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Ronald G. Prinn and John M. Reilly,
Program Co-Directors

For more information, contact the Program office:

MIT Joint Program on the Science and Policy of Global Change
Postal Address:
Massachusetts Institute of Technology
77 Massachusetts Avenue, E19-411
Cambridge, MA 02139 (USA)
Location:
Building E19, Room 411
400 Main Street, Cambridge
Access:
Tel: (617) 253-7492
Fax: (617) 253-9845
Email: ***globalchange@mit.edu***
Website: ***http://globalchange.mit.edu/***

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Flexible NO_x Abatement from Power Plants in the Eastern United States

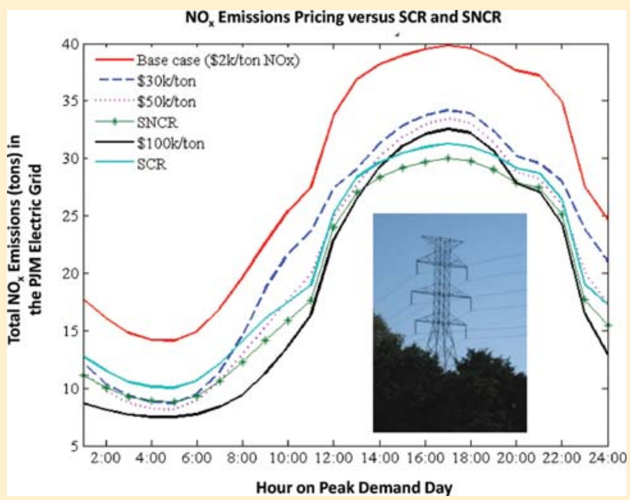
Lin Sun,[†,§] Mort Webster,[†] Gary McGaughey,[‡] Elena C. McDonald-Buller,*[,‡] Tammy Thompson,[†,‡] Ronald Prinn,[§] A. Denny Ellerman,[⊥] and David T. Allen[‡]

[†]Engineering Systems Division, [§]Department of Earth, Atmosphere and Planetary Sciences, and [⊥]Sloan School of Management, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, United States

[‡]Center for Energy and Environmental Resources, The University of Texas at Austin, Austin, Texas 78758, United States

S *Supporting Information*

ABSTRACT: Emission controls that provide incentives for maximizing reductions in emissions of ozone precursors on days when ozone concentrations are highest have the potential to be cost-effective ozone management strategies. Conventional prescriptive emissions controls or cap-and-trade programs consider all emissions similarly regardless of when they occur, despite the fact that contributions to ozone formation may vary. In contrast, a time-differentiated approach targets emissions reductions on forecasted high ozone days without imposition of additional costs on lower ozone days. This work examines simulations of such dynamic air quality management strategies for NO_x emissions from electric generating units. Results from a model of day-specific NO_x pricing applied to the Pennsylvania−New Jersey−Maryland (PJM) portion of the northeastern U.S. electrical grid demonstrate (i) that sufficient flexibility in electricity generation is available to allow power production to be switched from high to low NO_x emitting facilities, (ii) that the emission price required to induce EGUs to change their strategies for power generation are competitive with other control costs, (iii) that dispatching strategies, which can change the spatial and temporal distribution of emissions, lead to ozone concentration reductions comparable to other control technologies, and (iv) that air quality forecasting is sufficiently accurate to allow EGUs to adapt their power generation strategies.



■ INTRODUCTION

Elevated concentrations of ground-level ozone are among the most persistent and pervasive air quality concerns in the United States (U.S.). Ground-level ozone is a secondary pollutant formed by photochemical reactions of oxides of nitrogen (NO_x) and volatile organic compounds (VOCs). National Ambient Air Quality Standards (NAAQS) for ground-level ozone have become increasingly stringent over the past several decades, with significant changes in averaging time, level, and form. Although significant improvements in air quality have occurred across the eastern U.S. over the past two decades,[1−3] elevated ozone concentrations remain a regional concern. The Northeast States for Coordinated Air Use Management[4] found that the most severe episodes are associated with the passage of slow-moving, high-pressure systems during the summer that extend from the Midwest to the middle or southern Atlantic states. Clear skies and high temperatures that favor ozone formation and a circulation pattern that favors long-range pollution transport can lead to ozone episodes of strong intensity and long duration. Reductions of NO_x emissions, in particular from electric generating units (EGUs), have been critical for achieving regional ozone reductions, while reductions of VOC emissions alone or in combination with NO_x emissions reductions have been important in local circumstances.[4]

