An Oligopolistic Electricity Market Model with Tradable NO_x Permits

Yi-Hsu Chen[*] and Benjamin F. Hobbs[**]

ABSTRACT

Models based on linear complementarity problem (LCP) formulations have been applied previously to assess the potential for exercise of market power in transmission constrained electricity markets. Here, we use that approach to simulate the interaction of pollution permit markets (in particular, the USEPA Ozone Transport Commission (OTC) NO_x Budget Program) with electricity markets in the presence of market power. Because: the permits program is regional rather than national in scope and some power producers are relatively large consumers or sellers of permits, there could be significant interactions between market power in the permits and energy markets. In our model, the producers with substantial capacity share exercise Cournot (quantity) strategies in electricity markets, while anticipating that NO_x prices will respond to their permits purchase or sales decisions. Each firm's conjectures regarding this price response is modeled as a first-order approximation around the market equilibrium using an exogenous response assumption. The application is to the Pennsylvania – New Jersey – Maryland Interconnection (PJM) (US) market during 2000, which is represented by a 14-node, 18-arc linearized DC load flow model. A total of 730 generators are included in our analysis and five demand periods are considered. The results show that PJM market is relatively competitive during this period, as its prices are closer simulated competitive levels than to Cournot (oligopoly) prices. The NO_x market and Cournot energy markets influence each other in several ways. One is that Cournot competition lowers the price of NO_x permits, which in turn results in a large, high emissions producer actually expanding its output, contrary to simple Cournot energy-only markets. Further, some Cournot producers could be worse rather than better off under oligopoly than perfect competition. Meanwhile, higher energy prices and lower NO_x permit prices provide two reasons for smaller price-taking producers to expand energy generation. Total NO_x emission declines as a consequence of restraining output by Cournot producers. In general, because pollution permits are an important cost and their price is volatile, high concentration in the market for such permits can exacerbate the effects of market power in energy markets.

INTRODUCTION

Electric sector restructuring is underway in many parts in the world. While market designs and structure vary greatly from place to place, the rationale behind those activities are more or less the same. On the supply side, the rationale for restructuring is to create a competitive environment to enhance production efficiency, reduce prices, and provide incentives for efficient long-run investment in generation and transmission. On the demand-side, many hope that restructuring will provide more accurate signals for consumers to adjust their consumption in response to cost variations. However, the achievement of these goals is hindered by factors. First, the supply of electricity has to balance with demand in real-time since electricity storage is very expensive. Without inventories like other commodities, the short run supply curve for electricity is very inelastic as output approaches production capacity. Second, flows in the network need to follow physical rules, i.e., Kirchhoff's Voltage and Current Laws. Even without market power, transmission congestion will lead to some parts of network having higher electricity prices relative to overall system. Finally, although some retail markets have been opened, real-time pricing is still not well deployed yet because the cost incurred by installing real-time meters is too substantial. Consequently, there is little demand elasticity in the short run. All these factors together provide an opportunity for generators to exercise market power. Market power is defined as the ability of market participants to manipulate price in their favor.

The consequences of market power can include price changes, production inefficiencies, and a redistribution of income from consumers to suppliers. Many models have been developed to analyze market power in electricity markets (see reviews in (Kahn, 1998; Hobbs, 2001; Day et al., 2002). Such models are used to assess the impact of changes in market design (e.g., type of transmission rights or geographic scope of allowances markets) and market structure (e.g., size of generating firms, amount of transmission capacity) upon prices and market efficiency. Those models generally take either an empirical or process modeling approach (Kahn, 1998). Which is appropriate depends in part on the question of interest. The empirical (or ex post) approach compares observed prices to a hypothetical competitive benchmark (marginal cost) to assess whether market power has been exercised. Supply costs and technology are usually represented by aggregated marginal cost curves. In contrast, the process modeling approach is used in ex ante studies to assess the potential for market power under new or changed market designs or structures. Such models can build in considerable detail about generator characteristics, transmission constrains, locations of loads, etc. The process modeling approach is adopted in this paper.

---

[*] Ph.D. student, Department of Geography & Environmental Engineering, Whiting School of Engineering, The Johns Hopkins University, Baltimore, MD 21218 USA, yschen@jhu.edu; Tel: +1(410) 516-5151/Fax: +1(410) 516-8996

[**] Professor, Department of Geography & Environmental Engineering, Whiting School of Engineering, The Johns Hopkins University, Baltimore, MD 21218 USA, bhobbs@jhu.edu; Tel: +1(410) 516-4681/Fax: +1(410) 516-8996

This work was supported by NSF grants ECS 0080577 and 0224817 and USEPA STAR grant R82873101-0. The authors are solely responsible for any opinions or errors.

The restructuring of electricity industry has coupled with the introduction of cap-and-trade programs into environmental policies. The programs first establish a cap on total market emissions and then allocate permits to affected facilities. One unit of permit allows its holder to emit a fixed amount of pollutant, and permits can be traded in secondary markets or agency-sponsored auctions. To make sure that its emissions do not exceed the number of permits it holds, an affected facility can reduce pollution through operational or equipment changes, or purchase permits from other companies who have excess permits. Excess permits can be sold in this manner, or banked for future use. Examples of such programs include the national SO_2 emissions trading program of the 1990 Clean Air Act Amendments and the RECLAIM NO_x and VOC (volatile organic compound) program of the Southern California Air Quality Management District (SCAQMD, 2003). Under certain conditions, such as low transaction costs, perfect monitoring and complete compliance, those programs are believed to achieve predetermined emission reductions with least abatement costs (Tietenberg, 2003).[1] However, most of these conditions are at least partially violated in reality. For example, the existence of high transaction costs is studied by (Stavins, 1995; Cason and Gangadharan, 2003). The common finding is that the volume of permit trade will decline as a consequence of the presence of transaction costs in the permit markets, and aggregate abatement costs will exceed the minimum possible. In addition to high transaction costs, the prevalence of market power in the markets associated with those programs will also increase total compliance costs if same level of reductions is imposed (Hahn, 1984; Stavins, 1995).

