The Impact of State-Level Public Utility Commission
Regulation on the Market for Sulfur Dioxide Allowances,
Compliance Costs, and the Distribution of Emissions

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Abstract

The 1990 Clean Air Act Amendments (1990 CAAA) created a system of tradable allowances for the control of sulfur dioxide (SO$_2$) emissions from electric utilities. This market based system is a departure from traditional command and control (CAC) methods of controlling air pollution. However, the participants in this market are subject to regulation by state public utility commissions (PUC). This paper examines the impact of PUC regulation upon the compliance decisions, compliance costs, and the distribution of emissions of electric utilities and the market for SO$_2$ allowances. This research extends previous work by Bohi and Burtraw (1992) and Fullerton, McDermott, and Caulkins (1997) by extending utility compliance to an explicit market setting, and follows previous work done on the sulfur dioxide allowance market by Coggins and Smith (1993) and Winebrake, Farrell, and Bernstein (1995).

Utilities facing PUC regulation minimize the cost of electricity generation and emissions compliance subject to constraints on electricity demand and emissions allowed. In order to comply with the emissions constraint utilities can either buy/sell allowances, switch or blend fuels, or make a discrete choice on installation of a scrubber. Using utility data for the year 1996, the market for SO$_2$ allowances is simulated under various scenarios. The simulations indicate that the increase in utility compliance costs due to state-level PUC regulation ranges anywhere from 4.5% to 139% depending on scenario assumptions with the regulatory treatment of scrubbers leading to majority of cost increases. Moreover, the simulations indicate that despite holding generation constant, the move from a regulated to an unregulated environment has impacts on the distribution of emissions sources and compliance costs. In some scenarios, the change in the distribution of emission sources may have impacts on the Northeast, which is already concerned about sulfur deposition from plants in the Midwest and Mid-South. Despite lower costs in the aggregate in the unregulated regime, there may be some states where utilities see their compliance costs increase.
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Chapter 1

Introduction

1.1 A New Pollution Control Policy is Born

Title IV of the 1990 Clean Air Act Amendments (1990 CAAA) introduced a dramatic shift in policy to address one of the more highly publicized environmental problems over the past 30 years, sulfur dioxide emissions (SO\textsubscript{2}) from electric power plants.\footnote{First, the language of the law refers to permits as “allowances”. For the purposes of this paper, I will use the terms “allowance” and “permit” interchangeably. Second, there is a common misconception that Title IV affects only coal-fired plants. In fact, many oil-fired plants are affected as well.} In stark contrast to the command-and-control (CAC) policies of the 1970s and 1980s, Title IV created a cap-and-trade system of emissions permits to control the emissions of SO\textsubscript{2} that lead to acid rain and particulate sulfur deposition. If successful, the new program lowers emissions reduction costs, and also yields benefits in the form of reduced acidification of water and soil, decreased respiratory illness, and reductions in costs for repairing buildings and other structures that have been scarred by acid rain.

Prior to Title IV, CAC was the policy regime of choice to combat sulfur dioxide emissions and sulfur deposition. From 1970 through 1977, CAC was implemented in the form of emissions standards on new sources.\footnote{This standard was 1.2lbs. SO\textsubscript{2}/mmBtu of heat input.} Starting with the 1977 Clean Air Act Amendments and throughout the 1980s the mechanism of choice to control SO\textsubscript{2} emissions was a technology-based CAC standard requiring new sources to install post-
combustion control equipment or scrubbers. In either case, the CAC regimes of the 1970s and 1980s, while popular with environmental interests, do not provide polluting sources with the flexibility to choose the least-cost method of abating pollution. This lack of flexibility leads to emissions abatement costs that could significantly exceed the least-cost solution.\footnote{See Portney (1990, pp. 72-73) or Portney (2000 p. 113) for a summary of studies examining this problem. The summary of CAC costs to least-cost ranges anywhere from 1.72 to 1 up to 22 to 1.} Moreover, the CAC regimes implemented during the 1970s and 1980s also exempted (grandfathered) electricity generating units that were already in place and operating at the time the 1970 and 1977 CAAA were signed into law. Therefore, not only was the CAC policy costly and inflexible for new units, but this policy did little to reduce emissions from existing sources.

From an economic perspective, an emissions control policy should attempt to achieve the emissions reduction goal at the lowest possible cost. This is the central reason for implementing the cap-and-trade program for SO$_2$ emissions. The idea of a tradable permit system for the control of pollution can be traced back as far as Dales (1968) and was formalized in the seminal work of Montgomery (1972). Montgomery showed that a cap-and-trade system will achieve a given level of emissions reduction at the lowest possible cost. The two keys to an emissions trading program are flexibility for polluters regarding how to reduce emissions and the ability for low-cost reducers of pollution to sell permits to high-cost reducers of pollution, thus exploiting the differences between pollution sources in their respective marginal costs of abatement. Finally, in an effort to address existing sources that were exempt from the previous CAC policies, existing sources were mandated to participate in the cap-and-trade program so that a “two-class” system of pollution sources would no longer exist.

1.2 The SO$_2$ Market Is Not a Textbook Pollution Market

Despite the potential and promise of the SO$_2$ program to reduce emissions, the cap-and-trade market for SO$_2$ allowances faces operational and political difficulties. First,
most electric utilities in the United States face some form of “cost-of-service” or “rate-of-return” regulation on rates and profits by Public Utility Commissions (PUCs). In an effort to promote incentives to minimize cost under the rate-of-return regime, PUCs may also introduce cost-sharing mechanisms so that not all costs are simply passed through to captive customers. It is possible that cost recovery treatment or rate base treatment of abatement options could bias individual utility decisions on how to achieve emissions reductions in the SO$_2$ market under Title IV, leading to deviations from least-cost solutions for individual utilities. Moreover, if many utilities face different biases in cost recovery treatment, it is almost assured that the cap-and-trade program will not achieve emissions reduction at the lowest possible cost in the aggregate. This second problem may be exacerbated as some states move to competition in the electricity sector, thus leaving utilities “deregulated”.

Second, the market proposed and implemented by the EPA under Title IV is a national market and is not concerned with the spatial dimension of emissions and ultimately sulfur deposition, but only with the total amount of emissions.$^4$ This allowance market differs from other notions of pollution markets discussed in Montgomery (1972) and Baumol and Oates (1988) where allowances are defined over two dimensions: amount and location of deposition. In a pollution trading regime that acknowledges the potential importance of the spatial dimension of emissions, polluters would be required to hold a portfolio of allowances to pollute at specified sites, thus alleviating concerns about hot spots. Under the SO$_2$ market created by Title IV, the distribution of emissions after trading could potentially lead to so-called “hot spots” where emissions or deposition are greater under the cap-and-trade system than otherwise would be the case. To mitigate the potential for hot spots, PUCs may, as an extension of public policy, design cost recovery treatment of compliance options to guard against this potential problem. However, since there are multiple PUCs, it is possible that unintended consequences could result from such a policy, leading to an emissions outcome that may

\footnote{Tietenberg (1995) provides a survey of the issues surrounding implementation of pollution markets and spatial emissions outcomes.}
not be desirable.

Third, there is the issue of the distribution of compliance costs across states with affected utilities. While the aggregate cost of emissions reduction is minimized in a cap-and-trade market for pollution permits, utilities may bear very different compliance costs that can have very real impacts on the rates paid by captive customers of the utilities. Therefore, PUCs may disallow certain options that may decrease the compliance costs for utilities under its jurisdiction, but that lead to an overall increase in compliance costs in the aggregate. Moreover, it could also be the case that, in an effort to protect some interest groups such as local coal mining interests, a PUC could drive up the compliance costs for utilities in its own state while effectively lowering compliance costs for utilities in other states.\(^5\)

### 1.3 Policy Questions and Findings

This research concentrates on the impact of PUC regulation on the cap-and-trade market for SO\(_2\) allowances created by Title IV of the 1990 CAAA. In particular, I examine the impact of PUC regulation on:

1. Compliance choices and costs to individual utilities,
2. The industry-wide (aggregate) compliance cost as compared to the least-cost solution,
3. The change in the distribution of emissions arising from an SO\(_2\) allowance market in the presence of PUC regulation in comparison to the distribution of emissions without any PUC regulation, and
4. The change in the distribution of compliance costs arising from an SO\(_2\) allowance market in the presence of PUC regulation in comparison to the distribution of costs without any PUC regulation.

\(^5\)See Arimura (2002) for an econometric estimate of the impacts of coal protection on compliance choices.
Accordingly, this research extends previous work on SO$_2$ emissions compliance by incorporating utility compliance decisions in the presence of PUC regulation, which differs across utilities, into an explicit market setting where utilities make compliance decisions, including trading activity, related to an endogenously determined allowance price. First, I construct a model of individual utility decision-making in the presence of PUC regulation. This is a production cost model where utilities choose compliance options and fuel inputs to satisfy electricity demand and an emissions constraint. Aggregating individual utility decisions allows me to characterize the market for SO$_2$ allowances and to provide analytical results related to PUC regulatory impact on allowance prices and aggregate compliance costs. Next, I provide some simple computational examples of the kinds of impacts PUC regulation can have on compliance costs and the distribution of emissions and costs. Finally, I take the proposed production cost model and parameterize it to reflect the data from the year 1996 to examine the actual impacts of PUC regulation on the industry-wide compliance cost and the distribution of emissions and costs under various scenarios.

Analytically, I find that the existence of PUC regulation itself does not necessarily lead to deviations from the least-cost solution that pollution markets should yield. In fact, there are two types of symmetric regulatory treatment by PUCs that can lead the SO$_2$ market to achieve the least-cost solution in the presence of PUC regulatory rules.

- Each PUC treats compliance options symmetrically for cost recovery purposes, regardless of the cost share passed on to customers.
- The PUCs “coordinate” in the sense that, although they may treat fuel-switching options differently from allowance options, these treatments must be the same across PUCs and utilities.

Also, analytically it will be shown that the allowance price is weakly decreasing in the cost share borne by utilities in allowance transactions, while weakly increasing in the fuel cost share borne by utilities.
Computationally, the impact of PUC cost recovery rules can have a dramatic impact on compliance costs and the distribution of emissions and costs, as shown in three simple examples. However, taking the model to data and conducting simulations shows that, at least for 1996, the impact of PUC regulations are not as great as shown in the simple examples. Running simulations of the SO\(_2\) market for 1996 under a variety of assumptions regarding the cost of scrubber installation, scrubber choice, and the amount of emissions allowed shows that the presence of PUC regulation in the SO\(_2\) market leads to compliance costs 5-125% greater than the least-cost solution of the SO\(_2\) market without any PUC regulation, depending on the assumptions used. The compliance costs that result from the simulation exercises also compare favorably to other studies that attempt to estimate compliance costs associated with the EPA’s SO\(_2\) program.\(^6\) Moreover, there are potentially large changes in the distribution of emissions when moving from the regulated regime to an unregulated regime, including potential implications for the Northeastern United States, which is already sensitive to power plant emissions from the Midwest and mid-South. There are also changes in the distribution of compliance costs when changing from a regulated regime to an unregulated regime. Despite lower aggregate compliance costs in an unregulated regime, some states will see their compliance costs increase.

This research proceeds as follows. Chapter 2 provides an overview of the SO\(_2\) market created by Title IV and some observations about the market to date. I give an intuitive description of how PUC regulations can impact compliance costs, and the distribution of emissions and costs, and a review of related literature on the SO\(_2\) program. Chapter 3 presents the model and discusses results for individual utility behavior and the market as a whole, and the chapter concludes with some simple numerical simulations to highlight the impacts of PUC regulation on the SO\(_2\) market. Chapter 4 presents the data to be used in the simulations, discusses computational issues, and presents and discusses the simulation results. Chapter 5 offers concluding observations and possible extensions of this framework for future work.

\(^6\)See Schmalensee et al. (1997) and Carlson et al. (2000)
Chapter 2

Background

2.1 The SO2 Market Created By Title IV of the 1990 CAAA

The cap-and-trade program created by Title IV no longer “grandfathers” generating units that have been operating for years. To the contrary, the program would require the participation of 263 dirtiest units in its first five years (Phase I: 1995-1999) of the program, while making participation by other fossil-fired units voluntary until the year 2000. The SO2 trading program created by Title IV initially seems a vast improvement compared to the previous CAC policy. It provides flexibility to generating units, the prospect of lower costs, and the elimination of “grandfathering” for older generating units from emissions reductions.

Under Title IV of the 1990 CAAA, utilities have flexibility internally and can meet their emissions obligations through coal switching or blending, allowance transfers between units, scrubber installation, unit switching, unit repowering, unit retirement, or any combination of the above. This sort of flexibility allows utilities to choose the compliance option that will be least costly to them without any obligation of explicit participation in the SO2 market. Additionally, utilities may engage in purchases or sales from other utilities in the SO2 market if it is cost-effective.

The implementation of the market mechanism to control SO2 emissions was done in
two phases.\footnote{1 Much of this information can be found in USEPA (1997).} Phase I (1995-1999) required only the 110 largest polluting plants, which includes 263 generating units, to participate in the SO$_2$ allowance program.\footnote{2 These units are often referred to as Table A units since they appeared in Table A of Title IV.} Phase II, which started in 2000, includes all fossil fuel electric generators with a capacity exceeding 25 megawatts(MW). The goal was to reduce SO$_2$ emissions to 8.95 million tons by the year 2000, down from 19 million tons in 1980.

2.1.1 Other Participants

In addition to the 263 units required to participate in Phase I, other units could do so: substitution units, compensating units, and opt-in units. In 1996 431 units were participating in Phase I.

Substitution units are designated by Table A units so that the same overall emissions reduction can be made in a cost-effective manner. The Table A unit and its substitution unit(s) must have the same owner or operator. Essentially, if the Table A unit would incur great expenses by reducing emissions, it can bring in units that can reduce emissions more easily. There were 160 substitution units in 1996.

Compensating units can be designated by a Table A unit to provide compensating generation for its reduced utilization. There are no ownership restrictions here, but compensating units must be on the same grid interconnection and have some contract to do this. In 1996 there was only one compensating unit.

Finally, Phase II units can opt in to Phase I as well. In 1996 there were seven opt-in units. A possible explanation for units coming in early is that they wanted to begin accumulating allowances for use in Phase II.

2.1.2 Allowances

According to Title IV one SO$_2$ allowance allows the holder to emit one ton of SO$_2$ in the year it was issued or any year thereafter. That is, not all allowances issued in a
particular year need be used in that year, but can be held over for future use.\textsuperscript{3} While it is convenient to think of allowances as a property right, the right to emit SO\textsubscript{2}, Title IV makes it explicitly clear that allowances are not property rights and can be revoked by the Environmental Protection Agency (EPA) at any time for good cause. In Phase I, Table A units were initially allocated allowances \textit{gratis} based on average heat input (millions of Btu) during 1985-1987 multiplied by 2.5 lbs. of SO\textsubscript{2}. Phase II allocations are based on average heat input during 1985-1987 multiplied by 1.2 lbs. of SO\textsubscript{2}.

In addition to the formulaic allocations above, there are other types of allowance allocations. One that has garnered much attention is the yearly auction of allowances each March. This is a small part of the program, with only about 300,000 allowances available for auction each March.\textsuperscript{4} The market I am examining in this work is sometimes called the “secondary market” for allowances, where utilities trade with each other after allowances are initially allocated and where most allowance transfers are likely to take place.

Other allowance allocation mechanisms for Phase I included allocations for substitution units, compensating units, and opt-in units. For substitution units the allocation generally equals the historical 1985 emission rate. Other voluntary units, of which there were only eight in 1996, were allocated allowances on a case-by-case basis.

For Table A units, some extra allowances were allocated as a part of the political process to get Title IV passed and signed into law.\textsuperscript{5} For example, excess allowances were allocated to many units in Indiana, Illinois, and Ohio, presumably to ease the burden of emissions reduction for these generally dirty plants. Extension allowances were also allocated to utilities that needed time beyond 1995 to implement their emissions reduc-

\textsuperscript{3}The practice of holding allowances for future use is called banking. I do not examine banking in this work. For research that investigates the banking of allowances, see Kling and Rubin (1997) and Rubin (1996).


\textsuperscript{5}See Title IV, Sec. 404 (a). For the political debate surrounding allowance allocations, see Ellerman et al. (2000, Chapters 2 and 3).
tion strategies, as well as for those units that would be installing emissions reduction technologies such as scrubbers.

Allowances are tracked by the EPA’s Allowance Tracking System (ATS). Each participant in the program has an account with the EPA, and must report any transactions to the ATS so that they may be recorded and individual accounts updated. At the end of each year, each account must hold enough allowances to cover its emissions.\(^6\) To monitor emissions from each unit, the EPA requires that all participants install a continuous emissions monitoring system (CEMS), a computerized system that allows the EPA easy monitoring of emissions.

2.1.3 Some Early Observations

Early indications that utilities were taking advantage of Title IV flexibility are cited by Rico (1995) and Burtraw (1996), who indicate that half to two thirds of utilities switched or planned to switch from high sulfur coals to low and medium sulfur coals in order to meet emissions obligations. Furthermore, according to Burtraw (1996), the delivered price of low sulfur coals has not increased as predicted, so fuel switching has become a cheap and attractive compliance option. Additionally, fuel switching has become more attractive since potential technical problems have turned out to be quite minor. It had been thought that it would be costly to switch coals because of the different characteristics of coals.\(^7\) Meanwhile, one utility operator, Illinois Power, elected to buy allowances instead of installing scrubbers.\(^8\)

With respect to trading and allowances prices, the amount of trading for the purposes of compliance has been low, leading some to conclude that there are gains from

\(^6\)Technically, units have until January 30 of the next year to get all of the allowances they need. The penalties for non-compliance are steep. For each ton of SO\(_2\) not covered by an allowance in the account, the unit pays a penalty of $2,000 per ton in 1990 dollars, plus they must take actions to cover the extra emissions.

\(^7\)See Burtraw (1996), Winebrake et al. (1995), and Ellerman et al. (1997). For example, boilers sometimes have to be refitted to burn different coal types, and the amount of ash from combustion might require changes to smokestacks to control the extra ash.

\(^8\)See Rose (1997) and Energy Information Administration (1994).
trade still to be captured by the SO₂ market. In fact, it seems that many utilities followed self-sufficiency strategies in that they either switched to low sulfur coals to meet emissions obligations, or moved allowances around between generating units under the same corporate ownership as noted by Rose (2000) and Hart (2000). However, as Swift (2001) notes, even considering the intra-utility trading option, the number of allowances traded for the purpose of compliance was only 3.5 million over the five years of Phase I, an average of 700,000 per year. As Rose (1997, 2000) notes, this trading inactivity could likely be attributable to state PUCs’ lack of understanding of the allowance market, or to the unwillingness of utilities to participate in the market for fear of having PUCs disallow costs associated with allowance transactions. Moreover, the presence of PUC regulation may have also played a part in the much lower than expected prices of allowances.

As discussed below, some observers feared that the market for allowances would create so-called hot spots. According to Swift (2001) this has not occurred. However, it is interesting to note that, according to Burtraw and Mansur (1999), trading will potentially increase emissions in some states from the Title IV baseline emissions.

### 2.2 Potential Impacts of PUC Regulatory Treatment

The role played by PUCs and lawmakers, through policy implementation by PUCs, could potentially affect how well this new market functions. Traditionally, economic regulation by PUCs specifies the rate of return permitted on investment, and in doing so defines the costs to be considered in calculating the utility’s return. In particular, state PUCs determine the prudence of costs, whether already incurred or proposed for the

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9 See Carlson et al. (2000)
10 Self-sufficiency in this context means that no trading is occurring between economically distinct entities, though transferring allowances between units under the same ownership can still be considered "trading".
12 A hot-spot would occur when emissions in an area are greater under the cap-and-trade program than if no such program existed at all.
future, and the portion of those costs to be passed through to ratepayers. Traditional “cost-of-service” or “rate-of-return” regulation would pass on all prudently incurred variable costs, and capital expenditures would be allowed the regulated rate-of-return. As practiced through the 1970s, essentially all costs were passed through to ratepayers and all capital expenditures were allowed a rate-of-return. As Averch and Johnson (1962) point out, utilities could have an incentive to over-invest in capital projects when the allowed rate-of-return exceeds the cost of capital. In response to the over-investment of capital, cost overruns of some projects, and generally the lack of any incentive to minimize costs, state PUCs began disallowing some or all of these costs. Moreover, to combat the tendency of utilities to inflate costs, many state PUCs have implemented various incentive mechanisms that would reward utilities for keeping costs down.\(^{13}\)

In the context of the SO\(_2\) program, PUC treatment of allowance purchases or sales, purchases of low sulfur coals, or the purchase of a scrubber, a capital asset, may affect compliance choices and costs for individual utilities and the rates charged to their customers by altering the incentives for choosing one compliance option over another. Consequently, from an individual utility’s perspective, this may lead to sub-optimal decisions and inflate compliance costs. To provide cost minimizing incentives, Rose et. al. (1993) suggest that sharing mechanisms be put in place so that utilities have an incentive to minimize cost; both the utilities and ratepayers could then benefit from the induced cost-minimizing behavior.\(^{14}\)

In the aggregate, since PUC regulation likely differs in some dimension across state lines or even between utilities within a state, there may be potentially large deviations in industry-wide compliance costs from the least-cost solution that is achievable by the cap-and-trade program. Intuitively, this might occur since differential regulatory treat-

\(^{13}\)See Joskow and Schmalensee (1986).

\(^{14}\)Rose et al. suggest that compliance actions and costs be benchmarked to the allowance price. For action taken that result in per-ton reduction costs less than the allowance price, utilities and ratepayers would share the gains. For actions leading to per-ton reduction costs greater than the allowance price, utilities and ratepayers would share the cost.
ment may effectively alter how utilities perceive their marginal abatement costs relative to other utilities, thereby pushing low-cost reducers of pollution into buying allowances or high-cost reducers of pollution into selling allowances. Moreover, differential PUC regulatory treatment of compliance options will likely impact allowance prices and the distribution of emissions and costs. Adding to the variance in regulatory treatment are those utilities that are not under the jurisdiction of state regulators for ratemaking purposes: federal power agencies such as TVA, and state and local cooperative and municipal utilities. These public entities can face completely different incentives relative to the regulated investor-owned utilities. This difference in regulatory regimes across state lines, and across public and investor-owned utilities, may be exacerbated as deregulation of electric utilities takes place in some states, but not in others.\(^{15}\)

Through ratemaking treatment, PUCs may even choose to implement policies that would discourage some activities such as allowance sales or using some types of coal. Winebrake et. al. (1995) cite examples where state legislatures have tried to restrict allowance trades, restrict coal usage, or dictate compliance choices to utilities.\(^{16}\) Additionally, utilities may face uncertainty about the regulatory treatment of compliance options by PUCs.\(^{17}\) As Lyon (1995) concludes from his analysis of ex-post prudence reviews on technology adoption by electric utilities, the potential for the disallowance of costs for an innovative technology (in the context of this research pollution trading), despite the expectation of lower costs, will lead utilities to adopt older, more costly, but proven technologies.\(^{18}\)

\(^{15}\)See Joskow (1996) for an early overview of deregulation. For a summary of states that have moved to “deregulate”, see www.eia.doe.gov/cneaf/electricity/chg_str/regmap.html

\(^{16}\)It has been noted that New York and Wisconsin had proposed legislation that would severely limit allowance trading by utilities in those states. Also, Illinois enacted a law that would have required in-state utilities to buy high sulfur coal from within the state thereby forcing those utilities to install scrubbers. This law was later overturned by the courts. For other examples see Winebrake, et al.(1995).

\(^{17}\)This has been mentioned by Burtraw (1996), Rico (1995), and Rose (1997, 2000) as leading to deviations from least-cost solutions. For analysis of potential regulatory uncertainty in the market see Winebrake et al. (1995) and Bailey (1998))

\(^{18}\)To counteract this effect, Lyon suggests a cost-sharing mechanism be implemented to promote the
2.3 PUC Regulatory Impacts on the Distribution of Compliance Costs and Emissions

The market in SO$_2$ allowances created by Title IV will likely, in the presence of PUC regulatory rules, lead to differing distributions of costs and emissions across states as compared to an allowance market without PUC regulations. The distribution of SO$_2$ abatement costs has been a contentious issue for some time and was so when the 1990 CAAA were being debated in Congress.$^{19}$ Some state delegations heavily dependent on coal fired generation believed that costs would be primarily borne by their ratepayers (Ellerman et al. 2000). The concern about the distribution in compliance costs is clear in the allocation of allowances in Title IV. As discussed above, many states with high emitting units were able to secure additional allowances through various provisions of Title IV.

Meanwhile, other states were, and continue to be, concerned that trading would increase sulfur deposition in areas downwind from dirtier plants.$^{20}$ For example, wind patterns bring acid rain to New York and the New England states as a result of emissions from utility plants using coal in the Midwest and mid-South. If utilities in the Midwest and mid-South are able to purchase allowances in a market that only places a cap on emissions, it is certainly possible that the deposition of sulfur emissions in the Northeast may not be reduced by much, if at all, regardless of the overall reduction in SO$_2$ emissions.$^{21}$ Though early indications are that this has not occurred (see discussion above), it is possible that PUC regulatory rules could distort the SO$_2$ market and lead to increased emissions from Midwestern and mid-South plants versus a trading regime.

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$^{19}$See Ellerman et al. (2000, Chapters 2 and 3) for a summary.

$^{20}$The United States Department of Justice (USDOJ) has filed lawsuits on behalf of the EPA and various Northeastern states to force some utilities in the Midwest and mid-South to install scrubbers to satisfy New Source Performance Standards (NSPS) claiming that the units in question made major modifications effectively making them new units. See USDOJ (1999a, 1999b, 2000a, and 2000b).

2.4 Related Literature

While volumes have been written about the Title IV cap-and-trade program for SO$_2$, the amount of research on the impacts of PUC regulation on the SO$_2$ market has not been nearly as great. Research into the impact of utility regulation on pollution markets can be traced back to Tschirhart (1984). Tschirhart examines a model of a utility’s compliance choices, which consist of buying or selling pollution permits or installing a continuous, capital-intensive abatement technology (scrubbers), subject to an emissions constraint and a rate-of-return constraint. The model utility can place only scrubber capital in the rate base, while permits are treated as an expense. Tschirhart shows that in the presence of a rate-of-return constraint, the utility will install more scrubbers than would otherwise be optimal. Moreover, the over-installation of scrubbers leads to sub-optimal permit choices in that the utility will either purchase fewer permits than optimal or sell more permits than is optimal.

Since the passage of Title IV, more work has been done. Bohi and Burtraw (1992) examine how PUC regulation affects utility compliance with the CAAA. In particular, they were interested in the treatment of abatement capital versus allowances in the rate base. Their model develops a rich treatment of PUC regulation of a utility. The model utility is rate-of-return constrained and chooses an abatement strategy of an allowance position (net buyer or net seller) and a continuous abatement technology that maximizes expected earnings subject to an emissions constraint imposed by the CAAA requirements. With appropriate assumptions, the model allows for analysis of the impact of PUC regulation on compliance decisions. Bohi and Burtraw find that, if the allowed rate-of-return on both allowances and abatement capital is less than the market rate-of-return, there is an incentive to minimize costs and PUCs should treat

\[^{22}\text{The converse may also be true. It could be the case that PUC regulations could mitigate potential hot spots in comparison to a trading regime without PUC regulations.}\]
allowances and abatement capital symmetrically.\textsuperscript{23} If the allowed rate-of-return on both allowances and abatement capital is greater than the market rate-of-return, regulatory symmetry is probably not desirable.

This regulatory situation looks like an Averch-Johnson (1962) rate-of-return constraint. The utility has the incentive to increase its investment costs in meeting emissions requirements since this will increase its profits. Even with symmetric treatment of allowances and abatement technology, a utility will have the incentive to invest in the option that has the highest total cost, most likely scrubbers. Hence, Bohi and Burtraw recommend asymmetric treatment of abatement options, most likely a more favorable treatment of allowances since a compliance strategy using allowances is likely less costly. Finally, they extrapolate their one-firm model to the SO\textsubscript{2} market with two firms that differ only in their emissions rates, to analyze the effects of different regulatory schemes on the market for allowances when utilities are cost-minimizers. Their analysis indicates that when regulatory treatment of abatement options is symmetric, the market is not distorted. Moreover, the analysis finds that when control technology is favored over allowances, the allowance price will fall, although it is not clear how trading volume is impacted.\textsuperscript{24} This would indicate that, under most circumstances, differential treatment of abatement options will lead to deviations from the least-cost solution to pollution abatement. Moreover, when regulatory biases differ across states, there will unambiguously be deviations from the least-cost allocation of pollution abatement because of changed incentives arising from PUC rules.

Coggins and Smith (1993) examine a two firm SO\textsubscript{2} market where utilities choose electricity output to maximize profits subject to individual emissions constraint and a common Averch-Johnson rate-of-return constraint that places some fraction of both

\textsuperscript{23}Bohi and Burtraw make this statement with one proviso. Include only purchased allowances in the rate base. If the utility sells some of its allowance endowment, then treat those revenues as an offset to abatement capital costs.

\textsuperscript{24}The converse applies as well. If allowances are favored over abatement technology, then the price rises with an ambiguous impact on trading volume.
allowances and abatement capital in the rate base.\textsuperscript{25} In their model firms can choose to buy or sell allowances or invest in a continuous abatement technology to comply with their emissions constraint. The model is then parameterized, and numerical experiments compare a CAC regime to an allowance-trading regime. They find that trading regimes leads to higher social welfare, but with the qualification that this result could be reversed under some rate base policies. They further examine the impacts of rate base treatment of compliance options on social welfare.\textsuperscript{26} They conclude that under a CAC regime, all scrubber capital should be included in the rate base to maximize social welfare. In the trading regime, holding abatement capital treatment fixed, they find that permitting all allowance purchases to be included in the rate base will maximize social welfare. However, if all allowance purchases are put into the rate base, they find that the social-welfare-maximizing amount of abatement capital in the rate base is about 20%.

Winebrake, Farrell, and Bernstein (1995) attempt to estimate the costs of legislative intervention and regulatory uncertainty in the SO\textsubscript{2} market.\textsuperscript{27} They employ a dynamic, linear programming model that covers the five years of Phase I (1995-1999) and the first five years of Phase II (2000-2004), minimizing the cost of generation across Phase I affected units subject to demand and emissions constraints that include allowance banking.\textsuperscript{28} Parameterizing their model and solving it, they estimate the shadow price of SO\textsubscript{2} to be $143/ton in an environment without any regulatory rules on parameters and the cost of compliance is $5.02 billion over ten years (or approximately $500 million per year). In one experiment, they look at direct intervention by states in the mar-

\textsuperscript{25}For analytical and computational tractability they use Cobb-Douglas production technologies, and assume that emissions are a continuous function of abatement capital and electrical output. They do not consider fuel switching as an abatement option.

\textsuperscript{26}Coggins and Smith define social welfare as the sum of firm profits plus consumer surplus.

\textsuperscript{27}Direct interventions can include restrictions on the type of fuel used, abatement technologies used, or on allowance trading. Regulatory uncertainty can arise from unannounced policies or the proposed policies that have yet to be implemented.

\textsuperscript{28}They do not explicitly include cost minimizing of allowance purchases and sales in the model. Although emissions are a function of compliance strategies, it is unclear how this enters their model. Finally, to account for Phase II units, they simply model them all as one unit.
They find that the allowance price (shadow price of SO$_2$) does not change, but that overall compliance costs increase, interestingly, the increase in compliance costs in states with restrictions is greater than the overall increase in compliance cost, which implies that costs decrease elsewhere. They also run another numerical experiment that examines the impact of regulatory uncertainty, but only during the Phase I period. Participation, or lack thereof, in the market is used as a proxy for uncertainty. They find that the compliance costs and allowance prices will not increase until fewer than 30% of utilities are participating in the market. At participation rates between 20% and 30%, compliance costs will increase somewhat but not dramatically. At participation rates below 20% compliance costs increase dramatically.