NO_x emissions from EGUs represented 20% (3.7 million tons) of total U.S. anthropogenic NO_x emissions in 2005, behind on-road mobile sources (36%) and nonroad equipment (23%).[5] Prescriptive reductions of NO_x emissions from EGUs can be achieved by combustion modifications, such as low NO_x burners and boiler optimization, and postcombustion technologies, including selective noncatalytic reduction (SNCR) and selective catalytic reduction (SCR). SCR removes nitrogen oxides through reactions with ammonia in a catalyst bed. SNCR also uses ammonia or another reducing agent but without the

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catalyst. SCR is more effective, with up to 90% removal, but at a higher cost than SNCR, which achieves 30% to 80% removal depending on the specific unit. Recognition of the contribution of NO_x emissions from EGUs to the regional formation and transport of ozone and fine particulate matter in the eastern U.S. prompted programs such as the NO_x SIP Call in 1998 that required reductions of emissions from power plants and large combustion sources in 22 states and the District of Columbia.[4,6−12] The Clean Air Interstate Rule (CAIR) issued in 2005 included a NO_x control program aimed at a 28-state region in the eastern U.S.[13] The U.S. EPA[14,15] finalized the Cross-State Air Pollution Rule (CSAPR) as a likely replacement to CAIR for achieving reductions of NO_x and sulfur dioxide (SO_2) from power plants in the eastern half of the U.S in July 2011. A map of affected states under the CSAPR is given in Section S1, Supporting Information.[14] For affected states based on 2007 emissions data contained in the U.S. EPA's 2010 Emissions & Generation Resource Integrated Database (eGRID2010), approximately 84% of coal-fired utility boilers are already equipped with combustion controls, whereas SNCR and SCR are installed on only 9% and 20% of boilers.

Emissions cap and trading has become the preferred federal policy instrument for achieving reductions of NO_x and SO_2 from EGUs.[16] The NO_x Budget Trading Program of the NO_x SIP Call,[16,17] its predecessor the Ozone Transport Commission's NO_x Budget Program,[18] and the U.S. Acid Rain Program[2] have been among the most prominent of these programs. The recently issued CSAPR will allow both intra- and interstate emissions trading with provisions ensuring that states achieve pollution reductions.[14,15]

Generally, in emissions cap and trading programs, facilities are provided or purchase emission allowances; facilities that reduce their emissions below their allowances can trade or sell allowances in a market, and total emissions are reduced by lowering the number of allowances (the cap) over time. Routine emissions data are obtained from Continuous Emissions Monitoring Systems (CEMS) installed at affected facilities. An extensive body of previous studies has documented the successes as well as the challenges and concerns for these programs.[16,19−26]

Market-based NO_x cap and trade programs have historically treated emissions as equivalent regardless of where or when they occur. Mauzerall et al.[27] found that the amount of ozone formed by the same quantity of NO_x could vary by a factor of 5 under different meteorological conditions in the eastern U.S, and that variation in health damages depended strongly on the size of the exposed population. Mauzerall et al.[27] and Tong et al.[28] suggested that incentives for reducing NO_x emissions at times and locations where health damages are greatest could provide more effective reduction of damages from emissions permitted under a cap. Recent analyses of the use of NO_x emissions allocations by EGUs by Martin[29] in the northeastern U.S. have suggested that facilities disproportionately reduce NO_x emissions early in the summer, conserving allocations for later in the season when peak demand in July and August result in higher electricity prices, even though this is also the period during which elevated ozone concentrations are more frequent. In addition, states preparing attainment plans will be challenged with the higher marginal costs of additional permanent or seasonal emissions reductions in the future if the NAAQS for ozone are revised. These findings suggest the utility of considering differentiated NO_x regulation.

This work focuses on the effects of time-differentiated NO_x regulation of EGUs on ozone concentrations in the eastern U.S. Time-differentiated trading lowers NO_x emissions from EGUs even further on days with forecasted elevated ozone by utilizing pricing incentives for electricity redispatching. The incremental cost of this strategy is the added cost of operating more expensive units (less efficient or higher fuel cost), but this cost is only incurred on the targeted high ozone days. In contrast, a prescriptive approach mandating additional controls adds both capital and operating costs for each unit receiving controls. A major technical barrier to a time-differentiated approach is the necessary reliance on weather and atmospheric chemistry forecasting, which is generally perceived to have large uncertainty.[30−33] False positive events (a forecasted high ozone day that in actuality is a low ozone day) may increase costs unnecessarily, while false negative events (a forecasted low ozone day that in actuality is a high ozone day) decrease the amount of ozone that could otherwise be reduced. In this work, the air quality benefits and cost-effectiveness of time-differentiated trading are compared with SCR and SNCR, postcombustion technologies likely to be implemented in the future. Although these simulations considered time-varying NO_x pricing, such a system could be implemented as a time-varying redemption ratio for allowances under a cap, i.e., on designated high ozone days instead of surrendering a single allowance for each ton of NO_x emitted, the regulatory authority would require that a number of allowances greater than one be surrendered for each ton.