The problem of market power in permit market was first identified by (Hahn, 1984). In his study, one firm is designated as having market power while the remaining ones are price takers. He showed that the efficiency loss of this market is a function of the initial allocation of permits. More loss will occur when the initial allocation is further away from its competitive level. Hung and Sartzetakis (1998) constructed a two-sector model to study cross-industry emission trading, where one sector is perfectly competitive and another is monopoly. Their finding is the social welfare of traditional CAC (command–and–control) could be better than the cap-and-trade program if regulatory authority has complete information regarding pollution control costs such that proper levels of emission reductions can be imposed for each facility. However, obtaining such information could be costly or impossible, while transaction costs associated with cap-and-trade programs could be substantial. Therefore, a complete comparison would require fully inclusion of those costs. To compare the social welfare implication of CAC and cap-and-trade programs, Sartzetakis (1997b) considered a case in which an oligopolistic product market is in parallel with a perfectly competitive tradable permit market. In his setting, producers in the product market are assumed to adopt similar production technologies, while heterogeneity of pollution control technology is assumed. There are two partially offsetting forces that affect social welfare in that analysis. While market imperfections decrease social welfare, the tradable permit market increases social welfare, as most cost-effective pollution reductions would be achieved. He concluded that cap-and-trade programs always yield higher social welfare than CAC with the same level of emission limits applied in each case. Finally, Morch and Fehr (1993) studied how and under what conditions, emission rights can be used strategically by monopolistic firms for predatory and exclusionary purposes. He concluded that when the products are strategic substitutes and diseconomies of scale for production are not prevalent, there will be substantial incentive for firms to utilize permits to gain profits (producer surplus gains at an expense of consumer surplus). In terms of social welfare, it is possible that the profit gained by the monopolist outweighs the loss of consumer surplus, and social welfare increase.

While market power in electricity markets or emissions markets alone has been intensively studied, relatively little attention has been paid to look at their interaction. If permits are in short supply and there is significant market concentration, it may be possible for large generators to exercise market power in both energy and permits markets. Profit-maximizing strategies might differ for such firms when both markets are considered. For instance, an empirical analysis of the 2000-01 power crisis in California concluded that a large generator put a cost-squeeze on other firms by intentionally consuming more permits than necessary, raising permit costs for other companies who were short of permits (Kolstad and Wolak, 2003). The theoretical counterpart of such a strategy is investigated by (Sartzetakis, 1997a). He examined the effect of raising rivals' costs strategies via emission market. He found the resulting competition in product market can be lessened substantially, but the welfare effect is ambiguous. If leader expands its output at an expense of less efficient rivals, overall social welfare may increase. On the other hand, the social welfare may diminish significantly if the leader is less efficient than its rivals.

Most of the permit market studies discussed above provide qualitative conclusions by identifying the direction of the change of total abatement cost (efficiency concern) or social welfare given a variation of parameters of interest. However, none of them are applied to real markets to quantify the magnitude of the production inefficiency and welfare loss caused by interaction of market power in multiple markets. And none of them provide a representation of crucial elements of power systems (such as transmission constraints) nor a model how different participants exercise market power in both their output market and the permits market in a way that maximizes their interest. Therefore, the purpose of this paper is to fill this gap by building a process-based model which employs a transmission network representation and rich engineering detail. We apply our model to PJM US market and the USEPA OTC NO_x budget program during 2000. To quantify the magnitude of production

---

[1] Newell and Stavins (2003) investigated the potential savings from cap-and-trade programs given the cost heterogeneity (measured in generators' baseline emission rate and the slope of marginal abatement cost function). They estimated the potential savings for USEPA OTC NO_x budget program in comparison with a uniform emission standard is roughly 51%.

inefficiency resulting from the exercise of market power, a companion least-cost (competitive) model is developed and documented in the Appendix 1. Such a model is equivalent to the case in which all market participants (i.e., producers, consumers and grid operator) are price takers. The oligopoly model generalizes the competitive model so that energy sellers play a Cournot game, while anticipating (perhaps incorrectly) how permits prices will change with changes in permits sales or purchases. We display oligopoly model in the Appendix 2.

The results of our model provides insight with regard to the rationale for market participants' behaviors given their market roles (price-taking or strategic), individual positions in the electricity (large or small) and the position in the emission permits markets (short or long).

The remainder of this paper is organized as follows. In Section 2, the basic model will be summarized, while in Section 3, we introduce some background of our case study. We report our results, including electricity and permit prices, consumers and producers surplus in Section 4, followed by some closing remarks in Section 5. The appendix summarizes the competitive and oligopoly model.

MODEL

The model is a multiple-period version of (Hobbs, 2001) elaborated to account for the USEPA NO_x budget program. The USEPA NO_x budget program serves as a complicating constraint that creates an interdependency across periods; *i.e.*, suppliers have to coordinate their output level over periods to ensure compliance with the seasonal NO_x budget. The problem faced by individuals in the markets is summarized as follows.

A. Producers:

The objective of producers is to maximize their profit by engaging in two markets:

1. *Power Market:* We assume that the bulk of power sales are in the form of bilateral contracts between producers and consumers, with the producer paying the system operator for transmission services necessary to deliver the power. The prices in the market are determined with a conventional LMP (locational marginal pricing) scheme, as currently the case in PJM. We consider two behavior types: price-taking and strategic behavior. In the reference case, each producer in the market is assumed to be price-taker (as in the model in the Appendix 1). In the case of oligopolistic competition, a few firms with substantial capacity are designated as strategic firms, exercising Cournot (quantity) strategies in the energy market. Under that strategy, those firms adjust their generation and sales as if they believe that rival firms will not react to such output changes.
2. *NO_x Market:* In compliance with USEPA OTC regulations, producers can undertake pollution reduction (by dispatching cleaner plants), purchase NO_x permits, or over-comply selling excess permits in the NO_x emission market.[2] In the reference case, we assume that all producers are price-takers in the emission market. Under oligopolistic competition, large Cournot producers apply a conjectured price response[3] strategy (similar to Day et al. (2002) and Hobbs et al. (forthcoming)) in the NO_x permit market. The firm's conjectures regarding the response of permits price to changes in its sales or purchases is represented by a slope parameter *NCP*. A large value of *NCP* indicates that a producer believes it has sizeable influence on the NO_x permit market. In the oligopoly simulations, different values of *NCP* will be explored to study its implications for the power and NO_x emission markets.

B. Consumers:

The consumers are distributed among different nodes in the network, and their willingness-to-pay for using power is represented by linear demand curves. In our model, consumers are assumed have no market power and their objective is to maximize consumer surplus.

C. Grid Operator:

Consistent with (Hobbs, 2001), we assume that the grid operator is a regulated entity that allocates transmission capacity efficiently among demands for transmission service, which is equivalent to a price-taking assumption (Hogan, 1992).