Fullerton, Mc Dermott, and Caulkins (1997) model a single, multiple-unit utility that minimizes the cost of generating electricity subject to constraints on demand, capacity, and environmental compliance and that is subject to cost recovery rules on allowance purchases and sales, abatement capital, and coal usage. To comply with the environmental rules, the model utility may buy or sell allowances at a given price, switch or blend fuels, change unit utilization, or install abatement technology at one or more units. Advancing the previous work by Coggins and Smith and Bohi and Burtraw, they explicitly model the decision on whether to adopt abatement technology (scrubbers) as a discrete choice at each unit.

Modeling scrubber choice as a discrete decision along with the option of changing utilization at various units does not allow for any analytical solutions to the model; hence, it must be parametrized and solved numerically. Fullerton et al. conduct numerical experiments for a utility with two units and examine the impact of regulatory parameters and different price differentials between high and low sulfur coal on compliance decisions. Their numerical exercises confirm the previous finding by Bohi and

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29 They examine proposed laws in Wisconsin and New York forbidding in-state utilities from selling allowances to another utility.

30 The authors reason that if affected utilities are attempting to minimize risk, they will not participate in the market but will simply meet the emissions constraint on their own. Therefore, the more uncertainty there is, the fewer participants will be in the market.
Burtraw that symmetric regulatory treatment for compliance options is sufficient, but not necessary, to induce cost-minimizing behavior for an individual utility.\footnote{Symmetric treatment is not necessary because of the discreteness of choices made by the utility.} They also find that the cost of compliance in a trading regime is lower than in a technology-based CAC standard, although PUC incentives on allowance trading could lead to deviations from the least-cost solution, and could be more costly than the CAC performance standard for the utility.\footnote{This may be true for one utility, but it is not entirely clear it is true for the industry as a whole.} Finally, Fullerton et al. make some additional observations on the interaction of PUC cost-recovery rules on an allowance trading regime with respect to the geographic distribution of emissions. They surmise that some differing incentives for allowance trading can lead to different distributions of emissions. Moreover, a PUC that seeks to minimize emissions from its own jurisdictional units may encourage allowance sales, and actually make the environment in its state even worse because of air transport of emissions.

Bailey (1998) examines the effect PUC regulatory rulings have on whether “arms length” allowance transactions take place in a state, as well as the impact PUC rulings have on the volume of trading and the number of trades that take place. The empirical investigation specifies equations for determining the impact of PUC rulings on trading activity and the impact of trading activity on the likelihood of a PUC ruling. Performing a maximum likelihood logit estimation, Bailey finds that, whether the two equations are estimated simultaneously or separately, the presence of a PUC ruling on allowance transactions increases the likelihood of trading. Also trading activity significantly increases the likelihood that a PUC ruling has occurred. Bailey concludes that, as of 1995, trading activity has not been impacted by PUC regulations.\footnote{This conclusion is reached under the assumption that no gains from trade are being left on the table.}

Examining volume and number of trades, Bailey finds that PUC rulings have no explanatory power regarding the volume of trading activity, but the presence of a PUC ruling does have a positive impact on the number of trades that take place.

Arimura (2002) examines the impact of PUC regulation and coal protection policies
on the abatement choices of Phase I units, with a particular interest in whether the units buy allowances and continue to use high sulfur coal, or blend or switch completely to low sulfur coal. Arimura constructs a production cost model where the costs of abatement are a function of coal prices and characteristics, idiosyncratic unit characteristics, and PUC regulation. The allowance price is taken to be exogenous. From the cost minimizing conditions of the model, Arimura estimates a probit model to determine the effect of the existence of PUC regulation and coal protection on compliance choices. His results show that coal protection significantly biases units in favor of high sulfur coal and allowance purchases, while the existence of PUC regulation significantly biases units toward fuel switching strategies. Using these parameter estimates, Arimura conducts some simulation experiments changing the regulatory parameters on PUCs and coal protection. He finds that in the presence of no coal protection at all, and PUC regulations, most units in his sample would switch to low sulfur coal. In contrast, when there are no PUC regulations, regardless of coal protection, he finds that most units would choose to stay with high sulfur coal and buy allowances. Moreover, he draws the conclusion that without PUC regulations, allowance prices would have been higher.

2.5 Moving Forward

In the next chapter I will propose a production cost model of utility behavior in the context of Phase I SO$_2$ compliance that incorporates PUC cost recovery rules on various compliance options. The model I outline extends what has been done previously insofar as individual compliance choices and the allowance price will be determined simultaneously. This will allow for an examination of the cost and distributional effects of PUC cost recovery policies for the SO$_2$ program in Phase I for the year 1996.

34The only units he assumes in this model that do not face PUC regulation are those operated by TVA. Moreover, he excludes from his sample observations where scrubbers are installed and where only one coal type is observed.
Chapter 3

Model, Analytics, and an Example

In this chapter the model is developed and analytical results are shown, with explanations of policy implications where applicable. At the end of the chapter, a three-utility example is constructed and solved to show the potential distortions that PUCs could introduce by into the EPA Sulfur Dioxide Program’s tradable allowance market. The next chapter examines the impacts of PUC cost recovery policies on the Sulfur Dioxide Program’s allowance market for 1996.

Analytically, it can be shown that the existence of differential PUC cost recovery rules across affected utilities can lead to deviations from the hypothetical least-cost solution that the market created by the Sulfur Dioxide Program could potentially achieve. However, the existence of cost recovery rules alone does not necessarily imply that the market will not achieve the hypothetical least-cost solution. In addition to the results on industry-wide compliance costs, comparative statics results showing the impact of PUC cost recovery rules on the market price of sulfur dioxide allowances are developed. Unfortunately, none of these results can reveal definitively the impact on trading activity in the allowance market.

The small examples at the end of the chapter provide some context for the analytical
results. In addition to showing how PUC cost recovery rules can lead to deviations from least-cost compliance decisions, there are also potential implications for the distribution of emissions across pollution sources and the distribution of compliance costs across states. Both of these politically charged issues will be discussed further in the following chapter.

3.1 Model Environment and Parameters

The model developed here is a mixed integer programming production cost model that draws heavily from, and simplifies the individual utility’s decision problem in Fullerton, et. al. (1997), and extends the model to a market setting where the allowance price is endogenously determined. Utilities in this framework operate in a static world without uncertainty. Moreover, each utility has only one plant, and one generating unit at that plant. The utility minimizes the cost of generating electricity and compliance with Title IV of the CAAA subject to constraints on the demand for electricity and allowable emissions. The utility can comply with the emissions constraint by installing a scrubber, fuel switching or blending, or through participation in the allowance market. The utility also faces PUC regulation in the form of cost recovery rules on allowance sales and purchases, scrubber installation, and fuel purchases.

3.1.1 Technology Parameters

In what follows utilities are indexed by $i=1...I$.

Let $z_i \in \{0,1\}$ be a dummy variable indicating whether or not a scrubber is installed for utility $i$, where $z_i=1$ indicates a scrubber and $z_i=0$ indicates no scrubber. The cost of a scrubber is $P_{iz}$. This cost can be thought of as the operation and maintenance costs of the scrubber plus the cost from depreciation and use of capital.\(^1\)

Let $r_i$ be the sulfur removal efficiency of the scrubber at utility $i$. Depending on the

\(^1\)It may be desirable to add another technology parameter that affects generator efficiency if a scrubber is installed; however, omission of this does not affect the general results.
vintage and type, scrubbers can remove 25-99 percent of SO$_2$ from the exhaust stream.$^2$

$V_i$ is the inverse of the heat rate capability of generating unit $i$ in kWh/MMBTU. This can be considered a measure of generating unit efficiency and describes the technology for turning coal into electricity.

$D_i$ is the demand for electricity generated by utility $i$ measured in kWh. I assume that the demand for electricity remains fixed.$^3$

### 3.1.2 Coal

It is assumed utilities have only two different types of coal from which they choose to generate electricity. $^4$ Each coal type delivered to each utility differs by heat content, sulfur content, and price. Let $f$ denote coal types. Then, $f \in \{h, l\}$, where $h$ denotes high sulfur content and $l$ denotes low sulfur content. Hence, $C_{if}$ is the amount of coal type $f$ used at firm $i$, measured in tons; $H_{if}$ is the heat content of coal $f$ in MMBTU/ton delivered to utility $i$, and $S_{if}$ is the sulfur content of coal $f$ as a percentage by weight of coal delivered to utility $i$, where $S_{if} \in [0,1]$. $P_{if}$ is the delivered price per ton of coal type $f$. Coal can differ by mine location, delivery distance, sulfur content, and heat content and the delivered price $P_{if}$ already accounts for these differences. An additional assumption on coal is that the price per unit of heat for high sulfur coal is lower than the price per unit of heat for low sulfur coal. That is, $\frac{P_{ih}}{H_{ih}} < \frac{P_{il}}{H_{il}}$. $^5$

The transformation of sulfur to SO$_2$ through the combustion of coal is described by the constant $m$. The simulation model takes $m=1.9$ tons of SO$_2$ per ton of sulfur.$^6$

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$^2$This information can be found in 1995 Electric Power Annual, Volume II published by the Energy Information Administration.

$^3$According to Bohi and Burtraw (1992), the demand for electricity is inelastic over a wide range of prices.

$^4$Despite the fact that some Phase I units use oil or natural gas to generate electricity, the vast majority of units in Phase I are coal-fired units.

$^5$This is true in general, but there are some exceptions. This assumption is crucial in that it makes pollution reduction costly.

$^6$Coggins and Swinton (1996) cite a factor of 1.869 while Fullerton et. al. (1997) cite a number of 1.9. The Energy Information Administration uses 1.9.
Allowing the delivered price of coal and its heat and sulfur content to vary across utilities reflects the reality that utilities face. Spatially, some utilities may be located near their coal sources, while others may be far away. Hence, the farther away a utility is from its fuel source, the higher the transportation costs and the delivered price of coal, all other factors being equal. Moreover, utilities do not rely on the same sources of coal; therefore the heat and sulfur content of coal can vary for each utility. Differences in the delivered price of coal, heat content, and sulfur content are crucial since they give rise to differences in the marginal cost of abating pollution (aside from the installation of scrubbers) and so give utilities the incentive to trade allowances.

3.1.3 Allowances

Utilities in this model can choose to buy or sell allowances in the SO\textsubscript{2} market. It is useful to think of purchases or sales as the net of all the transactions that take place in a year. Hence, if net sales are greater than zero, net purchases are necessarily zero. Conversely, positive net purchases means net sales are zero. Let \( d_i \) be a dummy variable indicating whether a utility is a net buyer or a net seller. When \( d_i = 1 \), the utility is a buyer. When \( d_i = 0 \) the utility is a seller.

As described in Chapter 2, one allowance permits the holder to emit one ton of SO\textsubscript{2}. Let \( A^e_i \) denote the initial allocation (endowment) of allowances to firm \( i \) as dictated by the 1990 CAAA rules. \( A^b_i \) denotes net allowance purchases, and \( A^s_i \) denotes net...
allowances sales by utility $i$. The market price for allowances is $P_A$.

### 3.1.4 Regulatory Parameters

As stated above, the regulatory parameters represent cost share of expenditures that are determined by state PUCs.

Let $\beta_i \in [0, 1]$ be the share of allowance purchase costs borne by utility $i$. Then $1 - \beta_i$ is the share of allowance purchase costs passed on to the customers of utility $i$. Let $\alpha_i \in [0, 1]$ be the share of allowance sales kept by utility $i$. Then $1 - \alpha_i$ is the share of allowance sales that are passed on as savings to the customers of utility $i$. Let $\gamma_i \in [0, 1]$ be the share of fuel cost borne by utility $i$. Then $1 - \gamma_i$ is the portion of fuel costs passed on to customers of utility $i$. Finally, $\theta_i \in [0, 1]$ is the share of scrubber cost borne by utility $i$ if a scrubber is installed, and $1 - \theta_i$ is the portion of the scrubber cost that is passed on to customers of utility $i$.

### 3.2 Model

#### 3.2.1 A utility’s problem

In this simple model the firm chooses inputs of coal, allowances, and whether or not to install a scrubber to minimize cost over one year subject to constraints on electricity demand for the year and sulfur dioxide compliance for the year.\(^{11}\) It is assumed that all other inputs to electricity production are fixed. Electricity demand is also fixed and will not exceed the utility’s capacity during the year: hence, revenue is fixed and no capacity constraint is included. Utility $i$ solves the following problem.

\(^{10}\)If $\beta > \alpha$ then another interpretation of these two regulatory parameters could be a transaction cost, or brokerage fee charged for allowance transactions. See Stavins (1995).

\(^{11}\)For a more in-depth and rigorous examination of the model and a utility’s decision problem, see Appendix A. In this simple version of the model I do not include any legislative interventions. These could come as a constraint on coal usage, scrubber installation, or trading restrictions, as discussed in Chapter 2. For example, the content requirement constraint may look something like $cr \leq (C_h/(C_h + C_l))$, where $cr_i \in [0, 1]$ is the content requirement of coal used at a utility.
\[
\begin{align*}
\min_{z_i,d_i,A^b_i,A^s_i,C_{ih},C_{il}} & \quad \theta_i z_i P_{iz} + P_A(d_i \beta_i A^b_i - (1 - d_i) \alpha_i A^s_i) + \gamma (P_{ih} C_{ih} + P_{il} C_{il}) \\
\text{s.t.} & \quad A^c_i + d_i A^b_i - (1 - d_i) A^s_i \geq (1 - z_i r_i)(C_{ih} S_{ih} + C_{il} S_{il})m \\
& \quad (C_{ih} H_{ih} + C_{il} H_{il}) V_i \geq D_i \\
& \quad z_i \in \{0, 1\} \\
& \quad d_i A^b_i \geq 0 \\
& \quad (1 - d_i) A^s_i \geq 0 \\
& \quad d_i \in \{0, 1\}
\end{align*}
\]

The model is static (utilities have no incentive to bank allowances) so that 3.2, the constraint on emissions, binds. It is also assumed that utilities know their native load needs and wholesale power market participation with perfect foresight so that 3.3, the constraint on demand, binds as well.

The above problem for an individual utility cannot be solved by using standard linear or concave programming techniques since there are two discrete choices involved: scrubber choice and allowance choice. Moreover, to make the problem more tractable, fuel switching and blending is assumed to be costless in that there are no sunk costs.

However, given the scrubber choice, the problem can be broken up into two sub-problems: one for when a utility sells allowances, and the other for when a utility buys allowances. Each of these sub-problems is convex and can be solved by standard methods.

The net allowance position of a utility \(d_i\) is explicitly denoted since, if the PUC cost recovery rules allow for a utility to keep a greater percentage of its proceeds from

\[12\]This problem is a linear mixed integer programming problem. To solve this problem completely requires choosing the minimum of four solutions, with \(z=1, d=1\), \(z=1, d=0\), \(z=0, d=1\), and \(z=0\) and \(d=0\). This technique is known formally as the branch and bound method. See Hillier and Lieberman (1990), Chap. 13.

\[13\]As pointed out in Ellerman, et. al. (1997, 2000), there is often a fixed cost associated with fuel switching that can range anywhere from $10/kW of capacity to $75/kW of capacity. The level of cost is idiosyncratic to the generating unit and types of coal being used.
sales than from purchases ($\alpha_i > \beta_i$), the utility could simply churn the market by buying allowances and reselling immediately at a profit, though this opportunity is highly dependent on the marginal cost of abatement through coal switching. Applying cost recover rules to the net position after all trades are completed will prevent this regulatory-induced arbitrage opportunity.

Utilities participating in the allowance market can potentially have three different net allowance positions: a buyer of allowances, a seller of allowances, or neither buying nor selling. Each of these positions is dependent on the initial endowment of allowances and the respective prices and qualities of coal available. So, for each possible net allowance position, three possible combinations of coal could be used: burn all high sulfur coal, burn all low sulfur coal, or use a blend of high and low sulfur coal. With three coal use possibilities for each net allowance position, there are nine possible allowance and coal combinations that could be employed by a utility in this model.

Given the fixed demand for electricity faced by utilities, there is an upper bound on the amount of each type of coal used, and hence upper and lower bounds on the amount of $\text{SO}_2$ that can be emitted. Let the upper bound on high sulfur coal usage be defined as

$$C_{ih}^{\text{max}} = \frac{D_i}{H_{ih}V_i},$$

and the upper bound on low sulfur coal usage be defined as

$$C_{il}^{\text{max}} = \frac{D_i}{H_{il}V_i}.$$  

(3.9)

So the upper bound on emissions, when using all high sulfur coal, is

$$\text{SO}_{2i}^{\text{max}} = C_{ih}^{\text{max}} S_{ih} (1 - z_ir_i)m,$$

(3.10)

and the lower bound on emissions, when using all low sulfur coal is

$$\text{SO}_{2i}^{\text{min}} = C_{il}^{\text{max}} S_{il} (1 - z_ir_i)m.$$  

(3.11)
3.2.2 Characterization of a Utility’s Choices

For each of the sub-problems, let $\lambda_{i1}$ be the Lagrange multiplier on the emissions constraint (3.2), and $\lambda_{i2}$ be the Lagrange multiplier on the electricity demand constraint (3.3).\footnote{The case where the utility is neither a net buyer or net seller is treated below in this subsection.}

Net Buyer Sub-Problem

With the scrubber choice given, and assuming the decision variable $d_i = 1$ if it is a net buyer, the first-order necessary conditions for the utility’s problem are

$$PA\beta_i - \lambda_{i1} \geq 0, \quad = 0 \text{ if } A_i^b > 0 \quad (3.12)$$

$$\gamma_i P_{ih} + (1 - z_i)S_{ih}m\lambda_{i1} - \lambda_{i2}H_{ih}V_i \geq 0, \quad = 0 \text{ if } C_{ih} > 0 \quad (3.13)$$

$$\gamma_i P_{il} + (1 - z_i)S_{il}m\lambda_{i1} - \lambda_{i2}H_{il}V_i \geq 0, \quad = 0 \text{ if } C_{il} > 0 \quad (3.14)$$

Net Seller Sub-Problem

With the scrubber choice given and assuming the decision variable $d_i = 0$ if it is a net seller, the first order necessary conditions for the utility’s problem are

$$-PA\alpha_i + \lambda_{i1} \geq 0, \quad = 0 \text{ if } A_i^s > 0 \quad (3.15)$$

$$\gamma_i P_{ih} + (1 - z_i)S_{ih}m\lambda_{i1} - \lambda_{i2}H_{ih}V_i \geq 0, \quad = 0 \text{ if } C_{ih} > 0 \quad (3.16)$$

$$\gamma_i P_{il} + (1 - z_i)S_{il}m\lambda_{i1} - \lambda_{i2}H_{il}V_i \geq 0, \quad = 0 \text{ if } C_{il} > 0 \quad (3.17)$$

Similarities Between the Sub- Problems

The two sub-problems are linked through the choice of coal types to be used, and this linkage is important in determining whether the utility will be a net buyer, net seller, or a non-trader in the allowance market. Additionally, the multipliers from the first-order necessary conditions have two important interpretations. $\lambda_{i1}$ is the shadow
price of SO\textsubscript{2} allowances for the utility, given recovery factors and allowance position. \(\lambda_{i2}\) can be interpreted as the shadow price (marginal cost) of coal type \(f\) used by the utility per kWh of electricity produced, which includes the cost of pollution. \(\frac{\gamma_i P_i}{H_i V_i}\) is the portion associated with generation and \(\frac{(1-z_i r_i)S_{ih} m\lambda_{i1}}{H_i V_i}\) is the portion associated with sulfur dioxide emissions.

So, from 3.13 and 3.14 in the buying sub-problem and likewise from 3.16 and 3.17 in the selling sub-problem, a utility’s marginal costs of using high and low sulfur coal, respectively, are,

\[
\frac{\gamma_i P_{ih} + (1 - z_i r_i)S_{ih} m\lambda_{i1}}{H_{ih} V_i}, \quad (3.18) \\
\frac{\gamma_i P_{il} + (1 - z_i r_i)S_{il} m\lambda_{i1}}{H_{il} V_i}. \quad (3.19)
\]

Given the linear specification of electricity production, if 3.18 is greater than 3.19, then the utility will use all low sulfur coal to generate electricity. If 3.18 is less than 3.19, it will continue to use high sulfur coal to generate electricity, and if they are equal, the utility is indifferent between using high or low sulfur coal and could either use all of one type or another or blend the two types.

By rearranging 3.18 and 3.19 and solving for \(\lambda_{i1}\) we can learn how the allowance price will affect the utility’s decision on allowance purchases. \(\lambda_{i1}\) is less than, greater than, or equal to:

\[
\frac{\gamma_i (P_{il}/H_{il} - P_{ih}/H_{ih})}{(1 - z_i r_i)m(S_{ih}/H_{ih} - S_{il}/H_{il})} = MCA_i \quad (3.20)
\]

according to whether 3.18 is less than, greater than, or equal to 3.19. Equation 3.20 is the marginal cost of abating SO\textsubscript{2} emissions by switching from high to low sulfur coal. The magnitude of the marginal cost of abatement in 3.20 relative to the utility’s shadow price of allowances (both buying and selling) will, along with the initial allowance endowment, determine the net allowance position the utility takes, the amount of allowances bought or sold, and its choices of coal types to use in order to satisfy demand and meet its emissions constraint.
Utility as a Net Buyer

If the utility is a net buyer of allowances, then necessarily it must be the case that $A^b_i = 0$. To ensure that there is no incentive for the utility to sell, it must be the case that $MCA_i \geq \alpha_i P_A$, the shadow price of allowances when a net seller. The shadow price of allowances for the buyer is $\lambda_{1i} = \beta_i P_A$. Finally, the utility must at least be in need of allowances to meet its emissions constraint if it uses all high sulfur coal so that $A^c_i < SO^{max}_{2i}$. As a net buyer of allowances, there are three different allowance and coal combinations that the utility could take:

Case 1b: $A^b_i > 0, C_{ih} > 0, C_{il} = 0$,
Case 2b: $A^b_i > 0, C_{ih} = 0, C_{il} > 0$,
Case 3b: $A^b_i > 0, C_{ih} > 0, C_{il} > 0$.

Case 1b is perhaps the most intuitive of the buying scenarios. The utility chooses to continue using high sulfur coal exclusively and buys allowances. In this scenario it must necessarily be the case that $\beta_i P_A < MCA_i$; that is, the cost of abating emissions through coal switching is greater than the effective cost of an allowance.

Case 2b seems counterintuitive but is possible. Suppose that the environmental authority has not given the utility enough allowances to cover its emissions even if it switched completely to low sulfur coal. This implies a restriction on the allowance endowment of $A^c_i < SO^{min}_{2i}$. Moreover, to induce the utility to switch completely to low sulfur coal, it must be the case that $\beta_i P_A > MCA_i$; that is, the cost of abating emissions through switching to low sulfur coal is less than purchasing allowances. So the utility seeks to minimize its allowance purchases.

Case 3b is a knife-edge scenario for a buying utility. In order be able to use a combination of high and low sulfur coal, it must be the case that the utility is indifferent between buying allowances and fuel switching, or that $\beta_i P_A = MCA_i$.$^{15}$

$^{15}$Since the utility is indifferent between buying and switching, it is possible that $\beta_i P_A = MCA_i$ could also lead to the outcome in Case 1b, or the outcome in Case 2b if $A^c_i < SO^{min}_{2i}$. 

30
Utility as a Net Seller

If the utility is a net seller of allowances, then necessarily it must be the case that $A^s_i = 0$. To ensure that there is no incentive for the utility to buy allowances it must be the case that $MCA_i \leq \beta_i P_A$, the shadow price of allowances when a net buyer. The shadow price of allowances for the seller is $\lambda_{i1} = \alpha_i P_A$. Finally, the utility must at least be able to sell allowances if it switches completely to low sulfur coal so that $A^e_i > SO_{2i}^{min}$. Just as for net buyers, a net seller of allowances has three different allowance and coal combinations that could be chosen:

Case 1s: $A^s_i > 0, C_{ih} > 0, C_{il} = 0$,
Case 2s: $A^s_i > 0, C_{ih} = 0, C_{il} > 0$,
Case 3s: $A^s_i > 0, C_{ih} > 0, C_{il} > 0$.

Case 1s, like Case 2b, is slightly counterintuitive. The utility chooses to continue using high sulfur coal exclusively and is still able to sell allowances. For this to happen, the utility must have been given allowances greater than its maximum emissions level, $A^e_i > SO_{2i}^{max}$. Moreover, in this scenario it must necessarily be the case that $\alpha_i P_A < MCA_i$; that is, the cost of abating emissions through coal switching is greater than the effective revenue gained from selling an allowance, so there is no incentive to switch to low sulfur coal to sell additional allowances.

Case 2s is the most likely scenario for a net seller. The utility, after completely switching to low sulfur coal, has allowances to sell. For this to occur, it must be the case that $\alpha_i P_A > MCA_i$, indicating that the utility earns a profit from selling the excess allowances for each ton of pollution abated.

Case 3s, like Case 3b is a knife-edge scenario. To use a combination of high and low sulfur coal, the utility must be indifferent between selling allowances and fuel switching, $\alpha_i P_A = MCA_i$.\(^{16}\)

\(^{16}\)Since the utility is indifferent between selling and switching, it is possible that $\alpha_i P_A = MCA_i$ could also lead to the outcome in Case 2s, or the outcome in Case 1s if $A^e_i > SO_{2i}^{max}$. 

31
Utility Neither Buys Nor Sells Allowances

When would a utility choose to neither buy nor sell allowances ($A^b_i = 0$ and $A^s_i = 0$)? This could occur if the revenue generated from allowance sales is less than or equal to the cost of reducing emission by fuel switching, and the cost of buying allowances is greater than or equal to the cost of reducing emissions by fuel switching. That is,

$$\beta_i P_A \geq MCA_i \geq \alpha_i P_A.$$  

In addition to this restriction, the utility must have enough allowances to cover its emissions without trading $SO_{2i}^{\min} \leq A^e_i \leq SO_{2i}^{\max}$. So it simply comes down to choosing the amounts of high and low sulfur coal to generate electricity and meet the emissions constraint. Just as was the case for net buyers and sellers, there are three cases to examine:

Case 1n: $C_{ih} > 0, C_{il} = 0,$

Case 2n: $C_{ih} = 0, C_{il} > 0,$

Case 3n: $C_{ih} > 0, C_{il} > 0.$

Cases 1n and 2n are very specific cases that are dependent on the initial endowment of allowances. For a utility to use only high sulfur coal, and not buy or sell, as in Case 1n, the endowment of allowances must satisfy $A^e_i = SO_{2i}^{\max}$. For a utility to use only low sulfur coal and not buy or sell, as in Case 2n, the endowment of allowances must be $A^e_i = SO_{2i}^{\min}$. For a utility to use both high and low sulfur coal (Case 3n), the endowment of allowances must be $SO_{2i}^{\min} < A^e_i < SO_{2i}^{\max}$ in addition to the restriction on $MCA_i$.

Concurrent Incentives to Buy and Sell

The three previous sections outline conditions for a utility to be a net buyer or net seller. Restrictions on how the marginal cost of abatement relates to the effective buying and selling prices of allowances and allowance endowments so that there would be coinciding
incentives to buy and sell allowances at the same time. What will a utility do if the cost recovery parameters, concurrent with a utility’s marginal abatement cost and some set of allowance prices, provide the incentive to both buy and sell allowances, that is, $P_{A\alpha} > MCA_i > P_{A\beta}$? One thing it might do is buy as many allowances as it can and turn around and sell them. An arbitrage opportunity is available since the effective purchase price is below the effective sale price. However, that has been ruled out in this model by requiring cost recovery parameters to be applied only to the net buy/sell position. No problems will arise if the utility has an endowment of allowances greater than the upper bound on emissions, which constrains it to be a net seller, or an endowment below the lower bound on emissions, which constrains it to be a net buyer.

However, a problem might arise if the following two conditions coincide. It might be the case that, first, at a given allowance price, a utility might want to both buy allowances, and use all high sulfur coal, or second, want to switch to low sulfur coal and sell allowances at the same time ($P_{A\alpha} > MCA_i > P_{A\beta}$) when its allowance endowment is between the upper and lower bound on emissions, $SO^{min}_{2i} < A^e_i < SO^{max}_{2i}$.\textsuperscript{17}

As it turns out, there exists a price $\Pi^*_A \in (MCA_i/\alpha_i, MCA_i/\beta_i)$ such that, at $\Pi^*_A$, the utility is indifferent between buying allowances and using high sulfur coal, or selling allowances and using low sulfur coal. For $P_A > \Pi^*_A$, the utility will sell allowances and use only low sulfur coal. That is, as $MCA_i$ approaches the effective buying price $P_A/\beta$, the margin from switching to low sulfur coal and selling allowances becomes greater. Similarly, for $P_A < \Pi^*_A$, the utility will buy allowances and use only high sulfur coal. If $P_A = \Pi^*_A$ the utility is indifferent between these two options.

**Scrubber Installation**

The utility’s choice of whether to install a scrubber introduces a non-convexity into the utility’s problem. One way to characterize this scrubber decision is to take a branch and bound integer programming approach. Suppose the utility solves its cost minimization

\textsuperscript{17}It will never be cost minimizing for a utility in this situation to blend coals and sell or buy fewer allowances. See Appendix A, Section A.5, for a more technical explanation.
problem twice: once with a scrubber installed and once without a scrubber installed. The utility will choose to install a scrubber if the total cost with the scrubber is less than or equal to the total cost with no scrubber installed. That is, letting a hat denote cost minimizing-choices when no scrubber is installed and a prime denote cost-minimizing choices with a scrubber installed,

\[
\theta_i P_i + P_A(\beta_i A_i^b - \alpha_i A_i^s) + \gamma(P_{ih} C_{ih} + P_{il} C_{il}') \leq P_A(\beta_i \hat{A}_i^b - \alpha_i \hat{A}_i^s) + \gamma(P_{ih} \hat{C}_{ih} + P_{il} \hat{C}_{il}).
\]

Restating the above equation to isolate the cost of the scrubber borne by the utility on the left hand side yields

\[
\theta_i P_i \leq P_A(\beta_i(\hat{A}_i^b - A_i^b) - \alpha_i(\hat{A}_i^s - A_i^s)) + \gamma(P_{ih}(\hat{C}_{ih} - C_{ih}') + P_{il}(\hat{C}_{il} - C_{il}')). (3.21)
\]

Equation 3.21 says choose to install a scrubber if the cost is more than offset by reduced allowance purchases plus increased allowance revenues plus the difference in coal expenditures. Certainly this decision will be influenced by the cost share \( \theta \) on scrubber cost recovery.

Equation 3.21 can be rearranged to get an expression for allowance prices at which the utility will install a scrubber:

\[
P_A \geq \frac{\theta_i P_i - \gamma(P_{ih}(\hat{C}_{ih} - C_{ih}') + P_{il}(\hat{C}_{il} - C_{il}'))}{\beta_i(\hat{A}_i^b - A_i^b) - \alpha_i(\hat{A}_i^s - A_i^s)}. (3.22)
\]

A scrubber will certainly have a great impact on the utility’s allowance and coal choices once installed. A scrubber increases the marginal cost of abatement through coal switching by a factor of \( 1/(1 - r_i) \), as can be seen from the marginal cost of abatement equation. Without a scrubber, the marginal cost of abatement is

\[
\frac{\gamma_i(P_{il}/H_{il} - P_{ih}/H_{ih})}{m(S_{ih}/H_{ih} - S_{il}/H_{il})}, (3.23)
\]

while with a scrubber the marginal cost of abatement is

\[
\frac{\gamma_i(P_{il}/H_{il} - P_{ih}/H_{ih})}{(1 - z_i r_i)m(S_{ih}/H_{ih} - S_{il}/H_{il})}. (3.24)
\]
So installing a scrubber increases the likelihood that a utility will use high sulfur coal since the amount of abatement from coal switching is diminished by a factor of $1/(1 - r_i)$. Moreover, scrubber installation also implies that the maximum level of emissions is reduced by $1/(1 - r_i)$ so that the utility, despite using high sulfur coal, will likely be a net seller of allowances unless its allowance endowment is quite small.