METHODS

Simulation of the Electrical Power Grid. In the eastern U.S., most power plants that participate in the seasonal NO_x cap-and-trade programs also participate in one of three wholesale electricity markets: the New England Power Pool, the New York Power Pool, or the Pennsylvania−New Jersey−Maryland (PJM) Interconnect. The Classic PJM Interconnect, selected for this work, included Pennsylvania−New Jersey−Maryland as well as the District of Columbia and Delaware. PJM has since expanded to include 10 additional states and is currently the world's largest competitive wholesale electricity market. It is a federally regulated regional transmission organization (RTO) that coordinates buying and selling through central dispatching.

An optimal power flow (OPF) model was used to simulate generation dispatching accounting for transmission constraints, incremental generation costs, and NO_x emissions under different NO_x pricing scenarios in the Classic PJM grid based on previous work by Martin.[29] The model represented the set of EGUs as given in EPA's 2005 Emissions & Generation Resource Integrated Database (eGRID) database and the detailed transmission system obtained from the Independent System Operators (ISOs). Coal-fired facilities accounted for 48% of the electricity generation in Classic PJM, followed by nuclear (33%) and gas (8%) facilities. Section S2, Supporting Information, presents annual NO_x emissions for 280 Classic PJM facilities from the 2005 eGRID database. Total NO_x emissions were 2.7×10^5 tons/yr with 91% attributed to coal-fired facilities.

The PJM Financial Transmission Rights (FTR) base-case power flows simulated hours with average electricity demand, while the PJM FTR model was scaled to approximate the higher demand hours. Generation costs were estimated using plant-level data in eGRID and calibrated to reproduce historical observations. The model determined hourly generation in each unit to minimize cost, subject to transmission constraints and security contingencies. The OPF software used was PowerWorld Version 13. The optimal power flow model is a nonlinear optimization algorithm that minimizes total (fixed plus variable) operating cost subject to a set of equality and inequality constraints, including meeting demand, enforcing transmission line constraints, generator unit minimum and maximum power levels, and accounting for line losses. Instead of gradient-based and Newton solution methods, a linear programming (LP) approach was used, which allowed the inclusion of inequality constraints.[34] The basic approach was iterative, solving the load flow problem,[35] creating a linear objective function and linearizing constraints for those results, then solving the primal LP to obtain an improved solution for power output at each unit.

Cost Calculations. The cost of a time-differentiated policy was calculated as the change in variable cost of electricity generation under a different emissions price relative to the base case. The change in the electricity generation cost for an individual EGU was a function of the generator's output level, the unit's heat rate, the cost of fuel, the unit's emission rate, and the allowance price. In the OPF model, variable costs of the power plants were represented by linear cost curves, in which increased emissions were incorporated as an additional fuel cost:

$$c_i(\$/\text{MWh}) = H_i(p_{\text{fi}} + p_{\text{ni}}N_i) + \text{O\&M}_i \tag{1}$$

where for each generating unit i, H_i is its heat rate (mmBTU/MWh), p_{fi} is the price of fuel (\$/mmBTU), p_{ni} is the price of the pollutant permits (\$/ton), N_i is the unit's emission rate (short tons/mmBTU), and O&M$_i$ is the unit's variable operation and maintenance costs (\$/MWh). Data on the average delivered cost of fuel for natural gas, coal, petroleum products, and petroleum coke delivered to the electricity sector from the EIA's Electric Power Monthly for August 2005 were used to generate the cost curves. These data were matched to the generating units by state and fuel. Variable O&M data were from the Annual Energy Outlook for 2006 matched roughly by technology type and fuel. The U.S. EPA CEMS data were the source for 2005 ozone-season heat rates and NO_x emission rates. The increased cost of electricity generation under a higher emissions price relative to the base price for each generating unit i at a given hour was ΔC_i:

$$\Delta C_i = c_i'u_i' - c_iu_i \tag{2}$$

where for each generating unit i, u_i and u_i' are its outputs in MWh under the base emissions price and higher emissions price, and c_i and c_i' are its variable costs under the base emissions price and higher emissions price. The increased daily cost of time-differentiated policy was the summation of ΔC_i over each hour of the day and all EGUs within the electricity grid. For the base case, NO_x pricing was applied uniformly to all units in PJM with a price of \$2k/ton, approximately reproducing the observed NO_x price as of summer 2005.[29] In operating a time-differentiated or any similar flexible NO_x regulation that targets high ozone days, the system operator would set the following day's NO_x price based on the ozone forecast. In this study, we explored the impacts of increasing the NO_x price to \$30k/ton, \$50k/ton, or \$100k/ton on predicted high ozone days. It should be noted that the cost of abatement is not the NO_x price times the total abatement. The NO_x prices serve as signals of the relative scarcity. An equivalent system could be implemented using an allowance trading system, but on high ozone days, increasing the redemption ratio (allowances surrendered per ton emitted) to a value greater than unity. The measure of abatement costs, as described above, is the increased cost of generation from substituting sources with lower emissions.

Incremental costs of NO_x emissions reductions below base case (\$2k/ton) emissions were calculated for the SNCR and SCR scenarios as the levelized costs for the capital expenditure plus variable operating costs. Cost calculations for both technology scenarios are presented in detail in Section S3, Supporting Information. An average daily cost of \$0.98 ± 0.12 M/day during the June−Sept ozone season in 2005 dollars was determined for SNCR assuming that all coal-fired facilities install the technology. SCRs were assumed to be installed at 32% of coal-fired EGUs that had the highest NO_x emission rates in Classic PJM. The proportion of coal-fired EGUs that receive SCRs were calibrated such that the \$100k/ton trading case scenario and the SCR scenario had equivalent average daily abatement costs under an ozone concentration threshold of 75 ppb. This design allowed the reductions from similar cost scenarios to be compared. Controls were added to the highest NO_x emission rate units first until the costs were comparable. Because the time-differentiated scenarios assumed no costs outside of the ozone season, SCR costs were assumed to be incurred only during the ozone season for parallel comparison. The average daily SCR cost for the subset of coal plants was \$1.06 ± 0.35M/day.

Simulation of Ozone Impacts. The Comprehensive Air Quality Model with Extensions (CAMx) version 4.51 (http://www.camx.com) was used to examine the effects of NO_x emissions changes on ground-level ozone concentrations. The model was developed by ENVIRON[36] based on data from the Central Regional Air Planning Association (CENRAP) for annual modeling of regional haze and visibility in the eastern U.S. (http://www.epa.gov/scram001/reports/nox_sip.pdf). Meteorological data were developed by the Iowa Department of Natural Resources (IDNR) using the Pennsylvania State University (PSU)/National Center for Atmospheric Research (NCAR) Mesoscale Model Version 5 (MM5).[37] Two broad types of analyses were conducted: deterministic and stochastic. All scenarios differed only in their NO_x emissions from EGUs. Three deterministic simulations were conducted to examine the effects of increases in NO_x pricing (\$30k, \$50k, or \$100k/ton) implemented in Classic PJM *on all days of the ozone season*. Three stochastic scenarios were conducted to examine the effects of increases in NO_x pricing (\$30k/ton, \$50k/ton, or \$100k/ton) implemented *only on high ozone days* in Classic PJM. Results for the deterministic and stochastic scenarios were compared to the base case simulation with a NO_x price of \$2k/ton and to simulations with SNCR or SCR installed on all or a subset of coal plants, on all days of the ozone season. The horizontal grid configuration is shown in Section S4, Supporting Information, along with the locations of 37 Philadelphia/Baltimore area ozone ground monitoring stations. Simulated daily maximum 8-h averaged ozone concentrations in the Philadelphia/Baltimore region were used in the stochastic analysis described below.

Stochastic Analysis. A stochastic model integrated the results from the power system and photochemical models. Rather than using observed ozone concentrations, the modeled meteorology and ozone impacts for all days in the summer of 2002 were used as the population from which to sample future

