The Effects of Coal Contract Constraints on SO$_2$ Trading Program Compliance Decisions

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Abstract

Several studies on Phase I of the Title IV SO$_2$ Trading Program have found that actual compliance costs realized by the electric power industry have far exceeded the least-cost outcome in spite of allowance prices being much lower than expected. Prior work has either conjectured or shown that some of these excess costs could be a result of inefficiencies related to state regulatory constraints, but this does not explain all the additional costs above the least cost outcome. A possible explanation for these additional costs that has been offered, but neither modeled, simulated, nor estimated, is the presence of fuel contracting constraints or rigidities.

This paper models utility sulfur dioxide compliance incorporating the possibility for long-term coal contract constraints. During Phase I of the Title IV SO$_2$ Trading Program, long-term high sulfur coal contracts could restrict a utility’s ability to cost-effectively switch to low sulfur coal, and force generating units into more expensive compliance options such as scrubbing or allowance purchases. The existence of contract constraints in the model may force scrubber installation, which increases unit-level compliance costs, increases supply of allowances in the market, and may explain the lower than expected allowance prices observed during Phase I of the Title IV SO$_2$ Trading Program. Under the recently promulgated Clean Air Interstate Rule (CAIR), the use of low sulfur coal alone will likely no longer be sufficient to achieve the desired emissions reductions. Consequently, long-term low sulfur coal contracts may prevent utilities from cost-effectively switching back to high sulfur coal and scrubbing, forcing utilities to higher cost compliance options such as purchasing allowances or scrubber installation with low sulfur coal. The model shows under policies such as CAIR low-sulfur contract constraints raise both unit-level compliance costs and increase the demand for allowances in the market, which may lead to higher allowance prices than would exist in the absence of low sulfur contract constraints.
1 Introduction

Title IV of the 1990 Clean Air Act Amendments (CAAA) introduced the first sulfur dioxide (SO$_2$) 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 SO$_2$ Trading Program.$^1$ 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.$^2$ 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.$^3$

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 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$_2$ emissions.

In this paper a model of unit-level SO$_2$ compliance is constructed that incorporates the

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$^1$Burtraw et al. (2005); Sotkiewicz and Holt (2005)
$^1$Carlson et al. (2000); Ellerman et al. (1997); Sotkiewicz and Holt (2005)
$^2$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.

$^3$Sotkiewicz and Holt (2005) found actual compliance costs to be much higher than their estimated costs while controlling for the effects of state regulation.
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 SO₂ 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 Policy Background

2.1 Title IV of the Clean Air Act Amendment

Under the Title IV SO₂ emission trading program, affected units are allocated allowances, which permit the holder to emit one ton of SO₂ 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.⁴

⁴There are additional compliance options, including shutting down the affected unit and shifting dispatch away from the affected unit (Energy Information Association, 1997)
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 \textit{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 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. Other than a slight spike in 1999 as utilities positioned themselves for the start of Phase II, the allowance price

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5There 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 SO$_2$ 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).

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remained relatively stable around $150 (Burtraw et al., 2005).

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.

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 Clean Air Interstate Rule

In 2005, the EPA issued the Clean Air Interstate Rule (CAIR) that further restricts the emissions of SO2 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. SO2/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.

Figure 1: SO$_2$ Allowance Price

Source: Dallas Burtraw of Resources for the Future

The spike in allowance prices up to over $1,600 in 2006 seen in Figure 1 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.

3 Literature Review

3.1 Title IV: Phase I

There has been significant research done on the Title IV SO$_2$ Cap-and-Trade Program, both for Phase I and Phase II (Ellerman et al. (2000); Burtraw et al. (2005)). From Table 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.

Table 1: Phase I Compliance Cost Estimates

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<tr>
<td>ICF (1989, 1990)</td>
<td>$199-$226</td>
<td>$450-$860 mill.</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>EPRI (1993, 1995)</td>
<td>$879-$1238</td>
<td>$900-$1,340 mill.</td>
<td>N/A</td>
<td>N/A</td>
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<tr>
<td>GAO (1994)</td>
<td>$299</td>
<td>$1,170 mill.</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Winebrake, et al. (1995)</td>
<td>$143</td>
<td>$502 mill.</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td><strong>Pre-Policy Estimates</strong></td>
<td>$143-$1238</td>
<td><strong>$450-$1340</strong></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 mill.</td>
</tr>
<tr>
<td>Carlson et al. (2000)</td>
<td>$71</td>
<td>N/A</td>
<td>$571 mill.</td>
<td>$910 mill.</td>
</tr>
<tr>
<td><strong>Post-Policy Estimates</strong></td>
<td>$71-$800</td>
<td>N/A</td>
<td>$423-$571 mill.</td>
<td><strong>$730-$990</strong></td>
</tr>
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Sources: Bohi and Burtraw (1997); Carlson et al. (2000); Sotkiewicz and Holt (2005); Smith and Ellerman (1998)

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.\(^6\)

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

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\(^6\)Energy Information Association, The Effects of Title IV of the Clean Air Act Amendments of 1990 on Electric Utilities: An Update
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. The study conjectures long-term coal contracts may be responsible for what appears to be inefficient behavior resulting in additional compliance costs.

3.1.1 Utility-Level Models of Compliance Costs

Previous studies have estimated the compliance costs at the 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

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7 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.
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.
3.2 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 non-subsidiary of the same company. 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.8

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 SO2 emissions through fuel switching, which is reflected in the lower than expected

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8A 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.
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.

4 Inefficiencies Resulting from Coal Contract Constraints

There are three plausible scenarios where binding contract constraints results in suboptimal 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 cost-effective to do so. Consequently, the utility is forced to sub-optimally install a scrubber or purchase allowances.\(^9\)

Second, during Phase I spot coal prices were declining and often lower than 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\(_2\) emission rates greater than the \textit{Phase I allowed level} of 2.5 lbs. SO\(_2\)/mmBtu (pounds per million Btus of heat).\(^{10}\) Additionally, the 14 generating units with scrubbers and greater than 75% of

\(^9\)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.

\(^{10}\)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.
coal under contract all have emissions rates over 2.5 lbs. \( \text{SO}_2/\text{mmBtu} \). This indicates the possibility that high sulfur coal contract constraints are driving some compliance decisions.\(^5\)

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.\(^6\)

## 5 Model & 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.

\(^5\)Data used is available from the EIA FERC-423 database and Electric Power Annual 1996.

\(^6\)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.
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.\(^{11}\)

- \( r_i \in [0, 1] \) 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.\(^{12}\)

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 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:

- \( C_{ih}^{\text{s}}, C_{il}^{\text{s}} \) are the quantities, in tons, of high sulfur and low sulfur spot market coal use for a given unit, respectively.

- \( C_{ih}^{\text{c}}, C_{il}^{\text{c}} \) are the quantities, in tons, of high sulfur and low sulfur contract coal use for a

\(^{11}\)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 \( \left( \frac{d(1+d)^t}{(1+d)^t-1} \right) \). The operation and maintenance costs are assumed to be 2.0 mills/kWh under Phase I and 1.23 mills/kWh under CAIR.

\(^{12}\)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
given unit, respectively.

- \(P_{ih}^s, P_{ih}^l\) are the delivered prices, in dollars/ton, of high sulfur and low sulfur spot market coal for a given unit, respectively.
- \(P_{ih}^c, P_{ih}^l\) 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.\(^{13}\) 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.
- \(S_{ih}^c, S_{il}^c\) 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 SO\(_2\), which is assumed to be a constant (1.9) for simplicity.\(^{14}\)
- \(C_{ih}^c, C_{il}^c\) represent the contract constraints for a given unit, which requires the use of a minimum amount of each coal type.

\(^{13}\)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.

\(^{14}\)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. 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.
**Allowance Parameters:**

- $E_i$ represents a generating unit’s tons of SO$_2$ emissions.
- $A^e_i$ represents a generating unit’s initial allowance allocation in tons of SO$_2$ emissions.
- $A_i$ represents a generating unit’s net allowance position in tons of 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.

### 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 minimize its costs based on its constraints for emissions, electricity demand, and coal use for both high sulfur and low sulfur contract coal.
6.1 Generating Unit’s Problem

\[
\min_{z_i, A_i, \bar{C}^{ch}, \bar{C}^{cl}, C^{ch}, C^{cl}} \quad z_i P_{iz} + P_{iA_i} + P^s_{ih} C^{ch}_{ih} + P^s_{il} C^{cl}_{il} + P^c_{ih} \bar{C}^{ch}_{ih} + P^c_{il} \bar{C}^{cl}_{il} \quad (6.1)
\]

subject to...

\[
A_i + A_i \geq (1 - z_i r_i) (m) (C^{ch}_{ih} S^{ch}_{ih} + C^{cl}_{ih} S^{cl}_{ih} + C^s_{il} S^s_{il} + C^c_{il} S^c_{il}) \quad \lambda_{i1} \quad (6.2)
\]

\[
(C^{ch}_{ih} H^{ch}_{ih} + C^{cl}_{ih} H^{cl}_{ih} + C^s_{il} H^s_{il} + C^c_{il} H^c_{il}) \geq D_i \quad \lambda_{i2} \quad (6.3)
\]

\[
C^{ch}_{ih} = \bar{C}^{ch}_{ih} \quad \mu_{ih} \quad (6.4)
\]

\[
C^{cl}_{il} = \bar{C}^{cl}_{il} \quad \mu_{il} \quad (6.5)
\]

\[
C^s_{ih}, C^s_{il} \geq 0 \quad (6.6)
\]

\[
z_i \in \{0, 1\} \quad (6.7)
\]

Equation (6.1) represents the unit’s cost function. These costs include the cost of scrubber installation \((z_i P_{iz})\), net costs of allowance purchases \((P_{iA_i})\), and costs of coal purchases \((P^s_{ih} C^{ch}_{ih} + P^s_{il} C^{cl}_{il} + P^c_{ih} \bar{C}^{ch}_{ih} + P^c_{il} \bar{C}^{cl}_{il})\). The emissions constraint is shown in (6.2), 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 \([ (1 - z_i r_i) (m) (C^{ch}_{ih} S^{ch}_{ih} + C^{cl}_{ih} S^{cl}_{ih} + C^s_{il} S^s_{il} + C^c_{il} S^c_{il})] \). 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 \((C^{ch}_{ih} H^{ch}_{ih} + C^{cl}_{ih} H^{cl}_{ih} + C^s_{il} H^s_{il} + C^c_{il} H^c_{il})\) must cover the consumer demand \((D_i)\) for electricity expressed as heat input, which is seen in (6.3). 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, \(\bar{C}^{ch}_{ih}\) for high sulfur coal in (6.4) and \(\bar{C}^{cl}_{il}\) for low sulfur coal in (6.5). 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.
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.

$$P_A - \lambda_{i1} = 0$$ (6.8)

Since $A_i$ can be either positive or negative based on the net allowance position, (6.8) 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 ($S_{gf}$), heat content ($H_{gf}$), and delivered price ($P_{gf}$). The partial derivatives with respect to $C_{gf}$ 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.

$$P_{ih}^s + \lambda_{i1}(1 - z_ir_i)(m)(S_{ih}^s) - \lambda_{i2}H_{ih}^s \geq 0, = 0 \text{ if } C_{ih}^s > 0$$ (6.9)

$$P_{il}^s + \lambda_{i1}(1 - z_ir_i)(m)(S_{il}^s) - \lambda_{i2}H_{il}^s \geq 0, = 0 \text{ if } C_{il}^s > 0$$ (6.10)

$$P_{ih}^c + \lambda_{i1}(1 - z_ir_i)(m)(S_{ih}^c) - \lambda_{i2}H_{ih}^c - \mu_{ih} = 0$$ (6.11)

$$P_{il}^c + \lambda_{i1}(1 - z_ir_i)(m)(S_{il}^c) - \lambda_{i2}H_{il}^c - \mu_{il} = 0$$ (6.12)

The cost of using one more unit of $C_{gf}$ can be disaggregated into four different cost changes: $P_{gf}^s$ is the additional costs of purchasing one more unit of coal, $\lambda_{i1}(1 - z_ir_i)(m)(S_{gf}^s)$ is the additional costs of the extra emissions from one more unit of coal, $\lambda_{i2}H_{gf}$ is the benefit from meeting the demand remaining from using the additional unit of coal, and $\mu_{gf}$ represents the reduction in costs from meeting the contract constraint. If $C_{gf}^s > 0$, then (6.9) or (6.10) holds with equality. Since the contract constraint holds with equality, (6.11) and (6.12) always hold with equality.

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.