### 3.3 Allowance Market

The propositions and theorems proven in Appendix A not only characterize the solution for a utility but also yield firm demands and supplies of allowances. With this information we can construct the demands and supplies for the allowance market and define the equilibrium for this market.

#### 3.3.1 Utility Demand For Allowances

A utility’s demand for allowances is dependent not only on the price of allowances, $P_A$, but also on the initial endowment, $A_e$, and the other parameters of the model as well. The demand can be expressed in the following form.

$$A^b_i(P_A, A_e, \beta_i, P_{il}, P_{ih}, S_{ih}, S_{il}, \gamma_i, z_i, r, V_i, D_i). \quad (3.25)$$

To ease notational clutter, let $MCA_i = \frac{\gamma_i(P_{il}/H_{il} - P_{ih}/H_{ih})}{(1 - z_i r_i) m(S_{ih}/H_{ih} - S_{il}/H_{il})}$. $MCA_i$ is the marginal cost to utility $i$ of reducing emissions by switching from high to low sulfur coal.\(^{18}\)

The demand can take three forms according to the initial endowment of allowances and values of $\alpha$ and $\beta$. When $A^e_i < SO_{2i}^{min}$ and for all values of $\alpha$ and $\beta$,

$$A^b_i = \begin{cases} 
SO_{2i}^{min} - A^e_i & \text{if } \beta_i P_A > MCA_i \\
\rho SO_{2i}^{max} + (1 - \rho) SO_{2i}^{min} - A^e_i & \text{if } \beta_i P_A = MCA_i, \forall \rho \in [0, 1] \\
SO_{2i}^{max} - A^e_i & \text{if } \beta_i P_A < MCA_i
\end{cases} \quad (3.26)$$

\(^{18}\)If $\gamma_i = 0$, then $MCA_i = 0$. In this case the demands and supplies are simplified.
Figure 3.1: Demand when $A^e < SO_{2}^{min}$

3.26 follows from Proposition A.1 in Appendix A. The graph of this demand is an upper semicontinuous correspondence that is is vertical for $\beta_i P_A \neq MCA_i$, and horizontal for $\beta_i P_A = MCA_i$. See Figure 3.1.

The second case for the demand is when $SO_{2i}^{min} \leq A_{i}^{e} \leq SO_{2i}^{max}$, and for $\beta \geq \alpha$. It has the following form.

$$A_{i}^{b} = \begin{cases} 
0 & \text{if } \beta_i P_A > MCA_i > \alpha P_A \\
\rho(SO_{2i}^{max} - A_{i}^{e}) & \text{if } \beta_i P_A = MCA_i > \alpha P_A, \forall \rho \in [0, 1] \\
SO_{2i}^{max} - A_{i}^{e} & \text{if } \beta_i P_A < MCA_i \text{ and } MCA_i \geq \alpha P_A 
\end{cases} \quad (3.27)$$

3.27 (a) comes from Propositions A.7, A.8, and A.9 in Appendix A. 3.27 (b) comes from Propositions A.3 in Appendix A. 3.27 (c) comes from Propositions A.2 in Appendix A.
The graph of this demand is an upper semicontinuous correspondence which is vertical for $\beta_i P_A \neq MCA_i$ and horizontal for $\beta_i P_A = MCA_i$, see Figure 3.2.

The last case for the demand is when $SO_{2i}^{\min} < A_i^e < SO_{2i}^{\max}$ and for $MCA \in [\beta P_A, \alpha P_A]$. It has the following form.

$$A^b = \begin{cases} 
SO_{2i}^{\max} - A^e & \text{if } P_A \leq \Pi_A^* \\
0 & \text{if } P_A \geq \Pi_A^*
\end{cases} \quad (3.28)$$

$$\Pi_A^* = \frac{\gamma (P_lC_l^{\max} - P_hC_h^{\max})}{\beta (SO_{2i}^{\max} - A^e) + \alpha (A^e - SO_{2i}^{\min})}$$
Figure 3.3: Demand when $SO_{2}^{\min} < A^e < SO_{2}^{\max}$ and $\alpha P_A > MCA > \beta P_A$

3.28 follows from Propositions A.2 and A.10, Theorem A.1 and Corollaries A.1 and A.2 in Appendix A. This demand is upper semicontinuous at $\Pi_{A}^*$, but is not convex-valued at $\Pi_{A}^*$. The demand makes a discrete jump at this price (see Figure 3.3).

The market demand for allowances is simply the sum of all the firm demands at each price.

### 3.3.2 Utility Supply Of Allowances

Much like a utility’s demand for allowances, the supply of allowances is sensitive not only to the price of allowances, $P_A$, but also to the initial endowment, $A^e$, and other
parameters of the model. The supply can be expressed in the following form.

\[ A^s_i(P_A, A^e_i, \beta_i, P_h, P_l, S_{ih}, S_{il}, \gamma_i, z_i, r, V_i, D_i) \]  
(3.29)

The supply can take three forms based on the initial endowment of allowances and values of \( \alpha \) and \( \beta \). When \( A^e_i > SO^{\text{max}}_{2i} \) and for all values of \( \alpha \), \( \beta \), and \( \forall \rho \in [0, 1] \),

\[
A^s_i = \begin{cases} 
A^e_i - SO^{\text{max}}_{2i} & \text{if } \alpha_i P_A < MCA_i \\
A^e_i - [\rho SO^{\text{max}}_{2i} + (1 - \rho)SO^{\text{min}}_{2i}] & \text{if } \alpha_i P_A = MCA_i \\
A^e_i - SO^{\text{min}}_{2i} & \text{if } \alpha_i P_A > MCA_i 
\end{cases}
\]  
(3.30)

3.30 follows from Proposition A.4 in Appendix A. The graph of this supply is an upper semicontinuous correspondence that is vertical for \( \alpha_i P_A \neq MCA_i \) and flat for \( \alpha_i P_A = MCA_i \) (see Figure 3.4).

The second case for the supply is when \( SO^{\text{min}}_{2i} \leq A^e_i \leq SO^{\text{max}}_{2i} \) and for \( \beta \geq \alpha \). It has the following form.

\[
A^s_i = \begin{cases} 
0 & \text{if } \alpha_i P_A < MCA_i < \beta_i P_A \\
\rho (A^e_i - SO^{\text{min}}_{2i}) & \text{if } \alpha_i P_A = MCA_i < \beta_i P_A, \forall \rho \in [0, 1] \\
A^e_i - SO^{\text{min}}_{2i} & \text{if } \alpha_i P_A > MCA_i \text{ and } MCA \leq \beta_i P_A 
\end{cases}
\]  
(3.31)

3.31 (a) comes from Propositions A.6, A.7, A.8, A.9 in Appendix A. 3.31 (b) comes from Proposition A.6 in Appendix A. 3.31 (a) comes from Proposition A.5 in Appendix A. The graph of this supply is an upper semicontinuous correspondence that is vertical for \( \beta_i P_A \neq MCA_i \) and flat for \( \beta_i P_A = MCA_i \) (see Figure 3.5).

The last case for the supply is when \( SO^{\text{min}}_{2i} < A^e_i < SO^{\text{max}}_{2i} \) and for \( MCA \in [\beta P_A, \alpha P_A] \). It has the following form.

\[
A^s = \begin{cases} 
0 & \text{if } P_A \leq \Pi^*_A \\
A^e - SO^{\text{min}}_{2i} & \text{if } P_A \geq \Pi^*_A 
\end{cases}
\]  
(3.32)
Figure 3.4: Supply when $A^e > SO_2^{max}$
Figure 3.5: Supply when $SO_2^{\text{min}} < A_e < SO_2^{\text{max}}$

Price of Allowances

Quantity of Allowances

$A_e - SO_2^{\text{min}}$

$MCA_0$
Figure 3.6: Supply when $SO_2^{min} < A^e < SO_2^{max}$ and $\alpha P_A > MCA > \beta P_A$

\[
\Pi_A^* = \frac{\gamma (P_1 C_l^{max} - P_h C_h^{max})}{\beta (SO_2^{max} - A^e) + \alpha (A^e - SO_2^{min})}
\]

3.32 follows from Propositions A.5 and A.10, Theorem A.1, and Corollaries A.1 and A.2 in Appendix A. Much like the demand in this case, the supply is upper semicontinuous at $\Pi_A^*$ but is not convex-valued at $\Pi_A^*$. Note the discrete jump (see Figure 3.6).

The market supply for allowances is simply the sum of all the firm supplies at each price,
3.3.3 Equilibrium

In the allowance market it is assumed that there is perfect information and that all firms are price takers in the market. I start by defining an equilibrium for this market.

**Definition 3.1** An equilibrium for the SO$_2$ allowance market is a price $P_A^* \geq 0$, and allowance purchases $A_{i}^{bs} \geq 0$, allowance sales $A_{i}^{ss} \geq 0$, and other input choices $z_{i}^{*} \in \{0, 1\}$, $d_{i}^{*} \in \{0, 1\}$, $C_{ih}^{*} \geq 0$, $C_{il}^{*} \geq 0$ such that:

1) For each $i$, $A_{i}^{bs}$, $A_{i}^{ss}$, $d_{i}^{*}$, $z_{i}^{*}$, $C_{ih}^{*}$, and $C_{il}^{*}$ solve

\[
\min_{z_i, d_i, A_i^{bs}, A_i^{ss}, C_{ih}, C_{il}} \theta z_i P_z + P_A^* (d_i \beta_i A_i^b - \alpha_i (1 - d_i) A_i^s) + \gamma (P_{ih} C_{ih} + P_{il} C_{il})
\]

s.t. $(1 - z_ir_i)(C_{ih} S_{ih} + C_{il} S_{il}) m \leq A_i^e + d_i A_i^b - (1 - d_i) A_i^s$

\[
D_i \leq (C_{ih} H_{ih} + C_{il} H_{il}) V_i
\]

$z_i \in \{0, 1\}, \forall i = 1...I$

$d_i \in \{0, 1\}, \forall i = 1...I.$

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

\[
\sum_{i=1}^{I} A_{i}^{bs} - A_{i}^{ss} \leq 0 \quad \text{and} \quad P_A^* (\sum_{i=1}^{I} A_{i}^{bs} - A_{i}^{ss}) = 0.
\]

**Theorem 3.1** Take all scrubbers as given. If there does not exist a utility $j$ such that $\alpha_j > \beta_j$ and $SO_{2i}^{min} < A_j^e < SO_{2i}^{max}$, then an equilibrium exists for the SO$_2$ allowance market.

**Proof of Theorem 3.1**

In short, the demand and supply correspondences are upper semicontinuous, compact-valued, and convex-valued for any utility $i$ that has $\beta_i \geq \alpha_i$, and so is the sum of those correspondences. Given this, existence follows from Debreu (1959) and Kakutani’s Fixed Point Theorem. For the formal proof see Appendix B.\(^{19}\)

\(^{19}\)It is quite possible that the market equilibrium is not unique.
The existence proof simply says that if one utility has \( \alpha_j > \beta_j \) and \( SO_{2i}^{\min} < A_j^e < SO_{2i}^{\max} \), an equilibrium is not guaranteed. It does not say that an equilibrium will not exist.\(^{20}\) The same is true if scrubber choices are allowed. An equilibrium cannot be guaranteed, but may very well exist. The problems of such non-convexities such may well be diminished as the number of utilities becomes large.\(^{21}\)

With potential non-convexities arising from the regulatory data, Theorem 3.1 does indicate a possible problem in taking the model to the data, even if scrubber choices are ignored. Fortunately, Bailey (1998) and Lile and Burtraw (1998) outline many of the regulatory rules and guidelines passed down to utilities in Phase I, and none of these indicates that any state gives utilities favorable treatment in both buying and selling allowances. In fact, it seems that state PUCs treat allowance purchases and sales the same so that at least \( \alpha \leq \beta \) for these utilities.

Still, in the restricted context of this model, the existence theorem has an interesting implication for regulators who might have a bias toward favoring utilities over customers in both the sales and purchases of allowances. In attempting to reduce costs borne by the utility, a regulator may in fact drive up the utility’s costs if it cannot find buyers for its allowances, or sellers from whom it can buy allowances, thereby introducing or increasing transactions costs.\(^{22}\).

### 3.3.4 Comparative Statics

Recall that the marginal cost of abating \( SO_2 \) emissions by switching from high to low sulfur coal is

\[
\frac{\gamma_i(P_d/H_d - P_{ih}/H_{ih})}{(1 - z_i r_i)m(S_{ih}/H_{ih} - S_{il}/H_{il})} = MCA_i.
\]

Clearly, changes in the parameters of \( MCA \) along with other regulatory parameters will impact the market price of allowances.

\(^{20}\) An equilibrium cannot be guaranteed in this case since the demand and supply correspondences for any utility \( j \) with these characteristics are not convex valued.

\(^{21}\) See Arrow and Hahn (1971 Chap. 7).

\(^{22}\) See Stavins (1995) for a discussion of the impacts of transactions costs on pollution markets.
Proposition 3.1 The market price of allowances, $P_A$, is directly related to the price differential between low and high sulfur coal $(P_l - P_{ih})$. That is, if for some $i$, $(P_l - P_{ih})$ increases, $P_A$ is weakly increasing, or as $(P_l - P_{ih})$ decreases, $P_A$ is weakly decreasing. Moreover, as the fuel cost share for any utility $i$ increases (decreases), the price of allowances, $P_A$ is weakly increasing (decreasing).

Proof of Proposition 3.1 See Appendix B.

What is the intuitive reason behind Proposition 3.1? If $(P_l - P_{ih})$ or $\gamma_i$ increases, the marginal cost of reducing emissions from coal switching increases. This will make it more likely that the utility will want to buy allowances at a given price to meet its emissions constraint since it becomes relatively less expensive to do so. In turn, this will drive up the market demand for allowances and so drive up the price. If a utility was a seller of allowances, the increase in the cost of coal switching makes it less attractive to switch coal and sell allowances to offset the additional cost. This drives down the supply, which drives up the price.

Proposition 3.2 The market price of allowances, $P_A$, is inversely related to changes in $\alpha_i$ and $\beta_i$, $\forall i$. That is, if $\alpha_i$ and/or $\beta_i$ increases (decreases) for at least one $i$, then the market price, $P_A$, is weakly decreasing (increasing).

Proof of Proposition 3.2 See Appendix B.

If $\alpha_i$ increases, then the effective price received by a utility for its allowance sales increases, which gives a utility more incentive to sell allowances. Hence the increase in supply drives the price of allowances down. If $\beta_i$ increases, then it becomes less attractive for a utility to buy allowances since its effective purchase price increases. This drives down the demand for allowance and so drives down the price.
3.4 SO₂ Compliance Costs

Potentially, a utility can incur costs in complying with its emissions constraint over three dimensions. The first is the cost of a scrubber if one is installed. The cost of scrubbers not only includes capital costs, but also operation and maintenance costs. The second is the cost or revenue generated by allowance transactions. The third is the cost associated with switching from high to low sulfur coal. This is costly in this context in the sense that the price per unit of heat for low sulfur coal is higher than that of high sulfur coal. Hence, even though emissions are reduced by using low sulfur coal, the cost of electricity generation has increased. Therefore, the compliance cost associated with coal switching or blending is the sum of the cost of coal input to meet demand and emissions compliance minus the cost to generate electricity when there are no constraints on emissions and only high sulfur coal can be used exclusively. Below are definitions of compliance cost associated with a utility’s behavior and the associated shares of those cost components that are split between a utility and its customers, as determined by the PUC.

Definition 3.2 (a) The total compliance cost associated with the activities of utility $i$, given the equilibrium price of allowances $P_A^e \geq 0$, along with cost-minimizing combinations of allowance purchases and sales ($A^{bs}_i \geq 0$ and $A^{ss}_i \geq 0$) and other input choices ($z^*_i \in \{0, 1\}$, $C_{th}^e \geq 0$, $C_{il}^e \geq 0$) is:

$$P z^*_i + P_A^e (A^{bs}_i - A^{ss}_i) + (P_{th} C_{th}^e + P_{il} C_{il}^e - P_{th} C_{th}^{max}).$$ (3.33)

(b) The share of compliance costs for utility $i$, given the equilibrium price of allowances $P_A^e \geq 0$, along with cost-minimizing combinations of allowance purchases and sales ($A^{bs}_i \geq 0$ and $A^{ss}_i \geq 0$) and other input choices ($z^*_i \in \{0, 1\}$, $C_{th}^e \geq 0$, $C_{il}^e \geq 0$) is:

$$\theta_i P z^*_i + P_A^e (\beta_i A^{bs}_i - \alpha_i A^{ss}_i) + \gamma_i (P_{th} C_{th}^e + P_{il} C_{il}^e - P_{th} C_{th}^{max}).$$ (3.34)
The share of compliance cost for customers of utility $i$, given the equilibrium price of allowances $P_A^* \geq 0$, along with cost-minimizing combinations of allowance purchases and sales ($A_{ib}^* \geq 0$ and $A_{is}^* \geq 0$) and other input choices ($z_i^* \in \{0, 1\}$, $C_{ih}^* \geq 0$, $C_{il}^* \geq 0$) is:

$$
(1 - \theta_i) P_z z_i^* + P_A^* ((1 - \beta_i) A_{ib}^* - (1 - \alpha_i) A_{is}^*)
+ (1 - \gamma_i) (P_{ih} C_{ih}^* + P_{il} C_{il}^* - P_{ih} C_{ih}^{\text{max}}).
$$

The first term gives the scrubber expenditure, the second term gives the allowance expenditure (or revenue), and the third term gives the difference in cost for generating electricity when using any combination of high and low sulfur coal, versus using only high sulfur coal to generate electricity.

The total industry compliance cost is the sum of the total compliance costs for each utility as defined in Definition 3.2 (a). Since the purchases and sales of allowances cancel each other out in the aggregate, the industry-wide compliance cost will simply be the cost of scrubbers if installed and the cost of using combinations of low and high sulfur coal to satisfy the emissions constraints.

**Definition 3.3** The total industry compliance cost, given the equilibrium price of allowances $P_A^* \geq 0$, and cost minimizing combinations of allowance purchases and sales for all $i$ ($A_{ib}^* \geq 0$ and $A_{is}^* \geq 0$), as well as other input choices for all $i$ ($z_i^* \in \{0, 1\}$, $C_{ih}^* \geq 0$, $C_{il}^* \geq 0$) is:

$$
\sum_{i=1}^{I} \theta_i z_i P_z + (P_{ih} C_{ih}^* + P_{il} C_{il}^* - P_{ih} C_{ih}^{\text{max}}).
$$

When contemplating the minimum industry compliance cost, it is useful to think of minimizing all costs, including scrubber costs. However, since scrubbers are a discrete choice, it will also be useful to examine a “scrubber constrained” minimum compliance cost, which allows examination with standard analytical tools.
**Definition 3.4** (a) The minimum total industry compliance cost is a set of coal inputs for each \(i\) \(\mathcal{C}_{ih}^* \geq 0, \mathcal{C}_{il}^* \geq 0\), and scrubber choice for each \(i\) \(z_i^*\) such that the set of coal inputs and scrubber choice solves the following problem.

\[
\min_{z_i, C_{ih}, C_{il}} \sum_{i=1}^{I} z_i P_{iz} + (P_{ih} C_{ih} + P_{il} C_{il} - P_{ih} C_{ih}^{max})
\]

\[
\text{s.t. } \sum_{i=1}^{I} ((1 - z_i r_i) (C_{ih} S_{ih} + C_{il} S_{il}) m \leq \sum_{i=1}^{I} A_i^e \\
D_i \leq (C_{ih} H_{ih} + C_{il} H_{il}) V_i, \forall i \\
z_i \in \{0, 1\}, \forall i
\] (3.37)

(b) The “scrubber constrained” minimum total industry compliance cost is a set of coal inputs for each \(i\) \(\mathcal{C}_{ih}^* \geq 0, \mathcal{C}_{il}^* \geq 0\), with scrubber choices as given for each \(i\) such that the set of coal inputs solves the following problem.

\[
\min_{C_{ih}, C_{il}} \sum_{i=1}^{I} z_i P_{iz} + (P_{ih} C_{ih} + P_{il} C_{il} - P_{ih} C_{ih}^{max})
\]

\[
\text{s.t. } \sum_{i=1}^{I} ((1 - z_i r_i) (C_{ih} S_{ih} + C_{il} S_{il}) m \leq \sum_{i=1}^{I} A_i^e \\
D_i \leq (C_{ih} H_{ih} + C_{il} H_{il}) V_i, \forall i
\] (3.38)

### 3.4.1 Symmetric Treatment of Options to Minimize Compliance Costs

**Theorem 3.2** Given fixed demands for electricity for all utilities \(i\), taking scrubber choices \(z_i\) as given, if for all utilities \(i\), \(\alpha_i = \beta_i = \gamma_i\), then the market in SO2 allowances achieves the “scrubber constrained” minimum total industry compliance cost.

**Proof of Theorem 3.2**: See Appendix B.
If all of the regulatory parameters are equal to 1 (there is no PUC regulation on utility economic behavior), then Theorem 3.2 is equivalent to the classic result obtained by Montgomery (1972). Moreover, if the regulatory parameters are different from 1 but are all equal, then this matches the conclusion reached by Bohi and Burtraw (1992). The result is appealing in that the presence of economic regulation by PUCs does not impair the ability of the market for SO$_2$ allowances to achieve minimization of compliance costs if PUCs treat compliance options symmetrically for each utility. This is contrary to the intuitive belief that intervention in the SO$_2$ market in the form of PUC regulation will automatically lead to deviations from least-cost solutions.

However, it is interesting to think about the contrapositive to Theorem 3.2. If the market does not achieve the minimum total industry compliance cost, then at least one of the regulatory parameters for one utility is different from all of the others. In this case, it is necessarily true that the regulatory parameters are causing the burden of emissions reduction to be shifted from utilities with low marginal costs of coal switching to utilities that have high marginal costs of coal switching.

On a cautionary note, Theorem 3.2 does not say the that if there exists at least one utility with at least one regulatory parameter not equal to the others, then the market does not achieve the minimum total industry compliance cost. The equilibrium of the allowance market, and therefore utility behavior, might not be affected by the parameter change because of the linear nature of electricity production and emissions production. So, even if the parameters of cost recovery treatment are slightly different across utilities, the allowance market may still produce a minimum cost outcome. An example of this comes in another form of symmetry in which PUC regulation will not lead to deviations from the least-cost solution in abating SO$_2$ emissions through the allowance market.

---

$^{23}$Bohi and Burtraw draw this conclusion from a model where utilities face a rate of return constraint, and come to the conclusion that symmetry minimizes costs when the rate of return is less than or equal to the cost of capital.

$^{24}$This is similar to a result shown in Cronshaw and Kruse (1996) who model utilities facing profit regulation and a dynamic emissions constraint.
3.4.2 Symmetric Treatment Across PUCs to Minimize Compliance Costs

**Theorem 3.3** Given fixed demands for electricity for all utilities $i$, taking scrubber choices $z_i$ as given, if for all utilities $i$, $\alpha_i = \beta_i$ and for all $j \neq i$ $\alpha_i = \alpha_j$, $\beta_i = \beta_j$, $\gamma_i = \gamma_j$, then the market in SO$_2$ allowances achieves the “scrubber constrained” minimum total industry compliance cost.

**Proof of Theorem 3.3**: See Appendix B.

Theorem 3.3 seems counterintuitive at first glance. It allows for asymmetric treatment of compliance options internally. However, the restriction that there be symmetry across utilities simply implies that the marginal costs of abatement are shifted by a constant and there is no change in the ordering of marginal abatement costs, thus preserving the ability of the market to achieve the minimum compliance cost. Theorem 3.3 is more restrictive than Theorem 3.2 in that, despite allowing the cost share on fuel to differ from allowance treatment so that there is asymmetric treatment of compliance options within the utility, there must be symmetry across all utilities in regulatory treatment of compliance options. Moreover, Theorem 3.3 and Theorem 3.2 highlight the importance of symmetric treatment of allowance purchases and sales.

Unfortunately, as subsequent examples indicate and as the next chapter will show, utilities across different jurisdiction do not necessarily face symmetric cost recovery rules internally, nor do PUCs impose symmetric treatment over all utilities participating in the SO$_2$ market.

3.4.3 Conditions for an Emissions Cap to Equal a Mandated Low Sulfur Coal Usage

With the conditions for minimizing compliance cost through the allowance established, I present a result regarding the quantity of low sulfur coal that will be used which will help highlight the impact of PUC regulations on the distribution of compliance costs
Theorem 3.4 Given fixed demands for electricity for all utilities $i$, taking the scrubber choice $z_i$ as given and assuming that all scrubbers have identical removal efficiencies $r_i$, for all $i$, if the sulfur and heat content of high and low sulfur coal, respectively, is identical across utilities ($S_{ih} = S_{jh}, S_{il} = S_{jl}, H_{ih} = H_{jh}, H_{il} = H_{jl}, \forall i \neq j$) then the total number of allowances allocated initially implies a fixed amount of low sulfur coal to be used industry-wide. Furthermore, if the prices of high and low sulfur coal are also identical across utilities ($P_{ih} = P_{jh}, P_{il} = P_{jl}, \forall i \neq j$) and $z_i = 0$ for all $i$, then the market in SO$_2$ allowances achieves the “scrubber constrained” minimum total industry compliance cost regardless of the values of the regulatory parameters and allowance endowments.

Proof of Theorem 3.4: See Appendix B

The key assumptions of Theorem 3.4 concern coal characteristics and the fact that demand for each utility remains fixed. If all utilities face the same price for both high and low sulfur coal and nobody has a scrubber, then all utilities face the same marginal cost of reducing emissions in the absence of PUC regulation. Regardless of what PUCs do in this case, the burden of reducing emissions cannot be shifted from a utility with a low marginal cost of emissions reduction to a utility with a high marginal cost of emissions reduction. Shifting around who uses low sulfur coal only changes the distribution of costs and the distribution of emissions across utilities, as well as between utilities and their customers.

In general, if a PUC imposes a cost recovery policy that increases cost recovery of allowance purchases $\beta$ relative to cost recovery of fuel costs $\gamma$, that PUC encourages the utility to buy allowances at a lower price, reducing the utility’s overall compliance cost while increasing its emissions. Conversely, if the PUC imposes a policy that increases the revenue recovery of allowance sales $\alpha$ relative to fuel cost recovery $\gamma$, the utility is more likely to sell allowances at a lower price, increasing compliance costs, but reducing emissions from that utility. However, if any utility decides to install a scrubber or
already has one, there would be a difference in the marginal costs of reducing emissions, and the second part of Theorem 3.4 would fail to hold. Still, even without scrubbers, if utilities face different prices for high and low sulfur coal, differential PUC regulation can lead to a departure from the minimum total industry compliance cost.

3.5 Numerical Examples

Below I present three examples, using only three hypothetical utilities, to show the potential impact of PUC regulation on the allowance market. These examples should not be taken to reflect what is happening industry-wide. The parameters for this numerical exercise have been chosen to reflect certain facts in the data, and the examples do not consider the option of choosing scrubbers, but focus solely on the potential impacts of PUC regulation on fuel choices and allowance positions.\(^{25}\)

The code for the model is written in Fortran 77. At each price chosen, each utility’s problem is solved using a linear programming solver from the IMSL Math Library. To find the equilibrium price, an initial guess is submitted, and the price is updated by a bisection iteration method until the equilibrium price is found.\(^{26}\)

The heat content, sulfur content, and price of high sulfur coal have been chosen to be representative of coal found in Ohio, Indiana, Illinois, and parts of Kentucky (USEIA, 1997c). The heat and sulfur content of the high sulfur coal translates to an emissions rate of 4.2 lbs SO\(_2\)/ MMBTU of heat for the year 1985 (USEPA, 1997). The heat content, sulfur content, and price of low sulfur coal has been chosen to be representative of coal originating in the Powder River Basin of Wyoming and Montana (USEIA, 1997c).\(^{27}\)

\(^{25}\)Allowing the utilities in this example choose scrubbers is possible computationally. Given the large capital costs of scrubber installation, it is relatively easy to conclude that favorable cost recovery treatment for scrubbers will likely lead to deviations from the minimum cost solution. But what is quite interesting is the potential for large deviations from least-cost under different cost recovery rules for fuel and allowances.

\(^{26}\)There are other potential computational issues for this model as extended in the next chapter. See Chapter 4 for a more detailed explanation.

\(^{27}\)There are low sulfur coals being used that come from parts of West Virginia, Virginia, and Kentucky.
Table 3.1: Coal Qualities for Examples

<table>
<thead>
<tr>
<th>Coal Type</th>
<th>Heat Content</th>
<th>Sulfur Content</th>
</tr>
</thead>
<tbody>
<tr>
<td>High Sulfur ($C_h$)</td>
<td>24 MMBTU/ton</td>
<td>2.65% by wt.</td>
</tr>
<tr>
<td>Low Sulfur ($C_l$)</td>
<td>17.5 MMBTU/ton</td>
<td>0.5% by wt.</td>
</tr>
</tbody>
</table>

Table 3.2: Utility Characteristics for Examples

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Utility 1</th>
<th>Utility 2</th>
<th>Utility 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Price High Sulfur $P_{th}$</td>
<td>30.0</td>
<td>35.0</td>
<td>25.0</td>
</tr>
<tr>
<td>Price Low Sulfur $P_{il}$</td>
<td>25.0</td>
<td>30.0</td>
<td>35.0</td>
</tr>
<tr>
<td>Allowance Endowment $A^e$</td>
<td>9616</td>
<td>17500</td>
<td>8929</td>
</tr>
<tr>
<td>Demand (kWh) $D$</td>
<td>$7.0 \times 10^8$</td>
<td>$1.4 \times 10^9$</td>
<td>$8.0 \times 10^8$</td>
</tr>
<tr>
<td>Heat Rate (kWh/MMBTU) $V$</td>
<td>91.0</td>
<td>100.0</td>
<td>112.0</td>
</tr>
</tbody>
</table>

The sulfur and heat contents of the coal are assumed to be the same for each utility in the following examples.

The allowance allocations (endowments) are based upon a formula similar to that used by the EPA to allocate allowances in Phase I. The allowance allocation is equal to 2.5 lbs. SO$_2$/MMBTU of heat needed to meet the demand that each utility takes as given. The demands are taken to be representative of an individual generating unit at a plant in Phase I (USEIA, 1997b and USEPA, 1997). The heat rate capabilities at each plant are representative of Phase I affected units that are relatively efficient (high, $V=112$ kWh/MMBTU), average efficiency ($V=100$ kWh/MMBTU), and below average efficiency ($V=91$ kWh/MMBTU).\textsuperscript{28} The demands, heat rates, and prices for each coal type and allowance endowments for the examples are listed below.