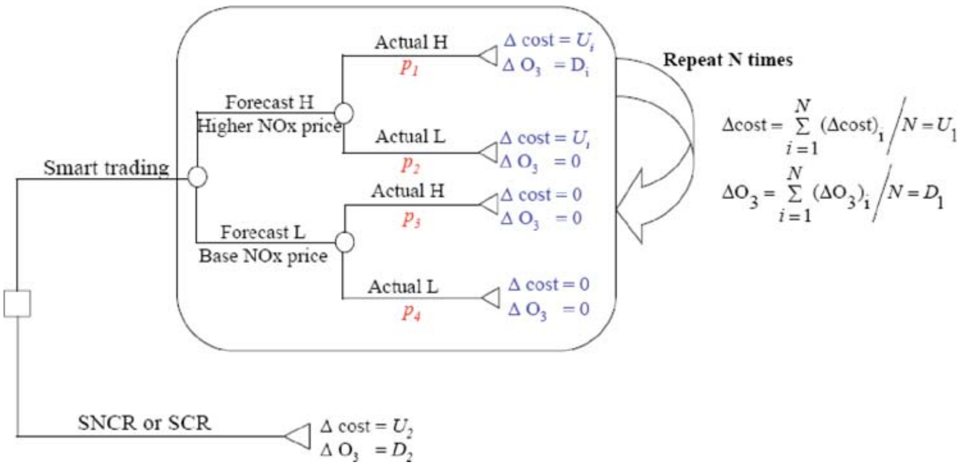

Figure 1. Decision framework for selecting time-differentiated NO_x pricing in the presence of risks in ozone forecasts during an N-day period. H and L represent high and low ozone days, respectively. On each day, four possible outcomes are associated with the time-differentiated policy with probabilities denoted as p_1, p_2, p_3, and p_4.

simulated days using a two-state Markov Chain, where the states were H or L, representing high or low ozone days. A high (or low) ozone day was defined as a day in which the 8-h ozone concentrations at 30 out of the 37 ozone monitoring sites (80% of the sites) in the Philadelphia/Baltimore region was higher (or lower) than an 8-h averaged threshold concentration. Three possible thresholds were considered: 65, 75, or 85 ppb. During June 1 to Sept 30, 2002, there were 27 high and 95 low ozone days for the 75 ppb threshold, 54 high and 68 low ozone days for the 65 ppb threshold, and 8 high and 114 low ozone days for the 85 ppb threshold. The transition probability matrices for the two-state Markov Chain were estimated as

$$P_{\text{thresholdozone}} = \begin{matrix} \\ H \\ L \end{matrix} \begin{bmatrix} H & L \\ 1-\pi & \pi \\ \theta & 1-\theta \end{bmatrix}$$

$$P_{65} = \begin{bmatrix} 0.72 & 0.28 \\ 0.22 & 0.78 \end{bmatrix}$$

$$P_{75} = \begin{bmatrix} 0.52 & 0.48 \\ 0.15 & 0.85 \end{bmatrix}$$

$$P_{85} = \begin{bmatrix} 0.25 & 0.75 \\ 0.05 & 0.95 \end{bmatrix} \tag{3}$$

where π denotes the conditional probability that a randomly chosen day was a low ozone day, given that the previous day was a high ozone day, and θ denotes the conditional probability that a randomly chosen day is a high ozone day, given that the previous day was a low ozone day. Modeled conditions were assumed to be the "actual" outcomes, and errors in ozone forecasts were simulated by sampling the forecast, conditional on the modeled ozone and a prescribed error rate. An analysis of the mean total cost and mean total reduction in peak ozone under each NO_x pricing policy was conducted for different pairs of false positive and false negative error rates in ozone forecasts to determine threshold values of ozone forecast errors below which each time-differentiated policy was more cost-effective than a prescriptive strategy.

A decision tree representation of this process is shown in Figure 1. The probability of a false positive (Type I error) or false negative (Type II error) are denoted as p and q:

$$p = \Pr[\text{forecast H}|\text{actual L}] \tag{4}$$

$$p = \Pr[\text{forecast L}|\text{actual H}] \tag{5}$$

The probabilities that a randomly chosen day was a high or low ozone day were defined as a and $1 - a$, where a was a function of the transition matrix of the two-state Markov model and the initial state of the model. On each day, four possible outcomes were associated with the time-differentiated policy, with probabilities denoted as p_1, p_2, p_3, and p_4 and obtained as:

$$p_1 = \Pr[\text{actual H}] \times \Pr[\text{forecast H}|\text{actual H}] = a(1-q) \tag{6}$$

$$p_2 = (1-a)q \tag{7}$$

$$p_3 = aq \tag{8}$$

$$p_4 = (1-a)(1-q) \tag{9}$$

Thus, 4^N outcomes were associated with each time-differentiated scenario during an N-day ozone season. Mean outcomes were estimated by applying Monte Carlo simulation for a sample size, N, of 50 000 days. The days in the stochastic analysis were sampled from the set of modeled days June 1 to Sept 30, 2002, with replacement. The set of modeled days was sorted into low ozone and high ozone days, and as we simulated the Markov Chain, we chose first whether to sample a high or low ozone day and then drew one day randomly from the appropriate subset.