6.3.1 Necessary Conditions for Using Both High Sulfur & Low Sulfur Coal

If a generating unit uses both high sulfur and low sulfur spot market coal \((C_{ih} > 0, C_{il} > 0)\), the additional costs of using each coal type are equal and (6.9) and (6.10) hold with equality, or

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

(6.13) 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 (6.14). Exploiting (6.8), the allowance price equals \(MCA_{i,s}^s\):

\[
PA = \lambda_{i1} = MCA_{i,s}^s = \frac{P_{si}^s - P_{si}^s}{H_{il}^s - H_{ih}^s}
\]

(6.14)

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

6.3.2 Necessary Conditions for Only High Sulfur Coal Use

If a generating unit uses only high sulfur spot market coal \((C_{ih} > 0)\), 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 (6.9) holds with equality while (6.10) holds with weak inequality, or

\[
\frac{P_{si}^s + \lambda_{i1}(1 - z_ir_i)(m)(S_{ih}^s)}{H_{ih}^s} \leq \frac{P_{si}^s + \lambda_{i1}(1 - z_ir_i)(m)(S_{il}^s)}{H_{il}^s}
\]

(6.15) can be rearranged to show the allowance price is weakly less than \(MCA_{i,s}^s\):

\[
PA \leq MCA_{i,s}^s = \frac{P_{si}^s - P_{si}^s}{H_{il}^s - H_{ih}^s}
\]

(6.16)
6.3.3 Necessary Conditions for Only Low Sulfur Coal Use

If a generating unit chooses to use only low sulfur spot market coal ($C_{si} > 0$), the additional costs of using low sulfur spot market coal is weakly less than using high sulfur spot market coal and (6.10) holds with equality while (6.9) holds with weak inequality, or

$$\frac{P_{ih}^s + \lambda_{i1}(1 - z_ir_i)(m)S_{ih}^s}{H_{ih}^s} \geq \frac{P_{il}^s + \lambda_{i1}(1 - z_ir_i)(m)S_{il}^s}{H_{il}^s}$$

(6.17)

(6.17) can be rearranged to show that the allowance price is weakly greater than $MCA_{i}^{s,s}$:

$$P_A \geq MCA_{i}^{s,s} = \frac{P_{ih}^s - P_{il}^s}{(1 - z_ir_i)(m)(S_{ih}^s - S_{il}^s)}$$

(6.18)

6.4 Coal Use Under a High Sulfur Coal Contract Constraint

$\mu_{ih}$ 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 $\mu_{ih} > 0$ and it increases fuel costs. If contract coal is cheaper than spot market coal, then $\mu_{ih} < 0$ 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 (6.10) and (6.11) hold with equality. Also, it has already been shown in (6.17) that when a unit uses only low sulfur spot market coal, $P_A \geq MCA_{i}^{s,s}$:

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

(6.19)

By rearranging (6.19) and exploiting (6.8), 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 $MCA_{i}^{s,s}$:

$$\lambda_{i1} = P_A = MCA_{i}^{c,s} + \frac{\mu_{ih}}{H_{ih}^c} \geq MCA_{i}^{s,s}$$

(6.20)

From (6.20), 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.

\[
\frac{\mu_{ih}}{H_{ih}^s} \geq MCA_{i}^{s,s} - MCA_{i}^{c,s} \quad (6.21)
\]

Now assume a unit has a high sulfur coal contract and uses only high sulfur spot market coal (no low sulfur spot market coal). (6.11) and (6.12) hold with equality while (6.10) 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:

\[
\Rightarrow P_A \leq MCA_{i}^{c,s} + \frac{\mu_{ih} H_{ih}^s}{(1 - z_i r_i)(m)(S_{ih}^c - S_{ih}^s)} \quad (6.22)
\]

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.

\[
\Rightarrow \frac{P_{ih}^s + \lambda_{ih}(1 - z_i r_i)(m)(S_{ih}^s)}{H_{ih}^s} = \frac{P_{ih}^c + \lambda_{ih}(1 - z_i r_i)(m)(S_{ih}^c - \mu_{ih})}{H_{ih}^c} \Rightarrow \frac{\mu_{ih}}{H_{ih}^s} = \frac{P_{ih}^c + \lambda_{ih}(1 - z_i r_i)(m)(S_{ih}^c)}{H_{ih}^c} - \frac{P_{ih}^s + \lambda_{ih}(1 - z_i r_i)(m)(S_{ih}^s)}{H_{ih}^s} \quad (6.23)
\]

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 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 (6.10) and (6.11) hold with equality. Also, it has been shown in (6.15) that when a unit uses both high and low sulfur spot market coal, \( P_A = MCA_{i}^{s,s} \):

\[
\Rightarrow P_A = MCA_{i}^{s,s} = MCA_{i}^{c,s} + \frac{\mu_{ih} H_{ih}^s}{(1 - z_i r_i)(m)(S_{ih}^c - S_{ih}^s)} \quad (6.24)
\]
By solving for $\mu_{ih}$ in (6.24), 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.

$$\frac{\mu_{ih}}{H_{ih}}(1 - z_ir_i)(m)\left(\frac{S_{ih}^s}{H_{ih}^s} - \frac{S_{il}^s}{H_{il}^s}\right) = MCA_{i}^{s,s} - MCA_{i}^{c,s}$$

(6.25)

### 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 (6.16) that when a unit uses only high sulfur spot market coal, $P_A \leq MCA_{i}^{s,s}$. (6.9) and (6.12) hold with equality while (6.10) holds with a weak inequality. Using the same approach as in the previous section yields:

$$\lambda_{il} = P_A = MCA_{i}^{s,c} - \frac{\mu_{il}}{H_{il}}(1 - z_ir_i)(m)\left(\frac{S_{ih}^s}{H_{ih}^s} - \frac{S_{il}^c}{H_{il}^c}\right) \leq MCA_{i}^{s,s}$$

(6.26)

Using (6.26), 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.

$$\frac{\mu_{il}}{H_{il}}(1 - z_ir_i)(m)\left(\frac{S_{ih}^s}{H_{ih}^s} - \frac{S_{il}^c}{H_{il}^c}\right) \geq MCA_{i}^{s,c} - MCA_{i}^{s,c}$$

(6.27)

Now assume a unit has a low sulfur coal contract and uses only low sulfur spot market coal. So (6.10) and (6.12) hold with equality while (6.9) holds with a weak inequality. It has already been shown in (6.17) that when a unit uses only low sulfur spot market coal,
\[ P_A \geq MCA_{i,s}^s. \]

\[ P_A \geq MCA_{i,s,c}^s - \frac{\mu_{il}}{H_{il}^c} \frac{S_{il}^s}{H_{il}^n} \left( \frac{S_{il}^s}{H_{il}^n} - \frac{S_{il}^c}{H_{il}^n} \right) \tag{6.28} \]

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

\[ \frac{P_{i,l}^s + \lambda_{i,l}(1 - z_ir_i)(m)(S_{il}^s)}{H_{il}^s} = \frac{P_{i,l}^c + \lambda_{i,l}(1 - z_ir_i)(m)(S_{il}^c) - \mu_{il}}{H_{il}^c} \]

\[ \Rightarrow \frac{\mu_{il}}{H_{il}^c} = \frac{P_{i,l}^c + \lambda_{i,l}(1 - z_ir_i)(m)(S_{il}^c) - \mu_{il}}{H_{il}^c} \frac{S_{il}^s}{H_{il}^n} \quad \frac{P_{i,l}^c + \lambda_{i,l}(1 - z_ir_i)(m)(S_{il}^c)}{H_{il}^c} \tag{6.29} \]

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 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 (6.9), (6.10), and (6.12) hold with equality and \( P_A = MCA_{i,s}^s \):

\[ P_A = MCA_{i,s}^s = MCA_{i,s,c}^s - \frac{\mu_{il}}{H_{il}^c} \frac{S_{il}^s}{H_{il}^n} \left( \frac{S_{il}^s}{H_{il}^n} - \frac{S_{il}^c}{H_{il}^n} \right) \tag{6.30} \]

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

\[ MCA_{i,s}^s = MCA_{i,s,c}^s - \frac{\mu_{il}}{H_{il}^c} \frac{S_{il}^s}{H_{il}^n} \left( \frac{S_{il}^s}{H_{il}^n} - \frac{S_{il}^c}{H_{il}^n} \right) \tag{6.31} \]

### 6.6 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 ($P_{si} C_{si} + P_{si} C_{si} + P_{si} C_{si} + P_{si} C_{si}$) minus the costs of purchasing only high sulfur spot market coal given any contracted coal ($P_{si} \hat{C}_{si}^{MAX} + P_{si} \hat{C}_{si}^{MAX} + P_{si} \hat{C}_{si}^{MAX}$), or (2) zero where:

$$\hat{C}_{si}^{MAX} = \frac{D_i - C_{si} H_{si} - C_{si} H_{si}}{H_{si}}$$  \hspace{1cm} (6.32)

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

$$z_i P_{iz} + P_A A_i + \max \{(P_{si} C_{si} + P_{si} C_{si} - P_{si} \hat{C}_{si}^{MAX}), 0\}$$  \hspace{1cm} (6.33)

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 ($\frac{S_{si}}{H_{si}}$) is greater than the sulfur to heat content ratio of high sulfur spot market coal ($\frac{S_{si}}{H_{si}}$), 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 ($\frac{S_{si}}{H_{si}}$) is greater than the sulfur to heat content ratio of high sulfur spot market coal ($\frac{S_{si}}{H_{si}}$), 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 ($\frac{S_{si}}{H_{si}}$) is greater than the sulfur to heat content ratio of low sulfur spot market coal ($\frac{S_{si}}{H_{si}}$), then a low
sulfur coal contract *increases* compliance costs.

(iv) If \( P_A < MCA\MCS, \) then a low sulfur coal contract *decreases* compliance costs.

See the Appendix A.1 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.

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

Assume there are no contract constraints \( (C^s_{ih} = 0, C^c_{il} = 0) \). 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 (6.2). From (6.2) and (6.3), the minimum and maximum excess demand for allowances can be formally derived.

If \( P_A < MCA\MCS, \) a unit will use the maximum amount of high sulfur spot market coal which can be derived from (6.3):

\[
C^{s,\text{MAX}}_{ih} = \frac{D_i}{H_{ih}} \tag{6.34}
\]

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

\[
E^{\text{MAX}}_i = (1 - z_i r_i)(m)(S^s_{ih})(\frac{D_i}{H_{ih}}) \tag{6.35}
\]

Inserting \( C^{s,\text{MAX}}_{ih} \) in for \( C^s_{ih} \) in (6.2) gives an expression for the **maximum allowance excess demand**, which is the difference between the maximum emissions level \( (E^{\text{MAX}}_i) \) and the initial allowance allocation \( (A^e_i) \):

\[
A^{\text{MAX}}_i = E^{\text{MAX}}_i - A^e_i = (1 - z_i r_i)(m)(S^s_{ih})(\frac{D_i}{H_{ih}}) - A^e_i \tag{6.36}
\]

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 (6.3):

$$C_{il}^{s,MAX} = \frac{D_i}{H_{il}} \tag{6.37}$$

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

$$E_i^{MIN} = (1 - z_i r_i) (m) (S_{il}^s) \left( \frac{D_i}{H_{il}} \right) \tag{6.38}$$

Inserting $C_{il}^{s,MAX}$ in (6.37) for $C_{il}^s$ in (6.3) 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 ($A^e_i$):

$$A_i^{MIN} = E_i^{MIN} - A^e_i = (1 - z_i r_i) (m) (S_{il}^s) \left( \frac{D_i}{H_{il}} \right) - A^e_i \tag{6.39}$$

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 $A_i = \left( \theta E_i^{MAX} - (1 - \theta) E_i^{MIN} - A_i^e \right)$ 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(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 $P_A = MCA_i^{s,s}$. 

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6.7.1 Cost Savings from 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 ($\frac{P_{ih}}{H_{ih}} < \frac{S_{ils}}{H_{il}}$), a generating unit that does not have an emissions constraint prefers to use high sulfur spot market coal to meet electricity demand.\textsuperscript{15} 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 ($A_{iMIN}^{MIN}$). 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 (6.39), where the excess demand will actually be negative.

The unit’s cost savings from switching fuels over purchasing allowances is $(P_A - MCA_{i,s,s})(A_{iMAX}^{MAX} - A_{iMIN}^{MIN})$, which is the area “a+b” seen in Figure 2(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.

\textsuperscript{15}The assumption that high sulfur coal is cheaper than low sulfur coal is supported by actual coal prices.
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 3, 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 $\frac{S_{ih}^c}{H_{ih}} \leq \frac{S_{ih}^s}{H_{ih}}$.