\textsuperscript{28}See Annual Generator Data, 1996 published by the EIA (USEIA, 1997a).
Table 3.3: Example: No PUC Regulation

<table>
<thead>
<tr>
<th>Equilibrium Allowance Price=$165.46</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quantity Traded=5,977.25</td>
</tr>
<tr>
<td>Industry Compliance Cost=3,397,474</td>
</tr>
<tr>
<td>Minimum Compliance Cost=3,397,474</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>β = 1.0</th>
<th>α = 1.0</th>
<th>γ = 1.0</th>
<th>θ = 1.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Utility 1</td>
<td>Utility 2</td>
<td>Utility 3</td>
<td>Total</td>
</tr>
<tr>
<td>A_b = 0.0</td>
<td>0.0</td>
<td>5,977.25</td>
<td>5,977.25</td>
</tr>
<tr>
<td>A_s = 5,462.15</td>
<td>515.10</td>
<td>0.0</td>
<td>5,977.25</td>
</tr>
<tr>
<td>C_h = 0.0</td>
<td>253,869</td>
<td>297,619</td>
<td>551,488</td>
</tr>
<tr>
<td>C_l = 439,560</td>
<td>451,836</td>
<td>0.0</td>
<td>891,396</td>
</tr>
<tr>
<td>SO₂ emit 4,153.85</td>
<td>16,984.90</td>
<td>14,906.25</td>
<td>36,045</td>
</tr>
</tbody>
</table>

Compliance Cost 469,835 | 1,938,619 | 989,020 | 3,397,474

3.5.1 Example 1: No PUC Regulation

In Example 1 a simulation is run without any PUC regulation. The market should identify the high-cost and low-cost reducers of emissions so that the low-cost reducers abate more pollution and high-cost reducers abate less pollution. In this example Utility 1 has a marginal cost, \( MCA_1 = $115.44 \); Utility 2 has a marginal cost, \( MCA_2 = $165.46 \); and Utility 3 has a marginal cost, \( MCA_3 = $619.53 \). From this it can be said Utilities 1 and 2 are relatively low cost reducers of emissions while Utility 3 is a high cost reducer. Example 1 shows Utilities 1 and 2 using low sulfur coal and selling allowances while Utility 3 continues to employ high sulfur coal and buys allowances.
Table 3.4: Example: Impact of PUC Regulation is Small

<table>
<thead>
<tr>
<th></th>
<th>Utility 1</th>
<th>Utility 2</th>
<th>Utility 3</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta =$</td>
<td>0.15</td>
<td>0.50</td>
<td>0.10</td>
<td></td>
</tr>
<tr>
<td>$\alpha =$</td>
<td>0.15</td>
<td>0.50</td>
<td>0.10</td>
<td></td>
</tr>
<tr>
<td>$\gamma =$</td>
<td>0.10</td>
<td>0.10</td>
<td>0.10</td>
<td></td>
</tr>
<tr>
<td>$\theta =$</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>$A^b =$</td>
<td>3,962.75</td>
<td>0.0</td>
<td>5,977.25</td>
<td>9,940</td>
</tr>
<tr>
<td>$A^s =$</td>
<td>0.0</td>
<td>9,940</td>
<td>0.0</td>
<td>9,940</td>
</tr>
<tr>
<td>$C_h =$</td>
<td>253,869</td>
<td>0.0</td>
<td>297,619</td>
<td>551,488</td>
</tr>
<tr>
<td>$C_l =$</td>
<td>91,396</td>
<td>800,000</td>
<td>0.0</td>
<td>891,396</td>
</tr>
<tr>
<td>SO$_2$ emit</td>
<td>13,578.75</td>
<td>7,560</td>
<td>14,906.25</td>
<td>36,045</td>
</tr>
<tr>
<td>Compliance Cost</td>
<td>590,587</td>
<td>2,818,350</td>
<td>460,009</td>
<td>3,868,946</td>
</tr>
</tbody>
</table>

3.5.2 Potentially Small Effect of PUC Regulations

Example 2 illustrates a regime of cost recovery rules on fuel and compliance options set by state PUCs. Utility 1 is allowed to keep 15 percent of its allowance sales, while it must bear 15 percent of allowance purchases. This situation is much like that in Connecticut. Utility 2 gets to keep 50 percent of its allowance sales while bearing 50 percent of allowance purchases. This represents a policy similar to that faced by Union Electric in Missouri. Utility 3 keeps only 10 percent of sales and bears only 10 percent of costs, much like many states. Each utility faces a cost recovery rule on fuel that allows utilities to pass on 90 percent of fuel cost, much like fuel adjustment clauses utilities face.

The first thing to notice about Example 2 is the 12 percent increase in industry

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29PUC information comes from Bailey (1998) unless otherwise indicated.
30For many states costs/sales associated with allowances are treated as fuel, and are accounted for in fuel adjustment clauses. Furthermore, it is not entirely clear that 100% of fuel costs are passed on through these clauses, so I have chosen a pass-through of 90% of costs.
compliance costs compared to Example 1. The rationale for this increase comes from the “distortions” caused by PUC regulation. In Example 2 all utilities perceive their marginal cost of emissions reduction is lower than Example 1 since they can pass on 90 percent of their fuel costs. However, what has changed is the marginal cost of emissions reduction relative to the cost of buying and selling allowances. This is true for Utilities 1 and 2. Utility 2 is willing to switch completely to low sulfur coal and sell allowances at a much lower allowance price than before. Utility 1 faces a similar situation, but cannot keep as much of its allowance sales as before. Hence, the price at which Utility 1 is willing to switch to low sulfur coal and sell allowances is higher than that price for Utility 2. In short, Utility 2 perceives itself to be a lower cost reducer of emissions than Utility 1, a result opposite to that in Example 1.\(^{31}\)

It is also worthwhile to take note of the distribution of emissions. Emissions for Utility 3 do not change from Example 1 to Example 2. However, Utility 1 emits about 9,400 more tons of SO\(_2\), and Utility 2 emits about 9,400 fewer tons of SO\(_2\) in Example 2. The change in emissions distribution could have unintended consequences. Suppose Utility 1 is located in the Midwest (Ohio, Illinois, Indiana). It is believed that emissions from this area lead to sulfur deposition in the northeastern U.S., which has been greatly affected by sulfur deposition in the past. It is conceivable that sulfur deposition problems could become worse for certain areas since the distribution of SO\(_2\) emissions is not considered under Title IV.

3.5.3 An Example of Large Impacts of PUC Regulations

Suppose that there exist some PUCs that attempt to create incentives for utilities in their jurisdiction to take a certain action. For instance, a PUC might want their utilities to reduce emissions as much as possible. In Example 3 the PUC with jurisdiction over

\(^{31}\)A simulation similar to this example was run by assuming that Utility 3 was in a deregulated state (all regulatory parameters are 1). The results of that simulation were the same as in Example 2 except for Utility 3’s share of costs. This might indicate that deregulation in only some states has little effect on the current state of affairs, but in a full-blown model with all utilities this may not be the case.
Utility 3 wants it to reduce pollution via fuel switching. Hence it allows 90 percent cost recovery on fuel and encourages allowance sales by allowing the utility to keep all of its revenues. To discourage purchasing allowances, the rules require the utility to bear all costs of purchases.

Another possibility might be that a PUC wants its utilities to reduce emissions through fuel switching alone, but does not want it to sell excess allowances on the chance that those allowances might be sold to utilities upwind. Utility 2 faces this kind of policy in Example 3. It is allowed to recover 90 percent of its fuel costs, but must pass on 90 percent of allowance sales revenue to ratepayers while bearing all costs of allowance purchases. Regulatory parameters for Utility 1 remain unchanged in Example 3.

First note that compliance costs are 263 percent greater than the minimum compliance costs. Secondly, the distribution of emissions is altered from the policy regime in Example 1. Utility 3 now perceives itself as a low-cost reducer of emissions, and Utility 1 now perceives itself as a high-cost reducer of emissions. This is just the opposite of...
the situation without PUC regulation. Therefore, the high-cost reducer of emissions is undertaking a larger portion of emissions abatement than it should, which drives up the overall compliance cost. Accordingly, the distribution of emissions shifts from Utility 3 to Utility 1. As already discussed, the change in emissions distribution can have unintended impacts on some regions. Suppose the PUC for Utility 3 had the intention of reducing emissions in formulating its recovery rules, but that Utility 3 is in an area downwind from Utilities 1 and 2. The PUC for Utility 3 has good intentions in reducing emissions at the utility it regulates, but could make sulfur deposition problems worse by shifting emissions to states upwind. And to add insult to injury, it also increases costs to consumers as Utility 3’s compliance costs have grown to almost $6.5 million versus the compliance cost in Example 2 of $460,000.

3.6 Conclusion

This chapter outlined a simple analytical model of utility compliance and participation in the SO$_2$ market. The model yields analytical characterizations of utility decisions, as well as the market in SO$_2$ allowances. Conditions under which an equilibrium exists have been established as well as conditions under which the market in SO$_2$ allowances will lead to the minimum industry compliance cost in the presence of PUC regulation. Finally, a characterization of the impacts of PUC cost recovery rules on the distribution rules has been shown. Illustrative simulations that employ only three utilities confirm that differential PUC regulation can lead to increases in compliance costs industry-wide, and that the distribution of emissions and costs across units can change greatly, though the magnitude of these impacts can be great or small.

The next chapter extends the model by examining the impact of PUC cost recovery rules on the EPA’s SO$_2$ Program allowance market for the year 1996. The analysis includes all 431 generating units participating in Phase I of the SO$_2$ allowance market in 1996. Given information on regulatory rules from Bailey (1996), Lile and Burtraw (1998), and correspondence with staff from various state PUCs, the regulatory envi-
ronment can be realistically characterized. Adding information on heat content, sulfur content, and price of coals; heat rate capabilities and electricity generation; scrubber efficiencies and costs (USEIA, 1997a,b,c and USEIA, 1996); and allowances prices, transactions, and holdings (USEPA, 1997) the model can be simulated to replicate the outcomes of the SO$_2$ market.

With all regulatory parameters set to 1 (no PUC regulation) for the baseline case, the market can be simulated to get the minimum total industry compliance cost outcome. Industry-wide compliance costs, the distribution of compliance costs, and distribution of emissions can then be compared under various scenarios.
Chapter 4

Simulation Model: Data and Results

This chapter takes the analytical model described in the previous chapter and parameterizes it to data collected for the year 1996. While PUC cost recovery rules can have a significant impact on overall compliance costs, as shown in the previous chapter, the simulation results indicate that these effects may large or small. Depending on the underlying assumptions of the simulation scenario, compliance costs exceed the least-cost solution by anywhere from 4.5 to 139 percent. The simulations indicate that the greatest cost impacts are derived from the regulatory treatment of scrubbers. Moreover, changes in the distribution of compliance costs related to PUC regulation can be significant depending on the simulation scenario and are also related to changes in the treatment of scrubber costs. Finally, changes in the distribution of emissions attributable to PUC regulation are not as apparent as one might expect.

The first part of this chapter describes the data used to parameterize the model for the simulations. A short description of the computational technique follows and some of the computational problems that I encountered are discussed. Finally, the results are presented and discussed.
4.1 Computational Model: Data and Parameterization

For the year 1996 431 generating units at 162 plants participated in the SO$_2$ program. 263 of these units were required to participate by the 1990 CAAA, while the remaining units participated through the substitution unit provision, compensating unit provision, or the opt-in provision. Of the 431 units in the program in 1996, 49 did not generate any electricity that year,$^1$ 358 units burned coal, and 24 units used oil or natural gas to generate electricity. This section describes the data used in the model and the methodology used to choose parameter values.

The following data were collected: (1) fuel data, including delivered costs, heat content, sulfur content and emissions factors; (2) allowance data, including initial allocations of allowances; (3) emissions data for 1996; (4) heat input by generating unit; and (5) technical data by generating unit, including scrubber data, heat rates, and unit capacities.$^2$

4.1.1 Fuel Data and Emission Factors

Fuel data were obtained from the EIA’s unpublished Cost and Quality of Fuels 1996. The EIA compiled this information from FERC Form 423. The data set describes the characteristics of all fuels delivered to utility plants. For every source of coal, by county, and state, delivered to a plant, the heat content (Btu per pound), sulfur content (percentage by weight and pounds per mmBtu), and average delivered price (dollars per ton and cents per mmBtu) are given. Although the model considers only two types of coal (high and low sulfur), coal characteristics can vary widely by both heat and sulfur content. Moreover, it need not be the case that low sulfur coal also has a low heat content.

In general there are three major coal-producing regions in the United States: Eastern, Interior, and Western. Eastern coal is found in Appalachia and generally has a

$^1$As reflected by a heat input of 0.

$^2$Copies of the data files are available from the author upon request. The data have not been reproduced in appendices to the length of the files.
Table 4.1: Coal Types

<table>
<thead>
<tr>
<th>Region</th>
<th>Heat Content</th>
<th>Sulfur Content</th>
</tr>
</thead>
<tbody>
<tr>
<td>Southern Appalachia</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Northern Appalachia</td>
<td>Medium to High</td>
<td>High</td>
</tr>
<tr>
<td>Interior (Illinois) Basin</td>
<td>Medium to High</td>
<td>High</td>
</tr>
<tr>
<td>Powder River Basin</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>Other Western</td>
<td>Medium to High</td>
<td>Low</td>
</tr>
</tbody>
</table>

Coal from Northern Appalachia\(^3\) has high heat and high sulfur content coal. Central and Southern Appalachian\(^4\) have coal deposits with high heat content but low sulfur content.

Interior basin coal\(^5\) burned at Phase I units is mined in Ohio, Indiana, Illinois, and western Kentucky. In general, this coal has a slightly lower heat content than Appalachian coal and a significantly higher sulfur content.\(^6\)

Western coal is found primarily in two regions. Powder River Basin coal, found in Wyoming and Montana, has the lowest heat and sulfur content of coal burned at Phase I units. Coal mined in Arizona, Colorado, New Mexico, and Utah has a sulfur content comparable to Powder River Basin coal, but has a heat content comparable to coal from the Interior Basin.

Although coal is the fuel of choice for most utilities participating in Phase I, 24 units employ fuel oil or natural gas for generation. Given that the model employs high and low sulfur fuels, I have designated fuel oil as the high sulfur fuel and natural gas as the low sulfur fuel for those units not burning coal.\(^7\)

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\(^3\)Northern West Virginia and Pennsylvania.

\(^4\)Southern West Virginia, Virginia, eastern Kentucky, Tennessee, Georgia, and Alabama.

\(^5\)States between the Appalachians and the Rockies.

\(^6\)Coal from the interior basin generally has a high sulfur content, but there are areas in the interior basin where relatively lower sulfur content coal can be found.

\(^7\)To the observer unfamiliar with the utility industry, it might seem unlikely that generators can switch between fuel oil and natural gas without some large fixed cost of refitting or retuning a boiler. However, most generators that employ natural gas can use fuel oil as an alternative fuel. Conversely, those generators that primarily use oil can use natural gas as an alternative fuel.
Table 4.2: Emissions Factors

<table>
<thead>
<tr>
<th>Fuel type</th>
<th>Emissions Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bituminous Coal</td>
<td>$38 \times S = \text{lbs. SO}_2/\text{ton of coal}$</td>
</tr>
<tr>
<td>Sub-bituminous Coal</td>
<td>$35 \times S = \text{lbs. SO}_2/\text{ton of coal}$</td>
</tr>
<tr>
<td>Fuel Oil #6</td>
<td>$162 \times S = \text{lbs. SO}_2/1000 \text{bbl.}$</td>
</tr>
<tr>
<td>Fuel Oil #2</td>
<td>$144 \times S = \text{lbs. SO}_2/1000 \text{bbl.}$</td>
</tr>
<tr>
<td>Natural Gas</td>
<td>0.60 lbs./MMCF</td>
</tr>
</tbody>
</table>

$S =$ percent by weight of sulfur in the fuel


Emission factors for fuel are taken from EIA’s *Electric Power Annual 1997* and are reproduced in the table below. The emissions factors multiplied by the sulfur content (S) as a percentage by weight yields the amount of sulfur dioxide produced per unit of fuel. Note that the sulfur content of fuel can vary almost continuously, but SO₂ emissions associated with fuel are just a multiple of the sulfur content.

4.1.2 Parameterization of Fuel Variables

The model assumes only two fuel types for each generating unit: high sulfur and low sulfur with each type having a single heat content, sulfur content, and price. Although the data indicate that coal types vary almost continuously with respect to heat and sulfur content and price, some simplifications are obviously necessary, including a subjective cut-off between high and low sulfur coal. Fortunately, the 1990 CAAA makes the choice of cut-off relatively straightforward. Recall that during Phase I, allowances are allocated based on an emission rate of 2.5 lbs. SO₂/mmBtu. Hence, for the purposes of this study, high sulfur coal is defined as having an emissions rate of 2.5 lbs. SO₂/mmBtu or greater, while low sulfur coal has an emissions rate of less than 2.5 lbs. SO₂/mmBtu.

To divide the coal delivered to each plant into high and low sulfur categories, one can divide the sulfur content of coal by the appropriate emissions factor to find lbs. SO₂/ton of coal. One then divides the emissions per ton by the heat content of the coal defined in mmBtu/ton to arrive at the emissions rate per unit of heat (lbs. SO₂/
Simplifying the data so that each coal type has a single heat content and single sulfur content requires additional manipulation. At each plant, I assign a weight to each source of coal based on the percentage of total tonnage of that coal type delivered to the plant. The weights are constructed so that their sum is equal to 1. Multiplying the heat content, sulfur content, and price of coal from each source by its assigned weight and adding up the weighted heat and sulfur contents and prices yields a weighted average price, heat and sulfur content for each coal type at each generating unit.

Unfortunately, not all plants participating in Phase I purchased both types of coal. For those that purchased only one coal type, I had to find proxies for the other coal type. Where possible, I used the characteristics of the coal types at other plants owned by the same operating company or holding company. Sometimes this was not possible, so I used coal of the missing type from the closest source.

4.1.3 Allowance, Emissions and Energy Demand Data

Allowances, emissions and heat input data come from the EPA’s 1996 Compliance Report. The allowance allocations, emissions, and heat input data do not require any manipulation and can be incorporated directly into the computational model.

In the computational model the demand for electricity will be measured by the heat input rather than directly by kilowatt-hours (kWh) or megawatt-hours (MWh) because there are missing observations for heat rates in the Annual Generator Data 1996. Since electricity output is a linear function of heat input and heat rates and since emissions can be expressed as a function of the sulfur content per unit of heat, the formulation is equivalent to using demand in terms of electrical output.
4.1.4 Technical Data for Generators

Data on generator capacity are drawn from EIA’s *Annual Generator Data 1996*, while missing heat rate observations were filled in, where possible, with *Annual Generator Data 1992-1995*. These data will be used to help compute the cost of scrubbers if they are installed.

Data relating to scrubber costs are drawn from EIA’s *Electric Power Annual 1997*, vol. 2, and from EIA (1994). The data from EIA (1997) gives historical state-by-state average installed costs in dollars per kilowatt of capacity, average operation and maintenance costs in mills per kilowatt-hour, capacity in megawatts for units with scrubbers installed, and sulfur removal efficiency.

In 1996, there were 46 generating units with scrubbers in the SO\textsubscript{2} program. Of these, 29 were installed after 1990, presumably in response to Title IV. The other 17 scrubbers were installed prior to 1990 in to meet new source performance standards (NSPS) under the 1977 CAAA. The data on scrubbed units include the capacity of each unit, sulfur removal efficiency, costs, and the in-service date. The in-service date indicates whether a scrubber has been installed in response to Title IV or NSPS. This is also confirmed in EIA (1997).\(^8\)

EIA (1994) provides engineering cost estimates for scrubber retrofits of $266/kw of capacity and operation and maintenance costs of 2.1 mills per kilowatt-hour. These numbers are used in simulations where units may choose to install a scrubber (but have not yet done so) using engineering cost data. Capacity data and heat rate data for generating units are used to compute the total capital cost and operation and maintenance cost of scrubbers.\(^9\)

In reality, the decision to install capital equipment such as a scrubber is a multi-

\(^8\)Though not listed as being installed in response to Title IV, two units in Wisconsin did install scrubbers after 1990. I include these as being installed in response to Title IV, although EIA (1997) does not.

\(^9\)Heat rates were not possible to find for a very few units. The heat rates would be used to compute variable costs for scrubbers, which are quite small when compared to capital costs. So in simulations in which scrubber choice is allowed, I assume zero variable costs.
period, forward-looking decision, but the model used in this exposition is a one-period model. Given this situation, it is necessary to annualize costs associated with scrubber installation. I have chosen to follow Fullerton, McDermott, and Caulkins (1997) with a discount rate of 10 percent, but to allow for an economic life of twenty years instead of the fifteen years chosen by Fullerton et al. (1997).\textsuperscript{10}

4.1.5 Regulatory Parameters

Under traditional cost-based or rate-of-return regulation it is customary for state regulatory commissions to pass through to ratepayers, dollar for dollar, the cost of doing business. Such costs include the cost of fuel for generator operation, maintenance costs, and the variable costs of environmental compliance. Under traditional utility regulation, then, one would expect all regulatory parameters associated with such costs to be zero. In this model the regulatory parameters associated with such costs are $\gamma$ for fuel, $\alpha$ for allowance sales, and $\beta$ for allowance purchases.\textsuperscript{11} The regulatory data presented below largely reflect the fact that most states pass these costs through completely.

Capital costs, however, are different from the other costs of doing business. Capital costs are rate-based and earn a regulated rate of return. Because capital is rate-based, all other things equal, utilities will invest in more capital than is optimal (Averch and Johnson (1962)). To combat this potential problem, state regulatory bodies have engaged in “prudence reviews”, or have dictated that capital investments be part of a least-cost solution and be “used and useful.” These regulatory practices have implications for the regulatory parameter on scrubber costs, $\theta$. A state PUC may allow the utility to file a compliance plan for pre-approval of certain costs, especially those for

\textsuperscript{10}The annualized capital cost for a capital investment $k$, with discount rate $\rho$ and economic life $l$ is $k \times \frac{\rho(1+\rho)^l}{(1+\rho)^l-1}$. Moreover, I have chosen an economic life of 20 years since many scrubbers installed in response to the NSPS have been in operation almost 20 years. Choosing a longer life will decrease the annualized cost and make it more likely that scrubbers will be installed.

\textsuperscript{11}Recall from our discussion in the previous chapter that there are computational problems with setting the regulatory parameters exactly equal to zero. For computational purposes these parameters are set to some positive value close to zero. This will be discussed below.
capital assets such as scrubbers. Consequently, some state PUCs allow cost recovery on the installation of scrubbers at some units, but not all, since it is clear that scrubber installation on all units is not a cost-effective means of environmental compliance. So, if a scrubber was installed at a unit, I assume that the cost recovery parameter, $\theta$, is equal to zero. If a scrubber is not installed, $\theta = 1$. This sort of *ex ante* prudence review has been common in many states where compliance plans including scrubbers can be submitted for pre-approval.

Moreover, not all regulatory commissions have pursued traditional regulation with regard to the costs of doing business. Some have engaged in incentive regulation with the idea that the regulated utilities have some incentive to keep costs down if they or their shareholders bear some of those costs. Accordingly, in states where incentive regulation is employed, the regulatory parameters may be somewhere between zero and 1. A positive value of a regulatory parameter indicates the portion of the cost borne by the utility.

It is important to note that some generating units are not under the jurisdiction of state commissions: units owned by municipal utilities, cooperatives, and federal power entities such as the Tennessee Valley Authority (TVA). Presumably, these entities set their own rates and try to keep these rates as low as possible. For example, TVA is a self-financing entity through revenues and debt issues, and it sets its own rates to cover costs including debt service. Any profits made by TVA are payable to the Treasury Department. Given this situation, one can surmise that the TVA’s interests are to minimize its costs of doing business. All regulatory parameters associated with TVA

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12 Installation of scrubbers may also be an extension of public policy to protect local coal mining operations.

13 For example, states like Indiana, Ohio, Kentucky, Pennsylvania, West Virginia, and Illinois have such plans in place. These were often done in part to protect local coal jobs.

14 For example, see Joskow and Schmalensee (1986)


16 A monopolist may take out some of the profits in the form of a more relaxed life; see Harvey Leibenstein’s concept of “x-efficiency” (AER, 1966). One could view the TVA as a cost minimizer subject to a constraint on aggravation.
are set equal to 1 \( \alpha = \beta = \gamma = \theta = 1 \). Finally, under full deregulation at the state level, utilities would bear the full cost of doing business and of capital investments; hence all the regulatory parameters would be equal to 1.

In what follows, the information about regulation at the state level comes from four sources. The first, and most comprehensive, is a study by Lile and Burtraw (1998) surveying state commissions and their regulatory policies regarding compliance with Title IV. The second is a study by Bailey (1998) examining the impact of state-level regulation on the decision to trade \( \text{SO}_2 \) allowances. As a part of her study, Bailey reviews the regulatory environment in each state. Third, Rose et al. (1993) also discuss some state regulatory policies. The last source is the author’s correspondence with various state commissions. Often times the author’s correspondence confirms what has already been published; at other times this correspondence helps fill in details that are missing from available sources.

I describe the regulatory treatment on a state-by-state basis in Table 4.3 to illuminate any differences in regulatory treatment across states. Moreover, the summary of regulatory treatment covers only those states that had units participating in Phase I of the \( \text{SO}_2 \) program in 1996, including all Phase I units, substitution units, and compensating units. One interesting facet of the data is how many state commissions have followed, consciously or not, the Bohi and Burtaw (1992) recommendation of treating allowances and scrubbers asymmetrically in favor of allowances. Other than this, there is relatively little deviation from symmetric treatment of fuel and allowances.

More detail for some of the more interesting states in terms of their regulatory treatment is presented to further explain some of the deviations from traditional cost-of-service ratemaking. The subsequent general discussion on the regulatory highlights some general conclusions that can be drawn from the data.

Massachusetts

According to Lile and Burtraw (1998) one Massachusetts utility has been permitted to pass only 80 percent of allowance revenues through to ratepayers, while shareholders
Table 4.3: Regulatory Parameters by State

<table>
<thead>
<tr>
<th>State</th>
<th>Allowance Sales $\alpha$</th>
<th>Allowance Purchases $\beta$</th>
<th>Fuel Cost $\gamma$</th>
<th>Scrubber Cost $\theta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>AL</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>FL</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>GA</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>IL</td>
<td>0</td>
<td>0</td>
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<td>0 or 1</td>
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<td>IN</td>
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<td>0 or 1</td>
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<td>0</td>
<td>1</td>
</tr>
<tr>
<td>KY</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0 or 1</td>
</tr>
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<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>MA</td>
<td>0.2</td>
<td>0.2</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>MI</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>MN</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>MS</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>MO</td>
<td>0 or 0.5</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>NH</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>NJ</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0 or 1</td>
</tr>
<tr>
<td>NY</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0 or 1</td>
</tr>
<tr>
<td>OH</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0 or 1</td>
</tr>
<tr>
<td>PA</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0 or 1</td>
</tr>
<tr>
<td>TVA</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>VA</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0 or 1</td>
</tr>
<tr>
<td>WV</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0 or 1</td>
</tr>
<tr>
<td>WI</td>
<td>0</td>
<td>0</td>
<td>0.02</td>
<td>0 or 1</td>
</tr>
<tr>
<td>WY</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

A parameter value of 0 means the utility passes through all costs to ratepayers.
A parameter value of 1 means the utility bears all the costs.
* Scrubbers installed as part of a demonstration project.
** Scrubbers pre-approved get cost recovery, but not all units installed scrubbers.
*** Union Electric gets to keep half of sales proceeds, but other utilities keep nothing.
**** The NJBPU strongly discouraged allowance purchases, and like many commissions, required pre-approval of compliance plans. I assume utilities must bear all costs associated with purchases.
# Wisconsin has a deadband on fuel costs of +/- 3 percent, so I assume 2 percent of costs are borne by the utility.
## Virginia has no units located in the state, but the Mt. Storm Units in West Virginia are owned by Virginia Electric Power, making them jurisdictional to the Virginia State Corporate Commission. Mt. Storm 3 did install a scrubber in response to Title IV.
will keep the other 20 percent as an incentive to maximize the revenues from allowance sales \((\alpha = 0.2, \beta = 0.2)\). I assume this holds for both Massachusetts units participating in the SO\(_2\) program. I have not found any information regarding fuel or scrubber costs. I will assume that Massachusetts follows the general trend for fuel; hence, the recovery parameter on fuel is equal to zero \((\gamma = 0)\). Given that no scrubbers have been installed in the state, I will assume the Massachusetts commission would not allow cost recovery for scrubbers, and thus assume the parameter on scrubber cost recovery is equal to 1 \((\theta = 1)\).

Missouri

The Missouri Public Service Commission has handled the treatment of allowances on a case-by-case basis. For Kansas City Power and Light (KCPL) all revenues associated with sales are to be deferred until a future rate case is heard. Empire District Electric has been ordered to pass through any revenues from sales to ratepayers. For KCPL and Empire, I assume that the parameter on sales is equal to zero \((\alpha = 0)\). Union Electric has been allowed to retain all profits from allowance sales as long as the margin is 11 percent or less.\(^{17}\) For any margin in excess of 11 percent, the proceeds must be split fifty-fifty between shareholders and ratepayers. For simplicity I assume that the recovery parameter on sales for Union is \(\alpha = 0.5\).

None of the Missouri utilities has purchased allowances or installed scrubbers for compliance because they have switched to low sulfur coal, so the treatment of allowance purchases has not been settled.\(^{18}\) I assume that the parameter on purchases is \(\beta = 0\) and the parameter on scrubber costs is \(\theta = 1\).

Fuel costs are passed through to ratepayers - not through a traditional FAC, but through rate cases. I assume \(\gamma = 0\) for fuel costs.\(^{19}\)

\(^{17}\)The margin is the difference between the price at which sold minus the allowance purchase price divided by the purchase price for the allowance.

\(^{18}\)E-mail correspondence with Bill Washburn of the Missouri PSC, April 28, 1998.

\(^{19}\)It was not entirely clear in my correspondence with Bill Washburn that all fuel costs would be passed through in every rate case, but given no better information, this seems a reasonable assumption.
**New Jersey**

According to Lile and Burtraw (1998), the New Jersey Board of Public Utilities (BPU) requires all state utilities to submit a compliance plan so the BPU can study compliance options such as scrubber installation and allowance purchases. Moreover, the state Department of Environmental Protection strongly recommended that the one Phase I, Table A unit install scrubbers over purchasing allowances. Given this regulatory environment, I assume $\theta = 0$ for the one unit that installed a scrubber in response to Title IV, and for the other unit $\theta = 1$. Regarding allowance purchases, I assume $\beta = 1$ for these units. Given the general leaning of the regulatory bodies within the state, I assume that the parameter on sales is zero ($\alpha = 0$). I have no information on the cost recovery for fuel, so I will assume traditional regulatory treatment of fuel, thus $\gamma = 0$.

**Wisconsin**

According to Lile and Burtraw (1998), the Wisconsin Public Service Commission eliminated its fuel rule (similar to a fuel adjustment clause) while it reduced Wisconsin Power & Light’s (WPL) revenue requirement on the grounds that its fuel purchases were too expensive. Under the old fuel rule WPL had a plus or minus 3 percent target in which they would either keep the savings from lower fuel purchases or be responsible for cost over-runs. Now, WPL simply has a target to hit for fuel costs, and any deviation from that is borne by the utility. Given the previous benchmark of 3 percent, I chose 2 percent, assuming Wisconsin utilities would do a better job at keeping fuel costs down and not bump up against the old target.

**Implications for the SO$_2$ Market and Compliance Costs**

An examination of the regulatory data presented in Table 4.3 indicates that the vast majority of states treat fuel and allowance compliance options symmetrically, albeit allowing a full pass through of costs. Theorem 3.2 in Chapter 3 states that it is this relationship between the parameters (symmetry), not the magnitude, that will lead
the SO$_2$ market to achieve the least-cost solution. Thus, the data would lead one to conclude that taking scrubbers as given, the SO$_2$ market should result in total compliance costs that do not deviate much from the minimum cost. However, allowing all regulatory parameters to be equal to zero leads to serious computational problems as discussed in the next section. Even if scrubbers are a choice variable, setting all regulatory parameters equal to zero results in a degenerate solution where utilities could undertake almost any compliance strategy and the costs borne by them would be all passed through. Mathematically, the value of the objective function would always be zero. Consequently, the result of compliance activity through the market, which would likely see an allowance price of zero, could result in the least-cost solution or in compliance costs well in excess of the least-cost solution.

4.2 Computational Issues

There are several issues that needed to be addressed before coding the model for simulation exercises. First, the model must be solved as a mixed integer program. The integer variables, which are both \{0,1\} choices, account for the choice to be either a buyer or a seller of allowances, and whether to install a scrubber or not. Second, there are issues surrounding the handling of regulatory parameters for the model to avoid degenerate solutions. Third, given the choice of scrubbers, the solution method of the linear programming solver requires an additional algorithm to speed up the convergence process to clear the market. The simulation model is coded in FORTRAN 77 and the linear program is solved by using the double precision variable linear programming solver in the FORTRAN IMSL Library.