The next step in developing model is to derive first order or KKT (Karush-Kuhn-Tucker) conditions for individual optimization problems. Together with market clearing and consistency conditions, the resulting mathematical problem is called a LCP (Linear Complementarity Problem). Theoretical analysis of the mathematical properties of the energy model, including uniqueness and existence of equilibria, is presented in (Pang and Hobbs, under review). The model can be solved by using commercial solver PATH.

---

[2] When facing a NO_x emission constraint, the only strategy available to firms in the short run is to rely on NO_x emission dispatch, in which more expensive but cleaner facilities are operated more than otherwise (Leppitsch and Hobbs, 1996). In contrast, many options, which involve capital investment in low NO_x burners or post-combustion control technologies such as NSCR (Non-selective Catalytic Reduction), are available in the long run. A model attempting to simulate those options requires additional variables for these investments and multiyear time horizons.

[3] The conjectured price response function is a first-order approximation of the producers' belief about their ability to influence NO_x permit market prices.

CASE STUDY BACKGROUND AND DATA SOURCES

A. PJM Market

PJM began operating power markets as an independent system operator (ISO) in 1998. It runs day-ahead and hourly-ahead energy markets. Its hourly load in 2000 ranged from 20,000 MW to 49,000 MW. Nuclear and coal plants serve the baseload, accounting for 57.9% of total generation capacity. Meanwhile, the capacity shares of oil, gas and hydro plants are 20.8%, 18%, and 3.3%, respectively. In our model, the PJM system is spatially represented by 14 aggregated nodes (each representing one Power Control Area or a portion thereof) and 18 transmission lines (Fig. 1). The highest average load among the nodes is 5,300 MW for Public Service Electric and Gas Co. (PSEG) and the lowest is 1,310 MW for Atlantic Electric Co. (AE). We apply a standard linearized DC approximation of load flows to derive PTDFs (Power Transmission Distribution Factors) to allocate flows in the network according to Kirchhoff's laws. During the ozone season of 2000, PJM exported respectively an average of 600 MW and 100 MW to the New York ISO (NYISO) and Virginia Electricity Power (VEP), and imported 1,200 MW and 315 MW from Allegeheny Power System (APS) and First Energy (FE), respectively. For simplicity, we treat these external flows as fixed in our model, although price responsive imports/exports could also be modeled (Mansur, 2001a). The market is moderately concentrated, with an average hourly HHI (Hirschman-Herfindahl Index) of 1,544 (PJM, 2001). There are 6 larger generating companies, owning between 6% and 19% apiece of the generating capacity. Although the PJM market monitor reports that prices have generally been near competitive levels, there has apparently been some market power exercised in the installed capacity market. Furthermore, other studies indicate that market concentration is high enough to present a risk of market power being exercised (Hobbs et al., 2000; Mansur, 2001b).

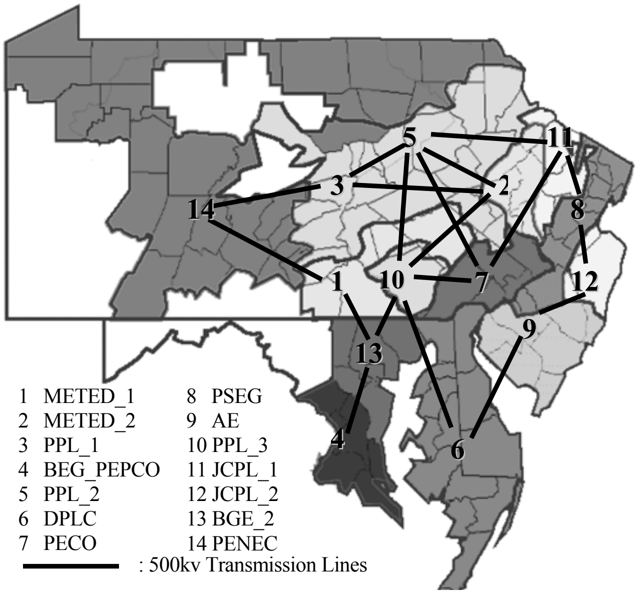

Fig. 1. Schemoatic f Linearized DC network for PJM

B. OTC NOx Budget Program

The OTC NO_x budget program is a cap-and-trade program that came into effect in 1999. The goal is to reduce summertime NO_x emissions region-wide to help northeastern states attain the National Ambient Air Quality Standard (NAAQS) for ground level ozone. The effective period is from May 1 to September 30 of every year. The program has evolved over time to encompass a larger geographic scope, from an initial nine states in 1999 to nineteen states in 2004 (Farrell et al., 1999). The tradable permits were initially allocated to affected facilities owners according to their historical seasonal heat inputs multiplied by a target NO_x emission rate. The flexibility of the program allows owners of permits to sell excess permits or bank them for future use. The program applies to electric generating units of a rated capacity of 25 MW or larger, along with larger industrial process boilers and refineries. There are a total of 470 individual sources affiliated with 112 distinct organizations in the program in 1999. Ninety percent of NO_x emissions covered in program are from power generators. In our PJM database, more than 70% of generator summer capacity comes under the NO_x budget program including 422 generators. Non-power sources are left out in our analysis because of their small size, and because our focus is on the power industry.

The mandated NO_x reductions take effect in two phases. The first phase began in May 1, 1999 when the program required affected facilities to cut total emission to 219,000 tons in 1999, less than half of the 1990 baseline emission of 490,000. The emissions cap is to be cut further to 143,000 tons in 2003 for the second phase, a reduction of 70%. Since our purpose is to illustrate the use of this methodology, we will model just the use and sales of allowances within PJM, even though the NO_x budget program covers a region larger than PJM. Thus, our analysis may overstate the extent to which market power can be exercised in the NO_x market because the model disregards trading outside of PJM. This will, in effect, overstate concentration in that market, but will serve the purpose of illustrating how the interactions between electricity and permits markets in the presence of market power.

C. Data Sources

1. Ownership: Generation ownership and location data are crucial to our analysis since they determine the potential to exercise market power. The primary source of this data is EIA Form 860 (EIA, 2003). For units not in EIA860, an internet search or personal contact was used to confirm ownership. To ensure an appropriate representation of the potential of market power under the current ownership, we assume that operational decisions (generation and sale) are controlled by the parent company, replacing any subsidiaries with the corresponding parent company. For the 29 units jointly owned by more than one incumbent company, we treat them as multiple units by splitting capacity in proportion to ownership percentage. Other assumptions, such as assigning control to the owner with majority ownership, could instead be applied (Amundsen and Bergman, 2002) to study market power in the presence of partial ownership. There are nine companies in our PJM model. For our purpose, we designate the six largest companies as strategic firms with respective capacity shares of 18.9%, 18.4%, 14.0%, 10.9%, 8.7% and 6.1%. The reason for modeling all six as strategic is the possibility that even a small one can exercise market power if its generators are located in a transmission-constrained area. With others companies having a capacity share of only 0.6% to 3.4%, we believe that the likelihood for them to exercise market power is much less. Therefore, we designate them as price takers (competitive).