(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 $\frac{S_{ih}^c}{H_{ih}} \geq \frac{S_{ih}^s}{H_{ih}}$.

**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:

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

(6.40)

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:

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

(6.41)

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:

$$\Rightarrow A_i^{MIN} < \hat{A}_i^{MIN} = \hat{E}_i^{MIN} - A_i^e$$

(6.42)

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 \( (A_i^{\text{MAX}}) \). A high sulfur coal contract forces a unit to decrease its high sulfur spot market coal use from \( C_{ih}^{s,\text{MAX}} \) to \( \hat{C}_{ih}^{s,\text{MAX}} \) where:

\[
C_{ih}^{s,\text{MAX}} > \hat{C}_{ih}^{s,\text{MAX}} = \frac{D_i}{H_{ih}^c} - \frac{C_i^c}{H_{ih}^c} \left( \frac{H_{ih}^c}{H_{ih}^c} - \frac{D_i}{H_{ih}^c} \right)
\]

(6.43)

If \( \frac{S_{ih}^c}{H_{ih}^c} < \frac{S_{ih}^s}{H_{ih}^s} \), the sulfur content per unit of heat content is lower for high sulfur contract coal than high sulfur spot market coal and will decrease the maximum emissions from \( E_i^{\text{MAX}} \) to \( \hat{E}_i^{\text{MAX}} \):

\[
\Rightarrow E_i^{\text{MAX}} < \hat{E}_i^{\text{MAX}} = (1 - z_i r_i)(m) \left( S_{ih}^s \hat{C}_{ih}^{s,\text{MAX}} + S_{ih}^c \hat{C}_{ih}^c \right)
\]

(6.44)

Lower emissions result in a decrease in a unit’s maximum excess demand from \( A_i^{\text{MAX}} \) to \( \hat{A}_i^{\text{MAX}} \) in Figure 3(i):

\[
\Rightarrow A_i^{\text{MAX}} > \hat{A}_i^{\text{MAX}} = \hat{E}_i^{\text{MAX}} - A_i^c
\]

(6.45)

Therefore, a high 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 \( \frac{S_{ih}^c}{H_{ih}^c} > \frac{S_{ih}^s}{H_{ih}^s} \), 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 \( E_i^{\text{MAX}} \) to \( \hat{E}_i^{\text{MAX}} \):

\[
\Rightarrow E_i^{\text{MAX}} > \hat{E}_i^{\text{MAX}} = (1 - z_i r_i)(m) \left( S_{ih}^s \hat{C}_{ih}^{s,\text{MAX}} + S_{ih}^c \hat{C}_{ih}^c \right)
\]

(6.46)

Greater emissions result in an increase in a unit’s maximum excess demand from \( A_i^{\text{MAX}} \) to \( \hat{A}_i^{\text{MAX}} \) in Figure 3(ii):

\[
\Rightarrow A_i^{\text{MAX}} < \hat{A}_i^{\text{MAX}} = \hat{E}_i^{\text{MAX}} - A_i^c
\]

(6.47)

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 \( A_i^{\text{MIN}} \) to \( \hat{A}_i^{\text{MIN}} \) and abate fewer emissions than the generating unit would prefer as shown in Figure 3(i). If
Figure 3: High Sulfur Contract: Shift in Minimum Excess Demand

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.\(^\text{16}\)

Figure 4: No Contract: Compliance Costs

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.

\(^{16}\)Available from FERC-423 Data.
In Figure 4, 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 5, a high sulfur coal contract will increase the minimum excess demand from $A_{iMIN}^i$ to $\tilde{A}_{iMIN}^i$ and may increase or decrease the maximum excess demand depending on the relative sulfur to heat content ratio of contract to spot market coal.

![Figure 5: High Sulfur Contract: Compliance and Total Costs](image)

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 5. 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 $\frac{S^h}{H^h_{th}} < \frac{S^s}{H^s_{th}}$, then the maximum emissions a unit can create will decrease and $\tilde{A}_{iMAX}^i < A_{iMAX}^i$. This will decrease the compliance costs by $(f)$ in Figure 5(i) for reducing emissions to the allowance allocation emissions level. If $\frac{S^h}{H^h_{th}} > \frac{S^s}{H^s_{th}}$, then the maximum emissions a unit can create will increase and $\tilde{A}_{iMAX}^i > A_{iMAX}^i$. 

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This will increase the compliance costs by area \((f)\) in Figure 5(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 5(i). Combining the two impacts results in net compliance costs of \((a - c)\) in Figure 5(i). If maximum excess demand increases, net compliance costs increase by area \((f)\) in Figure 5(ii). Combining the two impacts results in net compliance costs of \((a + f - c)\) in Figure 5(ii).

The third cost impact results from different prices for high sulfur spot market and contract coal, which is represented by area \((c)\). 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 2. 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 \(MCA_{c,s}^{s}\) can be computed if a unit faces no high sulfur coal contract \((C_{c}^{s} = 0)\). 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 \(P_{A} > MCA_{c,s}^{c,s}\).

### Table 2: High Sulfur Coal Contract: Assumptions

<table>
<thead>
<tr>
<th>Coal Type</th>
<th>Price/mmBtu</th>
<th>(H_{i}^{d})</th>
<th>Price/Ton</th>
<th>(S_{i}^{d})</th>
</tr>
</thead>
<tbody>
<tr>
<td>(C_{c}^{s})</td>
<td>$1.60</td>
<td>24</td>
<td>$38.40</td>
<td>0.6%</td>
</tr>
<tr>
<td>(C_{c}^{s})</td>
<td>$1.30</td>
<td>24</td>
<td>$31.20</td>
<td>2.0%</td>
</tr>
<tr>
<td>(C_{c}^{s})</td>
<td>$1.50</td>
<td>24</td>
<td>$36.00</td>
<td>2.0%</td>
</tr>
<tr>
<td>(C_{c}^{s})</td>
<td>$1.20</td>
<td>24</td>
<td>$28.80</td>
<td>2.0%</td>
</tr>
<tr>
<td>(C_{c}^{s})</td>
<td>$1.50</td>
<td>24</td>
<td>$36.00</td>
<td>2.0%</td>
</tr>
<tr>
<td>(C_{c}^{s})</td>
<td>$1.20</td>
<td>24</td>
<td>$28.80</td>
<td>2.0%</td>
</tr>
</tbody>
</table>

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 \(MCA_{c,s}^{s}\) 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 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 $MCA_{c,s}^i$ is $90.23$, which is much lower than the allowance price of $300.00 and $MCA_{s,s}^i$ 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.

**Table 3: High Sulfur Coal Contract: Results**

<table>
<thead>
<tr>
<th>Allowance Use (tons)</th>
<th>$MCA_{c,s}^i$</th>
<th>$MCA_{s,s}^i$ (Ex. 1)</th>
<th>$MCA_{c,s}^i$ (Ex. 2)</th>
<th>Total Costs (Ex. 2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum</td>
<td>11,400 tons</td>
<td></td>
<td></td>
<td>$270.68</td>
</tr>
<tr>
<td>Maximum</td>
<td>38,000 tons</td>
<td></td>
<td></td>
<td>$90.23</td>
</tr>
<tr>
<td>Constrained Min.</td>
<td>24,700 tons</td>
<td></td>
<td></td>
<td>$360.90</td>
</tr>
<tr>
<td>Costs</td>
<td></td>
<td>Compliance Costs (Ex. 1)</td>
<td>Total Costs (Ex. 1)</td>
<td>Compliance Costs (Ex. 2)</td>
</tr>
<tr>
<td>Unconstrained</td>
<td></td>
<td>$4.62 million</td>
<td>$35.82 million</td>
<td>$4.62 million</td>
</tr>
<tr>
<td>Constrained</td>
<td></td>
<td>$5.01 million</td>
<td>$38.61 million</td>
<td>$5.01 million</td>
</tr>
<tr>
<td>Change</td>
<td></td>
<td>$390,000</td>
<td>$2.79 million</td>
<td>$390,000</td>
</tr>
</tbody>
</table>

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 6, 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 \((a-c)\). 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.

Figure 6: High Sulfur Contract: Relative Savings from Contract 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. \(MCA_{c,s}^i\) 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.

6.7.3 Cost Savings of Allowance Purchases versus Fuel Switching when \(P_A < MCA_{s,s}^i\)

Assuming that high sulfur spot market coal is cheaper than low sulfur spot market coal \(\left(\frac{P_{sH}}{H_{sH}} < \frac{S_{sH}}{H_{sH}}\right)\), 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 \(P_A < MCA_{s,s}^i\).

Using high sulfur spot market coal leads to the maximum number of allowances used by the unit \(A_{iMAX}\). 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.

\(^{17}\)For simplicity, the sulfur to heat content ratio is assumed to be equal for high sulfur contract and spot market coal.
requirement. The excess demand for such a unit can be seen in (6.36), where the excess demand will be positive.

Given that a unit preferred to use high sulfur coal before SO₂ constraints, the unit’s cost savings from using allowances over switching fuels is \( (MCA_i^{s,s} - P_A)(A_i^{MAX} - A_i^{MIN}) \), which is the area “a+b” seen in Figure 7. 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.

![Figure 7: Cost Savings from Using Allowances Over Fuel Switching](image)

6.7.4 Effects of Low Sulfur Coal Contracts

Now consider how low sulfur coal contract will impact a generating unit’s allowance excess demand correspondence in Figure 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 \( \frac{S_i^{L}}{H_i^{L}} \leq \frac{S_i^{H}}{H_i^{H}} \).

(iii) For the range of allowance prices \( P_A \geq MCA_i^{s,s} \), a low sulfur coal contract will increase excess demand if \( \frac{S_i^{L}}{H_i^{L}} \geq \frac{S_i^{H}}{H_i^{H}} \).

**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 $\widehat{C}_{ih}^{s,MAX}$, which is the maximum amount of high sulfur spot market coal a unit will use given the low sulfur coal contract constraint:

$$C_{ih}^{s,MAX} > \widehat{C}_{ih}^{s,MAX} = \frac{D_i}{H_{ih}^s} - \frac{C_{il}^c H_{il}^c}{H_{ih}^s}$$

(6.48)

The decrease in maximum high sulfur coal use decreases a unit’s maximum emissions from $E_i^{MAX}$ to $\widehat{E}_i^{MAX}$:

$$\Rightarrow E_i^{MAX} > \widehat{E}_i^{MAX} = (1 - z_i r_i)(m)(S_{ih}^s \widehat{C}_{ih}^{s,MAX} + S_{il}^e \overline{C}_il^e)$$

(6.49)

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:

$$\Rightarrow A_i^{MAX} > \widehat{A}_i^{MAX} = \widehat{E}_i^{MAX} - A_i^e$$

(6.50)

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 $C_{il}^{s,MAX}$ to $\widehat{C}_{il}^{s,MAX}$:

$$C_{il}^{s,MAX} > \widehat{C}_{il}^{s,MAX} = \frac{D_i}{H_{il}^s} - \frac{C_{il}^c H_{il}^c}{H_{il}^s}$$

(6.51)

If $\frac{S_{il}^c}{H_{il}^s} < \frac{S_{il}^e}{H_{il}^s}$, 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 $E_i^{MIN}$ to $\widehat{E}_i^{MIN}$:

$$\Rightarrow E_i^{MIN} > \widehat{E}_i^{MIN} = (1 - z_i r_i)(m)(S_{il}^s \widehat{C}_{il}^{s,MAX} + S_{il}^e \overline{C}_il^e)$$

(6.52)

Lower emissions result in a decrease in a unit’s minimum excess demand from $A_i^{MIN}$ to $\widehat{A}_i^{MIN}$ in Figure 3(i):

$$\Rightarrow A_i^{MIN} > \widehat{A}_i^{MIN} = \widehat{E}_i^{MIN} - A_i^e$$

(6.53)

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 $\frac{S_i}{H_i} > \frac{S_s}{H_s}$, 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 $E_i^{MIN}$ to $\hat{E}_i^{MIN}$:

$$\Rightarrow E_i^{MIN} < \hat{E}_i^{MIN} = (1 - z_i r_i) (m) (S_i C_{il}^{MAX} + S_s C_{il}^{c})$$

(6.54)

Greater emissions result in an increase in a unit’s minimum excess demand from $A_i^{MIN}$ to $\hat{A}_i^{MIN}$ in Figure 3(ii):

$$\Rightarrow A_i^{MIN} > \hat{A}_i^{MIN} = \hat{E}_i^{MIN} - A_i$$

(6.55)

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

Figure 8: Low Sulfur Contract

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 $A_i^{MAX}$ to $\hat{A}_i^{MAX}$ and abate more emissions than the generating unit would prefer as shown in Figure 9. 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 9, 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.