On the ith day, the expected daily cost and the associated ozone reduction were:

$$(\Delta\text{cost})_i = (p_1 + p_2)U_i = [a(1-q) + (1-a)p]U_i \tag{10}$$

$$(\Delta O_3)_i = p_2 D_i = a(1-q)D_i \tag{11}$$

where U_i was the increased cost of electricity generation under a higher NO_x price on the ith day of the N-stage decision-making process and D_i was the associated reduction in the daily maximum 8-h ozone concentration. In this work, ΔO_3 (ppb) was defined as:

$$\Delta O_3 = \mathrm{Mc}_{j,k} = \sum_{i=1}^{37} (s_{i,j,\mathrm{base}} - s_{i,j,k}) \tag{12}$$

where

$$s_{i,j,k} = \begin{cases} c_{i,j,k} - \text{threshold}, \ c_{i,j,k} > \text{threshold} \\ 0, \ \text{otherwise} \end{cases}$$

for thresholds of 65, 75, or 85 ppb, $\mathrm{Mc}_{j,k}$ is the monitor integrated ozone impact on day j under policy scenario k, $c_{i,j,k}$ is the daily maximum 8-h ozone concentration in grid cell i where the ith ozone monitoring station is located, and reductions are summed over the 37 ozone monitoring sites in the Philadelphia/Baltimore area. The mean Δcost and ΔO_3 generated by the Monte Carlo simulation for the time-differentiated scenarios were denoted as U_1 and D_1. The Δcost and ΔO_3 under the technology-based scenarios were U_2 and D_2. The metric for comparing the time-differentiated and technology scenarios to the base case ($2k/ton) was the ratio of Δcost to ΔO_3. Because U_2 and D_2 were not a function of p and q, the values for U_1/D_1 obtained by the stochastic model were used to compare to the deterministic U_2/D_2.

■ RESULTS

Deterministic Scenarios: Seasonal NO_x Pricing versus Technology-Based Policies. NO_x price increases of $30k/ton, $50k/ton, or $100k/ton were implemented throughout the ozone season to examine the magnitude of emissions and ozone reductions achievable with pricing versus technology-based strategies in the Classic PJM grid. Figure 2 shows total NO_x emissions for an average electricity demand day and a peak demand day during the 2002 ozone season. As expected, NO_x emissions decreased with increases in NO_x price. More notably, even on a peak demand day and at the peak demand hours, sufficient flexibility existed in the electric grid to allow generation to be switched from high to low NO_x emitting facilities if given an incentive through higher NO_x prices. For most hours, SNCR controls resulted in reductions similar to the $50k/ton scenario. At peak demand hours (17:00), SNCR resulted in greater NO_x reductions, but SNCR and the NO_x pricing policies were generally similar in the midmorning when NO_x emissions can influence peak ozone concentrations later in the day.[38−41] Over the entire ozone season, the aggregate fraction of NO_x reduced over the Classic PJM system relative to the base case was 23%, 30%, and 41% for the $30k/ton, $50k/ton, and $100k/ton pricing policies, and 34% and 28% for the SNCR and SCR scenarios. Given that SCR installation at only 32% of coal-fired facilities was considered, it is expected that installation at all facilities would result in the greatest NO_x emissions reductions. The emissions reduction under the pricing polices resulted only from substituting lower-emitting, higher-cost generation from what would have been used in a least-cost dispatch, primarily switching from coal generation to gas generation. Demand was held fixed, and no power was imported from other regions. With the exception of peak demand afternoons, dispatching electricity generation from high to low NO_x emitting EGUs through NO_x pricing is as effective as SNCR controls at all coal-fired EGUs or SCR controls at a subset of facilities, while meeting demand in the Classic PJM grid. PJM, as with other power systems, has significant excess capacity for all except the peak demand hours of the year.