4.2.1 Mixed Integer Program

Mixed integer programs are non-convex programs that leave open the possibility that an equilibrium might not exist in linear prices. The computational model used has the
same problem, but the problem is not as large as it first appears. The first integer decision in the model is to determine whether it is cost minimizing to be a buyer or a seller of allowances. In general, this decision need not be integer in nature, but it has been modeled as such to account for the possibility that PUC regulation could provide utilities an incentive to “churn” the allowance market and generate profits from simply engaging in as many transactions as possible. In the extreme, it is possible that a PUC could allow utilities to sell allowances and keep all of the revenues while passing through to ratepayers all of the costs associated with allowance purchases.\(^\text{21}\)

Fortunately, given the choice of scrubber, the demand and supply correspondences are still upper-semicontinuous so the existence of an equilibrium can still be guaranteed. One could think of the above restriction on utilities in the computational model as a part of the regulatory policy insofar as the PUC allows this sort of recovery of costs on net sales.

Unfortunately, the integer choice of a scrubber is a traditional non-convexity. For scenarios in which the scrubber decision is endogenous, it is possible that an equilibrium in linear prices (the allowance price) might not exist. While this is a problem, it is not as bad as it first seems. In the event that an equilibrium does not exist, it will be the case that there is an allowance price around which the market is either in excess supply or excess demand. This is the price at which some generating unit is indifferent between installing a scrubber or not. This price could be thought of as a "quasi-equilibrium price.” One could think of this market outcome in the following manner. In the case of excess supply, it might be the case that the excess supply is sold to allowance brokers at the “quasi-equilibrium price”; or with excess demand, it might be the case that the excess is being purchased from a broker. Another way of thinking about the excess supply case is that the utility could be banking those allowances for future use.\(^\text{22}\)

In reporting simulations in which an equilibrium in the allowance price alone does not

\(^{21}\)From Chapter 3, this is the situation in which \(\alpha > \beta\).

\(^{22}\)In practice, there are several brokers in the market buying and selling past, current, and future-vintage year allowances. It also well established that allowance banking is a common practice.
exist, the excess supply case is reported rather than the excess demand case, since in
the excess demand case the aggregate emissions constraint will be violated.

4.2.2 Regulatory Parameters

An examination of the regulatory data presented in the previous chapter presents one
striking fact as discussed in the last section: Most states allow a 100 percent pass
through to ratepayers of fuel costs, allowance costs, and allowance revenues. This im-
plies that the regulatory parameters regarding these items are zero. This presents a
serious computational problem. If a value of zero is used to for allowance purchase and
sales, then the demand and supply correspondences are undefined. If the regulatory
parameter on fuel is equal to zero for many units, then it is likely that the market solu-
tion is degenerate and that the price of allowances will be zero under most scenarios.
Consequently, when the implied values on the above regulatory parameters are zero,
the value of 0.0001 has been used in the simulations. One could think of this value as
reflecting some small need for utilities to control costs and so avoid a prudence review
of costs or a new rate case. Another way of thinking about this value is that all costs
may not be recoverable immediately, so shareholders must bear a small portion of costs
until such time that they are recovered, or that the regulators have imperfect knowledge
about the true costs of a utility.

23 Of course there are exceptions. Massachusetts allows utilities to keep (bear) 20% of allowance
revenues (costs), and in Missouri one utility keeps (bears) 50% of revenues (costs) associated with
allowance transactions.

24 See Chapter 3 and the equations defining the demand and supply correspondences. When the fuel
parameter, \( \gamma \) equals zero the marginal cost of fuel switching is zero, which implies the demand and
supply correspondences for an individual unit are horizontal lines at a price of zero. Given the large
number of units that are allowed to pass through all of their fuels costs, this could lead to a degenerate
market solution. Furthermore, as discussed in the previous section, the objective function value is zero.

25 If the allowance and fuel parameters are zero, this still preserves the symmetric treatment of com-
plinace options.

26 This is how Fullerton et al. (1997) handle this situation in running simulations for their model
utility.
4.2.3 Market Clearing and the Linear Program

The market-clearing simulation model is solved by using a bisection iterative process. A price is arbitrarily chosen and each unit’s problem is solved at the given allowance price. The program then checks the market. If there is excess supply, the price is decreased; if there is excess demand, the price is increased. The program then solves each unit’s problem again and checks the market to determine if the market clears. This process continues until the market clears.

Recall from Chapter 3 that the demand and supply correspondences look like step functions with only one step (flat spot). The flat spot occurs at a price where a generating unit is indifferent between a continuum of solutions on its allowance position (how much to buy or sell) and its choice of fuel inputs. Indeed, it is highly likely that the equilibrium price of allowances occurs at some unit’s flat spot. The linear programming solver, in solving each unit’s cost minimization problem, will choose a corner solution for this firm, despite its indifference between the corner solution and interior solutions. Consequently, an algorithm was developed to compare each unit’s “indifference price” to the allowance price at each iteration. If the difference between the two prices is less than a prescribed tolerance level, the algorithm then searches over interior solutions that could clear the market. If the market does not clear, after this process, another iteration is performed, and the process is repeated until the market clears.\textsuperscript{27}

4.3 Simulation Scenarios

The comparisons between the PUC regulatory regime and the unregulated regime were carried out under six different scenarios designed to account for observed differences in the number of allowances allocated in 1996 and the actual emissions generated in 1996.

\textsuperscript{27}The fuel data offers additional evidence that utilities are likely to arrive at corner solutions in their fuel choices. An examination of the fuel data using the cutoff of 2.5 lbs. SO\textsubscript{2}/mmBtu as the determinant of high sulfur and low sulfur fuel, shows that a large number of the generating plants (86 of 162) had only one type of fuel delivered in 1996, which reinforces the idea that units will arrive at a corner solution for fuel choices.
Table 4.4: Scenario Definitions

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Allowance Allocation</th>
<th>Scrubber Costs</th>
<th>Scrubber Choice</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Actual 1996 allocation</td>
<td>Historical</td>
<td>None, 46 given</td>
</tr>
<tr>
<td>2</td>
<td>Actual 1996 emissions</td>
<td>Historical</td>
<td>None, 46 given</td>
</tr>
<tr>
<td>3</td>
<td>Actual 1996 allocation</td>
<td>Historical</td>
<td>17 given, others choose</td>
</tr>
<tr>
<td>4</td>
<td>Actual 1996 emissions</td>
<td>Historical</td>
<td>17 given, others choose</td>
</tr>
<tr>
<td>5</td>
<td>Actual 1996 allocation</td>
<td>Engineering</td>
<td>17 given, others choose</td>
</tr>
<tr>
<td>6</td>
<td>Actual 1996 emissions</td>
<td>Engineering</td>
<td>17 given, others choose</td>
</tr>
</tbody>
</table>

Table 4.5: Unrestricted and Restricted Emissions for Scenarios

<table>
<thead>
<tr>
<th>Allowances/Emissions</th>
<th>Scenarios</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actual 1996 Allowance Allocation</td>
<td>8,121,366 tons</td>
</tr>
<tr>
<td>Actual 1996 Emissions</td>
<td>5,433,351 tons</td>
</tr>
<tr>
<td>Unrestricted Emissions (46 scrubbers given)</td>
<td>7,269,411.24 tons</td>
</tr>
<tr>
<td>Unrestricted Emissions (17 scrubbers given)</td>
<td>8,943,481.77 tons</td>
</tr>
</tbody>
</table>

The scenarios are crafted to account for the choice of scrubber, given differences in the cost of scrubber installation incurred historically, and the engineering cost estimates of scrubber retrofits should they occur during 1996. Also, some scenarios take all the scrubbers as given. The six scenarios used are listed in Table 4.4; emissions level and unrestricted emissions level corresponding to the scenarios are listed in Table 4.5.

In the scenarios where affected units can choose whether to install a scrubber, note that seventeen scrubbers are taken as given to account for scrubbers installed prior to the passage of the 1990 CAAA. These scrubbers were installed in response to the 1977 CAAA New Source Performance Standards (NSPS) and should not be considered a compliance choice for the 1990 CAAA.

Also worth noting is the level of unrestricted emissions in Scenarios 1 and 2. This level of is less than the number of allowances allocated in 1996 because there are enough scrubbers installed in 1996 and there are enough units that would choose to use low sulfur coal even in the absence of Title IV to more than cover emissions reduction needs.
At the time the 1990 CAAA were passed by Congress, it was expected that the marginal cost of pollution reduction from fuel switching would be much higher (i.e., the delivered price for low sulfur coal would be much higher). However, by 1996, the delivered price of low sulfur coal had fallen dramatically, leading many utilities to switch to low sulfur coal for cost reasons and not necessarily environmental reasons.  

4.4 Compliance Costs and Allowance Prices

Running several different scenarios, it is clear that public utility commission regulatory treatment of compliance options will lead to higher compliance costs than the ideal least-cost solution under the unregulated regime. The results indicate that regulatory treatment of scrubbers, not fuel or allowances, is the driving force behind the compliance cost differences between the the regulated regime and the unregulated regime. This should not be a surprising result since scrubbers are considered the most expensive of compliance options and have been the focus of PUC proceedings related to cost recovery for emissions compliance (see Lile and Burtraw (1998)). The excess compliance costs incurred with regulation range from small increases of less than 5 percent of the least-cost solution, where scrubbers are taken as given, all the way up to an almost 140 percent increase in compliance costs over the unregulated least-cost solution where scrubber choice is allowed. A special case is Scenario 1 in which there is no change in compliance costs because of a combination of factors. One is that all scrubbers are taken as given, so the largest component of compliance cost is unchanging even in the unregulated regime. Another factor is that unrestricted emissions are less than the number of allowances allocated with all scrubbers given which results in a zero price for allowances.

As for the price of allowances, there are three scenarios that result in zero prices

28 As explained in Ellerman et al. (1997) and Carlson, et. al. (2000) there were many productivity improvements in the mining of Powder River Basin Coal, as well as reduced rail rates with deregulation. Neither of these events had been anticipated when the 1990 CAAA were passed. In terms of computing compliance costs in the simulations, units that would use low sulfur coal regardless of Title IV are taken to have a compliance cost of zero.
Table 4.6: Compliance Costs Taking Scrubbers as Given

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Compliance Costs</th>
<th>Avg. Abatement Costs</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PUC</td>
<td>No PUC</td>
</tr>
<tr>
<td>1</td>
<td>$392,761,402</td>
<td>$392,761,402</td>
</tr>
<tr>
<td>2</td>
<td>$549,858,553</td>
<td>$527,085,258</td>
</tr>
</tbody>
</table>

PUC (regulated) takes all regulatory parameters less than or equal to 1. No PUC (unregulated) takes all regulatory parameters equal to 1.

for allowances. In Scenario 1 this result should not be surprising since the number of allowances allocated is greater than the level of unrestricted emissions. Also, a zero allowance price is observed in the regulated regime under Scenarios 3 and 5. While the number of allowances allocated in these scenarios is less than the unrestricted emissions, some units have received regulatory approval to install scrubbers. Hence, the emissions constraint is no longer binding in practice resulting in an allowance price of zero. Allowance prices in Scenarios 2, 4, and 6 (using 1996 emissions as the allowance allocation) range from $120.99 per ton to $179.46, which are considerably greater than the prices of less than $100 per ton actually observed in the allowance market in 1996. Unfortunately, given the comparative statics results reported Chapter 3, moving from a completely regulated regime to an unregulated world gives no solid predictor of where the allowance price or the quantity traded will move.

4.4.1 Scenarios Taking Scrubbers as Given

As shown in Table 4.4.1 scrubbers account for $392,761,402 of compliance costs in Scenarios 1 and 2 regardless of the regulatory regime. This makes sense since the scrubbers are taken as given and scrubbers are generally the most expensive compliance option.

29 Under the command-and-control regime, the compliance costs are decidedly higher, and the over-compliance, in the sense that not all allowances will be used, is even greater.

30 These are prices reported by brokerage firms like Cantor Fitzgerald, but given the amount of allowance banking done, these are likely not equilibrium prices in the context of this model.

31 Recall from Chapter 3 that the allowance price is weakly increasing as the portion of fuel costs borne by a utility increases, and the price is weakly decreasing in the portion of allowance costs (revenues) borne (kept) by utilities.
Moreover, the average abatement cost is not defined for Scenario 1 since, given the scrubbers, the unrestricted emissions are below the allowance endowment. Consequently, the allowance price in Scenario 1 will be driven to zero under both regulatory regimes.

Tables 4.4.1 and 4.4.1 show that in Scenario 2, the allowance price, allowances traded, and compliance costs differ between the two regulatory regimes. As the theory predicts, the compliance costs under the PUC regulatory regime (regulated) are greater than the under the No PUC regime (unregulated), although the increase in compliance costs for the regulated regime is small, 4.3 percent higher than the costs in the unregulated regime. Since the scrubbers are taken as given, an equilibrium is guaranteed. Emissions in both regulatory regimes are equal to the allowance allocation.

It should not be surprising that taking the scrubbers as given yields such a small compliance cost difference between the regulated and unregulated regimes. Recall that symmetric treatment of compliance costs leads to the least-cost solution. And given the regulatory treatment of allowances and fuel, as shown in Table 4.3, only a few utilities are not facing symmetric treatment, so it should not be surprising that compliance costs do not deviate a great deal. It also seems that, taking scrubbers as given, changes in the regulatory treatment of allowances dominate the changes in the treatment of fuel as the allowance price falls in the unregulated regime relative to the regulated regime.

The results of the first two scenarios show a small impact of PUC regulations in terms of compliance costs. However, these scenarios take all scrubbers, including those installed in response to Title IV, as given. However, scrubber costs account for the vast majority of compliance costs. In the next section, I conduct a thought experiment in which it is assumed that scrubbers can be chosen for the year 1996 at the annualized
cost discussed above. Using the same regulatory treatment, I then examine the impact of recovery treatment for scrubbers on overall compliance costs.

4.4.2 Allowing Scrubbers to be Chosen

In Scenarios 3-6, where generators are allowed to make the scrubber choice, the cost increases under the regulated regime range from 31 percent to 139 percent as shown in Table 4.8. These large increases in compliance cost seem to be driven by the regulatory treatment of scrubbers, as can be seen in Table 4.9.\textsuperscript{32} Under Scenarios 3 and 5 where units receive the full 1996 allowance allocation, compliance costs are 131 percent and 139 percent higher, respectively. In contrast, in Scenarios 4 and 6, where the allowance allocation is equal to 1996 emissions, the cost increase relative to the unregulated least-cost regime are 31 percent and 56 percent respectively. The cost differences are more stark when the allowance allocation is equal to the actual 1996 allocation (Scenarios 3 and 5) since the amount of emissions that need to be abated is minimal, yet the regulatory incentives are such that far more scrubbers are installed than is optimal. However, in Scenarios 4 and 6, the amount of pollution abatement needed to meet the emissions cap is much greater, so scrubbers installed under the regulated regime (PUC) are better utilized. Even in the unregulated regime (No PUC), for Scenarios 4 and 6, it will be optimal to install some scrubbers. Still, the PUC regulatory regime provides incentives for over-investment in scrubbers in dollar terms as well as incorrect assignment of scrubber installation, so that in many cases the “wrong” units are installing scrubbers. For example, in the unregulated (No PUC) cases of Scenarios 4 and 6, of the scrubbers chosen to be installed, only nine of those scrubbers correspond to scrubbers actually installed in Phase I by affected utilities in each simulation case. This implies that in Scenario 6, without PUC regulation, nine units install scrubbers that in fact did not do

\textsuperscript{32} Suppose there were other units that could have received full cost recovery on scrubbers ($\theta = 0$), but chose not to install one in reality. The program solved by utility units in this model would automatically choose to install the scrubber when given full cost recovery since it would reduce emissions, but not add to the objective function thus resulting in even higher compliance costs.
Table 4.8: Compliance Costs Allowing Scrubbers to be Chosen

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Compliance Costs</th>
<th>Avg. Abatement Costs</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PUC</td>
<td>No PUC</td>
</tr>
<tr>
<td>3</td>
<td>$335,958,322</td>
<td>$145,134,782</td>
</tr>
<tr>
<td>4</td>
<td>$529,550,388</td>
<td>$340,126,321</td>
</tr>
<tr>
<td>5</td>
<td>$348,603,741</td>
<td>$146,621,149</td>
</tr>
<tr>
<td>6</td>
<td>$553,068,881</td>
<td>$421,841,367</td>
</tr>
</tbody>
</table>

Table 4.9: Number of Scrubbers Chosen and Scrubber Cost by Scenario

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Scrubbers Chosen</th>
<th>Scrubber Costs</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PUC</td>
<td>No PUC</td>
</tr>
<tr>
<td>3</td>
<td>25</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>$335,958,322</td>
<td>$128,233,441</td>
</tr>
<tr>
<td>4</td>
<td>34</td>
<td>47</td>
</tr>
<tr>
<td></td>
<td>$405,549,613</td>
<td>$267,392,292</td>
</tr>
<tr>
<td>5</td>
<td>25</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>$348,603,741</td>
<td>$127,371,284</td>
</tr>
<tr>
<td>6</td>
<td>28</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>$553,068,881</td>
<td>$232,253,486</td>
</tr>
</tbody>
</table>

so in response to Title IV. And in the unregulated (No PUC) case for Scenario 4, 38 units install scrubbers that actually did not do so in response to Title IV. A summary of the scrubbers chosen in Scenarios 3, 4, and 6 is presented in Table 4.10.

Scenario 4 presents a result which at first seems to be counter-intuitive: more scrubbers are installed in the unregulated regime than in the regulated regime. There are two reasons for this result. First, historical costs are being used for scrubbers in this scenario, and these are significantly lower than the engineering cost estimates used in Scenarios 5 and 6, as shown in Table 4.10. Second, the assumption of the disallowance of scrubber costs for those units that have not yet installed scrubbers is having an impact in the regulated regime in that there seem to be many units for which scrubber installation would be a least-cost solution in the absence of regulatory rules. However, given that fuel switching and allowance purchases receive a more favorable regulatory treatment than scrubbers are assumed to get, many scrubbers do not get installed that should be.

With respect to allowance prices and market volume, Scenarios 3-6 show a great
Table 4.10: Number of Scrubbers Chosen in Simulations But Not Actually Installed in 1996

<table>
<thead>
<tr>
<th>Scenario</th>
<th>State</th>
<th>No. of Units</th>
<th>Capital Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Historical 3, No PUC</td>
<td>OH</td>
<td>1</td>
<td>$90/kW</td>
</tr>
<tr>
<td>Historical</td>
<td>WI</td>
<td>2</td>
<td>$16/kW</td>
</tr>
<tr>
<td>Historical 4, No PUC</td>
<td>AL</td>
<td>5</td>
<td>$80/kW</td>
</tr>
<tr>
<td>Historical</td>
<td>FL</td>
<td>3</td>
<td>$73/kW</td>
</tr>
<tr>
<td>Historical</td>
<td>IL</td>
<td>1</td>
<td>$147/kW</td>
</tr>
<tr>
<td>Historical</td>
<td>IN</td>
<td>2</td>
<td>$145/kW</td>
</tr>
<tr>
<td>Historical</td>
<td>KY</td>
<td>4</td>
<td>$140/kW</td>
</tr>
<tr>
<td>Historical</td>
<td>MS</td>
<td>2</td>
<td>$70/kW</td>
</tr>
<tr>
<td>Historical</td>
<td>OH</td>
<td>18</td>
<td>$90/kW</td>
</tr>
<tr>
<td>Historical</td>
<td>WI</td>
<td>3</td>
<td>$16/kW</td>
</tr>
<tr>
<td>Engineering 6, No PUC</td>
<td>KY</td>
<td>2</td>
<td>$266/kW</td>
</tr>
<tr>
<td>Engineering</td>
<td>OH</td>
<td>7</td>
<td>$266/kW</td>
</tr>
</tbody>
</table>

detail of variability which are attributable to assumptions made on allowance allocation. The prices and volumes are shown in Table 4.11. For Scenarios 3 and 5 in the regulated regime (PUC), the price is zero and the market has excess supply. The reason for the zero price is that the regulatory treatment of scrubbers, in effect, makes the aggregate emissions constraint non-binding. However, in Scenarios 3 and 5, with no PUC regulation, the allowance price is $30.05, and allowing scrubber choice does not impede clearance of the market.

In Scenarios 4 and 6, there is only one simulation in which the market clears, Scenario 4 in the unregulated regime (No PUC). In this regime the price is $120.99. In the other three simulations for Scenarios 4 and 6, an equilibrium in the allowance price does not exist, but a price at which the market moves from excess supply to excess demand does exist. This is the price reported in Table 4.11. As was mentioned previously, this was a possibility because of the discrete choice on scrubber installation. In all the cases the “marginal” unit is Cumberland 2 owned by TVA. At the reported price, Cumberland 2

\[33\] This problem would be exacerbated by setting \( \theta = 0 \) for more units if somehow some units would have been given full cost recovery on scrubbers, but chose not to install one.

82
Table 4.11: Allowance Prices and Volume Traded When Scrubbers are Chosen

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Allowance Price</th>
<th>Market Volume</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PUC</td>
<td>No PUC</td>
<td>PUC</td>
<td>No PUC</td>
</tr>
<tr>
<td>3</td>
<td>$0.00</td>
<td>$30.05</td>
<td>excess supply</td>
<td>2,408,721</td>
</tr>
<tr>
<td>4</td>
<td>$179.46</td>
<td>$120.99</td>
<td>1,682,134 sold</td>
<td>1,809,976</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1,595,586 bought</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>$0.00</td>
<td>$30.05</td>
<td>excess supply</td>
<td>2,379,249</td>
</tr>
<tr>
<td>6</td>
<td>$179.46</td>
<td>$179.46</td>
<td>1,640,642 sold</td>
<td>1,722,529 sold</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1,594,394 bought</td>
<td>1,664,790 bought</td>
</tr>
</tbody>
</table>

is indifferent between scrubbing and using all high-sulfur coal, and not scrubbing and using all low-sulfur coal. When Cumberland 2 scrubs, its emissions are only 14,112 tons. When Cumberland 2 does not scrub its emissions are 124,894 tons, implying an emissions differential of 110,782 tons between scrubbing and not scrubbing. Given that the excess supply in each case is less than 110,782 tons, the price of $179.46 is something of a “quasi-equilibrium” in that any price higher will continue to lead to excess supply, but any price lower will lead to excess demand.

One way to think about this outcome is that the excess allowances are bought up by a broker at the $179.46 price to be sold later for future use. Or, the allowances could be analogously banked for future use by the utility in question. Both explanations are quite possible, given the extent of banking of allowances for future use and broker activity that have been observed in the market to date.

4.4.3 Discussion

The above results on compliance costs and allowance prices must be placed into context by comparing them to what has been observed and to other studies on compliance costs for Title IV. First, it must be pointed out that the simulation results reported assume that utilities take full advantage of trading opportunities, which is something other observers such as Rose (2000) and Carlson et al. (2000) contend has not happened. Some estimates for the actual costs of compliance come from a survey study conducted
by Ellerman et al. (1997) looking at compliance costs for 1995, and from Carlson et al. (2000), who estimate compliance costs for 1995 and 1996 and attempt to estimate the least-cost solution for compliance costs for those years to arrive at potential gains from trade that have not been captured.

As a comparison, it would be reasonable to assume that estimates of actual compliance costs as stated by Ellerman et al. (1997) and Carlson et al. (2000) provide an upper bound on the compliance costs produced by the simulations above. Ellerman et al. estimate compliance costs for 1995 to be about $725 million, while Carlson et al. estimate actual compliance costs at $882 million for 1995 and $910 million for 1996. So the compliance costs resulting from the simulations above are certainly below these estimates, as one would expect since utilities in the simulation above take full advantage of trading opportunities. In addition to the estimates of actual compliance cost, Carlson et al. estimate the least-cost solution for abatement in the year 1996, taking all scrubbers installed as of 1995 as given, at $571 million dollars, which compares favorably to the unregulated solution in Scenario 2 (see Table 4.4.1) of $527 million taking scrubbers as given.\textsuperscript{34}

With respect to allowance prices, Carlson et al. find a marginal cost of abatement in their least-cost solution of $71/ton, which is in line with allowances prices during 1996. However, the simulation results of Scenario 2 (see Table 4.4.1 yield an allowance price of $149.64. The difference in allowance price is quite likely attributable to the different methods of finding the marginal cost of abatement (econometric estimation versus a production-cost derivation). Moreover, as Carlson et al. point out, the allowance price in 1996, which is close to what they estimate, may not necessarily indicate that the market was operating efficiently. It could as well be arrived at with sub-optimal participation. Extending that logic further, leads to consideration that prices could be higher.

\textsuperscript{34}Carlson et al. estimate marginal cost of abatement curves econometrically, taking scrubbers as given. The $44 million cost difference between the simulation result of Scenario 2 and the Carlson et al. study could be explained by different treatment of scrubber costs (10-year recovery period of costs versus 20 years in this study) and the use of 1993 emissions rates as unrestricted emissions, in contrast to use of available high-sulfur coal inputs in 1996 here.
in a market with full participation and all participants capturing all gains from trade as is done in the simulation model here. In fact, as allowance trading has grown in volume since 1996, implying greater participation and presumably more efficient outcomes, allowances prices have moved closer to the simulation prices in Scenario 2.

Finally, there is the issue of scrubber choices. It should be noted that these results are more of a thought experiment in that scrubber installation is a dynamic and irreversible decision, whereas the simulations above are one-year snapshots of Title IV compliance using annualized costs for scrubbers. Still, Carlson et al. conclude that many scrubbers would in fact not be optimal compliance choices, as they estimate an average abatement cost from scrubbing in excess of $400/ton. This is similar to the results of simulations in Scenarios 3-6, where most of the actual scrubber choices for Title IV as of 1996 appear to be too many in number and at the “wrong” units.

4.5 Distribution of Compliance Costs

Despite lower industry compliance costs in the deregulated regime, there are potentially winners and losers in terms of changes in compliance costs across states, as shown below. This result seems counterintuitive at first since it is the case that compliance costs are lower in the unregulated regime in the aggregate. However, if the relative allowance market positions of utilities in a particular state does not change from one regime to another, then changes in allowance prices can result in increases in compliance costs. For example, if utilities in a state are net sellers of allowances in both regulatory regimes, then decreases in allowance prices will increase compliance costs (decrease revenues from allowance sales). Conversely, it could be the case that utilities in some states are net buyers under both regulatory regimes, and if the allowance price increases in the unregulated regime (No PUC), as it does in Scenarios 3 and 5, then compliance costs will increase for those states. Finally, it might be that net sellers in the regulated regime (PUC) could change allowance market position by becoming net buyers in the unregulated regime (No PUC).
4.5.1 Scenarios Using the Actual 1996 Allowance Allocation

Distributions of compliance costs are not reported for Scenario 1 since there is no change in the incidence of compliance costs in moving from the regulated regime to the unregulated regime. In Scenario 3 (Table 4.12), the price of allowances increases from zero to $30.05. In this case, states with utilities that are net buyers of allowances in both regimes will likely see their compliance costs increase in the unregulated regime. States with no change in their allowance position that are net buyers in both regimes are Alabama, Illinois, Massachusetts, Maryland, Michigan, and Mississippi. Tennessee and Wisconsin are net buyers in each regime, but utilities in each state have net purchases of allowances that are less in the unregulated regime.

Florida is a net buyer in the regulated regime, but switches to being a net seller in the unregulated regime. This is driven by relatively low cost of fuel switching at the state’s Big Bend units (marginal cost of abatement from switching is about $25). However, the net revenues from allowance sales in Florida are less than the savings from buying when the price is zero under regulation (PUC). Of particular note in Scenario 3 are the large decreases in compliance costs in Indiana, West Virginia, Ohio, and Pennsylvania. The explanation is that PUC regulation allowed full cost recovery for scrubbers, but utilities bear the entire scrubber cost in the unregulated regime. Utilities thus choose to either buy allowances or switch fuel in place of scrubbing.

Similar results are found in Scenario 5 (Table 4.13) when engineering cost estimates are used for scrubbers rather than historical costs. The biggest difference between Scenario 5 and Scenario 3 is that Wisconsin’s compliance costs fall in Scenario 5. In the unregulated regime, no Wisconsin utility installs a scrubber, whereas in Scenario 3 the number of scrubbers remained the same in both the regulated and unregulated regime. Not installing the scrubbers has led to lower overall compliance costs for Wisconsin in this scenario.
Table 4.12: Distribution of Compliance Costs by State for Scenario 3

<table>
<thead>
<tr>
<th>State</th>
<th>PUC</th>
<th>No PUC</th>
<th>PUC - No PUC</th>
</tr>
</thead>
<tbody>
<tr>
<td>AL</td>
<td>34.18</td>
<td>1,378,526.72</td>
<td>-1,378,492.54</td>
</tr>
<tr>
<td>FL</td>
<td>4,167,330.42</td>
<td>6,804,723.08</td>
<td>-2,637,392.66</td>
</tr>
<tr>
<td>GA</td>
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<td>7,478,896.85</td>
</tr>
<tr>
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</tr>
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Table 4.13: Distribution of Compliance Costs by State for Scenario 5

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<td>IA</td>
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<td>-112,180.35</td>
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<td>34,831,086.04</td>
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</tr>
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<td>MO</td>
<td>-212.81</td>
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<tr>
<td>NH</td>
<td>-4.43</td>
<td>-178,487.38</td>
<td>178,482.96</td>
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<tr>
<td>NJ</td>
<td>7,629,439.05</td>
<td>150,542.20</td>
<td>7,478,896.85</td>
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<tr>
<td>NY</td>
<td>12,537,736.07</td>
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<td>16,475,033.36</td>
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<td>36,394,022.05</td>
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<td>TN</td>
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<td>-3,412,056.49</td>
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<td>8,245,876.85</td>
<td>57,059,910.52</td>
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<td>WY</td>
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<td>1,893,636.30</td>
</tr>
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</table>
4.5.2 Scenarios Using Actual 1996 Emissions as Allowance Allocations

Changes in compliance costs for Scenario 2 can be seen in Table 4.14. Several states see their compliance costs increase in moving from a regulated (PUC) to an unregulated (No PUC) regime. Iowa, Illinois, Indiana, Kansas, Missouri, New Jersey, New York, Pennsylvania, Tennessee, and Wyoming do not see changes in their net allowance market positions (they are all net sellers), so the decrease in allowance price reduces allowance revenues. For Kentucky and Ohio, the allowance position changes slightly. They are net sellers in both regimes, but the number of allowances sold on net decreases for both states. One noteworthy change in compliance costs is in Wisconsin where costs decrease in the unregulated regime by almost $24 million. The reason stems from the differential treatment of fuel versus allowances in the regulated regime. When there is no PUC regulation, fuel and allowances are treated the same, and, given the low costs of abatement through fuel switching, more units switch to low-sulfur coal and sell allowances than under the regulated regime.

Table 4.15 shows the cost distributions for Scenario 4. Here the allowance price is lower in the unregulated regime (No PUC) than in the regulated regime (PUC). So states with utilities that are net sellers in both regimes will see their allowance revenues drop; hence overall compliance costs for these entities will increase. Kansas, Missouri, and Wyoming are in this situation. The only other state with an increase in its compliance costs in the unregulated regime is Illinois. Utilities in Illinois were net sellers in the regulated regime, but net buyers in the unregulated regime. The change in allowance price has made allowance purchases a better compliance choice, relative to the regulated regime and the higher allowance price. Much like Scenario 3, states that experience large decreases in compliance costs install fewer scrubbers than in the unregulated regime. In Ohio, more scrubbers were installed, but at units where scrubbers offered more for the money in terms of allowance revenues. Wisconsin also gains in terms of lower compliance costs, but like Scenario 2, this is because of the asymmetric treatment of fuel options in the regulated regime as opposed to treatment of scrubbers.
Table 4.14: Distribution of Compliance Costs by State for Scenario 2

<table>
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<th>PUC - No PUC</th>
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<td>33,988.74</td>
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Table 4.15: Distribution of Compliance Costs by State for Scenario 4

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</table>

91
In Scenario 6, shown in Table 4.16, no state sees increases in compliance costs in the unregulated regime. This is in part because many scrubbers are not being installed in the unregulated regime versus the regulated regime. This result is very different from Scenario 4 in that engineering cost estimates have been used for scrubbers, and these are at least three times higher than the historical costs used in Scenario 4. Large decreases in compliance costs with fewer scrubber installations are seen in Indiana, Pennsylvania, West Virginia, and Wisconsin. Smaller decreases with fewer scrubbers installed can be seen for Georgia, New York, and New Jersey. In all of these states except Wisconsin, utilities have switched from scrubbing to buying allowances.

