then it checks if the allowance market is in an equilibrium.

If market excess demand is positive, the allowance price is too low and the allowance price is increased by one-half the difference between the upper and lower limits. The old price now becomes the new lower limit while the upper limit remains the same. If the market excess demand is negative, the allowance price is too high and the allowance price is decreased by one-half the difference between the upper and lower limits. The old price becomes the new upper limit and the lower limit remains the same. In this case, the upper
limit is set high enough to guarantee the price is too low. So the price will decrease by 
$1,000-(1000-0)/2=500$ to a new price of $500$.

The program is then run again with the new allowance price, each iteration decreasing
the difference between the upper and lower limits by half until the program converges to
an allowance price. Once the program converges, it must ensure a market excess demand
of zero. A concern is that the program tends to push a unit’s choices towards a corner
solution where the market may not clear.

Given the scrubber choice, the allowance price will converge to a value equal to at
least one generating unit’s $MCA_{i}^{s,s}$, which allows those firms choices to be shifted to
an interior solution to clear the market without altering the unit’s total costs or total
industry costs because the unit is indifferent to purchasing allowances or switching fuels
from high to low sulfur coal at the equilibrium allowance price ($P_{A}^{*}$).

Allowing for the scrubber choice will result in the convergence of $P_{A}$ at an allowance
price where a generating unit is indifferent to installing a scrubber. In this case, there is
not a true equilibrium and must consider it a quasi-equilibrium as described above.
Figure B-1. Upper Semi-Continuous Correspondence

Figure B-2. Correspondence with Scrubber Choice
REFERENCES


BIOGRAPHICAL SKETCH

Joshua David Kneifel was born in 1981 in North Platte, Nebraska. He grew up in North Platte, graduating salutatorian from Hershey High School in 1999. Joshua received his bachelor’s degrees in economics and mathematics in 2003 from Doane College in Crete, Nebraska. He received his Master of the Arts in economics in 2005 from the University of Florida, where he specialized in industrial organization, public economics, and econometrics. From Fall 2006 through Spring 2008, Joshua instructed four semesters of a course in environmental economics. His classwork and research allowed him to obtain his PhD in economics from the University of Florida.

Upon completion of his PhD program, he will take an economist position at the National Institute of Standards and Technology (NIST) in Gaithersburg, Maryland. His responsibilities at NIST will include research on the life-cycle cost and environmental impacts of individual products used in the construction industry.