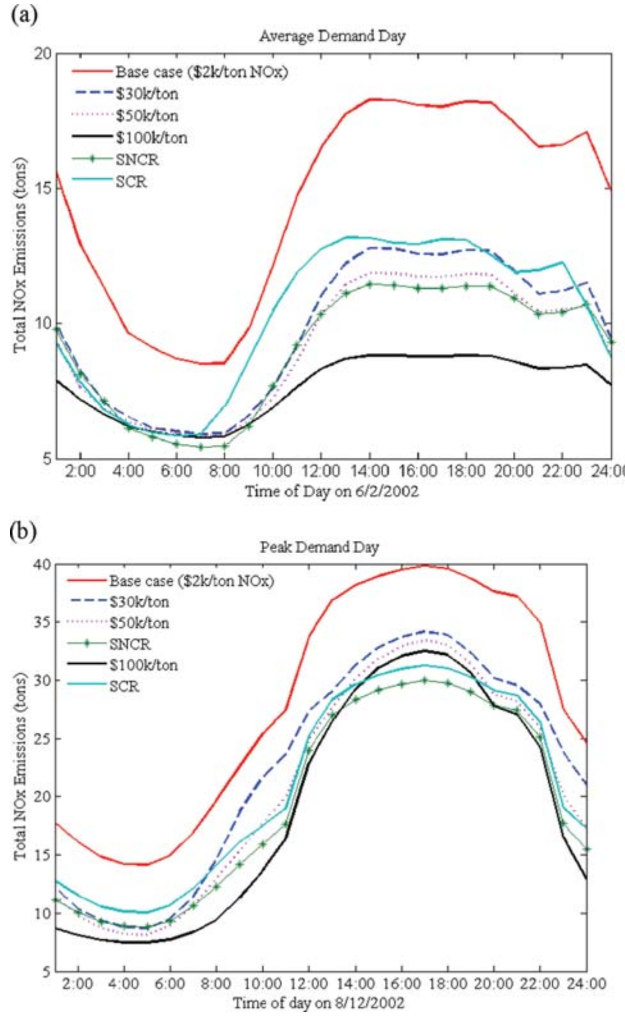

Figure 2. Time series of total NO_x emissions on (a) June 2 (average demand day) and (b) Aug 12, 2002 (peak demand day) under NO_x pricing of $2k/ton, $30k/ton, $50k/ton, and $100k/ton and with the installation of SNCR on all coal-fired units and SCR on 32% of the coal-fired facilities with the highest NO_x emissions.

In Section S5, Supporting Information, the average daily percentage of grid cells with Philadelphia/Baltimore ozone monitoring stations that have base case ozone concentrations of 75 ppb or greater during June to Sept 2002 and have increases or decreases in maximum 8-h averaged ozone concentrations are compared for seasonal NO_x pricing and the implementation of SNCR or SCR. Although daily variation existed, SCR was associated with the largest spatial area (>90%) of reduced ozone concentrations in Philadelphia/Baltimore grid cells with monitors, but all scenarios offered substantial benefits. On average, seasonal NO_x pricing of $30k/ton and SNCR reduced daily maximum 8-h ozone concentrations *by at least 1 ppb* over 14% of grid cells. Pricing at $50k/ton or $100k/ton or implementation of SCR at a subset of facilities reduced peak ozone concentrations by at least 1 ppb over 23%, 33%, and 55%, of Baltimore/Philadelphia grid cells with ozone monitors. Although all policy scenarios were associated with increased ozone concentrations ("hotspots"), these areas were comparatively smaller spatially than those associated with reduced ozone concentrations.

The average reduction in the predicted fourth-highest daily maximum 8-h averaged ozone concentration in the grid cells with the 37 Philadelphia/Baltimore monitoring stations, which is the metric used in determining attainment with the NAAQS, was greatest for SCR at 4.0 ppb followed by 1.2 ppb for the \$100k/ton scenario, 0.8 and 0.7 ppb for the \$50k/ton and SNCR scenarios, and 0.6 ppb for the \$30k/ton scenario. None or only one grid cell (<0.12 ppb) under each scenario was predicted to experience an increase in the fourth-highest ozone concentration, suggesting that both pricing and technology-based scenarios could be effective for reducing ozone design values at monitoring stations throughout the Philadelphia/Baltimore area. As shown in Figure S4, Supporting Information, the relative benefits of strategies were robust, regardless of the threshold ozone concentration (i.e., 65, 75, or 85 ppb).

Stochastic Scenarios: Ozone Abatement and Relative Costs without Forecast Errors. Three stochastic scenarios examined the relative cost effectiveness and ozone abatement of increases in NO_x pricing of \$30k/ton, \$50k/ton, or \$100k/ton implemented only on high ozone days. Initially, no ozone forecast errors were assumed. Figure 3 shows the average daily costs of these stochastic scenarios and SNCR, and SCR cases versus the average reduction in the daily 8-h maximum ozone concentrations with high ozone days defined by 65, 75, or 85 ppb thresholds, at 80% of the 37 Philadelphia–Baltimore area monitoring sites. Error bars ($\pm\sigma$) for the time-differentiated scenarios reflect uncertainty in the occurrence of high ozone events, which would narrow if the population size of the Markov model were increased by additional ozone season observations. Error bars on the SNCR prediction reflect uncertainty in cost described in Section S3, Supporting Information. Daily Δcost and ΔO_3 for SCR or SNCR were averaged over all simulated (both low and high ozone) days. For the time-differentiated NO_x pricing strategies, Δcost and ΔO_3 were calculated on forecast high ozone days, but for low ozone days no cost and no ozone reduction were assumed; the average daily cost was calculated over all simulated (both low and high ozone) days. The lines connecting the \$30k/ton, \$50k/ton, and \$100k/ton cases formed a cost-effectiveness frontier for ozone reductions. An ideal regulatory design would have zero cost and maximum ozone reductions, and would be located in the lower right corner. The frontier describes the trade-offs across the options modeled.