2. Load: The simulation period is the ozone season in year 2000, comprising 3,672 hours. The load is represented by 5 periods: a peak-load block with a width of 52 hours, and four non-peak blocks having 905 hours each. Hourly load data for each individual Power Control Area (PCA) or node are obtained from the PJM website, as are the boundary conditions (net imports.) The assumed price elasticity is 0.2 at the competitive price-quantity point for each node's demand curve.

3. NOx Tradable Permits Data: .We rely on EPA annual compliance reports for tradable permit data (USEPA, 2003b). A total of 131,440 permits were available at the end of 2000 for affected facilities in Maryland, Pennsylvania, New Jersey and Delaware. There were 109,227 permits allocated in 2000 by the NO_x budget program, and 22,163 permits were carried over (banked) from previous years. Only 92,107 permits are assigned to power plants; the remaining permits, which are owned by other industrial sources, are left out of our analysis. Consistent with empirical observation of generator behavior in PJM, we assume only 80% of available permits are used for compliance purpose, and the remaining 20% are banked for future use.[4]

4. Generator Characteristics and Network Data: A total of 730 generating units are included in the market model. We represent their marginal production cost as the sum of fuel cost, SO_2 permit costs (with the SO_2 emissions price assumed to be exogenous), and non-fuel variable operation and maintenance expenses. The required data, such as heat rate, capacity, emission rate and other information, are drawn from multiple sources including EIA databases, the USEPA Integrated Planning Model and Generation Resource Integrated Database (USEPA, 2003a) and the PowerWorld website (PowerWorld, 2003). For units without complete data, we estimates their values taking into account prime mover, fuel type, capacity, vintage year and other related factors. Capacity is derated by its forced outage rate (FOR) to account for unpredicted plant outages. The value of FOR depends on prime mover and size of plants, and is drawn from NERC data (NERC, 2003). In our database, the average fossil-fueled plant NO_x emission rate is 4.5 lbs/MWh, ranging from 1 lbs/MWh to 25 lbs/MWh. Network data including transmission thermal capacities and reactances required for deriving PTDFs, were obtained from the PowerWorld website (PowerWorld, 2003).

RESULTS

The resulting competitive and oligopolistic prices are first compared with actual LMPs reported by PJM for 2000. In general, our prices with a perfect competition assumption are a reasonable approximation to PJM LMPs during this period (Chen and Hobbs, submitted). Meanwhile, in the oligopoly simulations, producers with substantial capacity restrict their output, while the fringes (smaller price-taking producers) expand their output in response to higher prices caused by output withholding by Cournot producers. The overall power sales are less than perfect competition case. To our surprise, the NO_x permit price plummeted to zero in the oligopoly simulation because the energy output restrictions by Cournot producers resulted in lower demand for permits. Therefore, to investigate the interaction of the power and NO_x permit markets, we further reduce the allocation of NO_x permits by 20% for each producer. We hypothesize that such a restraint of NO_x permits supply will, under some circumstances, drive up the permit price to a level that makes manipulation by large producers attractive to those producers.

We examine four cases in detail here: Case 1: perfect competition; Case 2: oligopoly competition with Cournot assumption in the power market and price taking behavior in the permits market; and Case 3: oligopoly competition with NCP = 0.1[(\$/ton)/ton] for Cournot producers .[5] And in Case 4, the only producer with a long position (i.e., PECO) in the permit market in CASE 1 is assigned with a large value of NCP_{PECO} = 1.5 [(\$/ton)/ton], while the remaining assumptions are the same as in the Case 3. The purpose of so doing is to investigate how a producer can benefit from a cost-squeeze strategy in the PJM market.

Comparisons of these cases allow us to understand the impact of various strategic and market assumptions. In particular, a comparison of the first two cases allows us to quantify the impact of exercising a Cournot strategy in the power market, while the comparison between the 2nd and 3rd, and between 3rd and 4th cases let us examine the effect of different levels of price response conjectures on the NO_x permit and power markets. The comparative statics include comparisons of prices, outputs, and the components of social welfare (producer surplus, transmission (congestion) surplus, and consumer surplus).

---

[4] It is possible to undertake a more sophisticated multiyear analysis in which a generator optimizes the number of allowances it banks from year to year, recognizing how price changes over time along with opportunities to exercise market power. This extension is left to future research.

[5] This value is consistent with the actual response of the market in the competitive case (Table 1), in which a decrease of 900 tons in the markets results in an 84\$/ton increase in NO_x permit price.

Table 1: Comparison of Cases 1 and 2 (61,558 Tons of Allowances Available to OTC Facilities)

Perfect Competition (Case 1)		Oligopoly (Case 2: $NCP_f = 0$, all f) No Perceived Market Power in Permit Market	
Average Power Price [$/MWh]	32.7	Average Power Price [$/MWh]	40.0
Price of NO_x Permits [$/ton]	2,557	Price of NO_x Permits [$/ton]	1,595
Total (OTC) NO_x Emission [tons]	108,193 (61,558)	Total (OTC) NO_x Emission [tons]	98,687 (61,558)
Consumer Surplus [M$]	8,931	Consumer Surplus [M$]	8,086
Importer Revenue [M$]	142	Importer Revenue [M$]	171
Grid Operator Revenue [M$]	67	Grid Operator Revenue [M$]	24
Production Efficiency Loss [[M$]	NA	Production Efficiency Loss [[M$]	82.6
Social Welfare [M$]	11,660	Social Welfare [M$]	11,549
Total NO_x Permit Trading Volume [tons]	16,279	Total NO_x Permit Trading Volume [tons]	15,167

