Modeling NOx Emissions Trading in Competitive Electricity Markets

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Introduction

- The recent court rulings on EPA's NOx SIP Call indicate that there is a strong need to quantify the costs and benefits of NOx regulations in the US.
- There has been serious speculation that deregulating the electricity markets will degrade the environment and cause major harm to the Northeast region by emissions from Midwestern generation.
- The effectiveness of a tradable-permits markets in achieving efficient outcomes for environmental emissions has not yet been fully modeled and analyzed.

Market Model-Mathematical Formulation

The combined energy and tradable permits markets can be simulated as a single multi-period least-cost optimization problem with demand balance and emissions budget constraints.

$$\underset{g_i, E_{ri}}{Min} \qquad TotalCost = \sum_{\forall i} \sum_{t=1}^{T} \left[C_i(g_i(t)) + V_i(E_{ri}) g_i(t) \right] + I_i(E_{ri}) \qquad \textbf{(1)}$$

Subject to:

$$\sum_{\forall i} g_i(t) = Demand(t)$$ **:l(t)** **Energy Balance Constraint**

$$\sum_{t=1}^{T} \sum_{\forall i} g_i(t)(E_{Ai} - E_{ri}) \leq EmissionBudget$$ **:m** **Emissions Budget Constraint**

$$g_i(t), E_{ri} \geq 0$$

Market Model-Mathematical Formulation

Where:

$g_i(t)$:	Energy generated from unit *i* at time *t*.
$C_i(g_i(t))$:	The generation cost function for unit *i* at time *t*, i.e., cost of fuel and unit's variable operation and maintenance cost.
E_{Ai}:	Actual emission rate for generation unit *i* before any abatement technology addition. We assume the emission rate is fixed and independent of generation.
E_{ri} :	Emission rate reduction achieved by adding an abatement technology.
$V_i(E_{ri})$:	Variable cost associated with reducing emissions from unit *i*, by E_{ri} , we assume this cost to be a linear function of E_{ri} , $V_i(E_{ri}) = K_i E_{ri}$.
$I_i(E_{ri})$:	Fixed operating and capital cost function associated with emissions reductions, E_{ri} , over a period T. We assume this cost to be continuos, convex and monotonically increasing.
$l(t)$:	Shadow price of the energy balance constraint, or energy market-clearing price at time t.
m :	Shadow price of the emissions budget constraint, or market-clearing price of tradable allowances.
$t \in [1, T]$:	*T* is the set of ozone seasons, from May 1st to September 30th, over the average life expectancy of control technologies.
$i \in [1, N]$:	The set of all generators including optimal (chosen) entry and retirement profile.

Market Model-Mathematical Formulation

The Khun-Tucker conditions for the above optimization problem are:

$$l(t) = C_i^{'}(g_i(t)) + m(E_{Ai} - E_{ri}) + K_i E_{ri} \qquad \forall i, t \qquad \textbf{(2)}$$

$$I_i^{'}(E_{ri}) + K_i \sum_{t=1}^{T} g_i(t) = m \sum_{t=1}^{T} g_i(\mathrm{t}) \qquad \forall i \qquad \textbf{(3)}$$

$$m \geq 0 \text{ ,}$$

With complementary constraint:

$$m \left(\sum_{t=1}^{T} \sum_{\forall i} g_i(t)(E_{Ai} - E_{ri}) - EmissionBudget \right) = 0 \qquad \textbf{(4)}$$

CASE I : Perfect Compliance
Total Emissions at Budget

- **The market-clearing price for the tradable allowances is the shadow price of the emission budget constraint, or the system cost reduction achieved by relaxing the emission constraint by one per unit.**
- **The increase in market-clearing price value is the cost of used tradable allowances and variable O&M costs associated with abatement technology.**

- **From equation (3), for each unit, the total cost of trading is equal to the incremental cost of reducing emissions (assumption of continuos investment function).**

- **The tradable permit price does not vary with time, which rests on the assumption that investments are made simultaneously, at which time the market achieves equilibrium.**

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CASE II : Over Compliance
Total Emissions within Budget

- **The shadow price of the budget constraint is zero, thus as shown in equation (2a), the energy market-clearing price is function of marginal cost of the energy and control technology variable cost.**
- **Equation (3a) shows that this is not a feasible solution since the marginal cost of investment and the variable cost are both positive.**

  Thus over-investment is not an optimal solution for continuous investment function. However, in reality the market might reach that level because of discreteness and economies of scale in emission control technologies.