Figure 9: No Contract: Compliance Costs

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 seen in Figure 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.

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

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 10. 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 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 $MCA_{s,s}$ can be found if a unit faces no low sulfur coal contract ($C_{c,s}$). 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 $P_A < MCA_{c,s}$.

<table>
<thead>
<tr>
<th>Coal Type</th>
<th>Price/mmBtu</th>
<th>$H_{ij}$</th>
<th>Price/Ton</th>
<th>$S_{ij}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_{s,s}^{il}$</td>
<td>$1.60$</td>
<td>24</td>
<td>$38.40$</td>
<td>0.6%</td>
</tr>
<tr>
<td>$C_{s,s}^{ih}$</td>
<td>$1.30$</td>
<td>24</td>
<td>$31.20$</td>
<td>2.0%</td>
</tr>
<tr>
<td>$C_{c,l}^{il}$</td>
<td>$1.80$</td>
<td>24</td>
<td>$43.20$</td>
<td>0.6%</td>
</tr>
<tr>
<td>$C_{c,l}^{il}$</td>
<td>$1.80$</td>
<td>24</td>
<td>$43.20$</td>
<td>0.6%</td>
</tr>
<tr>
<td>$A_{i}^{c}$</td>
<td>20,000 tons</td>
<td></td>
<td>Allowance Price</td>
<td>$200.00</td>
</tr>
<tr>
<td>$D_{i}$</td>
<td>24,000,000 mmBtu</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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 $MCA_{i,s}^{c}$ 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 $MCA_i^{c,s}$ is $451.13, which is much higher than the allowance price of $200.00 and $MCA_i^{s,s}$ 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.

Table 5: Low Sulfur Coal Contract Examples: Results

<table>
<thead>
<tr>
<th>Allowance Use</th>
<th>Compliance Costs</th>
<th>Total Costs</th>
<th>$MCA_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum</td>
<td>11,400 tons</td>
<td>$3.6 million</td>
<td>$270.68</td>
</tr>
<tr>
<td>Maximum</td>
<td>38,000 tons</td>
<td>$34.8 million</td>
<td>$451.13</td>
</tr>
<tr>
<td>Constrained Max.</td>
<td>24,700 tons</td>
<td>$4.54 million</td>
<td>$180.45</td>
</tr>
</tbody>
</table>

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 11, where $MCA_i^{c,s} < MCA_i^{s,s}$ 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

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cost savings of using lower priced high sulfur contract coal over high sulfur spot market coal.

Figure 11: Low Sulfur Coal Contract: $MCA_i^{s,c}$

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. $MCA_i^{s,c}$ 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.\footnote{For simplicity, the sulfur to heat content ratio is assumed to be equal for low sulfur contract and spot market coal.} The unit actually gains by lowering its total costs by $260,000 through the coal contract even though it must increase its compliance costs.

6.7.5 Fuel Switching Versus Allowance Purchases when $P_A = MCA_i^{s,s}$

In the knife-edge case a generating unit has no strict preference between purchasing allowances and abating emissions because $P_A = MCA_i^{s,s}$. The unit’s excess demand may be any value in the range $[A_i^{MIN} - A_i^c, A_i^{MAX} - A_i^c]$. 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 12. A high sulfur coal contract will have the same impacts on the excess demand correspondence when $P_A = MCA_i^{s,s}$ as in Section 5.7.2 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 13 to Figure 5, 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 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 15 to Figure 10, 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.

Figure 14: Low Sulfur Coal Contract

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.

6.8.1 When will a Generating Unit Install a Scrubber?

Let \((\bar{C}_{ih}, \bar{C}_{il}, \bar{A}_i)\) and \((\hat{C}_{ih}, \hat{C}_{il}, \hat{A}_i)\) 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:

\[
P_{iz} + P^S_A \hat{A}_i + P^S_{ish} \bar{C}_{ih} + P^S_{il} \bar{C}_{il} = P^S_A \hat{A}_i + P^S_{ish} \hat{C}_{ih} + P^S_{il} \hat{C}_{il} \tag{6.56}
\]

\(P^S_A\) 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.\(^{19}\)

\(^{19}\)See Appendix A.2 for the derivation of this equation.
A generating unit’s decisions will hinge on this allowance price. (6.56) can be used to solve for $P_A^S$, the minimum allowance price at which a generating unit will install a scrubber:

$$P_A^S \geq \frac{P_{iz} + P_{ih}^s(\tilde{C}_{ih}^s - \tilde{C}_{ih}^s) + P_{il}^s(\tilde{C}_{il}^s - \tilde{C}_{il}^s)}{(\bar{A}_i - \bar{A}_i)} \quad (6.57)$$

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

### 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:

$$M\tilde{C}A_{i}^{s,s} = \frac{P_{il}^s - P_{ih}^s}{(1 - r_i)(m)(\frac{S_{ih}^s}{H_{ih}^s} - \frac{S_{il}^s}{H_{il}^s})}, \quad MCA_{i}^{s,s} = \frac{P_{il}^s - P_{ih}^s}{(m)(\frac{S_{ih}^s}{H_{ih}^s} - \frac{S_{il}^s}{H_{il}^s})} \quad (6.58)$$

Scrubber installation decreases the size of the denominator of $M\tilde{C}A_{i}^{s,s}$ by $(r_i)(m)(\frac{S_{ih}^s}{H_{ih}^s} - \frac{S_{il}^s}{H_{il}^s})$, 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.

### 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 $M\tilde{C}A_{i}^{s,s} < P_A$, a generating unit installs a scrubber because $P_A^S < P_A$, and switches fuels from high sulfur spot market to low sulfur spot market coal because $M\tilde{C}A_{i}^{s,s} < P_A$. So a generating unit will have minimum excess demand when a scrubber is installed ($\bar{A}_i^{SMIN}$), which has already been derived in (6.36) given that $z_i = 1$. 45
For allowance prices \( P_A^S < P_A < M\tilde{C}A_i^{s,s} \), a generating unit installs a scrubber because \( P_A^S < P_A \), and uses high sulfur coal because \( P_A < M\tilde{C}A_i^{s,s} \). So a generating unit will have maximum excess demand when a scrubber is installed \((A_i^{SMAX})\), which has already been derived in (6.39) given \( z_i = 1 \).

For allowance prices \( MCA_i^{s,s} < P_A < P_A^S \), a generating unit does not install a scrubber because \( P_A < MCA_i^{s,s} \), 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 (6.36) given \( z_i = 0 \).

For allowance prices \( 0 < P_A < MCA_i^{s,s} \), a generating unit does not install a scrubber because \( P_A < P_A^S \), 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 (6.39).

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 seen below.

\[
A_i = \begin{cases} 
A_i^{MAX} & \text{if } 0 < P_A < MCA_i^{s,s} < P_A^S \text{ or } 0 < P_A < P_A^S < MCA_i^{s,s} \\
\theta A_i^{MAX} - (1 - \theta)A_i^{MIN} & \text{if } (MCA_i^{s,s} = P_A < P_A^S) \forall \theta \in [0, 1] \\
A_i^{MIN} & \text{if } MCA_i^{s,s} < P_A \leq P_A^S \\
A_i^{SMAX} & \text{if } P_A^S \leq P_A < M\tilde{C}A_i^{s,s} \\
\theta A_i^{SMAX} - (1 - \theta)A_i^{SMIN} & \text{if } M\tilde{C}A_i^{s,s} = P_A \forall \theta \in [0, 1] \\
A_i^{SMIN} & \text{if } M\tilde{C}A_i^{s,s} < P_A 
\end{cases}
\]

The excess demand correspondence seen in Figure 15(i) includes a generating unit’s net allowance position under the four different allowance price ranges if \((\frac{P_{ih}}{H_{ih}} < \frac{P_{il}}{H_{il}})\). If \((\frac{P_{ih}}{H_{ih}} \geq \frac{P_{il}}{H_{il}})\) 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 15(ii). \(^{20}\)

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 \(MCA_i^{s,s} < P_A < P_A^S\)

\(^{20}\)An example where \(\frac{P_{ih}^s}{H_{ih}} \geq \frac{P_{il}^s}{H_{il}}\) in the actual data is the delivered prices of coal to generating units in the state of Wisconsin.

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does not exist for the excess demand correspondence. The excess demand correspondence under this case can be seen in Figure 16.

Figure 16: Excess Demand Correspondence: $MCA_{i,s}^{s,s} \geq P_A^S$

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 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.

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 \( (P^S_i C^s_{ih} + P^S_i C^s_{il}) \), to a unit’s costs when it does install a scrubber, which includes net allowance purchases \( (A^S_{SMAX}) \), fuel costs \( (P^S_i C^{s,MAX}_{ih}) \), and costs of a scrubber \( (P^S_i z) \). 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 \( M\tilde{C} A_i^{s,s} > P_A \). 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 \( MCA_i^{s,s} \).

By solving for the constant \( P^S_i z \) in (6.59) and (6.60) and setting the two expressions equal to each other, the sign and value of \( \epsilon \) can be derived.

### 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 $\left(\frac{S^s}{H^s} \geq \frac{S^h}{H^h}\right)$, 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 if it does install a scrubber. For this to hold, $(MCA^{s,s}_i < P_A < M\tilde{C}A^{s,s}_i)$ and $(MCA^{s,s}_i < P^S_A - \epsilon < P^S_A)$.

If a unit that has no high sulfur contract coal ($C_{ich}^c = 0$), 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 $P^S_A$:

$$P_{iz} + P^S_A A^s_{imin} + P^s_{ih} C^s_{ih} = P^S_A A^s_{imin} + P^s_{il} C^s_{il} \quad (6.61)$$

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

$$\Rightarrow P_{iz} = P^S_A (A^s_{imin} - A^s_{imax}) - P^s_{ih} C^s_{ih} + P^s_{il} C^s_{il} \quad (6.62)$$

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

$$P_{iz} + (P^S_A - \epsilon)\tilde{A}^s_{imin} + P^s_{ih} \tilde{C}^s_{ih} + P^c_{ih} \tilde{C}^c_{ih} = (P^S_A - \epsilon)\tilde{A}^s_{imin} + P^s_{il} \tilde{C}^s_{il} + P^c_{ih} \tilde{C}^c_{ih} \quad (6.63)$$

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

$$\Rightarrow P_{iz} = (P^S_A - \epsilon)(\tilde{A}^s_{imin} - \tilde{A}^s_{imax}) + P^s_{il} \tilde{C}^s_{il} - P^s_{ih} \tilde{C}^s_{ih} \quad (6.64)$$

Since $P_{iz}$ is a constant, the two expressions for $P_{iz}$ in (6.62) and (6.63) can be set equal to solve for the value of $\epsilon$:

$$\Rightarrow \epsilon = \frac{P^S_A (A^s_{imin} - A^s_{imin} + A^s_{imax} - A^s_{imax}) + P^s_{il} (\tilde{C}^s_{il} - C^s_{il}) - P^s_{ih} (\tilde{C}^s_{ih} - C^s_{ih})}{(A^s_{imin} - A^s_{imax})} \quad (6.65)$$
for coal price, sulfur content, heat content, and scrubber capture rate. By filling these expressions into (6.65), the expression for $\epsilon$ can be simplified to parameters for coal price, sulfur content, heat content, and scrubber capture rate.

$$A_i^{MIN} = \left(\frac{D_i}{H_i^d}\right)(S_i^a)(m) - A_i^e$$

$$A_i^{SMAX} = \left(\frac{D_i}{H_i^s}\right)(S_i^a)(m)(1-r_i) - A_i^e$$

$\Rightarrow \epsilon = \frac{(P_A^S)(m)[(r_i)(\frac{S_i^a}{H_i^d} - \frac{S_i^a}{H_i^d}) + (\frac{S_i^a}{H_i^d} - \frac{S_i^a}{H_i^d})] - (\frac{P_i^S}{H_i^d} - \frac{P_i^S}{H_i^d})}{(\hat{A}_i^{MIN} - \hat{A}_i^{SMAX})}$ (6.66)

An interpretable form is derived by separating terms, multiplying though by $(\hat{A}_i^{MIN} - \hat{A}_i^{SMAX})$, and dividing through by $m(S_i^a/H_i^d - S_i^a/H_i^d)$.

$$\Rightarrow \epsilon(\hat{A}_i^{MIN} - \hat{A}_i^{SMAX}) = \frac{P_A^S r_i (\frac{S_i^a}{H_i^d} - \frac{S_i^a}{H_i^d}) + P_A^S}{m(S_i^a/H_i^d - S_i^a/H_i^d)}$$ (6.67)

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 $(\frac{S_i^a}{H_i^d} \geq \frac{S_i^a}{H_i^d})$, then $\epsilon > 0$ and $\epsilon$ increases as the size of the high sulfur coal contract $(\hat{C}_i)$ increases. If $(\frac{S_i^a}{H_i^d} < \frac{S_i^a}{H_i^d})$, 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 7 is based on data from the a unit that installed a scrubber under Phase I.21 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

21 Gen. JM Gavin had 100% coal under contract.
sulfur contract coal. Given the assumptions in Table 7, a unit will prefer to use low sulfur coal if it does not install a scrubber because \(MCA_i^{s,s} = $244.26\) 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 \(\tilde{MCA}_i^{s,s} = $4,885.20\). 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.