An interesting result relating to compliance costs and decisions occurs in Ohio and Kentucky. While their compliance costs decrease, the location of scrubbers changes and the number of scrubbers actually increases, which could indicate that scrubbers actually installed were placed at the wrong units.

4.6 Distribution of Emissions

State governments and environmental groups in the Northeast claim that emissions originating from other parts of the United States has detrimental effects on the environment in the Northeast. Typically, these groups have argued that opening up the generation sector of the electricity industry could increase emissions from the Midwest and the upper South and thus increase pollution in the Northeast. Part of this argument centers around the assumption that generation in the Midwest and the upper South is much less expensive than in the Northeast, hence, under competition these utilities upwind from the Northeast will increase their generation and thus increase emissions. These worries have involved northeastern states in recent USDOJ suits against Midwestern utilities over their emissions levels in allegedly failing resulting to comply with requirements of the EPA’s New Source Review (NSR). New York State to enacted legislation that penalizes New York utilities for selling allowances to utilities in fourteen states in the
Table 4.16: Distribution of Compliance Costs by State for Scenario 6

<table>
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</tr>
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</tr>
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<td>30,590,753.87</td>
<td>0.00</td>
</tr>
<tr>
<td>Total</td>
<td>553,068,881.45</td>
<td>421,841,367.34</td>
<td>131,227,514.11</td>
</tr>
</tbody>
</table>
Midwest and the upper South.\textsuperscript{35}

As it turns out, holding the level of generation constant, completely freeing generation decisions including compliance from state-level ratemaking can radically change the distribution of emissions so that utilities upwind of the Northeast, and in closer proximity, will have increased emissions. For some scenarios this change is relatively small, while under others these changes are more pronounced. However, without incorporating environmental modeling of SO\textsubscript{2} transport, it is difficult to say whether acid precipitation will increase or air quality will decrease in the Northeast. For the purposes of discussion, I will look closely at the emissions from the states listed in footnote 35 that had units participating in the SO\textsubscript{2} program in 1996 as well as emissions in New York.

4.6.1 Scenarios with the Actual 1996 Allocation

The results for Scenario 1 are not reported as there is no change in the distribution of emissions in moving from the regulated to the unregulated regime. In considering the changes in the distribution of emissions for Scenarios 3 and 5, the first item of note is that emissions in simulations under the PUC regulatory regime are less than the allocation of allowances. This is because many scrubbers receive full cost recovery under regulation. Therefore, including all those scrubbers causes the aggregate emissions constraint to be non-binding.

The results are presented in Tables 4.17 and 4.18 for Scenarios 3 and 5, respectively. The presentation allows comparison of the emissions resulting from the simulation to the allowance allocation. Because there is trading, some states will experience emissions greater than the allocation and some will experience emissions less than the allocation. It is interesting to note that trading alone results in emissions greater than allocations in some states of concern to the Northeast (Illinois, Indiana, Kentucky, Maryland, West Virginia, Ohio, Michigan, Illinois, Kentucky, Indiana, and Wisconsin.

Comparing the distribution of emissions in states of concern for the Northeast between the regulated (PUC) and unregulated (No PUC) regimes reveals emissions are higher by approximately 400,000 tons for Scenario 3 and 500,000 tons for Scenario 5 in the unregulated regime in the aggregate, although some states (Indiana, Tennessee, and Wisconsin) see emissions reductions relative to the regulated regime. In fact, emissions increase even in New York in the unregulated regime. So it appears that under these Scenarios, that the fears of northeastern states like New York could be realized under an unregulated regime.

4.6.2 Scenarios Using Actual 1996 Emissions as the Allocation

In Scenarios 2, 4, and 6 the actual emissions are used as the allocation to compute the compliance costs for achieving the 1996 emissions level. Also recall that Scenario 2 takes scrubbers as given, while Scenarios 4 and 6 allow scrubbers to be chosen. Again, the results are presented to allow comparison of the simulation allocation to the resulting emissions from the simulation exercise.

For Scenario 2 (Table 4.19) trading results in emissions levels that are less than the allocation for some states of concern to the Northeast (Illinois, Indiana, Kentucky, Ohio, Pennsylvania, and Tennessee) while emissions exceed allocations in Maryland, Michigan, Wisconsin, and West Virginia. On net, it seems that New York and other states in the Northeast are no worse off if they are impacted by SO\textsubscript{2} transport. Moreover, in moving to the unregulated regime, emissions in the states of concern to the Northeast decrease in emissions and move further away from the Northeast.

In Scenario 4 (Table 4.20) in the regulated (PUC) simulation, net emissions from states of concern for the Northeast on aggregate are about 100,000 tons less than the allocation to the benefit Northeastern states. However, moving to the unregulated environment, the simulations show that states of concern increase emissions by about 150,000 tons relative to the regulated regime. This is explained in part by scrubbers not
<table>
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<th>AE - No PUC</th>
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<td>290,987.37</td>
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<td>-45,870.37</td>
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<td>137,833.11</td>
<td>-113,453.35</td>
<td>54,230.89</td>
</tr>
<tr>
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<td>693,192.45</td>
<td>533,335.83</td>
<td>86,066.55</td>
<td>245,923.17</td>
</tr>
<tr>
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<td>39,181.97</td>
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<td>1,363.03</td>
<td>8,537.79</td>
</tr>
<tr>
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<td>647,174.85</td>
<td>-179,611.85</td>
<td>-179,611.85</td>
</tr>
<tr>
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<td>23,644.39</td>
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<tr>
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<td>-161,092.21</td>
<td>-368,148.76</td>
</tr>
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<td>-14,963.30</td>
<td>-14,963.30</td>
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<td>-32,290.29</td>
</tr>
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<td>-127,356.11</td>
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<td>1,622.53</td>
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<td>173,148.47</td>
<td>285,631.24</td>
<td>300,481.53</td>
</tr>
<tr>
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<td>169,866.71</td>
<td>-97,269.71</td>
<td>-97,269.71</td>
</tr>
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<td>5,939.15</td>
</tr>
<tr>
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<td>14,786.52</td>
<td>-5,009.28</td>
</tr>
<tr>
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<td>69,615.58</td>
</tr>
<tr>
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<td>-166,450.68</td>
<td>-100,457.16</td>
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<td>-274,111.67</td>
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<td>16,816.84</td>
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Table 4.18: Distribution of Emissions by State for Scenario 5

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<th>AE - No PUC</th>
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<td>290,987.37</td>
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<td>-45,870.37</td>
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<td>54,230.89</td>
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<td>533,335.83</td>
<td>86,066.55</td>
<td>245,923.17</td>
</tr>
<tr>
<td>IA</td>
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<td>39,181.97</td>
<td>32,007.21</td>
<td>1,363.03</td>
<td>8,537.79</td>
</tr>
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<tr>
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<td>168,405.48</td>
<td>131,013.26</td>
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<td>69,615.58</td>
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Table 4.19: Distribution of Emissions by State for Scenario 2

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<td>0.00</td>
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</table>
being installed in the unregulated regime in Indiana, Pennsylvania, and West Virginia. While emissions have increased in one area of concern to New York and the Northeast, there are notable reductions in Ohio and Wisconsin. Also notable is the fact that New York utilities themselves have doubled their emissions.

Table 4.21 shows the results for Scenario 6. Much like Scenario 4, emissions in states of concern for the Northeast have decreased relative to the allowance allocation in the regulated regime by about 165,000 tons. However, in moving to the unregulated regime, emissions in these states of increase in total by about 75,000 tons relative to the regulated regime. Yet, emissions in states of concern to the Northeast, in the unregulated regime, are about 90,000 tons lower than the allowance allocation in the unregulated regime. Like Scenario 4, the most notable decreases in emissions moving to the unregulated regime are from Ohio and Wisconsin along with a small decrease in Kentucky. This is more than offset by large increases in the unregulated regime in Pennsylvania, West Virginia and Indiana.

### 4.6.3 Discussion of Emissions Distribution Results

The simulations show that too many scrubbers have been built to comply with Title IV and that compliance costs can be reduced significantly by reducing the number of scrubbers, so it should not be surprising that emissions increase in the unregulated regime in states that provided generous regulatory treatment of scrubber costs. Intuitively, one might conclude that emissions would increase dramatically in these states and lead to increased sulfur deposition in the Northeast from SO₂ transport. However, the changes in emissions have not increased in all of these states in the simulations. This may be due in part to lower than expected abatement costs from fuel switching and better placement of scrubbers at different units than those that had previously installed scrubbers.

One way to view the results on the distribution of emissions is to compare the results to previous work. Burtraw and Mansur (1999) examine the effects of trading and banking on the distribution of emissions and resulting sulfur deposition and show...
Table 4.20: Distribution of Emissions by State for Scenario 4

<table>
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<tr>
<th>State</th>
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Table 4.21: Distribution of Emissions by State for Scenario 6

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<td>7,116.75</td>
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<td>OH</td>
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<td>-324,327.78</td>
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<td>WY</td>
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<td>16,816.84</td>
<td>16,816.84</td>
<td>12,812.16</td>
<td>12,812.16</td>
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<td>46,247.70</td>
<td>23,680.04</td>
</tr>
</tbody>
</table>

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that emissions may indeed increase over baseline allocations at the state level under a trading regime. These emissions increase by close to 160,000 tons over the baseline allocation in 1995 for the states in which New York and the Northeast have some concern. However, modeling sulfur deposition that results from these increased emissions shows that deposition does not increase “downwind” in the Northeast, as some policymakers fear. Instead, sulfur deposition increases closest to the source of emissions. In the context of this research, the results of Burtraw and Mansur along with the distribution of emissions from the simulations call into question the damage from emissions in states “upwind” of the Northeast. If increased environmental damages in the Northeast do not take place, then the least-cost solution that results from trading in an unregulated market can provide significant cost savings to many states without degradation to the environment in the Northeast.
Chapter 5

Concluding Remarks

5.1 Current Research

In this research I examine the impact of PUC regulation on the cap-and-trade market for SO$_2$ allowances created by Title IV of the 1990 CAAA. Extending previous work on SO$_2$ emissions compliance in the presence of PUC regulations by Bohi and Burtraw (1992) and Fullerton et al. (1997) among others, I allow utilities to make compliance decisions, including trading activity, in the face of an endogenously determined allowance price. Constructing a production-cost model of individual utility decision-making in the presence of PUC regulation, where utilities choose compliance options and fuel inputs to satisfy electricity demand and an emissions constraint, and then aggregating individual utility decisions allows for a characterization of the market for SO$_2$ allowances in the presence of PUC regulations. Analytically, I find that the presence of PUC regulations does not necessarily imply that the market in SO$_2$ allowances will deviate from the least-cost solution. In fact there are two types of regulatory symmetry, taking scrubbers as given, that allows the market to achieve the least-cost solution.

1. If PUCs treat all compliance options symmetrically, then regardless of the cost shares across individual utilities or states, the market will achieve the least-cost solution.
2. If PUCs “coordinate” cost-recovery rules so that allowance purchases and sales are treated symmetrically and are the same across all utilities, and fuel costs have different cost share than allowances, but are the same across utilities, the market will achieve the least-cost solution.

However, simulating a small three-utility example shows that there is great potential for significant deviations from the least-cost solution if PUCs do not coordinate and attempt to reach various, often different, public policy goals through cost-recovery treatment of compliance options. Fortunately, it seems that state PUCs often allow a pass through of all costs associated with allowances and fuels, a symmetric treatment of compliance options, so that one would expect, given scrubbers, that PUC regulations will effectively cause only small deviations from the least-cost solution.

The first analytical result is similar to the result of Bohi and Burtraw (1992), which recommends identical treatment of compliance options under some circumstances. The second result is new, although it also relies heavily on the ability of PUCs to coordinate their actions. Moreover, the first result has some interesting policy implications as the electric utility industry moves forward with restructuring or “deregulation”. That is, given that the data show most states treat fuel and allowances identically as a full pass through of costs, moving to an unregulated regime where no costs are passed through, radical changes in compliance costs or the distribution of emissions should not be expected. Of course, the above statement is with the caveat that all scrubbers be taken as given.

From a public policy perspective, there is also the issue of distribution of costs across utilities and states and the distribution of emissions across states. As Ellerman et al. (2000) point out, these policy implications have been hotly debated and are still seemingly a matter of serious consideration as seen in recent actions of the USDOJ and USEPA against utilities. It is not feasible to examine such issues analytically, but they can be examined computationally. In the small three-utility example of Chapter 3, the impact of PUC cost recovery rules can have significant impacts on the distribution of
compliance costs and emissions. Moreover, these impacts may be counter-productive to the policy goals the PUC rules were designed to promote.

Taking the analytical model and parametrizing it to data for the year 1996, I attempted to investigate the potential impacts of PUC regulations on market performance. Taking scrubbers as given, the impact of PUC regulations on the ability of the SO$_2$ market to achieve the least-cost solution is a relatively small 4.3 percent increase in compliance costs. Moreover, in all but two states, the change in compliance costs was less than 10 percent, although some states would see compliance costs increase, they increase only modestly. The change in the distribution of emissions when moving from the PUC regulatory regime to the unregulated regime also shows only very small changes, if any at all. Of the 23 states that had participating units in 1996, only six saw their emissions change. And from the perspective of those in the Northeast, the net change in emissions distribution moving from the regulated to unregulated environment leaves them better off in the sense that SO$_2$ emissions are lower in states where emissions may lead to detrimental outcomes via transport.\footnote{These are states targeted by a proposed 1999 New York law that would have forbidden allowance sales, with units participating in 1996.}

PUC regulations also affect the choice of whether to install scrubbers. In fact many states allowed pre-approval of compliance plans that included scrubbers. Therefore, taking scrubbers as given does not tell the entire story with respect to compliance costs, although allowing the option of choosing such a long-lived capital-intensive option should be viewed cautiously in the context of this model. In simulations where scrubbers were a choice variable, compliance costs increase anywhere from 31 percent to 139 percent of the least-cost solution, depending on assumptions. Moreover, where there are no PUC regulations, fewer scrubbers are generally chosen, and even more remarkably, the units installing scrubbers in the unregulated simulations are generally not those units that have already installed scrubbers. Consequently, as the mix and number of scrubbers changes, moving from the regulated regime to the unregulated regime, the distribution of costs and emissions also changes dramatically. For the emissions abatement that was
actually undertaken in 1996, compliance costs either do not change or they decrease for all states.\textsuperscript{2} With respect to the distribution of emissions, the Northeast may perceive itself to be worse off, as emissions increase in the aggregate in states that are a concern for \( \text{SO}_2 \) emissions and transport. This is mainly attributable to fewer scrubbers being installed in these “upwind” states.

To summarize, the simulations for all units participating in the \( \text{SO}_2 \) market in 1996 indicate:

1. Taking scrubbers as given, PUC regulations do not lead to large deviations from the least-cost solution.

2. However, allowing scrubbers to be a chosen compliance option shows that PUC regulations lead to potentially large deviations away from the least-cost solution.

3. When scrubbers are an option, they are generally fewer in number in the unregulated simulations, and their locations are vastly different from those chosen by utilities for compliance under Title IV.

4. Because of the change in number and location of scrubbers in the unregulated simulations, the resulting distribution of emissions could be seen as detrimental to those living in the Northeast.

5.2 Future Work and Moving Forward

The work presented here looks at one year’s compliance decisions only. However, Title IV is a program that will run continuously over many years, and PUC regulation itself is dynamic and changing as well. Therefore, many compliance decisions are inherently dynamic in nature. One possible extension of this model is to look at the impact of PUC regulation on compliance decisions made over many years. This would allow an examination of the impact of PUC regulations on allowance banking, a feature of the

\textsuperscript{2}Except in those states that are always net sellers. In this case compliance costs “increase” in that the revenues from selling may fall if the allowance price decreases.
Title IV SO$_2$ Program that was prevalent in the early years. Moreover, given the results of the simulations when scrubbers are a choice variable, it would be interesting to see how scrubber decisions change over time as states continue to contemplate restructuring (less PUC regulation of generation decisions) compared to a regime where PUC regulation is likely to remain in place. Certainly, one could surmise that the threat of restructuring in a particular state and the associated uncertainty of cost recovery might lead to decisions that differ quite substantially from the regime of certain PUC regulation. And differing allowance banking and scrubber installation decisions will clearly not only have implications for the spatial distribution of costs and emissions, but also there will now be intertemporal distribution issues that might arise from PUC regulations and the changing regulatory environment.

One associated extension of this work would be to include more stringent emissions standards that may employed at the state level to examine whether the impacts of such restrictions are greater than the impacts of PUC regulation. Another potential extension would be the inclusion of scrubber installation following the settlements the USDOJ and USEPA have reached with various utilities over NSR rules to examine the impact on compliance costs with, and without PUC regulations. Additionally, perhaps this framework could be applied to the newly created markets for nitrogen oxide (NO$_x$) emissions with an examination of joint SO$_2$ and NO$_x$ compliance decisions.

One thing seems clear in moving forward. PUC regulation of generation seems likely to stay around for some time in the wake of the California restructuring disaster. Many states that were ready to “deregulate” have either postponed or cancelled those plans for fear of seeing rates increase dramatically; other states have continued to move forward. From a policy perspective, it is important that those states that remain regulated understand the implications of PUC regulatory rules on compliance decisions and compliance costs for the utilities they regulate, and, where necessary, attempt to coordinate their actions to the greatest extent possible so that compliance costs can be minimized.
References


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Appendix A

Characterizing Supply and Demand

In this appendix a more rigorous and detailed characterization is undertaken of utility behavior discussed in Chapter 3, Sections 3.2 and 3.3, regarding demand and supply in the allowance market. In Sections A.1, A.2, and A.3 the necessary conditions for buying, selling or doing neither are given. Then in the following section sufficient conditions to characterize each case are given. As the reader will see, in most cases the necessary conditions are not sufficient to characterize a utility’s decision.

Recall from Chapter 3 the utility’s cost minimization problem:

\[
\begin{align*}
\min_{z_i,d_i,A_i^b,A_i^s,C_{ih},C_{il}} & \quad \theta_i z_i P_{iz} + P_A (d_i \beta_i A_i^b - (1 - d_i) \alpha_i A_i^s) + \gamma (P_{ih} C_{ih} + P_{il} C_{il}) \\
\text{s.t.} & \quad (1 - z_i r_i) (C_{ih} S_{ih} + C_{il} S_{il}) m \leq A_i^z + d_i A_i^b - (1 - d_i) A_i^s \\
& \quad D_i \leq (C_{ih} H_{ih} + C_{il} H_{il}) V_i \\
& \quad z_i \in \{0, 1\} \\
& \quad d_i A_i^b \geq 0 \\
& \quad (1 - d_i) A_i^s \geq 0
\end{align*}
\]

\footnote{For a discussion of such methods see Takayama (1985).}
Given the scrubber choice, the problem above can be broken into two sub-problems: 
\( d_i = 1 \) for buying and \( d_i = 0 \) for selling. Let \( \lambda_{i1} \) be the Lagrange multiplier on the 
emissions constraint A.2, and \( \lambda_{i2} \) be the Lagrange multiplier on the electricity demand 
constraint A.3. Also recall that the two sub-problems are linked through the choice of 
coal types to be used, and this linkage is important in determining whether the utility 
will be a net buyer, net seller, or a non-trader in the allowance market. Additionally, the 
multipliers from the first-order necessary conditions have two important interpretations. 
\( \lambda_{i1} \) is the shadow price of SO\(_2\) allowances for the utility, given recovery factors and 
allowance position. \( \lambda_{i2} \) is the shadow price (marginal cost) of coal type \( f \) used by the 
utility, \( f \in \{h, l\} \) per kWh of electricity produced, which includes the cost of pollution.

The first-order necessary conditions for both sub-problems will also yield the marginal 
cost of abating SO\(_2\) emissions by switching from high to low sulfur coal. The magnitude 
of the marginal cost of abatement relative to the utility’s shadow price of allowances 
(both buying and selling) will, along with the initial allowance endowment, provide suf-
ficient conditions to characterize the net allowance position the utility takes, the amount 
of allowances bought or sold, and choices regarding coal types to use to satisfy demand 
and meet its emissions constraint.

**A.1 Necessary Conditions for Buying**

Taking the scrubber choice as given and assuming the decision variable \( d_i = 1 \), the 
first-order necessary conditions for the utility’s problem are

\[
\begin{align*}
PA_i\beta_i - \lambda_{i1} & \geq 0, \quad = 0 \text{ if } A_i^b > 0 \quad (A.8) \\
\gamma_i P_{ih} + (1 - zr)S_{ih}m\lambda_{i1} - \lambda_{i2}H_{ih}V_i & \geq 0, \quad = 0 \text{ if } C_{ih} > 0 \quad (A.9) \\
\gamma_i P_{il} + (1 - zr)S_{il}m\lambda_{i1} - \lambda_{i2}H_{il}V_i & \geq 0, \quad = 0 \text{ if } C_{il} > 0 \quad (A.10)
\end{align*}
\]

As was discussed in Chapter 3, Section 3.2, there are three cases to consider when
buying: buying and using only high sulfur coal, buying and using only low sulfur coal, and buying and using both kinds of coal. In what follows $i$ subscripts and $b$ superscripts have been dropped to reduce clutter.

**A.1.1 Case 1b: $A^b > 0, A^s = 0, C_h > 0, C_l = 0$**

From the first-order conditions we get

$$\gamma P_h + (1 - zr)S_h m \beta P_A - \lambda_2 H_h V \leq \gamma P_l + (1 - zr)S_l m \beta P_A - \lambda_2 H_l V.$$  

Rearranging this equation we get the following restriction on the relationship between the allowance price and other parameters:

$$\beta P_A \leq \frac{\gamma (P_l/H_l - P_h/H_h)}{(1 - zr)m(S_h/H_h - S_l/H_l)} = MCA,$$  \hspace{1cm} \text{(A.11)}

where $\frac{\gamma (P_l/H_l - P_h/H_h)}{(1 - zr)m(S_h/H_h - S_l/H_l)}$ equals the marginal cost of abatement ($MCA$) switching from high to low sulfur coal. The effective cost of purchasing an allowance is less than or equal to the marginal cost of reducing emissions by fuel switching. Furthermore, this case implies a restriction on the endowment of allowances. High sulfur coal is used exclusively and the maximum amount used is $C_h = D/H_h V = C_{h}^{\text{max}}$. Moreover, since the utility is a net buyer using all high sulfur coal, the restriction on the allowance endowment is

$$A^e < (1 - zr)\left(\frac{D}{H_h V} S_h m\right) = SO_{2}^{\text{max}}.$$  \hspace{1cm} \text{(A.12)}

**A.1.2 Case 2b: $A^b > 0, A^s = 0, C_h = 0, C_l > 0$**

From the first-order conditions we get

$$\gamma P_h + (1 - zr)S_h m \beta P_A - \lambda_2 H_h V \geq \gamma P_l + (1 - zr)S_l m \beta P_A - \lambda_2 H_l V.$$  

Rearranging this equation we get the following restriction on the relationship between the allowance price and other parameters:

$$\beta P_A \geq \frac{\gamma (P_l/H_l - P_h/H_h)}{(1 - zr)m(S_h/H_h - S_l/H_l)} = MCA$$  \hspace{1cm} \text{(A.13)}

The effective cost of purchasing an allowance is greater than or equal to the marginal cost of reducing emissions by fuel switching. But the utility must purchase allowances to
meet its emissions constraint even when it switches to all low sulfur coal, which implies a restriction on the allowance endowment of

\[ A^e < (1 - zr)(\frac{D}{H_i V} S_l m) = SO^2_{min}. \]  

(A.14)

A.1.3 Case 3b: \( A^b > 0, A^e = 0, C_h > 0, C_l > 0 \)

From the first-order conditions we get

\[ \gamma P_h + (1 - zr)S_h m \beta P - \lambda_2 H_i V = \gamma P_l + (1 - zr)S_l m \beta P - \lambda_2 H_i V \]

Rearranging this equation we get the following restriction on the relationship between the allowance price and other parameters.

\[ \beta P = \frac{\gamma(P_l/H_l - P_h/H_h)}{(1 - zr)m(S_h/H_h - S_l/H_l)} = MCA \]  

(A.15)

The effective cost of purchasing an allowance is equal to the marginal cost of reducing emissions by fuel switching. Since in this case \( A^e + A^b = (1 - zr)(C_h S_h + C_l S_l) m \) and \((C_h H_h + C_l H_l) V = D\), the utility using all high sulfur coal does not have enough allowances to cover emissions, which implies a restriction on the allowance endowment of

\[ A^e < (1 - zr)(\frac{D}{H_h V} S_h m) = SO_{max}^2. \]  

(A.16)

A.2 A.2 Necessary Conditions for Selling

Taking the scrubber choice as given and assuming the decision variable \( d_i = 0 \), the first order necessary conditions for the utility’s problem are

\[ -P_A \alpha_i + \lambda_i i \geq 0, = 0 \text{ if } A^e_i > 0 \]  

(A.17)

\[ \gamma_i P_{ih} + (1 - zr)S_{ih} m \lambda_i i - \lambda_2 H_{ih} V_i \geq 0, = 0 \text{ if } C_{ih} > 0 \]  

(A.18)

\[ \gamma_i P_{il} + (1 - zr)S_{il} m \lambda_i i - \lambda_2 H_{il} V_i \geq 0, = 0 \text{ if } C_{il} > 0 \]  

(A.19)

Just as in the case of buying, there are three cases to consider when selling: selling and using only high sulfur coal, selling and using only low sulfur coal, and selling and
using both kinds of coal. In what follows, $i$ subscripts and $s$ superscripts have been dropped to reduce clutter.

**A.2.1 Case 1s: $A^b = 0, A^s > 0, C_h > 0, C_l = 0$**

From the first-order conditions we get

$$\gamma P_h + (1 - zr) S_h m \alpha P_A - \lambda_2 H_h V \leq \gamma P_l + (1 - zr) S_l m \alpha P_A - \lambda_2 H_l V.$$ 

Rearranging this equation we get the following restriction on the relationship between the allowance price and other parameters.

$$\alpha P_A \leq \frac{\gamma (P_l/H_l - P_h/H_h)}{(1 - zr)m(S_h/H_h - S_l/H_l)} = MCA$$ (A.20)

The effective revenue from selling an allowance is less than or equal to the marginal cost of reducing emissions by fuel switching. However, the utility must be endowed with more allowances than it needs when using all high sulfur coal. Therefore, it sells the excess, and the restriction on the allowance endowment is

$$A^e > (1 - zr)(D/H_h V S_h m) = SO_2^{max}.$$ (A.21)

**A.2.2 Case 2s: $A^b = 0, A^s > 0, C_h = 0, C_l > 0$**

From the first-order conditions we get

$$\gamma P_h + (1 - zr) S_h m \alpha P_A - \lambda_2 H_h V \geq \gamma P_l + (1 - zr) S_l m \alpha P_A - \lambda_2 H_l V.$$ 

Rearranging this equation we get the following restriction on the relationship between the allowance price and other parameters.

$$\alpha P_A \geq \frac{\gamma (P_l/H_l - P_h/H_h)}{(1 - zr)m(S_h/H_h - S_l/H_l)} = MCA$$ (A.22)

The effective revenue from selling an allowance is greater than or equal to the marginal cost of reducing emissions by fuel switching. Since the utility is using all low sulfur coal and it still has allowances to sell, this necessarily means the restriction on the allowance endowment is

$$A^e > (1 - zr)(D/H_l V S_l m) = SO_2^{min}.$$ (A.23)
A.2.3 Case 3s: \( A^b = 0, A^s > 0, C_h > 0, C_l > 0 \)

From the first-order conditions we get
\[
\gamma P_h + (1 - zr) S_h m \alpha P_A - \lambda_2 H_h V = \gamma P_l + (1 - zr) S_l m \alpha P_A - \lambda_2 H_l V.
\]
Rearranging this equation we get the following restriction on the relationship between the allowance price and other parameters.
\[
\alpha P_A = \frac{\gamma (P_l/H_l - P_h/H_h)}{(1 - zr)m(S_h/H_h - S_l/H_l)} = MCA \tag{A.24}
\]
The effective revenue from selling an allowance is equal to the marginal cost of reducing emissions by fuel switching. Since in this case \( A^e - A^s = (1 - zr)(C_h S_h + C_l S_l)m \) and \( (C_h H_h + C_l H_l)V = D \), the utility using all low sulfur coal must have at least enough allowances to cover emissions, which implies a restriction on the allowance endowment of
\[
A^e > (1 - zr)\left( \frac{D}{H_lV} S_l m \right) = SO_2^{\text{min}}. \tag{A.25}
\]

A.3 Necessary Conditions: No Buying or Selling

When the utility does not engage in any trading of allowances, the first-order necessary conditions to the buyer’s problem are:
\[
P_A \beta_i - \lambda_{i1} \geq 0, \quad = 0 \text{ if } A^b_i > 0, \tag{A.26}
\]
which implies that \( P_A \beta_i \geq \lambda_{i1} \).

And from the first order necessary conditions to the seller’s problem
\[
-P_A \alpha_i + \lambda_{i1} \geq 0, \quad = 0 \text{ if } A^b_i > 0, \tag{A.27}
\]
which implies that \( P_A \alpha_i \leq \lambda_{i1} \). Therefore, if a utility does not buy or sell allowances, it must be the case that the shadow price of \( SO_2 \) is less than or equal to effective purchase price, but greater than or equal to effective sale price. So, for each case, it must at least be the case that
\[
\beta P_A \geq \lambda_1 \geq \alpha P_A. \tag{A.28}
\]
A.3.1 Case 1n: \( A^b = 0, A^s = 0, C_h > 0, C_l = 0 \)

From the first-order conditions from both the buyer’s and seller’s problems we get
\[
\gamma_i P_{ih} + (1 - z_i r_i) S_h m \lambda_{i1} - \lambda_{i2} H_h V_i \leq \gamma_i P_{il} + (1 - z_i r_i) S_l m \lambda_{i1} - \lambda_{i2} H_l V_i.
\]
Rearranging these equations we get the following restriction on the relationship between the allowance price and other parameters.

\[
\lambda_{i1} \leq \frac{\gamma_i (P_{i}/H_l - P_{h}/H_h)}{(1 - z r)m(S_h/H_h - S_l/H_l)} = MCA.
\] (A.29)

This says that the shadow price of allowances is less than or equal to the marginal cost of reducing pollution from coal switching. Given the necessary conditions in equation A.28 it must be the case that the marginal cost of abatement is less than or equal to the effective selling price,

\[ MCA \geq \alpha P_A. \] (A.30)

However, it could still be the case that the marginal cost of abatement is less than, greater than, or equal to the effective buying price \( \beta P_A \).