$$l(t) = C_i^{'}(g_i(t)) + K_i E_{ri} \qquad \textbf{(2a)}$$

$$I_i^{'}(E_{ri}) + K_i \sum_{t=1}^{T} g_i(\mathrm{t}) = 0 \qquad \forall i \qquad \textbf{(3a)}$$

Insights from the Mathematical Model

- **Generators should bid their marginal production cost, fuel cost plus trading opportunity cost, plus any VOM associated with emission reduction technologies.**
- **The energy market-clearing price will be set by the marginal unit(s)' marginal production cost.**
- **Generators should invest in emission reduction technologies as long as their total cost of investment (capital and operating) is less than the tradable permits cost.**
- **The tradable permits market-clearing price will exceed, equal, or be below the incremental cost of emission reduction in the case of under, perfect or over compliance, respectively.**
- **The incremental cost of emission reduction is related to the incremental investment cost in reduction technology divided by the total energy generated plus the technology VOM.**

General Market Simulation Methodology

- **We utilized GE-MAPS to model the electric power generation markets, in an iterative approach to solve the "real" version of the above formulated problem.**
  - **GE-MAPS is a security-constrained least-cost chronological production cost model.**
  - **It is used to determine the locational energy market-clearing prices, the revenues, costs and profitability of generation units.**
  - **We used the most up to date data on load forecast, fuel price, thermal units availability (nuclear), thermal units heat rates and fixed and operating costs, transmission constraints, and market rules.**
- **Why an iterative approach?**
  - **Model capabilities to solve joint optimization of energy dispatch and investment decisions are not readily available.**
  - **The generation investment problem is solved separately in an iterative approach (new entry and retirements).**

Emissions Modeling Assumptions

- **Assume a perfect competitive market for tradable permits with no transaction cost.**
- **Assume a cap-and-trade emission reduction program with budget constraints only (no unit or time specific constraints).**
- **The cap-and-trade program is applied on a regional (22-state, including Northeast and Midwest) basis rather than on a state by state basis.**

Investment in Emission Reduction - Algorithm

STRATEGY → Invest / Trade / Retire?

	Invest	Trade
Fixed Cost	Annual carrying cost of NOx abatement technology	None
Variable Cost (in energy bid)	• Operating cost of abatement technology + • Opportunity cost of used allowances	• Cost of purchased allowances + • Opportunity cost of used allowances + • Opportunity cost of lower dispatch

Retire?

Investment in Emission Reduction - Algorithm

1. Start with least-cost dispatch ignoring environmental costs, determine units' generation, revenues and costs.
2. Select a projected equilibrium trading allowance price, and compare the cost of trading to the cost of investing (evaluate different technologies), given the performance level assumed in 1. Choose the option that results in lower costs for each evaluated unit.
3. For those units that opted to invest, add the variable O&M of the selected technology to their generation bid. For all units add the emission opportunity costs as the tradable allowance price times their emission rate (either original or post-investment).
4. Solve for least-cost dispatch with the new unit marginal costs, determine units' generation, revenues and costs, and total NO_x emissions.
5. Check to see if total emissions are within budget. If yes, stop iterations, if no, go back to 2 (increasing the projected equilibrium allowance price).