![Table 6: Example Epsilon Magnitude: Case 1](image)

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 it does install a scrubber because \((MCA_i^{s,s} < P_A < \tilde{MCA}_i^{s,s})\) and \((MCA_i^{s,s} < P_A^S)\). However, with a high sulfur coal contract, a unit prefers to use high sulfur spot market coal both with and without a scrubber because \((P_A^S - \epsilon < MCA_i^{s,s})\).
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 $P^S_A$:

$$P_{iz} + P^S_A A_i^{SMAX} + P^s_{ih} C_{ih}^{MAX} = P^S_A A_i^{MIN} + P^s_{il} C_{il}^{MAX}$$  \hspace{1cm} (6.68)

(6.68) shows that the costs with and without a scrubber are equal for a given $P^S_A$, and can be rearranged to find an expression for $P_{iz}$:

$$\Rightarrow P_{iz} = P^S_A (A_i^{MIN} - A_i^{SMAX}) - P^s_{ih} C_{ih}^{MAX} + P^s_{il} C_{il}^{MAX}$$  \hspace{1cm} (6.69)

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

$$P_{iz} + (P^S_A - \epsilon)\hat{A}_i^{SMAX} + P^s_{ih} \hat{C}_i^{MAX} + P^c_{ih} C_{ih}^c = (P^S_A - \epsilon)\hat{A}_i^{MAX} + P^s_{ih} \hat{C}_i^{MAX} + P^c_{ih} C_{ih}^c$$  \hspace{1cm} (6.70)

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

$$\Rightarrow P_{iz} = (P^S_A - \epsilon)(\hat{A}_i^{MAX} - \hat{A}_i^{SMAX})$$  \hspace{1cm} (6.71)

The two expressions for $P_{iz}$ in (6.69) and (6.71) can be set equal to solve for the value of $\epsilon$:

$$\Rightarrow \epsilon = \frac{P^S_A (\hat{A}_i^{MAX} - \hat{A}_i^{MIN}) + A_i^{SMAX} - \hat{A}_i^{SMAX} - P^s_{il} C_{il}^{MAX} + P^s_{ih} C_{ih}^{MAX}}{(\hat{A}_i^{MAX} - \hat{A}_i^{SMAX})}$$  \hspace{1cm} (6.72)

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

$$A_i^{MIN} = \left(\frac{D_i}{H_{it}}\right)(S_{il}^c)(m) - A_i^e$$  \hspace{1cm} \hat{A}_i^{MAX} = \left(\frac{D_i - C_{ih}^c H_{ih}^c}{H_{ih}^c} S_{ih}^c + C_{ih}^c C_{ih}^c \right) m - A_i^e$$

$$A_i^{SMAX} = \left(\frac{D_i}{H_{ih}^c} \right)(S_{ih}^c)(m)(1-r_i) - A_i^e$$  \hspace{1cm} \hat{A}_i^{SMAX} = \left(\frac{D_i - C_{ih}^c H_{ih}^c}{H_{ih}^c} S_{ih}^c + C_{ih}^c C_{ih}^c \right) (m)(1-r_i) - A_i^e$$

$$C_{ih}^{MAX} = \frac{D_i}{H_{ih}^c}$$  \hspace{1cm} C_{il}^{MAX} = \frac{D_i}{H_{il}^c}$$

By filling into (6.72), the expression for $\epsilon$ can be simplified to parameters for coal price, sulfur content, heat content, and scrubber capture rate:

$$\Rightarrow \epsilon(\hat{A}_i^{MAX} - \hat{A}_i^{SMAX}) = m P^S_A \left[r_i C_{ih}^c H_{ih}^c \left(\frac{S_{ih}^c}{H_{ih}^c} - \frac{S_{ih}^s}{H_{ih}^s}\right) + D_i \left(\frac{S_{ih}^s}{H_{ih}^s} - \frac{S_{il}^s}{H_{il}^s}\right)\right] - D_i \left(\frac{P^s_{il}}{H_{il}^c} - \frac{P^s_{ih}}{H_{ih}^c}\right)$$  \hspace{1cm} (6.73)
The new form in (6.73) 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 $m(S_{ih} - S_{il})$.

$$\Rightarrow \epsilon (\hat{A}_{i}^{MIN} - \hat{A}_{i}^{SMAX}) = P_{A}S_{i} r_{ih}H_{ih}^c \left( \frac{S_{ih}}{H_{ih}} - \frac{S_{il}}{H_{il}} \right) + P_{A}S_{i} D_{i} - D_{i} \left( \frac{P_{A}S_{i} - P_{A}}{m(S_{ih} - S_{il})} \right) \quad (6.74)$$

The last two terms in (6.74) can be combined to get $D_{i}(P_{A} - MCA_{i}^{s,s})$:

$$\Rightarrow \epsilon (\hat{A}_{i}^{MIN} - \hat{A}_{i}^{SMAX}) = P_{A}S_{i} r_{ih}H_{ih}^c \left( \frac{S_{ih}}{H_{ih}} - \frac{S_{il}}{H_{il}} \right) + D_{i}(P_{A} - MCA_{i}^{s,s}) \quad (6.75)$$

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 $P_{A} > MCA_{i}^{s,s}$. If $(\frac{S_{ih}}{H_{ih}} \geq \frac{S_{il}}{H_{il}})$, 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 $(C_{ih}^c)$ increases the value of $\epsilon$. However, if $(\frac{S_{ih}}{H_{ih}} < \frac{S_{il}}{H_{il}})$ then it is uncertain whether $\epsilon$ is positive or negative.

Assuming the data in Table 7, 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 ($P_{A} > MCA_{i}^{s,s}$ and $P_{A} - \epsilon < MCA_{i}^{s,s}$).

A unit must also prefer to use high sulfur coal with a scrubber both with and without a high sulfur coal contract ($P_{A} - \epsilon < P_{A} < MCA_{i}^{s,s}$). The allowance price at which a unit will initially install a scrubber is $P_{A} = $1,592.61, which is much higher than the assumed allowance price ($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} - \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} - \epsilon) = $242.79 < $MCA_{i}^{s,s} = $244.26. Also, a unit will now install a scrubber because $(P_{A} - \epsilon < P_{A})$, 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 \(\overline{C}_{ih} = 0\), a unit is indifferent to installing a scrubber at allowance price \(P_A^S\):

\[
P_{iz} + P_A^S A_i^{SMAX} + P_{ih} C_{ih}^{s,MAX} = P_A^S A_i^{MAX} + P_{ih} C_{ih}^{c} \tag{6.66}
\]

(6.66) 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:

\[
\Rightarrow P_{iz} = P_A^S (A_i^{MAX} - A_i^{SMAX}) \tag{6.67}
\]

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:

\[
P_{iz} + (P_A^S - \epsilon) \tilde{A}_i^{SMAX} + P_{ih} \tilde{C}_{ih}^{s,MAX} + P_{ih} \tilde{C}_{ih}^{c} = (P_A^S - \epsilon) \tilde{A}_i^{MAX} + P_{ih} \tilde{C}_{ih}^{s,MAX} + P_{ih} \tilde{C}_{ih}^{c} \tag{6.68}
\]

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

\[
\Rightarrow P_{iz} = (P_A^S - \epsilon)(\tilde{A}_i^{MAX} - \tilde{A}_i^{SMAX}) \tag{6.69}
\]

The two expressions for \(P_{iz}\) in (6.67) and (6.69) can be set equal to solve for the value of \(\epsilon\):

\[
\Rightarrow \epsilon = \frac{P_A^S (\tilde{A}_i^{MAX} - A_i^{MAX} + A_i^{SMAX} - \tilde{A}_i^{SMAX})}{(A_i^{MAX} - \tilde{A}_i^{SMAX})} \tag{6.70}
\]

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

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

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

By filling into (6.70), the expression for \(\epsilon\) can be simplified to parameters for coal price, sulfur content, heat content, and scrubber capture rate:

\[
\Rightarrow \epsilon(\tilde{A}_i^{MAX} - \tilde{A}_i^{SMAX}) = P_A^S m r_i \overline{C}_{ih}^c H_{ih}^c (\frac{S_{ih}^c}{H_{ih}^s} - \frac{S_{ih}^s}{H_{ih}^s}) \tag{6.71}
\]

If high sulfur contract coal has a weakly higher sulfur to heat content ratio than high sulfur spot market coal \(\left(\frac{S_{ih}^c}{H_{ih}^s} \geq \frac{S_{ih}^s}{H_{ih}^s}\right)\), then \(\epsilon > 0\) and as the amount of coal under contract \((\overline{C}_{ih}^c)\) increases, the size of \(\epsilon\) increases. If \(\left(\frac{S_{ih}^c}{H_{ih}^s} < \frac{S_{ih}^s}{H_{ih}^s}\right)\), then \(\epsilon < 0\).
Table 7: Example Epsilon Magnitude: Case 3

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Characteristics</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low Sulfur Coal (Spot)</td>
<td>Price $2.79/mmBtu</td>
<td>Pct. ↓ $416.14</td>
</tr>
<tr>
<td>Heat Content 24 mmBtu/ton</td>
<td>$460.80</td>
<td>Pct. ↓ $416.14</td>
</tr>
<tr>
<td>Sulfur Content 0.5%</td>
<td>$44.66</td>
<td>Pct. ↓ $416.14</td>
</tr>
<tr>
<td>High Sulfur Spot Coal (Spot)</td>
<td>Price $1.52/mmBtu</td>
<td>$460.80</td>
</tr>
<tr>
<td>Heat Content 24 mmBtu/ton</td>
<td>$416.14</td>
<td>Pct. ↓ $416.14</td>
</tr>
<tr>
<td>Sulfur Content 1.91%</td>
<td>$44.66</td>
<td>Pct. ↓ $416.14</td>
</tr>
<tr>
<td>High Sulfur Coal (Contract)</td>
<td>Price $1.72/mmBtu</td>
<td>$460.80</td>
</tr>
<tr>
<td>Heat Content 24 mmBtu/ton</td>
<td>$416.14</td>
<td>Pct. ↓ $416.14</td>
</tr>
<tr>
<td>Sulfur Content 2.32%</td>
<td>$44.66</td>
<td>Pct. ↓ $416.14</td>
</tr>
</tbody>
</table>

Under the initial assumptions, $P_A^S < MCA_i^{s}\$. The example in Table 8 uses data representative of a unit that installed a scrubber under Phase I.  A unit facing these coal characteristics prefers to use high sulfur coal with or without a scrubber installed because $MCA_i^{s}\$ $= \$1,137.74 > P_A = \$250.00 \text{ and } MCA_i^{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.

Based on the above three 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 $(\frac{S_{ih}^{c}}{H_{ih}} \geq \frac{S_{ih}^{c}}{H_{ih}})$.

(ii) the sign of $\epsilon$ is unknown if $(\frac{S_{ih}^{c}}{H_{ih}} < \frac{S_{ih}^{c}}{H_{ih}})$.

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...
Proposition 5(a): Assuming \( \frac{S_h}{H_{ih}} \geq \frac{S_h}{H_{ih}} \) and allowing for the scrubber choice
(i) For the range of allowance prices \( P_A \geq M\tilde{CA}_{i}^{s,s} \), a high sulfur coal contract will weakly increase a unit’s excess demand.
(ii) For the range of allowance prices \( P_A^{S} \leq P_A \leq M\tilde{CA}_{i}^{s,s} \), a high sulfur coal contract will weakly increase 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 if \( A_{i}^{MIN} \geq \tilde{A}_{i}^{SMAX} \) and weakly increase excess demand if \( A_{i}^{MIN} \leq \tilde{A}_{i}^{SMAX} \).
(iv) For the range of allowance prices \( M\tilde{CA}_{i}^{s,s} \leq P_A \leq (P_A^{S} - \epsilon) \), 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 increase a unit’s excess demand.