Producer	Producer Surplus [M$]	Permit Trade[a] [tons]	Total Sale [10^6MWh]	Gen. Cost [$M]	Producer	Producer Surplus [M$]	Permit Trade[a] [tons]	Total Sale [10^6MWh]	Gen. Cost [$M]
1 Connective	36.9	-661.9	1.9	37.2	1.Connective	58.8	2,198.5	3.5	89.1
2 CONS.[b, c,d]	321.2	1,128.7	16.9	195.3	2 CONST[b, c,d]	414.5	-23.2	12.9	109.0
3 Mirant[b, c]	143.7	0.0	11.3	211.6	3 Mirant[b, c]	213.0	0.0	9.4	146.6
4 PECO[b, c]	800.4	-7,880.4	28.6	98.4	4 PECO[b, c]	921.3	-12,602.9	25.0	42.5
5 PPL[b, c]	354.0	10,115.5	16.7	135.3	5 PPL[b, c]	483.0	7,363.4	15.0	108.4
6 PSEG[b, c]	460.6	2,804.0	17.6	114.3	6 PSEG[b, c]	549.7	-2,540.7	15.1	59.6
7 Reliant[b, c]	91.1	2,076.8	5.4	87.9	7 Reliant[b, c]	151.8	5,224.9	7.0	113.5
8 Allegheny	24.3	153.5	1.1	7.7	8 Allegheny	33.5	246.5	1.1	8.5
9 Others	287.8	-7,736.0	16.4	309.5	9 Others	442.3	133.5	20.7	426.1
Total	2,520.0	0.0	115.9	1,197.2	Total	3,267.9	0.0	109.7	1,103.3

[a]: Positive indicates purchase of NO_x permits and negative indicates sale of NO_x permits

[b]: Indicates that this firm exercises a conjectured NO_x permit price strategy in emissions market in oligopolistic competition

[c]:Cournot firm in oligopoly simulation

[d]: Constellation

Table 2: Comparison of Cases 3 and 4, Representing Different Degrees of Conjectured Market Power in Permits Market

Oligopoly (Case 3: $NCP_{2,3,4,5,6,7} = 0.1$, $NCP_{1,8,9}=0$)		Oligopoly (Case 4: $NCP_{2,3,5,6,7} = 0.1$, $NCP_4=1.5$, $NCP_{1,8,9}=0$)	
Average Power Price [$/MWh]	40.1	Average Power Price [$/MWh]	40.0
Price of NO_x Permits [$/ton]	1,505	Price of NO_x Permits [$/ton]	2,174
Total (OTC) NO_x Emission [tons]	98,909 (61,558)	Total (OTC) NO_x Emission [tons]	99,200 (61,558)
Consumer Surplus [M$]	8,084	Consumer Surplus [M$]	8,096
Importer Revenue [M$]	171	Importer Revenue [M$]	171
Grid Operator Revenue [M$]	26	Grid Operator Revenue [M$]	26
Production Efficiency Loss [[M$]	82.9	Production Efficiency Loss [[M$]	79.1
Social Welfare [M$]	11,545	Social Welfare [M$]	11,554
Total NO_x Permit Trading Volume [tons]	14,220	Total NO_x Permit Trading Volume [tons]	10,333

Producer	Producer Surplus [M$]	Permit Trade[a] [tons]	Total Sale [10^6MWh]	Gen. Cost [$M]	Producer	Producer Surplus [M$]	Permit Trade[a] [tons]	Total Sale [10^6MWh]	Gen. Cost [$M]
1 Connective	59.0	2,692.9	3.7	93.7	1.Connective	57.2	1,825.0	3.3	81.9
2 CONST[b, c,e]	415.0	28.4	13.0	110.2	2 CONST[b, c,e]	411.3	-371.9	12.9	109.4
3 Mirantt[b, c]	213.6	0.0	9.5	147.6	3 Mirant[b, c]	212.6	0.0	9.5	148.8
4 PECO[b, c]	928.5	-12,289.7	25.1	44.3	4 PECO[b, c]	957.1	-6,240.2	27.2	89.0
5 PPL[b, c]	472.8	6,499.1	14.6	102.3	5 PPL[b, c]	454.2	4,764.9	13.8	89.1
6 PSEG[b, c]	550.7	-1,930.5	15.2	60.6	6 PSEG[b, c]	549.5	-2,748.8	15.0	57.7
7 Relliant[b, c]	150.0	4,620.6	6.8	109.5	7 Reliant[b, c]	145.2	3,496.7	6.5	104.8
8 Allegheny	33.3	246.5	1.1	8.5	8 Allegheny	33.4	246.5	1.1	8.5
9 Others	441.0	132.7	20.7	426.4	9 Others	440.5	-972.4	20.3	412.1
Total	3,263.9	0.0	109.7	1,103.1	Total	3,261.0	0.0	109.6	1,101.3

Notes: Same as Table 1

A. Comparison of with- (not shown) and without 20% Reduction of NO_x Permit Supply (Reference Case vs. Case1)

Tables 1 and 2 summarize the comparative statics for the four aforementioned cases. (We omit nodal prices and only report average power prices. However, a comparison of nodal prices will be made wherever relevant.) In comparison with the reference competitive case (in which 76,947 permits are allocated to the OTC facilities, not shown), a cutback of 20% supply of NO_x permits results in an increase of the permit price from 1,074 to 2,557 $/ton in the competitive simulation. The overall sale-weighted power prices goes up by 1.8 $/MWh, accompanied by a decline of 1.8×10^6 [MWh] in power sales. Such a price impact is less than what might be anticipated for an average NO_x emission rate of 4.5 lbs/MWh for fossil units, namely 3.3 $/MWh[6]. This is because first, not all the fossil units are affiliated with USEPA NO_x budget program. Because the price increase has no direct impact on those nonaffiliated generators, those generators have a relative advantage over affiliated units under a tighter cap. They expand their output, dampening the effect of the NO_x price increase on power prices.

---

[6] Assuming an average NO_x emission rate of 4.5 lbs/MWh and an increased permit price of 1,483 $/ton, the corresponding impact on production cost would be 4.5 [lbs/MWh]*1/2000 [ton/lb] *1483 [$/ton] = 3.3 $/MWh.

Second, elastic demand means that not all of the input price increase can be passed on to consumers. Social welfare declines by 17.1 million dollars, while producers and consumers surplus change by 164.8 and -189.9 million dollars over six months, respectively. In general, a tighter cap has a negative impact on consumers since it leads to higher power prices. Meanwhile, producer surplus improves because, in effect, the tighter NO_x cap encourages all producers to cut back production (similar to the exercise of market power), while all NO_x permit payments are, in the end, retained by the producers.