For a utility to use all high sulfur coal and not buy or trade any allowances, the endowment of allowances must be equal to the maximum amount of emissions

\[ A^e = (1 - z r)(\frac{D}{H_h V} S_h m) = SO_2^{max}. \] (A.31)

A.3.2 Case 2n: \( A^b = 0, A^s = 0, C_h = 0, C_l > 0 \)

From the first-order conditions for both the buyer’s and seller’s problems we get
\[
\gamma_i P_{ih} + (1 - z_i r_i) S_h m \lambda_{i1} - \lambda_{i2} H_h V_i \geq \gamma_i P_{il} + (1 - z_i r_i) S_l m \lambda_{i1} - \lambda_{i2} H_l V_i.
\]
Rearranging these equations we get the following restriction on the relationship between the allowance price and other parameters.

\[
\lambda_{i1} \geq \frac{\gamma_i (P_{i}/H_l - P_{h}/H_h)}{(1 - z r)m(S_h/H_h - S_l/H_l)} = MCA.
\] (A.32)

This says that the shadow price of allowances is greater than or equal to the marginal cost of reducing pollution from coal switching. Given the necessary conditions in equa-
tion A.28 it must be the case that the marginal cost of abatement is less than or equal to the effective buying price,

\[ MCA \leq \beta P_A. \] (A.33)

Furthermore, if there is no trading and the utility uses all low sulfur coal, it must be the case that the restriction on the allowance endowment is

\[ A^e = (1 - zr)(\frac{D}{H_i V} S_l m) = SO_2^{min}. \] (A.34)

**A.3.3 Case 3n: \( A^b = 0, A^e = 0, C_h > 0, C_l > 0 \)**

From the first-order conditions for the buyer’s and seller’s problems we get

\[ \gamma_i P_{ih} + (1 - z_i r_i) S_h m \lambda_{i1} - \lambda_{i2} H_h V_i = \gamma_i P_{il} + (1 - z_i r_i) S_l m \lambda_{i1} - \lambda_{i2} H_l V_i. \] (A.35)

Rearranging these equations we get the following restriction on the relationship between the allowance price and other parameters.

\[ \lambda_{i1}^b = \frac{\gamma (P_l/H_l - P_h/H_h)}{(1 - zr)m(S_h/H_h - S_l/H_l)}. \] (A.36)

This says that the shadow price of allowances is equal to the marginal cost of reducing pollution from coal switching. Given the necessary conditions in equation A.28 it must be the case that

\[ \beta P_A \geq MCA \geq \alpha P_A. \] (A.37)

Furthermore, this case implies a restriction on the endowment of allowances since emissions are between the minimum and the maximum level from using a blend of coal, \( A^e = (1 - zr)(C_h S_h m + C_l S_l m) \). So the restriction on allowances is

\[ (1 - zr)\left(\frac{D}{H_i V} S_l m\right) < A^e < (1 - zr)\left(\frac{D}{H_i V} S_h m\right) \equiv SO_2^{min} < A^e < SO_2^{max}. \] (A.38)
A.4 Sufficient Conditions

To simplify notation, define the following for minimum emissions, maximum emissions, maximum high and low sulfur coal use, and the marginal cost of abatement, respectively (while dropping $i$ subscripts):

\[
SO_{2}^{\text{min}} = (1 - zr) \left( \frac{D}{H_iV_i} S_i m \right)
\]
\[
SO_{2}^{\text{max}} = (1 - zr) \left( \frac{D}{H_hV_h} S_h m \right)
\]
\[
C_{ih}^{\text{max}} = \frac{D_i}{H_iV_i}
\]
\[
C_{il}^{\text{max}} = \frac{D_i}{H_iV_i}
\]
\[
MCA = \frac{\gamma(P_l/H_l - P_h/H_h)}{(1 - zr)m(S_h/H_h - S_l/H_l)}.
\]

A.4.1 Allowance Demand

**Proposition A.1** Let $A^e < SO_{2}^{\text{min}}$, take the scrubber choice $z$ as given, and for all $\alpha$ and $\beta$,

(a) If $MCA > \beta P_A$ then the solution to the utility’s cost minimization problem is characterized by Case 1b: $A^b > 0, A^s = 0, C_h > 0, C_l = 0$. Moreover, $C_h = C_h^{\text{max}}$ and $A^b = SO_{2}^{\text{max}} - A^e$.

(b) If $MCA < \beta P_A$ then the solution to the utility’s cost minimization problem is characterized by Case 2b: $A^b > 0, A^s = 0, C_h = 0, C_l > 0$. Moreover, $C_l = C_l^{\text{max}}$ and $A^b = SO_{2}^{\text{min}} - A^e$.

(c) If $MCA = \beta P_A$ then the solution to the utility’s cost minimization problem is characterized by Case 1b, 2b, or 3b: $A^b > 0, A^s = 0, C_h \geq 0, C_l \geq 0$. Moreover, $A^b \in [SO_{2}^{\text{min}} - A^e, SO_{2}^{\text{max}} - A^e]$.

**Proof of Proposition A.1** Since $A^e < SO_{2}^{\text{min}}$ it is guaranteed that no matter what type of coal is used, the utility must purchase at least some allowances to meet its
emissions constraint, so $A^b > 0$ for (a), (b), and (c).

For (a), suppose the utility wishes to use low sulfur coal, $C_l > 0$. For a utility to buy and use low sulfur coal, it necessarily must be the case that $\beta P_A \geq MCA$ from Case 2b, equation A.13 in Section A.1, which contradicts the assumption that $MCA > \beta P_A$. So the utility uses high sulfur coal exclusively, $C_h = C_h^{\text{max}}$, and its emissions are at the maximum level, which implies that $A^b = SO_2^{\text{max}} - A^e$.

For (b), suppose the utility wishes to use high sulfur coal, $C_h > 0$. For a utility to buy and use high sulfur coal, it necessarily must be the case that $\beta P_A \leq MCA$ from Case 1b, equation A.11 in Section A.1, which contradicts the assumption that $MCA < \beta P_A$. So the utility uses low sulfur coal exclusively, $C_l = C_l^{\text{max}}$, and its emissions are at the minimum level, which implies that $A^b = SO_2^{\text{min}} - A^e$.

For (c), the assumptions satisfies the necessary conditions in Cases 1b, 2b, and 3b, respectively, equations A.11, A.13, and A.15 from Section A.1 for all three cases. The utility is indifferent between all high sulfur, all low sulfur, or a mix of coal types. Therefore, any coal combination minimizes cost, and emissions could be anywhere between the minimum and the maximum levels. #

**Proposition A.2** Let $A^e < SO_2^{\text{max}}$ and take the scrubber choice, $z$, as given. If for all $\alpha$ and $\beta$ such that $MCA > \beta P_A$ and $MCA \geq \alpha P_A$, then the solution to the utility’s cost minimization problem is characterized by Case 1b: $A^b > 0, A^e = 0, C_h > 0, C_l = 0$. Moreover, $C_h = C_h^{\text{max}}$ and $A^b = SO_2^{\text{max}} - A^e$.

**Proof of Proposition A.2** Suppose the utility wishes not to buy, but to either sell allowances or not trade at all and still use high sulfur coal. This is not possible since the utility does not have enough allowances to cover its emissions when using all high...
sulfur coal by assumption. So using all high sulfur coal makes the utility a buyer.

If the utility wants to use some low sulfur coal and still buy allowances, then necessarily it must be that $MCA \leq \beta P_A$ from Cases 2b and 3b, equations A.13 and A.15 in Section A.1. This contradicts the assumption that $MCA > \beta P_A$. Therefore the utility cannot use some low sulfur coal and buy.

Suppose instead the utility doesn’t trade and wants to blend coals or use all low sulfur coal. If it blends coal, it necessarily must be the case that $\beta P_A \geq MCA \geq \alpha P_A$ from Case 3n, equation A.37. However, that contradicts the assumption that $MCA > \beta P_A$, so the utility cannot blend coal and not participate in the market. If it tries to use only low sulfur coal and not trade allowances, then it must be that $MCA \leq \beta P_A$ from Case 2n, equation A.33 which also contradicts $MCA > \beta P_A$.

Finally, suppose that the utility wants to sell allowances and use low sulfur coal. Then it necessarily must be that $MCA \leq \alpha P_A$ from Cases 2s and 3s, equations A.22 and A.24 in Section A.2. If the assumption $MCA \geq \alpha P_A$ holds with a strict inequality, this results in a contradiction. However, if the assumption $MCA \geq \alpha P_A$ holds with equality, switching to low sulfur coal increases costs since the utility can buy allowances relatively less expensively than it can switch coal type, as shown below.

Suppose that when $MCA = \alpha P_A$ it will be cost minimizing to use some low sulfur coal and sell allowances instead of using all high sulfur coal and buying allowances. This assertion implies the following must hold:

$$P_A \beta (SO_2^{\text{max}} - A^e) + \gamma P_h C_h^{\text{max}} \geq -P_A \alpha A'_s + \gamma (P_h C'_h + P_l C'_l),$$  \hspace{1cm} (A.39)

where $'$ denotes the hypothetical least-cost outcome when using low sulfur coal and selling.

Now substituting $C'_h = \frac{D}{H_h V} - \frac{C'_H}{H_h}$ from the electricity demand constraint and $A'_s = A^e - (C'_h S_h + C'_i S_i) m$ from the emissions constraint into the right hand side of the equation yields the following.

$$P_A \beta (SO_2^{\text{max}} - A^e) + \gamma P_h C_h^{\text{max}} \geq -$$
\[ PA\alpha(A^e - \frac{D}{Hhv} - \frac{C'_iH_i}{H_h}S_hm + C'_iS_im) \]
\[ \gamma Ph(\frac{D}{Hhv} - \frac{C'_iH_i}{H_h}) + \gamma P_lC'_l \]

Rearranging the right hand side and exploiting the fact that \( C_{h}^{max} = \frac{D}{H_hv} \) and \( SO_{2}^{max} = \frac{D}{H_hv} S_hm \) yields the following.

\[ PA\beta(SO_{2}^{max} - A^e) + \gamma PhC_{h}^{max} \geq \]
\[ -PA\alpha A^e + PA\alpha SO_{2}^{max} - \]
\[ PA\alpha \frac{C'_iH_i}{H_h} S_hm + PA\alpha C'_iS_im + \gamma PhC_{h}^{max} - \gamma Ph \frac{C'_iH_i}{H_h} + \gamma P_lC'_l \]

Subtracting \(-PA\alpha A^e + PA\alpha SO_{2}^{max}\) and \(\gamma PhC_{h}^{max}\) from both sides of the equation and rearranging the remaining terms on the right hand side yields the following.

\[ (\alpha - \beta)PA(A^e - SO_{2}^{max}) \geq \]
\[ -PA\alpha S_hm - \gamma PhC'_iH_i + (PA\alpha S_lm + \gamma P_l)C'_l \]

Exploiting the condition \( MCA = \alpha PA \), and from the first-order necessary conditions that \( \frac{\gamma Ph + PA\alpha S_lm}{H_hv} = \frac{\gamma Ph + PA\alpha S_hm}{H_hv} \) allows the right hand side to be restated so that

\[ (\alpha - \beta)PA(A^e - SO_{2}^{max}) \geq \]
\[ -PA\alpha S_hm - \gamma PhC'_iH_i + \frac{PA\alpha S_hm + \gamma PhC'_iH_i}{H_h} \]

The terms on the right hand side cancel out, equaling zero, and the left hand side is less than zero by virtue of \( \alpha > \beta \) by assumption, so this is a contradiction. Therefore, when \( MCA = \alpha PA \) and \( MCA > \beta PA \) the utility will use all high sulfur coal and buy allowances.

**Proposition A.3** Let \( SO_{2}^{min} < A^e < SO_{2}^{max} \) and take the scrubber choice, \( z \), as given. If for all \( \alpha \) and \( \beta \) such that \( MCA = \beta PA \) and \( MCA > \alpha PA \), then the solution to the
utility’s cost minimization problem is characterized by Cases 1b, 3b, or 3n: $A^b > 0, A^s = 0, C_h > 0, C_l = 0, A^b > 0, A^s = 0, C_h > 0, C_l > 0, \text{ or } A^b = 0, A^s = 0, C_h > 0, C_l > 0$. Moreover, $A^b \in [0, SO_2^{\text{max}} - A^e]$.

**Proof of Proposition A.3** If a utility wishes to sell allowances, it must necessarily use enough low sulfur coal to facilitate allowance sales. Then it must be the case that $MCA \leq \alpha P_A$ from Cases 2s and 3s, equations A.22 and A.24 in Section A.2, which contradicts the assumption that $MCA > \alpha P_A$, so selling while using low sulfur coal is not cost minimizing. Moreover, the utility cannot sell and use all high sulfur coal since the allowance endowment is less than the maximum emissions.

Suppose that the utility wants to buy allowances, and use all low sulfur coal. This cannot happen, since the allowance endowment must necessarily be less than the minimum emissions level in Case 2b, equation A.14. Moreover, using all low sulfur coal would put the utility in the position of selling allowances, which would violate equation A.22 by assumption. Therefore, the utility must use at least some high sulfur coal.

Suppose the utility wants to neither buy nor sell allowances. It cannot use all high sulfur coal or all low sulfur coal since the endowment must necessarily exactly equal the minimum or maximum emissions level, as in Cases 1n and 2n, equations A.34 and A.38. Since the $MCA = \beta P_A$, the utility is indifferent between buying allowances and blending fuels. Moreover, since selling allowances is ruled out, and using all low sulfur coal has been ruled out, this leaves the utility with either blending fuels and buying allowances, blending and not buying or selling allowances, or using all high sulfur coal and buying allowances, which are the only options that cannot be ruled out.

**A.4.2 Allowance Supply**

**Proposition A.4** Let $A^e > SO_2^{\text{max}}$, take the scrubber choice, $z$, as given, and for all $\alpha$ and $\beta$,

(a) If $MCA > \alpha P_A$ then the solution to the utility’s cost-minimization problem is characterized by Case 1s: $A^b = 0, A^s > 0, C_h > 0, C_l = 0$. Moreover, $C_h = C_h^{\text{max}}$ and
\[ A^s = A^e - SO_2^{\text{max}}. \]

(b) If \( MCA < \alpha P_A \) then the solution to the utility’s cost-minimization problem is characterized by Case 2s: \( A^b = 0, A^s > 0, C_h = 0, C_l > 0 \). Moreover, \( C_l = C_l^{\text{max}} \) and \( A^s = A^e - SO_2^{\text{min}} \).

(c) If \( MCA = \alpha P_A \) then the solution to the utility’s cost-minimization problem is characterized by Case 1s, 2s, or 3s: \( A^b = 0, A^s > 0, C_h \geq 0, C_l \geq 0 \). Moreover, \( A^s \in [A^e - SO_2^{\text{max}}, A^e - SO_2^{\text{min}}] \).

Proof of Proposition A.4 Since \( A^e > SO_2^{\text{max}} \) it is guaranteed that no matter what type of coal is used, the utility has more than enough allowances to meet its emissions constraint, so \( A^s > 0 \) for (a), (b), and (c).

For (a), suppose the utility wishes to use low sulfur coal, \( C_l > 0 \). For a utility to sell allowances and use low sulfur coal, it must necessarily be the case that \( \alpha P_A \geq MCA \) from Case 2s, equation A.22 in Section A.2, which contradicts the assumption that \( MCA > \alpha P_A \). So the utility uses high sulfur coal exclusively, \( C_h = C_h^{\text{max}} \), and its emissions are at the maximum level, which implies that \( A^s = A^e - SO_2^{\text{max}} \).

For (b), suppose the utility wishes to use high sulfur coal, \( C_h > 0 \). For a utility to sell allowances and use high sulfur coal, it must necessarily be the case that \( \alpha P_A \leq MCA \) from Case 1b, equation A.20 in Section A.2, which contradicts the assumption that \( MCA < \alpha P_A \). So the utility uses low sulfur coal exclusively, \( C_l = C_l^{\text{max}} \), and its emissions are at the minimum level, which implies that \( A^s = A^e - SO_2^{\text{min}} \).

For (c), the assumption satisfies the necessary conditions in Cases 1s, 2s, and 3s, equations A.20, A.22, and A.24, respectively, from Section A.2 for all three cases. The utility is indifferent between all high sulfur, all low sulfur, or a mix of coal types. Therefore, any coal combination minimizes cost, and emissions could anywhere between the minimum and maximum levels. #
**Proposition A.5** Let $A^e > SO_2^{min}$ and take the scrubber choice, $z$, as given. If for all $\alpha$ and $\beta$ such that $MCA \leq \beta P_A$ and $MCA < \alpha P_A$, then the solution to the utility’s cost-minimization problem is characterized by Case 2s: $A^b = 0, A^s > 0, C_h = 0, C_l > 0$. Moreover, $C_l = C_i^{\text{max}}$ and $A^s = A^e - SO_2^{min}$.

**Proof of Proposition A.5** Suppose the utility wishes not to sell allowances, but to either buy or not trade at all and still use all low sulfur coal. This is not possible since it will emit $SO_2^{min}$ if it uses all low sulfur coal. Using all low sulfur coal makes the utility a seller.

Suppose the utility wants to use some high sulfur coal and still sell allowances, then it must necessarily be that $MCA \geq \alpha P_A$ from Cases 1s and 3s, equations A.20 and A.24 in Section A.2, which contradicts the assumption that $MCA < \alpha P_A$. Therefore the utility cannot use any high sulfur coal and sell.

Suppose the utility would not trade allowances and would either blend coals or use only high sulfur coal. Then it must be that $MCA \geq \alpha P_A$ from Cases 1n and 3n, equations A.30 and A.37, but this contradicts $MCA < \alpha P_A$.

Finally, suppose that the utility wants to buy and use some high sulfur coal. Then it must necessarily be that $MCA \geq \beta P_A$ from equation A.11 in Section A.1. If the assumption $MCA \leq \beta P_A$ holds with a strict inequality, then this is a contradiction. But if $MCA \leq \beta P_A$ holds with equality, using high sulfur coal, as will be shown below, increases costs since the utility can sell allowances relatively less expensively than it can switch coal types.

Suppose that when $MCA = \beta P_A$ it will be cost minimizing to use some high sulfur coal and buy allowances instead of using all low sulfur coal and selling allowances. This assertion implies the following must hold:

$$-P_A \alpha(A^e - SO_2^{min}) + \gamma P_l C_i^{\text{max}} \geq P_A \beta A^b + \gamma (P_h C_h^i + P_l C_l^i),$$  \hspace{1cm} (A.40)
where ′ denotes the hypothetical least-cost outcome when using high sulfur coal and buying.

Now substituting \( C'_t = \frac{D}{H_lV} - \frac{C'_hH_h}{H_l} \) from the electricity demand constraint and \( A'_b = (C'_hS_h + C'_lS_l)m - A^e \) from the emissions constraint into the right hand side of the equation yields the following.

\[
-P_A\alpha(A^e - SO_2^{min}) + \gamma P_lC'^{max}_l \geq P_A\beta\left([\frac{D}{H_lV} - \frac{C'_hH_h}{H_l}]S_l m + C'_hS_h m - A^e\right) \\
+\gamma P_h\left(\frac{D}{H_lV} - \frac{C'_hH_h}{H_l}\right) + \gamma P_hC'_h
\]

Rearranging the right hand side and exploiting the fact that \( C'^{max}_l = \frac{D}{H_lV} \) and \( SO_2^{min} = \frac{D}{H_lV}S_l m \) yields the following.

\[
-P_A\beta(A^e - SO_2^{min}) + \gamma P_lC'^{max}_l \geq -P_A\beta A^e + P_A\beta SO_2^{min} \\
-P_A\beta\frac{C'_hH_h}{H_l}S_l m + P_A\beta C'_hS_h m + \gamma P_lC'^{max}_l - \gamma P_l\frac{C'_hH_h}{H_l} + \gamma P_hC'_h
\]

Subtracting \(-P_A\beta A^e + P_A\alpha SO_2^{min} \) and \( \gamma P_lC'^{max}_l \) from both sides of the equation and rearranging the remaining terms on the right hand side yields the following.

\[
(\alpha - \beta)P_A(SO_2^{min} - A^e) \geq \\
\frac{-P_A\beta S_l m - \gamma P_lC'_hH_h + P_A\beta S_h m + \gamma P_hC'_h}{H_l}
\]

Exploiting the condition \( MCA = \beta P_A \), and from the first-order necessary conditions \( \frac{\gamma P_l + P_A\beta S_l m}{H_l V} = \frac{\gamma P_h + P_A\beta S_h m}{H_h V} \), allows the right hand side to be restated so that

\[
(\alpha - \beta)P_A(SO_2^{min} - A^e) \geq \\
\frac{-P_A\beta S_l m - \gamma P_lC'_hH_h + P_A\beta S_h m + \gamma P_hC'_h}{H_l}
\]

The terms on the right hand side cancel out, equaling zero, and the left hand side is less than zero by virtue of \( \alpha > \beta \) by assumption, so this is a contradiction. Therefore,
when $MCA = \beta P_A$ and $MCA < \alpha P_A$, the utility will use all low sulfur coal and sell allowances.#

**Proposition A.6** Let $SO_2^{\text{min}} < A^e < SO_2^{\text{max}}$ and take the scrubber choice, $z$, as given. If $MCA < \beta P_A$ and $MCA = \alpha P_A$, for all $\alpha$ and $\beta$, then the solution to the utility’s cost-minimization problem is characterized by Cases 2s, 3s, or 3n: $A^b = 0, A^s \geq 0, C_h \geq 0, C_l \geq 0$. Moreover, $A^e \in [0, A^e - SO_2^{\text{min}}]$.

**Proof of Proposition A.6** If the utility wishes to buy allowances, it necessarily must use enough high sulfur coal to cause the need for allowance buying, so it must be the case that $MCA \geq \beta P_A$ from Cases 1b and 3b, equations A.11 and A.15 in Section A.1. Since this contradicts the assumption that $MCA < \beta P_A$, buying is not cost minimizing. Moreover, to buy and use all low sulfur coal requires $A^e < SO_2^{\text{min}}$, which has been ruled by assumption.

Suppose that the utility wants to sell allowances and use all high sulfur coal. This cannot happen since the assumption $A^e < SO_2^{\text{max}}$ violates equation A.21 in Case 1s. Moreover, using all high sulfur coal would put the utility in the position of buying allowances, which would violate equation A.11 by assumption. Therefore, the utility must use at least some low sulfur coal.

Suppose the utility does not trade allowances and uses either high or low sulfur coal exclusively. Then the necessary conditions for allowances from Cases 1n and 2n, equations A.31 and A.34 violate the assumption that $SO_2^{\text{min}} < A^e < SO_2^{\text{max}}$. Since the $MCA = \alpha P_A$, the utility is indifferent between selling allowances and blending fuels. Moreover, since buying is ruled out and using all high sulfur coal has been ruled out, the utility is left with blending fuels and selling, blending and not buying or selling, or using all low sulfur coal and selling. These are the only options that cannot be ruled out.#
A.4.3 No Trading

**Proposition A.7** Let $A^e = SO_2^{min}$ and take the scrubber choice, $z$, as given. If $\beta P_A > MCA > \alpha P_A$, then the cost-minimizing solution can be characterized by Case 2n: $A^b = 0, A^e = 0, C_h = 0, C_l > 0$. Moreover, $C_l = C_l^{max}$.

**Proof of Proposition A.7** Suppose the utility is a buyer of allowances and uses some high sulfur coal. Then it must be from Cases 1b and 3b, equations A.11 and A.15 that $MCA \geq \beta P_A$. However, this contradicts the assumption that $\beta P_A > MCA$. So the utility cannot buy and use any high sulfur coal. Moreover, it cannot buy allowances and use all low sulfur coal since the necessary condition for allowance endowment is $A^e < (1 - zr)(\frac{D_{HV}}{M} S_{lm}) = SO_2^{min}$ from Case 2b, equation A.14, which violates the assumption on allowance endowment of $A^e = SO_2^{min}$.

Suppose the utility sells allowances and uses all low sulfur coal. Then it must be that $A^e > SO_2^{min}$ from Case 2s, equation A.23. However, if it sells allowances and uses some high sulfur coal, then necessarily $\alpha P_A \geq MCA$ from Cases 2s and 3s, equations A.22 and A.24. Because this violates the assumption that $MCA > \alpha P_A$, the utility cannot be a seller of allowances.

Finally, suppose the utility does not trade allowances and uses some high sulfur coal. The assumption on allowances violates the necessary conditions in Cases 1n and 3n, equations A.31 and A.38.

**Proposition A.8** Let $A^e = SO_2^{max}$ and take the scrubber choice, $z$, as given. If $\beta P_A > MCA > \alpha P_A$, then the cost-minimizing solution can be characterized by Case 1n: $A^b = 0, A^e = 0, C_h > 0, C_l = 0$. Moreover, $C_h = C_h^{max}$.

**Proof of Proposition A.8** Suppose the utility is a seller of allowances and uses some low sulfur coal. Then it must be the case that $MCA \leq \alpha P_A$, from Cases 2s and 3s, equations A.22 and A.24. But this contradicts the assumption that $\alpha P_A < MCA$. So the utility cannot sell allowances and use any low sulfur coal. Moreover, it cannot sell and use all high sulfur coal since the necessary condition for allowance endowment is
\(A^e > (1 - zr)(\frac{D}{DhV}S_hm) = SO_{2}^{max}\) from Case 1s, equation A.21, which violates the assumption on allowance endowment of \(A^e = SO_{2}^{max}\).

Suppose the utility is a buyer of allowances and uses all high sulfur coal. Then it must be the case that \(A^e < SO_{2}^{min}\) from Case 2b, equation A.14. However, if the utility buys allowances and uses some high sulfur coal, then necessarily \(\beta P_A \leq MCA\) from Cases 1b and 3b, equations A.11 and A.15. However, this violates the assumption that \(MCA < \beta P_A\); therefore, the utility cannot be a buyer of allowances.

Finally, suppose the utility does not trade allowances and uses some low sulfur coal. The assumption on allowances violates the necessary conditions in Cases 2n and 3n, equations A.34 and A.38.\

**Proposition A.9** Let \(SO_{2}^{min} < A^e < SO_{2}^{max}\) and take the scrubber choice, \(z\), as given. If \(\beta P_A > MCA > \alpha P_A\), for all \(\alpha\) and \(\beta\), then the solution to the utility’s cost-minimization problem is characterized by Case 3n: \(A^b = 0, A^e = 0, C_h > 0, C_l > 0\).

**Proof of Proposition A.9** Suppose the utility buys allowances and uses some high sulfur coal. Then it must be the case that \(MCA \geq \beta P_A\), from Cases 1b and 3b, equations A.11 and A.15. But this contradicts the assumption that \(\beta P_A > MCA\), so the utility cannot buy allowances and use any high sulfur coal. Moreover, it cannot buy allowances and use all low sulfur coal since the necessary condition for allowance endowment is \(A^e < (1 - zr)(\frac{D}{DhV}S_hm) = SO_{2}^{min}\) from Case 2b, equation A.14, which violates the assumption on allowance endowment.

Suppose the utility sells allowances and uses all high sulfur coal. Then it must be the case that \(A^e > SO_{2}^{max}\) from Case 1s, equation A.21, which violates the assumption on the allowance endowment. However, if the utility sells allowances and uses some low sulfur coal, then necessarily \(\alpha P_A \geq MCA\) from Cases 2s and 3s, equations A.22 and A.24, which violates the assumption that \(MCA > \alpha P_A\). Therefore, the utility cannot be a seller of allowances.

Finally, suppose the utility does not trade allowances and uses only either high or low sulfur coal exclusively. The assumption on allowances violates the necessary conditions
in Cases 1n and 2n, equations A.31 and A.34.

A.5 Utility behavior when $\alpha > \beta$

A utility has incentives to both buy and sell allowances if $\alpha P_A > MCA > \beta P_A$, which possibly leads it to buy as many allowances as it can and turn around and sell them. There is an arbitrage opportunity available since the effective purchase price is below the effective sale price. However, such arbitrage has been ruled out by requiring the utility to be only a net buyer or a net seller. Therefore, it is the net position after transactions that are affected by PUC cost recovery rules. No problems with nonconvexities arise if the utility has an endowment of allowances greater than the upper bound on emissions or below the lower bound on emissions. These respective situations constrain a utility to be either a net buyer or seller.

What a utility will do if its allowance endowment is between the upper and lower bound on emissions will now be considered. Recall that the marginal cost of emissions abatement from switching to low sulfur coal from high sulfur coal is

$$\frac{\gamma(P_l/H_l-P_h/H_h)}{(1-zr)m(S_h/H_h-S_l/H_l)} = MCA.$$ 

Also, let the endowment of allowances be between the upper and lower bounds on emissions: $SO_{2 min}^c = (1-zr)(\frac{D}{\eta V} S_l m) < A^c < (1-zr)(\frac{D}{\eta V} S_h m) = SO_{2 max}^c$.

**Proposition A.10** If the utility’s allowance endowment is between the minimum and maximum emissions level ($A^c \in (SO_{2 min}^c, SO_{2 max}^c)$) and for $\alpha > \beta$, $MCA \in (\beta P_A, \alpha P_A)$, the utility will either use all high sulfur coal and buy the maximum number of allowances or it will use all low sulfur coal and sell the maximum number of allowances.

**Proof of Proposition A.10** From Proposition A.2, when $MCA = \alpha P_A > \beta P_A$, the utility uses all high sulfur coal and buys the maximum number of allowances, and from Proposition A.5, when $\alpha P_A > \beta P_A = MCA$, the utility will use all low sulfur coal and sell the maximum number of allowances. What remains is to show that when
$MCA \in (\beta P_A, \alpha P_A)$, the utility either uses only high sulfur coal and buys allowances or uses only low sulfur coal and sells allowances.

The utility cannot use all low sulfur coal and either buy or not trade allowances because that would require the allowance endowment to be greater than or equal to the minimum emissions level, which violates the assumption that $A^e \in (SO_2^{min}, SO_2^{max})$. Similarly, the utility cannot use all high sulfur coal and either buy or not trade allowances since this would require the allowance endowment to be greater than or equal to the maximum emissions level, also violating the assumption on allowance endowment.

Suppose the utility wants to either buy allowances and blend coal or sell allowances and blend coal. Necessarily, the marginal cost of abatement must equal the effective buying or selling price, respectively, which violates the assumption that $MCA \in (\beta P_A, \alpha P_A)$. Moreover, the utility will never blend coal types and not trade allowances since that requires $MCA \in (\alpha P_A, \beta P_A)$ and $\alpha \leq \beta$. 

With the possible outcomes established, the next task is to find a price, $\Pi_A^* \in (\beta P_A, \alpha P_A)$ such that the cost of using all high sulfur coal and buying allowances is equal to the cost of using all low sulfur coal and selling allowances.

**Theorem A.1** If $\alpha > \beta$ and $\alpha P_A > MCA > \beta P_A$, then there exists $\Pi_A^* \in (MCA/\alpha, MCA/\beta)$ such that

$$\Pi_A^* \beta A^b_{max} + \gamma (P_h C^\max_h) = -\Pi_A^* \alpha A^s_{max} + \gamma (P_l C^\max_l),$$

where $A^b_{max} = (1 - zr)(\frac{D}{H_{Hh}} S_{Hh} m) - A^e$,

$A^s_{max} = A^e - (1 - zr)(\frac{D}{H_{Hl}} S_{Hl} m)$,

$C^\max_h = \frac{D}{H_{Hh}}$,

and $C^\max_l = \frac{D}{H_{Hl}}$. 

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Proof of Theorem A.1
If there does exist such a $\Pi^*_A$, then substituting in terms for the maximum amounts of coal and allowances bought and sold and then solving for $\Pi^*_A$ yields

$$\Pi^*_A = \frac{(D/V)\gamma(P_l/H_l - P_h/H_h)}{(D/V)(1 - zr)m(\beta S_h/H_h - \alpha S_l/H_l) + A^e(\alpha - \beta)}$$

Now it is necessary to verify that $\Pi^*_A$ lies in the interval $(MCA/\alpha, MCA/\beta)$. If so, the proof is complete. It suffices to show now that $\Pi^*_A - MCA/\alpha$ is greater than zero, that $MCA/\beta - \Pi^*_A$ is greater than zero, and that $\Pi^*_A \in (MCA/\alpha, MCA/\beta)$. 

$$\Pi^*_A - MCA/\alpha = \frac{(D/V)\gamma(P_l/H_l - P_h/H_h)}{(\alpha - \beta)A^e + (D/V)(1 - zr)m(\beta S_h/H_h - \alpha S_l/H_l) - \frac{\gamma(P_l/H_l - P_h/H_h)}{\alpha(1 - zr)m(S_h/H_h - S_l/H_l)} - \frac{\gamma(P_l/H_l - P_h/H_h)}{\alpha(1 - zr)m(S_h/H_h - S_l/H_l)}$$

Multiplying both the numerator and denominator of $MCA/\alpha$ by $D/V$ will yield terms on the right hand side with identical numerators. Therefore, it suffices to show that the denominator of $P^*_A$ is less than the denominator of $MCA/\alpha$, which would imply that $\Pi^*_A - MCA/\alpha > 0$ since the numerators in both terms are equal.