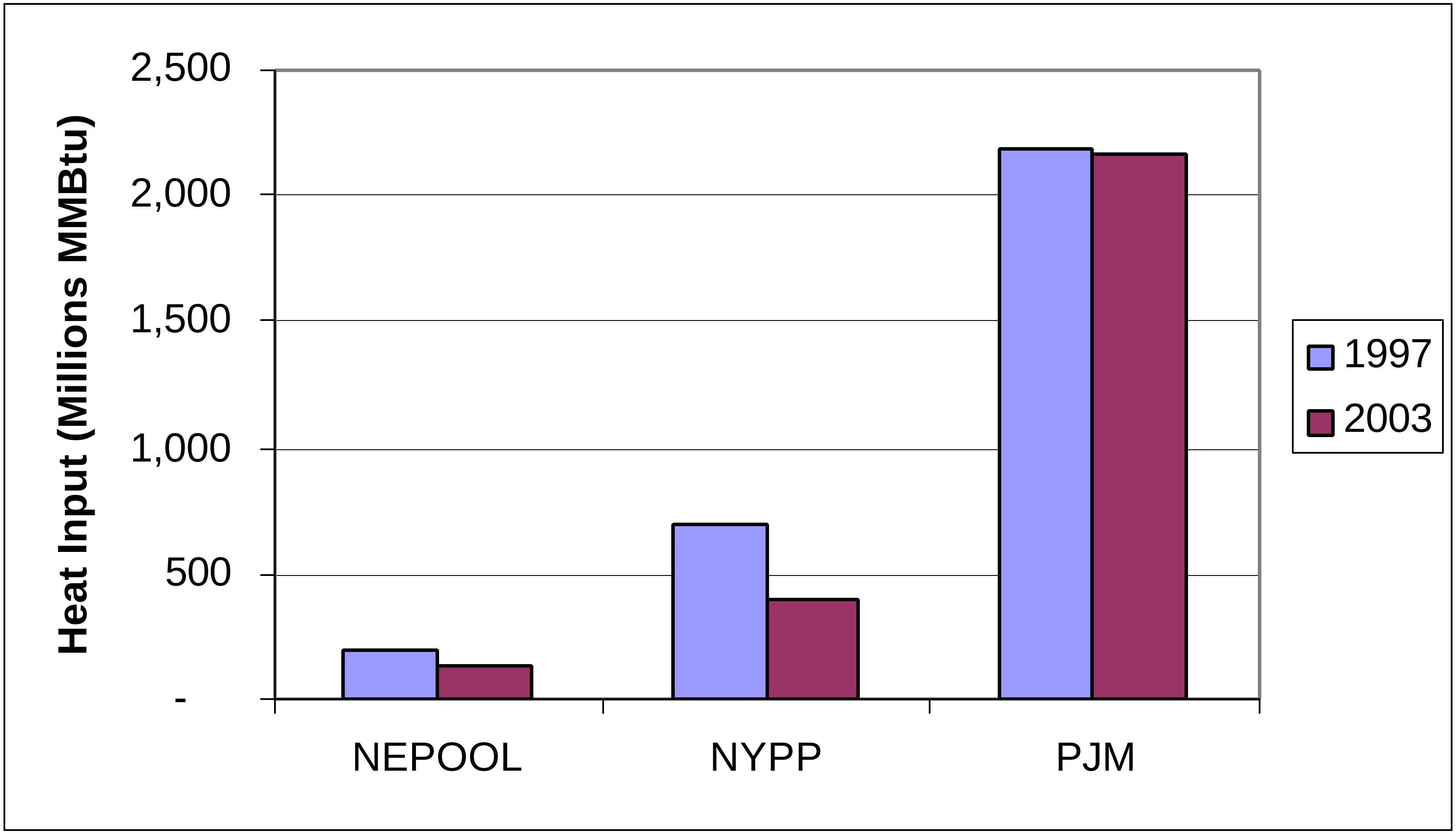
Application to the Northeastern and Midwest US Electricity Markets

- In 1997, EPA issued the State Implementation Plan Call, which require 22 states in the Eastern US to submit plans to address the transport of ozone across state boundaries.
- This proposal followed in the footsteps of the Memorandum of Understanding (MOU) in the 12-state Northeast Ozone Transport Region (OTR), where states volunteered to reduce emissions to a level almost as stringent as the SIP Call by 2003, through institution of a cap-and-trade program.
  - Phase II of the MOU allocates allowances based on the less stringent of a 75% reduction and a reduction to 0.15lb/MMBtu.
- Under the SIP Call, states were allocated budgets based on a NOx emission rate of 0.15 lb/MMBTU and projected generation levels. The total budget for the 22 states is 544,000 tons

Impact on Northeast Markets

- **Market Prices: prices increase by up to 5% in PJM, 2-4% in NYPP and NEPOOL. However, the combined impact of environmental regulations and new entry is to reduce the prices relative to today.**
- **Investment cost: a very small incremental cost associated with the Nox SIP Call was estimated (around $40 Million/year), because several investments have been made as part of Phase I of MOU in the OTR.**
- **Capacity Profile: significant new entry helps in displacing dirtier units, and causes some retirements. The new entry significantly exceed the load growth and is more economic than many existing units.**