Proof of Proposition 5(a):
(i) When a unit faces \( P_A \geq M\tilde{CA}_{i}^{s,s} \), 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 \( P_A^{S} \leq P_A \leq M\tilde{CA}_{i}^{s,s} \), a unit prefers to install a scrubber and use
all high sulfur coal. From Proposition 2(iii), given \((S_{ci}^h \geq S_{si}^h)\), 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 \((P_A^S - \epsilon) \leq P_A \leq P_A^S\), a high sulfur coal contract decreases a unit’s indifference allowance price of installing a scrubber below the allowance price 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 \((S_{ci}^h \geq S_{si}^h)\), a high sulfur coal contract will weakly increase a unit’s emissions and excess demand. If \(A_i^{MIN} \geq \hat{A}_i^{SMAX}\), the combined net effect of the countering shifts is weakly negative and weakly decreases excess demand. If \(A_i^{MIN} \leq \hat{A}_i^{SMAX}\), the combined net effect is weakly positive and weakly increases excess demand.

(iv) When a unit faces \((S_{ci}^h \geq S_{si}^h)\), 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 \(0 \leq P_A \leq MCA_{s,s}^i\), a unit does not install a scrubber and prefers to use high sulfur coal. From Proposition 2(iii), given \((S_{ci}^h \geq S_{si}^h)\), a high sulfur coal contract increases a unit’s maximum emissions level and excess demand.

Proposition 5(a) is shown graphically in Figure 17(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 \((S_{ci}^h \leq S_{si}^h)\), \(\epsilon \geq 0\), 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 $M\tilde{C}A_{i,s} \leq P_A \leq (P_A^S - \epsilon)$, a high sulfur coal contract will weakly increase a unit’s excess demand.

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

Figure 18: Impact of a High Sulfur Coal Contract: $MCA_{i,s} > P_A^S$

Proof of Proposition 5(b):

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

(iii) 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 $(\frac{S_{ih}^{c}}{H_{ih}^{c}} \leq \frac{S_{ih}^{h}}{H_{ih}^{h}})$, 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.

(iv) From Proposition 2(i), when a unit faces $M\tilde{C}A_{i,s} \leq P_A \leq (P_A^S - \epsilon)$, 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.

(v) 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 \( (\frac{S_{h}^{s}}{H_{ih}} \leq \frac{S_{h}^{s}}{H_{ih}}) \), a high sulfur coal contract decreases a unit’s maximum emissions level and excess demand.

Proposition 5(b) is shown graphically in Figure 17(ii).

There are conditions under which some of these allowance price ranges do not exist. For example, \( P_{SA} < MCA_{i}^{s,s} \) in the third case described above. So there is no price range \( (MCA_{i}^{s,s}, P_{SA}) \) in Figure 18. 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 17 to 18.

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 \( (MCA_{i}^{s,s} < P_A < M\tilde{C}A_{i}^{s,s}) \) and \( (MCA_{i}^{s,s} < P_{SA}^{s}) \).

If a unit has no low sulfur contract coal \( (\overline{C}^{c}_{il} = 0) \), 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 \( P_{SA}^{s} \):

\[
P_{iz} + P_{SA}^{s}A_{i}^{sMAX} + P_{ih}^{s}C_{ih}^{sMAX} = P_{SA}^{s}A_{i}^{sMIN} + P_{ih}^{s}C_{ih}^{sMAX} \quad (6.82)
\]
(6.82) can be rearranged to find an expression for $P_{iz}$:

$$
\Rightarrow P_{iz} = P^s_A(A^i_{MIN} - A^i_{SMAX}) - P^s_{ih}C^i_{ih} + P^s_{il}C^i_{il} \tag{6.83}
$$

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

$$
P_{iz} + (P^s_A - \epsilon)\hat{A}^i_{SMAX} + P^s_{ih}\hat{C}^i_{ih} + P^s_{il}\hat{C}^i_{il} = (P^s_A - \epsilon)\hat{A}^i_{MIN} + P^s_{il}\hat{C}^i_{il} + P^s_{il}C^i_{il} \tag{6.84}
$$

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

$$
\Rightarrow P_{iz} = (P^s_A - \epsilon)(\hat{A}^i_{MIN} - \hat{A}^i_{SMAX}) + P^s_{il}\hat{C}^i_{il} - P^s_{ih}C^i_{ih} \tag{6.85}
$$

The two expressions for $P_{iz}$ in (6.83) and (6.85) can be set equal to solve for the value of $\epsilon$:

$$
\Rightarrow \epsilon = \frac{P^s_A(\hat{A}^i_{MIN} - A^i_{MIN} + A^i_{SMAX} - \hat{A}^i_{SMAX}) - P^s_{il}(C^i_{il} - \hat{C}^i_{il}) + P^s_{ih}(C^i_{ih} - \hat{C}^i_{ih})}{(\hat{A}^i_{MIN} - \hat{A}^i_{SMAX})} \tag{6.86}
$$

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

$$
A^i_{MIN} = \left(\frac{D_i}{H^s_{il}}\right)(S^s_{il})(m) + A^e \quad \hat{A}^i_{MIN} = \left[\left(\frac{D_i - C^e_{il}H^s_{il}}{H^s_{il}}\right)(S^s_{il}) + \bar{C}^e_{il}s^c_{il}\right] \quad (m) - A^e
$$

$$
A^i_{SMAX} = \left(\frac{D_i}{H^s_{ih}}\right)(S^s_{ih})(1-r_i) - A^e \quad \hat{A}^i_{SMAX} = \left[\left(\frac{D_i - C^e_{il}H^s_{il}}{H^s_{il}}\right)(S^s_{il}) + \bar{C}^e_{il}s^c_{il}\right] \quad (m)(1-r_i) - A^e
$$

$$
C^i_{ih} = \frac{D_i}{H^s_{ih}} \quad \hat{C}^i_{ih} = \frac{D_i - C^e_{il}H^s_{il}}{H^s_{il}} \quad C^i_{il} = \frac{D_i}{H^s_{il}} \quad \hat{C}^i_{il} = \frac{D_i - C^e_{il}H^s_{il}}{H^s_{il}}
$$

By filling these expressions into (6.86), the expression for $\epsilon$ can be simplified to parameters for coal price, sulfur content, heat content, and scrubber capture rate.

$$
\Rightarrow \epsilon = \frac{\bar{C}^e_{il}H^s_{il}\left[(P^s_A)(m)\left(r_i\left(S^s_{il}/H^s_{il} - S^s_{ih}/H^s_{ih}\right) - \left(S^s_{il}/H^s_{il} - S^s_{ih}/H^s_{ih}\right)\right)\right] + \frac{P^s_{il} - P^s_{ih}}{H^s_{il}}}{(\hat{A}^i_{MIN} - \hat{A}^i_{SMAX})} \tag{6.87}
$$

A more interpretable expression is derived by multiplying through by $((\hat{A}^i_{MIN} - \hat{A}^i_{SMAX}))$ and dividing through by $m(S^s_{ih}/H^s_{ih} - S^s_{il}/H^s_{il})$.

$$
\Rightarrow \epsilon(\hat{A}^i_{MIN} - \hat{A}^i_{SMAX}) = \bar{C}^e_{il}H^s_{il}\left[(P^s_A)\left(r_i\left(S^s_{il}/H^s_{il} - S^s_{ih}/H^s_{ih}\right)\right)\right] + \frac{P^s_{il} - P^s_{ih}}{m(H^s_{il} - H^s_{ih})} \tag{6.88}
$$
\[ \Rightarrow \epsilon (A_i^{MIN} - A_i^{SMAX}) = C_{i}^{c} H_{i}^{c} \left[ (P_{A}^{S})(r_{i}) \left( \frac{S_{i}^{c} - S_{i}^{h}}{H_{i}^{c} - H_{i}^{h}} \right) - (P_{A}^{S} - MCA_{i}^{s,s}) \right] \]  

(6.89)

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 \((S_{i}^{c} < S_{i}^{h})\), then \(\epsilon < 0\) and its magnitude increases as the size of the low sulfur coal contract \(C_{i}^{c}\) 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 \(\epsilon < 0\).\(^{23}\) 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 \(M\hat{CA}_{i}^{s,s} = $11,228\). 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 for 50% of coal use results in \(\epsilon = -$42.00\), which increases the indifference price to \((P_{A} - \epsilon) = $773.46\). 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 \((P_{A}^{S} < MCA_{i}^{s,s})\). 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 \((MCA_{i}^{s,s} < P_{A}^{S} - \epsilon < M\hat{CA}_{i}^{s,s})\).

If a unit has no low sulfur contract coal \((C_{i}^{c} = 0)\), 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 \(P_{A}^{S}\):

\[ P_{i}^{z} + P_{A}^{S} A_{i}^{SMAX} + p_{i}^{h} C_{i}^{h,MAX} = P_{A}^{S} A_{i}^{MAX} + p_{i}^{h} C_{i}^{h,MAX} \]  

(6.90)

(6.90) shows that the costs with and without a scrubber are equal for a given \(P_{A}^{S}\), and can

\(^{23}\)The data can be found in Table 15.A of the 2000 Electric Power Annual Volume II.
be rearranged to find an expression for $P_{iz}$:

$$ \Rightarrow P_{iz} = P_A^s (A_i^{MAX} - A_i^{SMAX}) \quad (6.91) $$

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 $\epsilon$:

$$ P_{iz} + (P_A^s - \epsilon) \hat{A}_i^{SMAX} + P_{ih}^c \hat{C}_{ih}^{s,MAX} + P_{il}^c \hat{C}_{il}^{c,il} = (P_A^s - \epsilon) \hat{A}_i^{MIN} + P_{il}^c \hat{C}_{il}^{s,MAX} + P_{ih}^c \hat{C}_{ih}^{c,ih} \quad (6.92) $$

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

$$ \Rightarrow P_{iz} = (P_A^s - \epsilon)(\hat{A}_i^{MIN} - \hat{A}_i^{SMAX}) + P_{il}^c \hat{C}_{il}^{s,MAX} + P_{ih}^c \hat{C}_{ih}^{c,ih} \quad (6.93) $$

The two expressions for $P_{iz}$ in (6.91) and (6.93) can be set equal to solve for the value of $\epsilon$:

$$ \Rightarrow \epsilon = \frac{P_A^s (\hat{A}_i^{MIN} - A_i^{MAX} + A_i^{SMAX} - \hat{A}_i^{SMAX}) + P_{il}^c \hat{C}_{il}^{s,MAX} - P_{ih}^c \hat{C}_{ih}^{c,ih}}{(\hat{A}_i^{MIN} - \hat{A}_i^{SMAX})} \quad (6.94) $$

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

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

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

$$ \hat{C}_{il}^{s,MAX} = \frac{D_i - \overline{C}_{il}^c H_i^c}{H_i^s} \quad \hat{C}_{ih}^{c,MAX} = \frac{D_i - \overline{C}_{ih}^c H_i^c}{H_i^s} $$

By filling into (6.94), the expression for $\epsilon$ can be simplified to parameters for coal price, sulfur content, heat content, and scrubber capture rate:

$$ \Rightarrow \epsilon(\hat{A}_i^{MIN} - \hat{A}_i^{SMAX}) = mP_A^s H_i^c C_{il}^c \left[ \frac{S_{ih}^s}{H_i^s} - \frac{S_{il}^s}{H_i^s} \right] + \frac{r_i(S_{il}^c}{H_i^c} + \frac{S_{il}^c}{H_i^c}) - H_i^c C_{il}^c \left( \frac{P_{il}^c}{H_i^s} - \frac{P_{ih}^c}{H_i^s} \right) - D_i \left[ mP_A^s \left( \frac{S_{ih}^s}{H_i^s} - \frac{S_{il}^s}{H_i^s} \right) - \frac{P_{il}^c}{H_i^s} - \frac{P_{ih}^c}{H_i^s} \right] \quad (6.95) $$

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

$$ \Rightarrow \epsilon(\hat{A}_i^{MIN} - \hat{A}_i^{SMAX}) = P_A^s r_i \left( \frac{S_{il}^c}{H_i^s} - \frac{S_{il}^s}{H_i^s} \right) + (D_i - H_i^c C_{il}^c) \left[ P_A - \frac{P_{il}^c}{H_i^s} - \frac{P_{ih}^c}{H_i^s} \right] \quad (6.96) $$
$$\Rightarrow \epsilon(\hat{A}_i^{MIN} - \hat{A}_i^{SMAX}) = P_A^S r_i \left( \frac{S^c_i}{H^c_i} - \frac{S^h_i}{H^h_i} \right) + (D_i - H^c_i C^c_i)(P_A - MCA_i^{s,s}) \quad (6.97)$$

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 ($H^c_i C^c_i$) 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 ($\frac{S^c_i}{H^c_i} < \frac{S^h_i}{H^h_i}$) and ($\frac{S^c_i}{H^c_i} > \frac{S^h_i}{H^h_i}$), which means $\epsilon < 0$ and an increase in the size of the high sulfur coal contract ($C^c_i$) increases the magnitude of $\epsilon$.