If the denominator of $\Pi^*_A$ is greater than or equal to the denominator of $MCA/\alpha$, then the following holds.

$$(\alpha - \beta)A^e + (D/V)(1 - zr)m(\beta S_h/H_h - \alpha S_l/H_l) \geq \alpha(D/V)(1 - zr)m(S_h/H_h - S_l/H_l)$$

Canceling terms yields:

$$A^e \geq (1 - zr)(\frac{D}{H_hV}S_hm),$$

which is a contradiction of the assumption that $A^e < (1 - zr)(\frac{D}{H_hV}S_hm)$. Therefore $\Pi^*_A - MCA/\alpha > 0$. Now, it remains to verify that $MCA/\beta - \Pi^*_A$ is greater than zero.
\[ MCA/\beta - P^*_A = \frac{\gamma(P_l/H_l - P_h/H_h)}{\beta(1 - zr) m(S_h/H_h - S_l/H_l)} - \frac{(D/V)\gamma(P_l/H_l - P_h/H_h)}{(\alpha - \beta)A^e + (D/V)(1 - zr)m(\beta S_h/H_h - \alpha S_l/H_l)} \]

Multiplying both the numerator and denominator of \( MCA/\beta \) by \( D/V \) yields terms on the right hand side with equal numerators. Therefore, it suffices to show that the denominator of \( \Pi^*_A \) is greater than the denominator of \( MCA/\beta \), which would imply \( MCA/\beta - \Pi^*_A > 0 \) since the numerators in both terms are equal.

Suppose that the denominator of \( \Pi^*_A \) is less than or equal to the denominator of \( MCA/\beta \). Then the following holds

\[
(\alpha - \beta)A^e + (D/V)(1 - zr)m(\beta S_h/H_h - \alpha S_l/H_l) \leq \beta(D/V)(1 - zr)m(S_h/H_h - S_l/H_l).
\]

Canceling terms yields:

\[ A^e \geq (1 - zr)(\frac{D}{H_lV} S_l m), \]

which is a contradiction of the assumption that \( A^e < (1 - zr)(\frac{D}{H_lV} S_l m) \). Therefore, \( MCA/\beta - \Pi^*_A \) greater than zero. #

**Corollary A.1** For all \( P \in [MCA/\alpha, MCA/\beta] \) such that \( P < \Pi^*_A \), the utility will buy as many allowances as it can and use only high sulfur coal. That is, \( P\beta A^b_{max} + \gamma(P_hC^h_{max}) < -P\alpha A^s_{max} + \gamma(P_lC^l_{max}) \).

**Proof**

By contradiction. Suppose it is the case that \( P \in [MCA/\alpha, MCA/\beta] \) such that \( P < \Pi^*_A \), and have the following hold: \( P\beta A^b_{max} + \gamma(P_hC^h_{max}) \geq -P\alpha A^s_{max} + \gamma(P_lC^l_{max}) \).

This implies that \( P \geq \frac{\gamma(P_lC^l_{max} - P_hC^h_{max})}{\beta A^b_{max} + \alpha A^s_{max}} \). However, by assumption we have \( P < \Pi^*_A = \frac{\gamma(P_lC^l_{max} - P_hC^h_{max})}{\beta A^b_{max} + \alpha A^s_{max}} \), which is a contradiction. #
**Corollary A.2** For all $P \in [MCA/\alpha, MCA/\beta]$ such that $P > \Pi^*_A$, the utility will sell as many allowances as it can and use only high sulfur coal. That is, $P\beta A^b_{\text{max}} + \gamma(P_h C^\text{max}_h) > -P\alpha A^s_{\text{max}} + \gamma(P_l C^\text{max}_l)$.

**Proof** By contradiction. Suppose it is the case that $P \in [MCA/\alpha, MCA/\beta]$ such that $P > \Pi^*_A$, and have the following hold: $P\beta A^b_{\text{max}} + \gamma(P_h C^\text{max}_h) \leq -P\alpha A^s_{\text{max}} + \gamma(P_l C^\text{max}_l)$.

This implies that $P \leq \frac{\gamma(P_l C^\text{max}_l - P_h C^\text{max}_h)}{\beta A^b_{\text{max}} + \alpha A^s_{\text{max}}}$. However, by assumption we have $P > \Pi^*_A = \frac{\gamma(P_l C^\text{max}_l - P_h C^\text{max}_h)}{\beta A^b_{\text{max}} + \alpha A^s_{\text{max}}}$, which is a contradiction. #

From Propositions A.2 and A.5, Proposition A.10, Theorem A.1, and Corollaries A.1 and A.2, it is possible to construct the demand and supply for this utility.

$$A^b = \begin{cases} SO^\text{max}_2 - A^e & \text{if } P_A \leq \Pi^*_A \\ 0 & \text{if } P_A \geq \Pi^*_A \end{cases}$$

Note that this demand is upper semicontinuous at $\Pi^*_A$ but is not convex-valued at $\Pi^*_A$. The demand makes a discrete jump at this price. See Figure 3.

$$A^s = \begin{cases} 0 & \text{if } P_A \leq \Pi^*_A \\ A^e - SO^\text{min}_2 & \text{if } P_A \geq \Pi^*_A \end{cases}$$

Much like the demand in this case, the supply is upper semicontinuous at $\Pi^*_A$, but is not convex-valued at $\Pi^*_A$. Note the discrete jump. See Figure 6.
Appendix B

Theoretical Market Results

B.1 Conditions for Existence of an Equilibrium

Theorem 3.1
Take all scrubbers as given. If there does not exist a utility $j$ such that $\alpha_j > \beta_j$ and $SO_{2i}^{min} < A_j^e < SO_{2i}^{max}$, then an equilibrium exists for the SO$_2$ allowance market.

Proof of Theorem 3.1
The proof is an application of Kakutani’s Fixed Point Theorem which states:

If $S$ is a non-empty, compact, convex subset of $R^m$ and if $\phi$ is an upper semicontinuous correspondence from $S$ into itself such that $\forall x \in S$ the set $\phi(x)$ is non-empty and convex, then $\phi$ has a fixed point. See Debreu (1959) p. 26.

The remainder of the proof follows Debreu (1959), Theorem 1, p. 82-83.

Taking all other parameters as given, for each utility $i$, allowance demand and allowance supply is a function of the allowance price: $A_i^d(P_A)$ and $A_i^s(P_A)$, and could take on the following forms under the assumptions of the theorem.

When $A_i^e < SO_{2i}^{min}$, and for all values of $\alpha$ and $\beta$ demand is
\[ A_b^i = \begin{cases} 
SO_{2i}^{\min} - A^e_i & \text{if } \beta_i P_A > MCA_i \\
\rho SO_{2i}^{\max} + (1 - \rho) SO_{2i}^{\min} - A^e_i & \text{if } \beta_i P_A = MCA_i, \forall \rho \in [0, 1] \\
SO_{2i}^{\max} - A^e_i & \text{if } \beta_i P_A < MCA_i 
\end{cases} \]  

When \( SO_{2i}^{\min} \leq A^e_i \leq SO_{2i}^{\max} \), and for \( \beta \geq \alpha \), demand has the following form.

\[ A_b^i = \begin{cases} 
0 & \text{if } \beta_i P_A > MCA_i > \alpha P_A \\
\rho(SO_{2i}^{\max} - A^e_i) & \text{if } \beta_i P_A = MCA_i > \alpha P_A, \forall \rho \in [0, 1] \\
SO_{2i}^{\max} - A^e_i & \text{if } \beta_i P_A < MCA_i \text{ and } MCA \geq \alpha P_A 
\end{cases} \]

When \( A^e_i > SO_{2i}^{\max} \) and for all values of \( \alpha \) and \( \beta \), the supply is

\[ A_s^i = \begin{cases} 
A^e_i - SO_{2i}^{\max} & \text{if } \alpha_i P_A < MCA_i \\
A^e_i - [\rho SO_{2i}^{\max} + (1 - \rho) SO_{2i}^{\min}] & \text{if } \alpha_i P_A = MCA_i, \forall \rho \in [0, 1] \\
A^e_i - SO_{2i}^{\min} & \text{if } \alpha_i P_A > MCA_i 
\end{cases} \]

The second case for the supply is when \( SO_{2i}^{\min} \leq A^e_i \leq SO_{2i}^{\max} \) and for \( \beta \geq \alpha \). It has the following form.

\[ A_s^i = \begin{cases} 
0 & \text{if } \alpha_i P_A < MCA_i < \beta_i P_A \\
\rho(A^e_i - SO_{2i}^{\min}) & \text{if } \alpha_i P_A = MCA_i < \beta_i P_A, \forall \rho \in [0, 1] \\
A^e_i - SO_{2i}^{\min} & \text{if } \alpha_i P_A > MCA_i \text{ and } MCA \leq \beta_i P_A 
\end{cases} \]

Define the excess demand correspondence for each \( i \),

\[ E_i(P_A) = A_b^i(P_A) - A_s^i(P_A). \]

Define the market excess demand correspondence as

\[ E(P_A) = \sum_{i=1}^{l} E_i(P_A). \]
The market excess demand is bounded above by the sum of maximum emissions minus allowance endowments and below by the negative of the sum of allowance endowments minus minimum emissions so that excess demand must lie on the closed interval 

\[-\sum_{i=1}^{l} A_{i}^e - SO_{2i}^{min}, \sum_{i=1}^{l} SO_{2i}^{max} - A_{i}^e]\]

which will be defined as the set X. X being an closed interval on the real line is non-empty, compact, and convex.

To ensure that the space of prices is compact, bound the set of prices so that this set is compact. So define \(P^{upper} = 2\arg\min\{E(P_A)\}\) so that the space of prices is the closed interval on the real line \([0, P^{upper}]\) which is also clearly non-empty, compact, and convex.

Therefore \(E(P)\), the market excess demand, is a mapping from \([0, P^{upper}]\) into X.

To show that \(E(P)\) is non-empty, convex valued at each \(P \in [0, P^{upper}]\) and upper semicontinuous, it suffices to show that each individual demand and supply correspondence is non-empty, convex valued and upper semicontinuous since the sum of a finite number of non-empty, convex valued, upper semicontinuous correspondences is also non-empty, convex valued, and upper semicontinuous.

If the individual demands and supplies, \(A_{i}^b(P_A)\) and \(A_{i}^s(P_A)\), are defined to be mappings from \([0, P^{upper}]\) into X, they are clearly non-empty by construction. Additionally, the graphs of \(A_{i}^b(P_A)\) and \(A_{i}^s(P_A)\) are closed since X is compact, so \(A_{i}^b(P_A)\) and \(A_{i}^s(P_A)\) upper semicontinuous for all \(i\). Finally, \(A_{i}^b(P_A)\) and \(A_{i}^s(P_A)\) are either single valued or interval valued, hence they are convex valued as well.

Now, define the mapping \(\mu(x)\) from X into \([0, P^{upper}]\) such that

\[
\mu(x) = \begin{cases} 
\{ P \in [0, P^{upper}] : P x = \max_{Q \in [0, P^{upper}]} Q x \} & \text{if } x \neq 0 \\
\{ P \in [0, P^{upper}] : P x = 0 \} & \text{if otherwise} 
\end{cases}
\]

Since \([0, P^{upper}]\) is non-empty, \(\mu(x)\) must also be non-empty. \(\mu(x)\) is also convex valued at each \(p \in [0, P^{upper}]\) since for \(x = 0, \mu(x) = [0, P^{upper}]\), for \(x > 0, \mu(x) = P^{upper}\) and for \(x < 0, \mu(x) = 0\). Moreover, since \([0, P^{upper}]\) is compact, the graph of \(\mu(x)\) is closed implying \(\mu(x)\) is upper semicontinuous.

Finally, define \(F(x, P) = \mu(x) \times E(P)\). \(\mu(x)\) and \(E(P)\) satisfy all of the properties
needed to apply Kakutani’s Fixed Point Theorem, hence there exists a fixed point 
\( (x^*, P_A^*) \) \( P_A^* \in [0, P_{upper}] \) and an \( x^* \in X \) such that \( P_A^* \in \mu(x^*) \) and \( x^* \in E(P_A^*) \). #

### B.2 Proofs of Comparative Statics Results

**Proposition 3.1** The market price of allowances, \( P_A \), is directly related to the price differential between low and high sulfur coal \( (P_{il} - P_{ih}) \). That is, if for some \( i \), \( (P_{il} - P_{ih}) \) increases, \( P_A \) is weakly increasing, or as \( (P_{il} - P_{ih}) \) decreases, \( P_A \) is weakly decreasing. Moreover, as the fuel cost share for any utility \( i \) increases (decreases), the price of allowances, \( P_A \) is weakly increasing (decreasing).

**Proposition 3.2** The market price of allowances, \( P_A \), is inversely related to changes in \( \alpha_i \) and \( \beta_i \), \( \forall i \). That is, if \( \alpha_i \) and/or \( \beta_i \) increases (decreases) for at least one \( i \), then the market price, \( P_A \), is weakly decreasing (increasing).

**Proof of Propositions 3.1 and 3.2**

To ease notational clutter let \( MCA_i = \frac{\gamma_i(P_{il}/H_{il} - P_{ih}/H_{ih})}{(1-z_i/r_i)m(S_{ih}/H_{ih} - S_{il}/H_{il})} \). \( MCA_i \) is the marginal cost to utility \( i \) of reducing emissions by switching from high sulfur coal to low sulfur coal.

Recall that the allowance price at which a utility will blend coals and buy allowances is \( \frac{MCA}{\beta} \), and the allowance price at which a utility will blend coals and sell allowances is \( \frac{MCA}{\alpha} \).

Define \( A^b_i(P_A) \) and \( A^s_i(P_A) \) to be the demand and supply respectively before any change in parameters.

Define \( A^b_i(P_A)' \) and \( A^s_i(P_A)' \) to be the demand and supply respectively after any change in parameters.
If \((P_l - P_h)\) or \(\gamma_i\) increases, this implies that \(MCA\) increases, which implies an increase in \(\frac{MCA}{\beta}\), the allowance price at which a utility wishes to blend coals and buy fewer allowances, or \(\frac{MCA}{\alpha}\), the allowance price at which a utility wishes to blend coals and sell fewer allowances. Graphically, it is a shift upward of the horizontal section of the demand and supply in figures 1, 2, 4, and 5. This implies that at each price, \(P_A\), \(A_b^i(P_A)' \geq A_b^i(P_A)\) and \(A_s^i(P_A)' \leq A_s^i(P_A)\). This implies that when the demands and supplies are summed up over all utilities at each price, the excess demand will be greater than or equal to what it was before, which implies the price at which excess demand is zero will be greater than or equal to what it was before.

If \((P_l - P_h)\) or \(\gamma_i\) decreases, this implies that \(MCA\) decreases, which implies a decrease in \(\frac{MCA}{\beta}\), the allowance price at which a utility wishes to blend coals and buy fewer allowances, or \(\frac{MCA}{\alpha}\), the allowance price at which a utility wishes to blend coals and sell fewer allowances. Graphically, it is a shift downward of the horizontal section of the demand and supply in figures 1, 2, 4, and 5. This implies that at each price, \(P_A\), \(A_b^i(P_A)' \leq A_b^i(P_A)\) and \(A_s^i(P_A)' \geq A_s^i(P_A)\). This implies that when the demands and supplies are summed up over all utilities at each price, the excess demand will be less than or equal to what it was before, which implies the price at which excess demand is zero will be less than or equal to what it was before.

If \(\alpha_i\) or \(\beta_i\) increase, this implies that \(\frac{MCA}{\beta}\) or \(\frac{MCA}{\alpha}\) decreases. Graphically, it is a shift downward of the horizontal section of the demand and supply in figures 1, 2, 4, and 5. This implies that at each price, \(P_A\), \(A_b^i(P_A)' \leq A_b^i(P_A)\) and \(A_s^i(P_A)' \geq A_s^i(P_A)\). This implies that when the demands and supplies are summed up over all utilities at each price, the excess demand will be less than or equal to what it was before, which implies the price at which excess demand is zero will be less than or equal to what it was before.
If $\alpha_i$ or $\beta_i$ decrease, this implies that $\frac{MCA}{\beta}$ or $\frac{MCA}{\alpha}$ increases. Graphically, it is a shift upward of the horizontal section of the demand and supply in figures 1, 2, 4, and 5. This implies that at each price, $P_A$, $A_b^i(P_A)' \geq A_b^i(P_A)$ and $A_s^i(P_A)' \leq A_s^i(P_A)$. This implies that when the demands and supplies are summed up over all utilities at each price, the excess demand will be greater than or equal to what it was before, which implies the price at which excess demand is zero will be greater than or equal to what it was before.

### B.3 Symmetric Treatment of Options for Cost Minimization

**Theorem 3.2**

Given fixed demands for electricity for all utilities $i$, taking scrubber choices $z_i$ as given, if for all utilities $i$, $\alpha_i = \beta_i = \gamma_i$, then the market in SO$_2$ allowances achieves the “scrubber constrained” minimum total industry compliance cost.

**Proof of Theorem 3.2**

It suffices to show that the first order conditions, for each $i$, from the industry-wide cost minimum problem matches up with each the first order conditions for each utility’s cost minimization problem.

The industry-wide cost minimum problem taking is

$$\min_{z_i, C_{ih}, C_{il}} \sum_{i=1}^{I} P_i z_i + (P_{ih} C_{ih} + P_{il} C_{il} - P_{ih} C_{ih}^{\text{max}})$$

s.t. \( \sum_{i=1}^{I} (1 - z_i r_i) (C_{ih} S_h + C_{il} S_l) m \leq \sum_{i=1}^{I} A_i^e \)

\( D_i \leq (C_{ih} H_h + C_{il} H_l) V_i, \forall i \)

\( z_i \in \{0, 1\} \forall i. \)
The first order conditions for this problem are, given $z_i, \forall i$,

\[ P_{ih} + \lambda_e(1 - z_ir_i)mS_h - \lambda_{ci}^m H_h V_i \geq 0, = 0 \text{ if } C_{ih} > 0, \forall i \]  
\[ (B.1) \]

\[ P_{il} + \lambda_e(1 - z_ir_i)mS_l - \lambda_{ci}^m H_l V_i \geq 0, = 0 \text{ if } C_{il} > 0, \forall i \]  
\[ (B.2) \]

where $\lambda_e$ is the Lagrange multiplier on the emissions constraint and is the shadow price of emissions (an allowance). $\lambda_{ci}$ is the Lagrange multiplier on the demand constraint for utility $i$ and is the marginal cost of producing power inclusive of environmental costs.

For a utility that uses only high sulfur coal, from the first order conditions, the marginal cost of abatement is greater than or equal to $\lambda_e$.

\[ \lambda_e \leq \frac{(P_{il}/H_{il} - P_{ih}/H_{ih})}{(1 - z_ir_i)m(S_{ih}/H_{ih} - S_{il}/H_{il})} \]

For a utility that uses only low sulfur coal, from the first order conditions, the marginal cost of abatement is less than or equal to $\lambda_e$.

\[ \lambda_e \geq \frac{(P_{il}/H_{il} - P_{ih}/H_{ih})}{(1 - z_ir_i)m(S_{ih}/H_{ih} - S_{il}/H_{il})} \]

For a utility that uses a combination of high and low sulfur coal, from the first order conditions, its marginal cost of abatement is equal to $\lambda_e$.

\[ \lambda_e = \frac{(P_{il}/H_{il} - P_{ih}/H_{ih})}{(1 - z_ir_i)m(S_{ih}/H_{ih} - S_{il}/H_{il})} \]

Recall the individual utility’s problem,

\[
\begin{align*}
\min_{d_i, z_i, A_i^b, A_i^s, C_{ih}, C_{il}} & \quad \theta_i z_i P_{rz} + P_A (d_i \beta_i A_i^b - (1 - d_i) \alpha_i A_i^s) + \gamma (P_{ih} C_{ih} + P_{il} C_{il}) \\
\text{s.t.} & \quad (1 - z_ir_i)(C_{ih} S_{ih} + C_{il} S_{il}) m \leq A_i^e + d_i A_i^b - (1 - d_i) A_i^s \\
& \quad D_i \leq (C_{ih} H_{ih} + C_{il} H_{il}) V_i \\
& \quad d_i A_i^b \geq 0 \\
& \quad (1 - d_i) A_i^s \geq 0 \\
& \quad d_i \in \{0, 1\} \\
& \quad z_i \in \{0, 1\}
\end{align*}
\]
The first order conditions for a buyer of allowances are, given $z_i$,

$$P_A \beta_i - \lambda_i^b \geq 0, = 0 \text{ if } A_i^b > 0$$

$$\gamma_i P_{ih} + (1 - z_i r_i) S_h m \lambda_i^b - \lambda_i^b H_h V_i \geq 0, = 0 \text{ if } C_{ih} > 0$$

$$\gamma_i P_{il} + (1 - z_i r_i) S_l m \lambda_i^b - \lambda_i^b H_l V_i \geq 0, = 0 \text{ if } C_{il} > 0,$$

and the first order conditions for a seller of allowances are, given $z_i$,

$$-P_A \alpha_i + \lambda_i^a \geq 0, = 0 \text{ if } A_i^a > 0$$

$$\gamma_i P_{il} + (1 - z_i r_i) S_l m \lambda_i^a - \lambda_i^a H_l V_i \geq 0, = 0 \text{ if } C_{il} > 0$$

$$\gamma_i P_{ih} + (1 - z_i r_i) S_h m \lambda_i^a - \lambda_i^a H_h V_i \geq 0, = 0 \text{ if } C_{ih} > 0.$$

By assumption, all regulatory parameters are equal for each utility $i$, that is $\theta_i = \gamma_i = \alpha_i = \beta_i, \forall i$. Therefore, regardless of whether a utility is a buyer, seller, or neither the shadow price of an allowance (emissions) for each utility is equal to the market price of allowances, $P_A$. Moreover, for each utility $i$, the first order conditions can be simplified down to the following:

$$\gamma_i P_{ih} + (1 - z_i r_i) S_h m \beta_i P_A - \lambda_i^b H_h V_i \geq 0, = 0 \text{ if } C_{ih} > 0$$

(B.3)

$$\gamma_i P_{il} + (1 - z_i r_i) S_l m \beta_i P_A - \lambda_i^a H_l V_i \geq 0, = 0 \text{ if } C_{il} > 0.$$ (B.4)

For a utility that uses only high sulfur coal, from the first order conditions, the marginal cost of abatement is greater than or equal to the effective marketprice of allowances.

$$\beta_i P_A \leq \frac{\gamma_i (P_{il}/H_{il} - P_{ih}/H_{ih})}{(1 - z_i r_i) m(S_{ih}/H_{ih} - S_{il}/H_{il})}$$

For a utility that uses only low sulfur coal, from the first order conditions, the marginal cost of abatement is less than or equal to the effective marketprice of allowances.

$$\beta_i P_A \geq \frac{\gamma_i (P_{il}/H_{il} - P_{ih}/H_{ih})}{(1 - z_i r_i) m(S_{ih}/H_{ih} - S_{il}/H_{il})}$$
For a utility that uses a combination of high and low sulfur coal, from the first order conditions, the marginal cost of abatement is equal to the effective market price of allowances.

\[ \beta_i P_A = \frac{\gamma_i (P_{il}/H_{il} - P_{ih}/H_{ih})}{(1 - z_i r_i) m(S_{ih}/H_{ih} - S_{il}/H_{il})} \]

Since \( \beta_i = \gamma_i, \forall i \) those terms cancel leaving the \( P_A \) equal to the marginal cost of abatement for those utilities using a combination of coal. From the industry-wide cost minimization problem, therefore

\[ \lambda_e = \frac{(P_{il}/H_{il} - P_{ih}/H_{ih})}{(1 - z_i r_i) m(S_{ih}/H_{ih} - S_{il}/H_{il})} = P_A \]

Now the first order conditions in the industry-wide cost minimum problem for each utility match up exactly with the first order conditions from each utility’s individual.

# B.4 Symmetric Treatment by PUCs for Cost Minimization

**Theorem 3.3**

Given fixed demands for electricity for all utilities \( i \), taking scrubber choices \( z_i \) as given, if for all utilities \( i \), \( \alpha_i = \beta_i \) and for all \( j \neq i \) \( \alpha_i = \alpha_j, \beta_i = \beta_j, \gamma_i = \gamma_j \), then the market in SO\( _2 \) allowances achieves the “scrubber constrained” minimum total industry compliance cost.

**Proof of Theorem 3.3**

Much like the proof to Theorem 3.2, it suffices to show that the first order conditions, for each \( i \), from the industry-wide cost minimum problem matches up with each the first order conditions for each utility’s cost minimization problem.
Recall from the proof to Theorem 3.2 the following conditions from the industry-wide cost minimization problem.

For a utility that uses only high sulfur coal, from the first order conditions, the marginal cost of abatement is greater than or equal to \( \lambda_e \).

\[
\lambda_e \leq \frac{(P_{il}/H_{il} - P_{ih}/H_{ih})}{(1 - z_ir_i)m(S_{ih}/H_{ih} - S_{il}/H_{il})}
\]

For a utility that uses only low sulfur coal, from the first order conditions, the marginal cost of abatement is less than or equal to \( \lambda_e \).

\[
\lambda_e \geq \frac{(P_{il}/H_{il} - P_{ih}/H_{ih})}{(1 - z_ir_i)m(S_{ih}/H_{ih} - S_{il}/H_{il})}
\]

For a utility that uses a combination of high and low sulfur coal, from the first order conditions, the marginal cost of abatement is equal to \( \lambda_e \).

\[
\lambda_e = \frac{(P_{il}/H_{il} - P_{ih}/H_{ih})}{(1 - z_ir_i)m(S_{ih}/H_{ih} - S_{il}/H_{il})}
\]

By assumption, all regulatory parameters are equal for each utility \( i \), that is \( \alpha_i = \beta_i, \forall i \). Therefore, regardless of whether a utility is a buyer, seller, or neither the shadow price of an allowance (emissions) for each utility is the same.

For a utility that uses only high sulfur coal, from the first order conditions, the marginal cost of abatement is greater than or equal to the effective market price of allowances.

\[
\beta_i P_A \leq \frac{\gamma_i(P_{il}/H_{il} - P_{ih}/H_{ih})}{(1 - z_ir_i)m(S_{ih}/H_{ih} - S_{il}/H_{il})}
\]

For a utility that uses only low sulfur coal, from the first order conditions, the marginal cost of abatement is less than or equal to the effective market price of allowances.

\[
\beta_i P_A \geq \frac{\gamma_i(P_{il}/H_{il} - P_{ih}/H_{ih})}{(1 - z_ir_i)m(S_{ih}/H_{ih} - S_{il}/H_{il})}
\]

For a utility that uses a combination of high and low sulfur coal, from the first order conditions, the marginal cost of abatement is equal to the effective market price of allowances.

\[
\beta_i P_A = \frac{\gamma_i(P_{il}/H_{il} - P_{ih}/H_{ih})}{(1 - z_ir_i)m(S_{ih}/H_{ih} - S_{il}/H_{il})}
\]

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The industry-wide cost minimization problem and the individual problem for utilities therefore yield

\[
\lambda_e = \frac{(P_d/H_d - P_{ih}/H_{ih})}{(1 - z_i r_i)m(S_{ih}/H_{ih} - S_{il}/H_{il})} = (\beta_i/\gamma_i) P_A
\]

Since \( \beta_i = \beta_j, \forall i \neq j \) and \( \gamma_i = \gamma_j, \forall i \neq j \), \((\beta_i/\gamma_i) P_A = \lambda_e\) for all utilities.

Now the first order conditions in the industry-wide cost minimum problem for each utility match up exactly with the first order conditions from each utility’s individual problem taking scrubbers as fixed. #

B.5 Conditions for an Emissions Cap to Equal a Mandate on Low Sulfur Coal Usage

**Theorem 3.4**

Given fixed demands for electricity for all utilities \( i \), taking the scrubber choice \( z_i \) as given and assuming that all scrubbers have identical removal efficiencies \( r_i \), for all \( i \), if the sulfur and heat content of high and low sulfur coal, respectively, is identical across utilities \( S_{ih} = S_{jh}, S_{il} = S_{jl}, H_{ih} = H_{jh}, H_{il} = H_{jl}, \forall i \neq j \) then the total number of allowances allocated initially implies a fixed amount of low sulfur coal to be used industry-wide. Furthermore, if the prices of high and low sulfur coal are also identical across utilities \( P_{ih} = P_{jh}, P_{il} = P_{jl}, \forall i \neq j \) and \( z_i = 0 \) for all \( i \), the market in SO\(_2\) allowances achieves the “scrubber constrained” minimum total industry compliance cost regardless of the values of the regulatory parameters and allowance endowments.

**Proof of Theorem 3.4**

With \( S_{ih} = S_{jh}, S_{il} = S_{jl}, H_{ih} = H_{jh}, H_{il} = H_{jl}, \forall i \neq j \) it can be established that given the sum of allowance endowments, the amount of low sulfur coal used industry-wide is fixed.
If utilities did not face an emissions constraint, they would use only high sulfur coal to generate electricity. Hence, unconstrained emissions industry-wide would be

\[ \sum_{i=1}^{I} C_{ih}^{\text{max}} (1 - z_i r_i) S_{ih} m, \]

where \( C_{ih}^{\text{max}} = \frac{D_i}{H_{ih} V_i} \).

With aggregate emissions capped at \( \sum_{i=1}^{I} A_i^e \), the amount that emissions will be reduced is

\[ \sum_{i=1}^{I} (C_{ih}^{\text{max}} S_{ih} m - A_i^e) \]

In order to meet the aggregate emissions constraint, and still meet demand, each utility must use a combination of high sulfur and low sulfur coal so that

\[ D_i \leq (C_{ih} H_h + C_{il} H_l) V_i, \forall i, \]

\[ (C_{ih} S_{ih} + C_{ih} S_{ih}) (1 - z_i r_i) m \leq A_i^e. \]

Solving for \( C_{ih} \) using the demand constraint yields

\[ C_{ih} = (C_{ih}^{\text{max}} - C_{il} \frac{H_{il}}{H_{ih}}), \]

The amount that emissions must be reduced from the unconstrained level must then be equal to the amount of low sulfur coal used times the difference in emissions from using low sulfur coal.

\[ \sum_{i=1}^{I} (C_{ih}^{\text{max}} S_{ih} m - A_i^e) = \sum_{i=1}^{I} (C_{il} \frac{H_{il}}{H_{ih}} S_{ih} - C_{il} S_{il}) (1 - z_i r_i) m \]

Since scrubber characteristics and the heat and sulfur contents are constant across utilities, the \( i \) subscripts can be dropped on those terms and brought outside the summation to yield
\[
\sum_{i=1}^{I} (C_{ih}^{\max} S_h m - A_i^i) = \left( \frac{H_i}{H_h} S_h - S_l \right) m \sum_{i=1}^{I} C_{il}(1 - z_i r_i)
\]

Since the scrubbers are taken as given, for those utilities with scrubbers \( r_i \) is the same, the right hand side can be re-written as

\[
\left( \frac{H_i}{H_h} S_h - S_l \right) m \sum_{is.tz=1}^{I} C_{il} + \left( \frac{H_i}{H_h} S_h - S_l \right) m \sum_{is.tz=0}^{I} C_{il}
\]

which implies that the amount of low sulfur coal is fixed.

Now, assume additionally that \( P_{ih} = P_{jh} \) and \( P_{il} = P_{jl}, \forall i \neq j \), and that no utility has a scrubber installed.

Since \( z_i^* = 0 \), for all \( i \), the total industry compliance cost simply becomes

\[
\sum_{i=1}^{I} (P_h C_{ih}^* + P_l C_{il}^* - P_h C_{ih}^{\max}),
\]

where * indicate choices from the industry-wide cost minimization problem.

Now since the price of both high and low sulfur coal is the same, and \( \sum_{i=1}^{I} C_{il} \) is fixed, the total industry-wide compliance costs must be the same regardless of which utility uses low sulfur coal. #