B. Comparison of Competitive (Case 1) and Oligopoly (Case 2)

Under our assumption, moving from a competitive to an oligopolistic market cause the NO_x permit price to decrease by 962 \$/ton and the average power price to increase by 7.3 \$/MWh. Aggregate power sales decrease by $6.2x10^6$ [MWh]. Such a result is well known in the theory that Cournot producers restrain their generation, and in turn, dampen the demand for NO_x permits, so the NO_x permit price declines. However, one of Cournot producers, Reliant, in contrast, expands its output by 1.6 $x10^6$ [MWh]. This is because the decline of NO_x permit price together with the increase in power prices provides Reliant (a producer that is short in the permits market) an incentive to operate its dirty generators (which would otherwise shut down due to the substantial expenses incurred with permit costs) in the oligopoly solution. Interestingly, the under-consumption of NO_x permits due to a less generation by PSEG and CONST results in a switch of market position from short in Case 1 to long in Case 2. A symmetric argument is applied to the fringe producers: Connective and Other. The competitive fringes take advantage of higher power prices and a lower permit price to increase their output. All producers benefit from the exercise of market power by Cournot producers, although this is not a general result.[7] Social welfare shrinks by 111 million dollars over the ozone season, with a gain of 748 million by producers and a loss of 845 million for consumers. The production efficiency loss amounts to 82.6 million dollars in Case 2. That is, the minimum cost of serving the same exact quantities demanded as in Case 2 is \$82.6M less than the Case 2 cost (an increase of more than 7.4 %). This is because high cost power from the competitive fringe (who expand output) replaces the withdrawn inexpensive power no longer provided by Cournot producers (who have decreased output to increase price).

C. Comparison of Oligopoly Without and With Market Power in the Permits Trading Market (Case 2 versus Case 3)

There are two counteracting forces affecting the price of NO_x permits. On the one hand, the contraction of generation by Cournot producers as well as the exercise of oligopsonistic market power by producers who are short in the NO_x permit market (i.e., PPL and Reliant) put a downward pressure on the permit price. On the other hand, producers in a long position (i.e., CONST, PECO and PSEG) restrict their sales of NO_x permits (by expanding their output or burning allowances inefficiently) with the hope to drive up permit price. As a result, CONST found it is worthwhile to inflate its output to a level such that it switches back to a short position in the permit market in Case 3. . The net effect is a decline in NO_x permit price by 90 \$/ton and a slight increase of 0.1 \$/MWh in average power prices in Case 3 (in which oligopoly producers anticipate that they can manipulate NO_x prices) compared with Case 2 (where all producers are price takers in the permits market). All the Cournot producers are better off; they increase their output and profit (except PPL and Reliant), while the fringe's generation goes down because of the increased price of allowances. The overall social welfare drops by 4 million dollars and the change in consumer and producer surplus is –2 and –4 million dollars, respectively. The only sector that benefits is the grid operator, whose surplus increases by 2 million dollars. The production inefficiency amounts to roughly \$83 M both cases.

D. Comparison of Oligopoly with All Firms Having Market Power in Permit Market with PECO Having High Market Power (Case 3 versus Case 4)

With NCP_{PECO} equaling to 1.5 [(\$/ton)/ton] (simulating a expectation by the producer with the longest position that it can exert a large amount of market power in the NO_x market), the NO_x permit price increases by 669 \$/ton in comparison with Case 3. Such an increase in the NO_x permit price will in average increase rivals' production cost by about 1.5 \$/MWh,[8] with a larger impact for dirty generators than for clean ones. Under this assumption, PECO found it worthwhile to increase its output by 2.1 $x10^6$ [MWh] (8.3%), and burn 6,050 more tons of NO_x permits. Its profit increases by 28.6 million dollars, from 928.5 to 957.1 million dollars. PECO's revenues from NO_x permit sales actually decrease by 27% (i.e., 12,289*1,505 - 6,240*2,174 = 4.9 [M\$]), but this is more than made up by its increased sales and profits in the power market. In response to a NO_x permit price of 2,174 \$/ton, all other producers restrict output to a total of 2.2 $x10^6$ [MWh]. The net is a decrease of total power sale of $0.1x10^6$ [MWh]. The sale-weighted power price declines by 0.1 [\$/MWh]. Interestingly, the social welfare increases by 9 million dollars. This is because most of the additional generation by PECO occurs at nodes associated with high power prices. For example, its output increases by 170 MW (or 2.6%) in the PECO node during peak period, which in turn results in a decrease of power price by 9.6 \$/MWh. Moreover, this higher value of NCP_{PECO} leads to the convergence of nodal prices across nodes (e.g., the standard deviation of nodal prices at peak period declines from 6.0 to 3.2 \$/MWh) and periods (e.g., an increase of power price during the 3rd to 5th period when dirty coal plants are on the margin, and a decrease of nodal prices during the 1st and 2nd periods when PECO expands its output). The total producer surplus goes down by 2.9 millions dollars, which is the net

---

[7] However, counter-intuitively, it is possible in general for a pure Cournot producer with a long position in permit market to become worse off in the Case 2. This is because he loses revenue from his sale of allowances, and this loss in the permit market outweighs his revenue gain in the power market. This does not occur in our simulations, however.

[8] Assuming an average NO_x emission rate of 4.5 lbs/MWh and an increased permit price of 669 \$/ton, the corresponding impact on production cost would be 4.5 [lbs/MWh]*1/2000 [ton/lb] *669 [\$/ton] = 1.5 \$/MWh. This is about 4% of the average oligopoly power price.

result of PECO's gain and other producers' losses. Consumer surplus increases 12 million dollars with the lower Case 4 power. The production inefficiency declines by $4 million (to $79 million.).

E. NO_x Trading Volume and Efficiency of the USEPA NO_x Budget Program

We use total NO_x trading volume as an index to gauge the efficiency of the USEPA NO_x budget program under different case. The trading volume is calculated as 0.5 times the sum of absolute value of NO_x permit trade for individual producers. In general, efficiency declines from a NO_x trading volume of 16,279 tons in Case 1 to 10,333 tons in Case 4. The Cournot assumption in the power market and conjectured price response with $NCP_f = 0.1$ [(\$/ton)/ton] in the permit market roughly have same impact on trading volume, 1,112 and 947 tons for Cournot and $NCP_f = 0.1$, respectively. A substantial impact occurs when $NCP_{PECO} = 1.5$, with a decline of 3,887 tons in contrast to Case 1. This is consistent with the conclusion of (Stavins, 1995) that the existence of market power will diminish the efficiency and the amount of trade in the permit market.