The second example in Table 9 uses data that reflects this case. Without a coal contract, $P_A^S = $520.35, which is less than $MCA_i^{s,s} = $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_A^S < 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 $MCA_i^{s,s}$ and $P_A$ to $(P_A^S - \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 $P_A^S < (P_A^S - \epsilon) < MCA_i^{s,s}$. Given that a unit has no low sulfur contract coal ($C^c_{ih} = 0$), a unit is indifferent to installing a scrubber at allowance price $P_A^S$:

$$P_{iz} + P_A^S A_i^{SMAX} + P_{ih}^s C_{ih}^{s,MAX} = P_A^S A_i^{MAX} + P_{ih}^s C_{ih}^{s,MAX} \quad (6.98)$$

(6.98) 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. $P_A^S$ is equal to the average cost of reducing a unit of emissions from scrubber installation:

$$\Rightarrow P_{iz} = P_A^S (A_i^{MAX} - A_i^{SMAX}) \quad (6.99)$$

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:

$$P_{iz} + (P_A^S - \epsilon)\hat{A}_i^{SMAX} + P_{ih}^s \hat{C}_{ih}^{s,MAX} + P_c^c C_{ih}^c = (P_A^S - \epsilon)\hat{A}_i^{MAX} + P_{ih}^s \hat{C}_{ih}^{s,MAX} + P_c^c C_{ih}^c \quad (6.100)$$
(6.100) can be rearranged to find an expression for $\hat{P}_{iz}$:

$$\Rightarrow \hat{P}_{iz} = (P^S_A - \epsilon)(\hat{A}_i^{MAX} - \hat{A}_i^{SMAX}) \quad (6.101)$$

The two expressions for $\hat{P}_{iz}$ in (6.99) and (6.101) can be set equal to solve for the value of $\epsilon$:

$$\Rightarrow \epsilon = \frac{P^S_A(\hat{A}_i^{MAX} - A_i^{MAX} + A_i^{SMAX} - \hat{A}_i^{SMAX})}{(\hat{A}_i^{MAX} - \hat{A}_i^{SMAX})} \quad (6.102)$$

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

$$A_i^{MAX} = (\frac{D_i}{H_{ih}^s})(S_{ih}^s)\alpha(m) - A_i^e \quad \hat{A}_i^{MAX} = (\frac{D_i - \bar{C}_{ui}^e H_{ih}^c}{H_{ih}^s} S_{ih}^c + \bar{C}_{ui}^c S_{ui}^c)\alpha(m) - A_i^e$$

$$A_i^{SMAX} = (\frac{D_i}{H_{ih}^s})(S_{ih}^s)\alpha(1-r_i) - A_i^e \quad \hat{A}_i^{SMAX} = (\frac{D_i - \bar{C}_{ui}^e H_{ih}^c}{H_{ih}^s} S_{ih}^c + \bar{C}_{ui}^c S_{ui}^c)\alpha(1-r_i) - A_i^e$$

By filling into (6.102), the expression for $\epsilon$ can be simplified to parameters for coal price, sulfur content, heat content, and scrubber capture rate.

$$\Rightarrow \epsilon(\hat{A}_i^{MAX} - \hat{A}_i^{SMAX}) = P^S_A m r_i \bar{C}_{ui}^e H_{ih}^c (\frac{S_{ui}^c}{H_{ui}^c} - \frac{S_{ih}^c}{H_{ih}^c}) \quad (6.103)$$

Since $(\frac{S_{ui}^c}{H_{ui}^c} < \frac{S_{ih}^c}{H_{ih}^c})$, $\epsilon < 0$ and an increase in the size of the coal contract $(\bar{C}_{ui}^c)$ increases the magnitude of $\epsilon$.

The third example in Table 9 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 ($P_A = \$600.00 < (MCA_{i,s} = \$3,887.56)$. A unit will prefer to install a scrubber in this example because the indifferent price is $P^S_A = \$565.60$. A low sulfur coal contract for 50% of coal use will increase the indifference price to $(P^S_A - \epsilon) = \$642.42$, 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 \(\frac{S_{c_i} H_{c_i}}{H_{u_i}} \geq \frac{S_{s_i} H_{s_i}}{H_{u_i}}\) and allowing for the scrubber choice...

(i) 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.

(ii) 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.

(iii) 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.

(iv) 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.

(v) 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.

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 \(\frac{S_{c_i} H_{c_i}}{H_{u_i}} \geq \frac{S_{s_i} H_{s_i}}{H_{u_i}}\), 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 \(\frac{S_{c_i} H_{c_i}}{H_{u_i}} \geq \frac{S_{s_i} H_{s_i}}{H_{u_i}}\), 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 \(\frac{S_{c_i} H_{c_i}}{H_{u_i}} \geq \frac{S_{s_i} H_{s_i}}{H_{u_i}}\), 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 19(i).

![Figure 19: Impact of a Low Sulfur Coal Contract: $MCA_i^{s,s} > P_A^S$](image)

**Proposition 7(b):** Assuming that ($\frac{s_c}{\psi_{cl}} < \frac{s_s}{\psi_{sl}}$) and allowing for the scrubber choice...

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

(ii) For the range of allowance prices $(P_A^S - \epsilon) \leq P_A \leq MCA_i^{s,s}$, 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 $MCA_i^{s,s} \leq P_A \leq P_A^S$, 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 $P_A \geq MCA_i^{s,s}$, a unit prefers to install a scrubber and use all low
Proposition 3(ii), given \( \frac{S^c_i}{H^c_i} < \frac{S^h_i}{H^h_i} \), 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 \((P^S_A - \epsilon) \leq P_A \leq M\tilde{C}A_i^{s,h}\), 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 \(P^S_A \leq P_A \leq (P^S_A - \epsilon)\), 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 \(\frac{S^c_i}{H^c_i} < \frac{S^h_i}{H^h_i} \), a high sulfur coal contract will weakly decrease a unit’s emissions and excess demand. If \(\hat{A}^\text{MIN}_i \geq A_s^\text{SMAX}_i\), the combined net effect of the countering shifts is weakly positive and weakly increases excess demand. If \(\hat{A}^\text{MIN}_i \leq A_s^\text{SMAX}_i\), the combined net effect is weakly negative and weakly decreases excess demand.

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

(v) When a unit faces \(0 \leq P_A \leq MCA_i^{s,h}\), 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 19(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.

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 shown 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.

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 SO₂ 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 \(\frac{S_{ih}^c}{H_{ih}^c} > \frac{S_{ih}^h}{H_{ih}^h}\). 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 3 except if the allowance market price falls in the price range \((P_A^S, P_A^S - \epsilon)\) and \(\frac{S_{il}^c}{H_{il}^c} < \frac{S_{il}^h}{H_{il}^h}\). 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.
References


[18] Environmental Protection Agency. www.epa.gov/airmarkets/epa-ipm/index.html. For the documentation on the model used by EPA. The IPM model used by the EPA aggregates units and plants into “model” plants losing unit and plant level detail. Additionally, existing coal contracts do not appear to be modeled nor are state public utility commission regulations governing cost recovery rules. We use the 2.5 lbs. SO$_2$/mmBtu as the cut-off for high sulfur coal in Phase I as allowance allocations were based on this emissions rate.


A Appendix

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.

\[ P_{s_{ih}}C_{s_{ih}} + P_{s_{il}}C_{s_{il}} \]  

(A.1)

With the emissions constraint from the program, a unit will minimize its costs of coal use, net allowance purchases, and scrubber installation.

\[ z^*_i P_{iz} + P_{A_i}^* + P_{s_{ih}}^* (C_{s_{ih}} - C_{s_{ih}}') + P_{s_{il}}^* (C_{s_{il}} - C_{s_{il}}') \]  

(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.

\[ z^*_i P_{iz} + P_{A_i}^* A_i^* + P_{s_{ih}}^* (C_{s_{ih}} - C_{s_{ih}}') + P_{s_{il}}^* (C_{s_{il}} - C_{s_{il}}') \]  

(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.

\[ P_{c_{ih}} \tilde{C}_{c_{ih}} + P_{c_{il}} \tilde{C}_{c_{il}} + P_{s_{ih}}^* \hat{C}_{s_{ih}} + P_{s_{il}}^* \hat{C}_{s_{il}} \]  

(A.4)

With the emissions constraint from the program, a unit will minimize its costs for coal use, net allowance purchases, and scrubber installation given its emissions and coal contract constraint.

\[ \hat{z}^*_i P_{iz} + P_{A_i}^* A_i^* + P_{s_{ih}}^* \tilde{C}_{s_{ih}} + P_{s_{il}}^* \tilde{C}_{s_{il}} + P_{s_{ih}}^* \hat{C}_{s_{ih}} + P_{s_{il}}^* \hat{C}_{s_{il}} \]  

(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.

\[ z^*_i P_{iz} + P^*_A A^*_i + P^s_{ih} (\hat{C}^{ss}_{ih} - \hat{C}^{s'}_{ih}) + P^s_{il} (\hat{C}^{ss}_{il} - \hat{C}^{s'}_{il}) \]  \hspace{1cm} (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 \(((A.6) \text{ minus } (A.3))\).

\[ \begin{aligned} &\left[ z^*_i P_{iz} + P^*_A A^*_i + P^s_{ih} (\hat{C}^{ss}_{ih} - \hat{C}^{s'}_{ih}) + P^s_{il} (\hat{C}^{ss}_{il} - \hat{C}^{s'}_{il}) \right] \\ &\quad - \left[ z^*_i P_{iz} + P^*_A A^*_i + P^s_{ih} (C^{s*}_{ih} - C^{s'}_{ih}) + P^s_{il} (C^{s*}_{il} - C^{s'}_{il}) \right] \end{aligned} \]  \hspace{1cm} (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 \( P_A > MCA_{i, s} \), 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 \((C^{s*}_{il} = C^{s, MAX}_{il} \text{ and } C^{ss}_{ih} = 0)\) and require the fewest allowances to cover the minimum emissions level \((A^{MIN}_{i})\). With a high sulfur coal contract, a unit will use less low sulfur coal \((\hat{C}^{s, MAX}_{il} < C^{s, MAX}_{il})\), which will increase the emissions level and require additional allowances \((\hat{A}^{MIN}_{i} > A^{MIN}_{i})\).

\[ \begin{aligned} &\left[ P^*_A A^{MIN}_{i} + P^s_{ih} (0 - \hat{C}^{s, MAX}_{ih}) + P^s_{il} (\hat{C}^{s, MAX}_{il} - 0) \right] \\ &\quad - \left[ P^*_A A^{MIN}_{i} + P^s_{ih} (0 - C^{s, MAX}_{ih}) + P^s_{il} (C^{s, MAX}_{il} - 0) \right] \end{aligned} \]  \hspace{1cm} (A.8)

The change in compliance costs will be:

\[ P^*_A (\hat{A}^{MIN}_{i} - A^{MIN}_{i}) + P^s_{ih} (\hat{C}^{s, MAX}_{ih} - C^{s, MAX}_{ih}) + P^s_{il} (\hat{C}^{s, MAX}_{il} - C^{s, MAX}_{il}) \]  \hspace{1cm} (A.9)
The first term is positive because \( \hat{A}_{i}^{MIN} - A_{i}^{MIN} \). The second term is also positive because \( C_{ih}^{s,MAX} \geq C_{il}^{s,MAX} \). The third term is negative because \( C_{il}^{s,MAX} \leq C_{il}^{s,MAX} \).