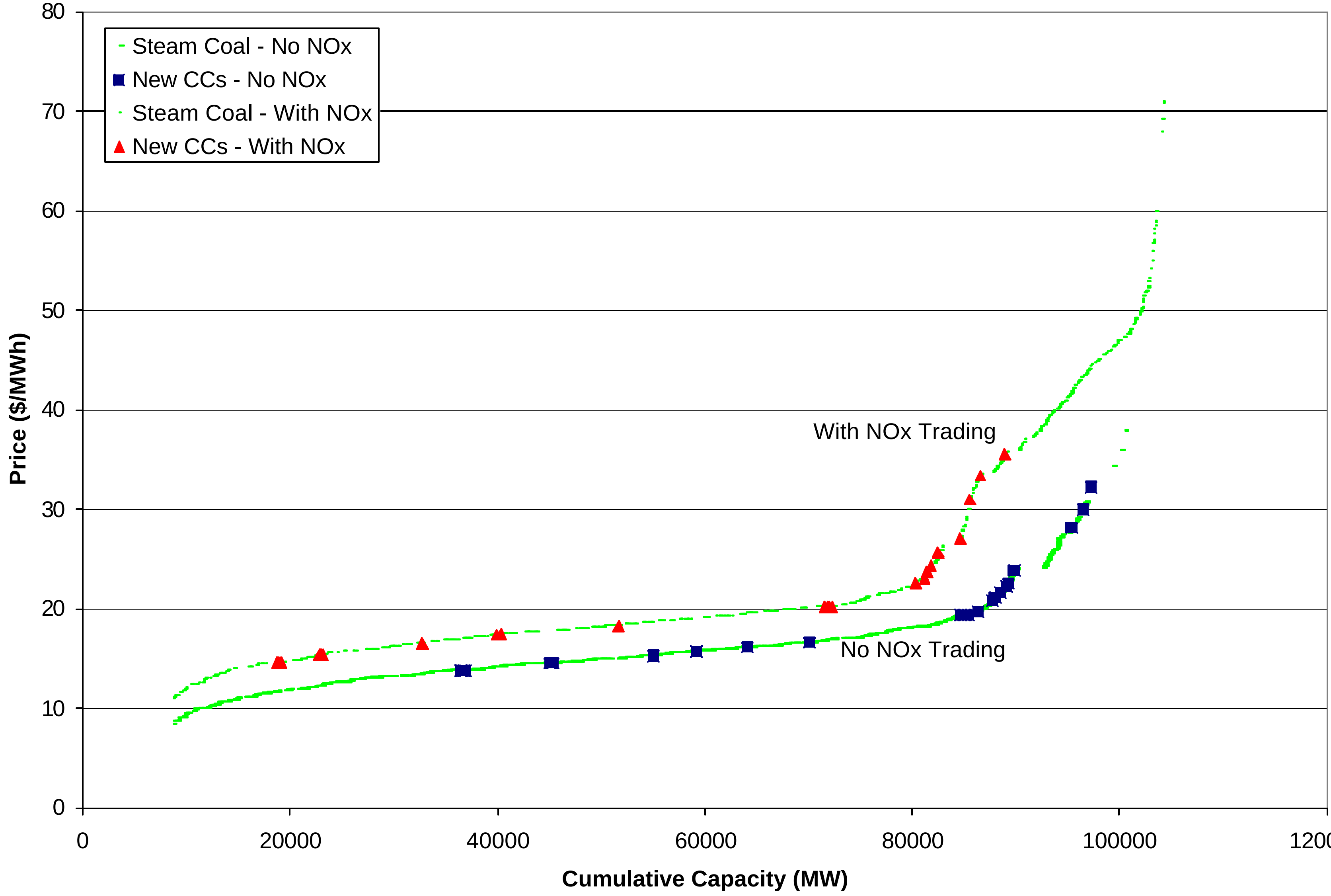
Impact on Coal-Fired Generation Units



Impact on Midwest Electricity Markets

- **Market Prices: prices increase by up to 15% in ECAR. However, the combined impact of environmental regulations and new entry is to reduce the prices relative to today.**
- **Investment cost: the cost associated with abatement technology associated with the SIP Call is significantly higher than in the Northeast, and many more units will be impacted. The reason for this higher cost is the higher portion of coal in the generation mix in the Midwest.**
- **Capacity Profile: significant new entry helps in displacing dirtier units, and causes some retirements. The new entry significantly exceed the load growth and is more economic than many existing units.**

Impact of Nox Emissions Trading on ECAR Supply Curve



Conclusions

- **The above proposed formulation can be used by the industry to make informed policy decisions, and to evaluate the impact of environmental regulations on market clearing prices of electricity and the costs of emission reduction for generators.**
- **The impact of EPA's NOx SIP Call on energy market-clearing prices in the Northeastern and Midwest US can be up to 5% in PJM and up to 15% in ECAR.**
- **The competitive entry will reduce the stringency and the incremental cost associated with the NOx SIP Call.**
- **The analysis shows that the deregulation of the electric power markets and the environmental regulations can join hands in reducing emissions from power plants.**