CONCLUSIONS

A process–based market equilibrium model formulated as a complementarity problem is demonstrated to be potentially useful tool for studying the exercise of market power in interacting energy, transmission, and pollution emission permits markets. The complementarity approach to modeling transmission-constrained power markets has been extended by creating an intertemporal constraint over an entire ozone season and allowing permit trading taken place between firms. In our model, firms can exercise market power in the energy market (Cournot game) and in the emissions permits market (using the notion of a conjectured price response function (Day et al., 2002)). We show that strategic behavior of strategic firms can be made more complex by the inclusion of this additional market.

The richness of engineering details allows a user to gain insight on the types of strategies that might be exercised while quantifying various economic efficiency measures under different producer strategies. Here, we use this approach to understand producer behavior given its generation capacity and net position in the permit market. The overall production inefficiency can be estimated by comparing generation costs with those resulting from a companion perfect competition linear programming model that minimizes the cost of meeting the same demand (see the Appendix 1). Our illustrative application to the PJM market shows that strategic behavior would have a substantial impact on NO_x permit prices, and that the price of permits can influence electricity generation. Furthermore, sensitivity analyses show that when allowance supplies are tight, it is sometimes possible for a generator that is long in allowances to profitably restrict its sale of allowances, thereby raising the price of allowances, its rivals marginal costs, and ultimately the price of power. The detail that the model includes on generation, the network, and emissions enables a user to address a variety of "what-if" type of policy questions, such as: "*What would the NO_x permit price be if the cap is imposed throughout an entire year?"; "What would be the profitability to a large generator of a strategy designed to manipulate the price of allowances in order to increase production costs for rival firms?" ; "What would be the permit prices if some restrictions are imposed on inter-zone permit trading?"*

REFERNCE

Amundsen, E. S. and L. Bergman (2002). "Will Cross-Ownership Restablish Market Power in the Nordic Power Market?" Energy Journal **23**(2): 73-95.

Cason, T. N. and L. Gangadharan (2003). "Transactions Costs in Tradable Permit Markets: An Experimental Study of Pollution Market Designs." J. Regul. Econ. **23**(2): 145-165.

Day, C. J., B. F. Hobbs and J. S. Pang (2002). "Oligopolistic Competition in Power Networks: A Conjectured Supply Function Approach." IEEE Trans. Power Syst. **17**(3): 597-607.

EIA (2003). Form EIA-860A Database Annual Electric Generator Report-Utility, www.eia.doe.gov/cneaf/electricity/page/eia860a.html.

Farrell, A., R. Carter and R. Raufer (1999). "The NOx Budget: Market-Based Control of Tropospheric Ozone in the Northeastern United States." Resour. and Energy Econ. **21**(2): 103-124.

Hahn, R. W. (1984). "Market Power and Transferable Property-Rights." Q. J. Econ. **99**(4): 753-765.

Hobbs, B. F. (2001). "Linear Complementarity Models of Nash-Cournot Competition in Bilateral and POOLCO Power Market." IEEE Trans. Power Syst. **16**(2): 194-202.

Hobbs, B. F., F. A. M. Rijkers and A. F. Wals (forthcoming). "Market Power in Power Networks: Conjectured Transmission Price Responses in a Mixed Transmission Pricing System." IEEE Trans. Power Syst.

Hobbs, B. F., M. H. Rothkopf, L. C. Hyde and R. P. O'Neill (2000). "Evaluation of a Truthful Revelation Auction in the Context of Energy Markets with Nonconcave Benefits." J. of Regul. Econo. **18**(1): 5-23.

Hogan, W. W. (1992). "Contract Networks for Electric-Power Transmission." J. of Regul. Econ. **4**(3): 211-242.

Hung, N. M. and E. S. Sartzetakis (1998). "Cross-Industry Emission Permits Trading." J. Regul. Econ. **13**(1): 37-46.

Kahn, E. P. (1998). "Numerical Techniques for Analyzing Market Power in Electricity." The Elec. J. **11**(6): 34-43.

Kolstad, J. T. and F. A. Wolak (March, 2003). Using Environmental Emissions Permit Prices to Raise Electricity Prices: Evidence from the California Electricity Market. Berkeley, CA, UCEI Power Conference.

Leppitsch, M. J. and B. F. Hobbs (1996). "The Effect of NOx Regulations on Emissions Dispatch: A Probabilistic Production Costing Analysis." IEEE Trans. Power Syst. **11**(4): 1711-1717.

Mansur, E. T. (2001a). Environmental Regulation in Oligopoly Markets: A Study of Electricity Restructuring, POWER Working Paper PWP-088, UCEI, University of California, Berkeley.

Mansur, E. T. (2001b). Pricing Behavior in the Initial Summer of the Restructured PJM Wholesale Electricity Market, POWER Working Paper PWP-083, UCEI, University of California, Berkeley.

Morch, N.-H. and V. D. Fehr (1993). "Tradable Emission Rights and Strategic Interaction." Environ. and Resour. Econ. **3**: 129-151.

NERC (2003). Generating Availability Reports, www.nerc.com/~filez/gar.html.

Newell, R. G. and R. N. Stavins (2003). "Cost Heterogeneity and the Potential Savings from Market-Based Policies." J. Regul. Econ. **23**(1): 43-59.

Pang, J.-S. and B. F. Hobbs (under review). "Spatial Oligopolistic Equilibria with Arbitrage, Shared Resources, and Price Function Conjectures." Mathematical Programming.

PJM (2001). PJM Interconnection State of the Report 2000.

PowerWorld (2003). www.powerworld.com/downloads.html.

Sartzetakis, E. S. (1997a). "Raising Rivals' Costs Strategies via Emission Permits Markets." Rev. Ind. Organ. **12**(5-6): 751-765.

Sartzetakis, E. S. (1997b). "Tradable Emission Permits Regulations in the Presence of Imperfectly Competitive Product Markets: Welfare Implications." Environ. and Resour. Econ. **9**: 65-81.

SCAQMD (2003). Regional Clean Air Incentives Market, www.aqmd.gov/reclaim/reclaim.html.

Stavins, R. N. (1995). "Transaction Costs and Tradable Permits." J.Environ.Econ.Manage. **29**(2): 133-148.

Tietenberg, T. (2003). Environmental and Natural Resource Economics. Boston, MA, Addison Wesley.

USEPA (2003a). EGRID, www.epa.gov/cleanenergy/egrid.htm.

USEPA (2003b). NOx Budget Program, www.epa.gov/airmarkt/fednox/index.html.