Now fill in for coal use:

\[
C_{ih}^{s,MAX} = \frac{D_{i}}{H_{ih}^{s}} \quad \hat{C}_{ih}^{s,MAX} = \frac{D_{i} - C_{ih}^{c}H_{ih}^{c}}{H_{ih}^{s}} \quad C_{il}^{s,MAX} = \frac{D_{i}}{H_{il}^{s}} \quad \hat{C}_{il}^{s,MAX} = \frac{D_{i} - C_{ih}^{c}H_{ih}^{c}}{H_{il}^{s}}
\]

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.

\[
P_{A}(\hat{A}_{i}^{MIN} - A_{i}^{MIN}) + \left( \frac{P_{s}^{s}}{H_{ih}^{s}} - \frac{P_{il}^{s}}{H_{il}^{s}} \right)C_{ih}^{c}H_{ih}^{c} \tag{A.10}
\]

Now fill in for the net allowance position:

\[
A_{i}^{MIN} = \frac{D_{i}}{H_{il}^{s}}S_{il}^{m} - A_{i}^{c} \quad \hat{A}_{i}^{MIN} = \frac{D_{i} - C_{ih}^{c}H_{ih}^{c}}{H_{il}^{s}}S_{il}^{s} + C_{ih}^{c}S_{ih}^{c}m - A_{i}^{c}
\]

\[
\Rightarrow mP_{A}(C_{ih}^{c}S_{ih}^{c} - \frac{C_{ih}^{c}H_{ih}^{c}}{H_{il}^{s}}S_{il}^{s}) + \left( \frac{P_{s}^{s}}{H_{ih}^{s}} - \frac{P_{il}^{s}}{H_{il}^{s}} \right)C_{ih}^{c}H_{ih}^{c}
\]

By adding and subtracting \( mP_{A}S_{ih}^{s} \), 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:

\[
\Rightarrow C_{ih}^{c}H_{ih}^{c}\left[ P_{A}\left( \frac{S_{ih}^{s}}{H_{ih}^{s}} - \frac{S_{il}^{s}}{H_{il}^{s}} \right) + P_{A} - \frac{P_{il}^{s}}{H_{il}^{s}} - \frac{P_{il}^{s}}{H_{il}^{s}} \right]
\]

\[
\Rightarrow C_{ih}^{c}H_{ih}^{c}\left[ P_{A}\left( \frac{S_{ih}^{s}}{H_{ih}^{s}} - \frac{S_{il}^{s}}{H_{il}^{s}} \right) + P_{A} - MCA_{i}^{s,s} \right] \tag{A.11}
\]

For this case, it is assumed the \( P_{A} > MCA_{i}^{s,s} \). So if \( \frac{S_{ih}^{c}}{H_{ih}^{s}} > \frac{S_{il}^{c}}{H_{il}^{s}} \), 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 \((\frac{S_{ch}}{H_{ch}} > \frac{S_{sh}}{H_{sh}})\), 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:

\[
P_{A}^{*}(\hat{A}_{i}^{MAX} - A_{i}^{MAX}) = P_{A}^{*}C_{ch}^{c}H_{ch}^{c} \left( \frac{S_{ch}}{H_{ch}} - \frac{S_{sh}}{H_{sh}} \right)
\]

All coal use remains the same, which means the change in compliance costs will be the increase in costs from additional allowances. If \(\frac{S_{sh}}{H_{sh}} > \frac{S_{ch}}{H_{ch}}\), 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 \((C_{il}^{s} = C_{il}^{s,MAX} \text{ and } C_{il}^{s} = 0)\) 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 \((\frac{S_{cl}}{H_{cl}} > \frac{S_{sl}}{H_{sl}})\), 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:

\[
A_{i}^{MIN} = \frac{D_{i}}{H_{il}^{s}}S_{il}^{s}m - A_{i}^{e} \quad \hat{A}_{i}^{MIN} = \frac{D_{i} - C_{il}^{c}H_{il}^{c}}{H_{il}^{s}}S_{il}^{s} + C_{il}^{c}S_{il}^{c}m - A_{i}^{e}
\]

\[
P_{A}^{*}(\hat{A}_{i}^{MIN} - A_{i}^{MIN}) = P_{A}^{*}C_{il}^{c}H_{il}^{c} \left( \frac{S_{cl}}{H_{cl}^{c}} - \frac{S_{sl}}{H_{sl}^{c}} \right)
\]

The change in compliance costs will be the increase in costs from the increase in a unit’s net allowance position. If \(\frac{S_{sl}}{H_{sl}^{c}} > \frac{S_{cl}}{H_{cl}^{c}}\), 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 \((C_{s}^*_{ih} = C_{s,MAX}^*_{ih} = C_{s,MAX}^*_{il} = 0)\) 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 \((\hat{C}_{s,MAX}^*_{ih} < C_{s,MAX}^*_{ih})\), which will decrease the emissions level and requires fewer allowances \((\hat{A}_i^{MAX} > A_i^{MAX})\). 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:

\[
P^*_A(\hat{A}_i^{MIN} - A_i^{MIN}) + P^*_s(C_{s}^*_{ih} - \hat{C}_{s,MAX}^*_{ih} + \hat{C}_{s,MAX}^*_{il} + C_{s}^*_{il}) = P^*_A(\hat{A}_i^{MIN} - A_i^{MIN}) \tag{A.14}
\]

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:

\[
A_i^{MAX} = \frac{D_i - C_{c}^*_{il} H_{c}^*_{il}}{H_{s}^*_{ih}} S_{s}^*_{ih} m - A_i^c \quad \hat{A}_i^{MAX} = \frac{D_i - C_{c}^*_{il} H_{c}^*_{il}}{H_{s}^*_{ih}} S_{s}^*_{ih} + C_{c}^*_{il} S_{s}^*_{ih} m - A_i^c
\]

\[
\Rightarrow \hat{C}_{c}^*_{il} H_{c}^*_{il} P^*_s m \left[ \frac{S_{c}^*_{il}}{H_{c}^*_{il}} - \frac{S_{s}^*_{ih}}{H_{s}^*_{ih}} \right] < 0 \tag{A.15}
\]

Since \(\frac{S_{c}^*_{il}}{H_{c}^*_{il}} < \frac{S_{s}^*_{ih}}{H_{s}^*_{ih}}\), 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:

\[
z^*_i P_{sz} + P^*_A(\hat{A}_i^{*} - A_i^{*}) + P^*_s C_{c}^*_{ih} + P^*_s \hat{C}_{c}^*_{ih} + P^*_s(\hat{C}_{s,MAX}^*_{ih} - C_{s,ih}^{*}) + P^*_s C_{c}^*_{il} (\hat{C}_{c,MAX}^*_{il} - C_{c,il}^{*}) \tag{A.16}
\]

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.

\[
P^*_A(\hat{A}_i^{MIN} - A_i^{MIN}) + P^*_s \hat{C}_{c,MAX}^*_{ih} + P^*_s (\hat{C}_{c,MAX}^*_{il} - C_{c,il}^{*}) \tag{A.17}
\]

To be able to interpret this expression, it is necessary to add and subtract \((P^*_s \hat{C}_{c,ih} H_{c,ih}^* - P^*_s H_{c,ih}^*)\).

\[
\hat{C}_{c,ih}^* (P^*_s - P^*_s \frac{H_{c,ih}^*}{H_{c,ih}^*}) + P^*_A(\hat{A}_i^{MIN} - A_i^{MIN}) + P^*_s \hat{C}_{c,ih}^* \frac{H_{c,ih}^*}{H_{c,ih}^*} + P^*_s (\hat{C}_{c,MAX}^*_{il} - C_{c,il}^{*}) \tag{A.18}
\]
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.

\[ C_{c_{ih}}(P_{c_{ih}} - P_{s_{ih}}) + P_{A}^{*}(\tilde{A}_{i_{ih}}^{MIN} - A_{i_{ih}}^{MIN}) + (\frac{P_{s_{ih}}}{H_{s_{ih}}} - \frac{P_{s_{il}}}{H_{s_{il}}})C_{c_{ih}}H_{c_{ih}}^{i_{ih}} \]  
(A.19)

| Change in Fuel Costs | Change in Compliance Costs |

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).

\[ C_{c_{ih}}H_{c_{ih}}^{i_{ih}}\left[P_{A}^{s}\left(\frac{S_{c_{ih}}}{H_{c_{ih}}} - \frac{S_{s_{ih}}}{H_{s_{ih}}}\right) + P_{A} - MCA_{i_{ih}}^{s,s}\right] \]  
(A.20)

A unit’s compliance costs increase if \( \frac{S_{c_{ih}}}{H_{c_{ih}}} > \frac{S_{s_{ih}}}{H_{s_{ih}}} \).

**A.2 Derivation of Cost-Minimizing Input Use to find \( P_{A}^{s} \)**

Assuming no scrubber, the cost-minimizing combination of coal and allowances solves the problem below.

\[ min_{\tilde{A}_{i_{ih}}, \tilde{C}_{c_{ih}}, \tilde{C}_{c_{il}}} (P_{A}A_{i_{ih}}^{MAX} + P_{s_{ih}}\tilde{C}_{c_{ih}}^{s,MAX}, P_{A}A_{i_{ih}}^{MIN} + P_{s_{il}}\tilde{C}_{c_{il}}^{s,MAX}) \]  
(A.21)

Assuming a scrubber is installed, the cost-minimizing combination of inputs is expressed below.

\[ min_{\tilde{A}_{i_{ih}}, \tilde{C}_{c_{ih}}, \tilde{C}_{c_{il}}} (P_{A}A_{i_{ih}}^{s,MAX} + P_{s_{ih}}\tilde{C}_{c_{ih}}^{s,MAX}, P_{A}A_{i_{ih}}^{s,MIN} + P_{s_{il}}\tilde{C}_{c_{il}}^{s,MAX}) \]  
(A.22)

Notice that contract coal use and the cost of installing a scrubber can be ignored because all are constants.
Table 8: Example Epsilon Magnitude

<table>
<thead>
<tr>
<th>Scrubber</th>
<th>Capital Cost $141.34/kW</th>
<th>Gen. Unit Capacity 365.3 MW</th>
<th>O and M Cost 1.23 mills/kWh</th>
<th>Heat Rate 10,000 Btu/kWh</th>
<th>$P_{iz}$ $9,016,616.85$</th>
<th>$r_i$ 95%</th>
<th>$\bar{C}_{ch}$ 50% of Coal Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_A$</td>
<td>$700.00, 600.00$</td>
<td>$D_i$ 24,000,000 mmBtu</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Characteristics</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low Sulfur Coal (Alabama)</td>
<td>Price $1.50/mmBtu</td>
<td>Case 1 (Alabama)</td>
</tr>
<tr>
<td>Heat Content 24 mmBtu/ton</td>
<td></td>
<td>$P_S = $731.46</td>
</tr>
<tr>
<td>Sulfur Content 0.7%</td>
<td></td>
<td>$\epsilon = -$42.00</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$P_A - \epsilon =$773.46</td>
</tr>
<tr>
<td>Pct. ↑ $P_S = 6%$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>High Sulfur Spot Coal (Alabama)</td>
<td>Price $1.10/mmBtu</td>
<td>Case 2 (CAIR)</td>
</tr>
<tr>
<td>Heat Content 24 mmBtu/ton</td>
<td></td>
<td>$P_S = $520.35</td>
</tr>
<tr>
<td>Sulfur Content 1.6%</td>
<td></td>
<td>$\epsilon = -$352.99</td>
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<tr>
<td></td>
<td></td>
<td>$P_A - \epsilon =$873.34</td>
</tr>
<tr>
<td>Pct. ↑ $P_S = 68%$</td>
<td></td>
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<tr>
<td>High Sulfur Spot Coal (CAIR Example)</td>
<td>Price $2.00/mmBtu</td>
<td>Case 3 (Florida)</td>
</tr>
<tr>
<td>Heat Content 25 mmBtu/ton</td>
<td></td>
<td>$P_S = $565.60</td>
</tr>
<tr>
<td>Sulfur Content 1.0%</td>
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<td>$\epsilon = -$76.82</td>
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<td></td>
<td>$P_A - \epsilon =$642.42</td>
</tr>
<tr>
<td>Pct. ↑ $P_S = 14%$</td>
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<tr>
<td>Low Sulfur Coal (CAIR Example)</td>
<td>Price $2.20/mmBtu</td>
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</tr>
<tr>
<td>Heat Content 25 mmBtu/ton</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sulfur Content 0.6%</td>
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<tr>
<td>High Sulfur Spot Coal (Florida)</td>
<td>Price $2.30/mmBtu</td>
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</tr>
<tr>
<td>Heat Content 24 mmBtu/ton</td>
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</tr>
<tr>
<td>Sulfur Content 0.6%</td>
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<tr>
<td>Low Sulfur Coal (Florida)</td>
<td>Price $3.50/mmBtu</td>
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</tr>
<tr>
<td>Heat Content 25 mmBtu/ton</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sulfur Content 0.7%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>