APPENDIX 1 - Perfect Competition LP (Linear Programming) Least-Cost Dispatch Model

This model calculates the minimum cost of meeting a set of power demands for a transmission- and emissions-constrained power system. This cost can be compared to the cost in an oligopoly simulation with the same quantities demanded to determine the production inefficiency resulting from market power.

Sets and Indices:

$f, g \in F$	Producers
$t \in T$	Periods
$i, j \in I$	Nodes in network
$k \in K$	Interface in network
$h \in H$	Generators
$H(i, f) \subset H$	Set of producer *f's* generators at node *i*
$H^{OTC}(f, i) \subset H$	Set of producer *f's* generators at node *i* whose emissions are included in NO_x program

Parameters

C_{fih}	Marginal production cost of generator *fih* [\$/MWh]
X_{fih}	Production Capacity of generator *fih* [MW]
E_{fih}	Emission rate of generator *fih* [lbs/MWh]
FOR_{fih}	Forced outage rate of generator *fih* [dimensionless]
T_k	Capacity limit for interface *k* [MW]
L_{it}	Demand of power at node *i* in period *t* [MW]
B_t	Duration of period *t* in the load duration curve approximation [hours]
$PTDF_{ki}$	Power transfer distribution factor for a unit power injection at an arbitrage hub node and unit withdrawal at node *i* for transmission interface *k* [MW/MW]
Z_{it}	Power imported from outside the study region to node *i* in period *t* [MW]
CAP_{NO_x}	NO_x emission cap [tons]
$P_{it}^0 (Q_{it}^0)$	Vertical (Horizontal) intercepts of demand curve at node *i* in period *t* [\$/MWh (MW)]
NPC_f	Slope of NO_x conjectured price function for producer f [(\$/ton)/ton]
N_f	NO_x permit held by f firm at the beginning of ozone season [tons]

Primal Variables and Market Prices

x_{fiht}	Output level of generator *fih* in period *t* [MW]

s_{fit}	Power sold by firm *f* at node *i* in period *t* [MW]
y_{it}	Power delivered from hub to node *i* in period *t* [MW]
p_f^N (p^{N*})	Conjectured (equilibrium) NO$_x$ price by producer *f* [\$/ton]
p_{it}^E	Power price at node *i* in period *t* [\$/MWh]
tot_f^{N*}	Total OTC NO$_x$ emission of *f* firm in equilibrium [tons]

The model is as follows. Dual variables for each constraint are shown in parentheses:

$$MIN_{x_{fiht},s_{fit}} \sum_{i,f,h\in H(i,f),t} C_{fih} B_t x_{fiht} \tag{1}$$

Subject to:

$$x_{fiht} \le X_{fih}(1-FOR_{fih}) \ \ \forall i,f,h\in H(i,f),t \qquad (\rho_{fiht}) \tag{2}$$

$$\sum_{i,h\in H(i,f)} x_{fiht} - \sum_i s_{fit} = 0 \ \ \forall f,t \qquad (\theta_{ft}) \tag{3}$$

$$\sum_f s_{fit} + Z_{it} \ge L_{it} \ \ \forall i,t \qquad (p_{it}^E) \tag{4}$$

$$\sum_{i,f,h\in H(i,f),t} B_t E_{fih} x_{fiht} \le CAP_{NO_x} \qquad (p^{N*}) \tag{5}$$

$$\sum_i y_{it} PTDF_{ki} \le T_k \ \ \forall k,t \qquad (\lambda_{kt}) \tag{6}$$

$$y_{it} - \sum_{f,h\in H^{OTC}(i,f)} x_{fiht} - Z_{it} + \sum_f s_{fit} = 0 \ \ \forall i,t \qquad (W_{it}) \tag{7}$$

$$s_{fit}, x_{fiht} \ge 0$$

APPENDIX 2 - Oligopoly Competition Model

The following models correspond to the individual optimization problems described in the Model section of the paper. After taking the first-order (KKT conditions) for the producer and grid operator problems and then adding the market clearing conditions, a set of equilibrium conditions of the oligopolistic power and permits markets is defined, which can be solved by complementarity algorithms (Chen and Hobbs, submitted).

<u>Producers:</u>

$$\begin{aligned} &MAX_{x_{fiht},s_{fjt}} \sum_{j,t} (P_{jt}^0 - P_{jt}^0 / Q_{jt}^0 \sum_g s_{gjt} - w_{jt}) B_t s_{fjt} \\ &- \sum_{i,h\in H(i,f),t} (C_{fih} - w_{it}) B_t x_{fiht} - p_f^N (\sum_{i,h\in H^{OTC}(i,f),t} B_t E_{fih} x_{fiht} - N_f) \end{aligned} \tag{1^O}$$

Subject to:

$$x_{fiht} \le X_{fih}(1-FOR_{fih}), \forall i,h\in H(i,f),t \qquad (\rho_{fiht}) \tag{2^O}$$

$$\sum_j s_{fjt} = \sum_{i,h\in H(i,f)} x_{fiht} \forall t \qquad (\theta_{ft}) \tag{3^O}$$

$$p_f^N = p^{N*} + NPC_f (\sum_{i,h\in H^{OTC}(i,f)} B_t E_{fih} x_{fiht} - tot_f^{N*}) \tag{4^O}$$

$$\forall s_{fj}, x_{fiht} \ge 0$$

<u>Consumers:</u>

$$p_{jt}^E = P_{jt}^0 - P_{jt}^0 / Q_{jt}^0 \sum_f s_{fjt} \forall j,t \tag{5^O}$$

<u>Grid Operator:</u>

$$MAX_{y_{it}} \sum_{i,t} B_t W_{it} y_{it} \tag{6^O}$$

Subject to:

$$\sum_i PTDF_{ki} y_{it} \le T_k \ \ \forall k,t \qquad (\lambda_{kt}) \tag{7^O}$$

<u>Market Clearing and Consistency Conditions:</u>

$$\sum_f s_{fit} - \sum_{f,h\in H(i,f)} x_{fiht} - Z_{it} = y_{it}, \forall i,t \tag{mc1}$$

$$0 \le p^{N*} \perp \sum_f (\sum_{f,i,h\in H^{OTC}(i,f),t} B_t E_{fih} x_{fiht} - N_f) \le 0 \tag{mc2}$$

$$tot_f^{N*} = \sum_{i,h\in H^{OTC}(i,f),t} B_t E_{fih} x_{fiht}, \forall f \tag{mc3}$$