Under a threshold high ozone concentration of 65 ppb, the cost of time-differentiated NO_x pricing of \$50k/ton was competitive with the ozone abatement achieved by and costs associated with SNCR but not SCR. Time-differentiated pricing of \$100k/ton was more competitive with the abatement achieved by SCR but at twice the daily cost. Under ozone thresholds of 75 or 85 ppb without ozone forecast error, one would almost never prefer the SNCR approach to any of the time-differentiated policies or to SCR. Under a 75 ppb threshold in Figure 3b, the mean cost-effectiveness of SCR exceeded that of the \$100k/ton NO_x scenario, but their uncertainty ranges overlapped. Costs for time-differentiated pricing under an 85 ppb ozone threshold were substantially lower than that of SCR and SNCR; mean ozone reductions achieved by SCR were greater than but within the range of uncertainty for the time-differentiated \$100k/ton NO_x pricing policy. As the threshold increases, fewer days are defined as high ozone days, such that a time-differentiated policy is triggered less often, decreasing its cost relative to postcombustion control strategies.

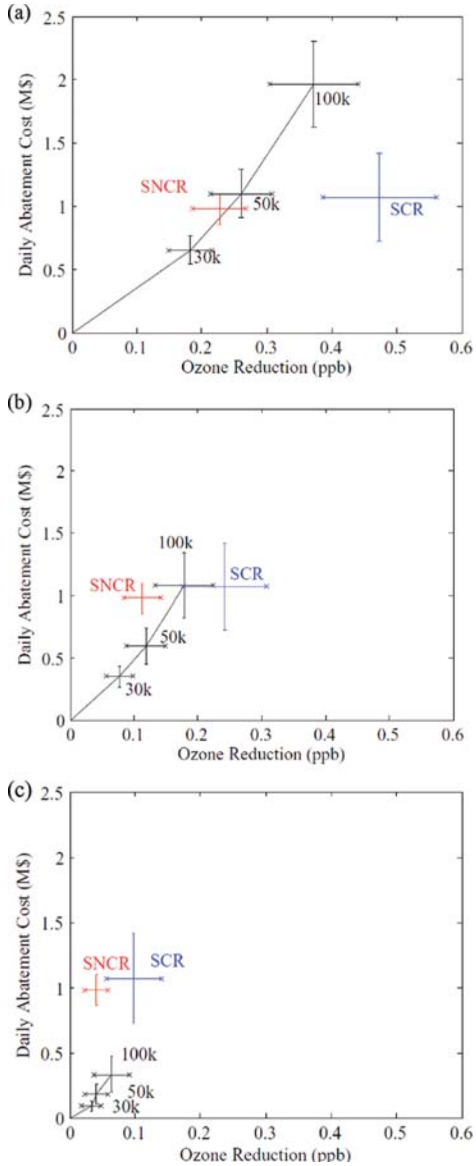

Figure 3. Average daily costs of time-differentiated NO_x pricing, SNCR, and SCR versus average reductions in daily 8-h maximum ozone concentrations over 37 monitoring sites in the Philadelphia/Baltimore area with high ozone days defined for thresholds of (a) 65 ppb, (b) 75 ppb, and (c) 85 ppb.

Stochastic Scenarios: Ozone Abatement and Relative Costs with Forecast Errors. Ozone forecast errors were introduced by assuming different pairs of false positive and false negative error rates. For each pair, 50 000 days were simulated to examine cost-effectiveness thresholds for time-differentiated NO_x pricing relative to SNCR. The comparison of smart trading scenarios with SNCR, but not SCR, was the focus because at the current ozone standard of 75 ppb, SCR reduced ozone at similar or lower cost even without forecast errors. Sensitivity analyses were performed to examine the effects of forecast accuracy on time-differentiated pricing versus SCR. No possible combinations of false positive and false negative forecast rates were found for which the time-differentiated strategy was preferred. The primary trade-off between installing

SCRs and implementation of a time-differentiated pricing policy is between the higher cost for SCR or the smaller ozone reduction of time-differentiated pricing. A critical caveat is that the SCR scenario considered in this work assumed controls on a subset of coal-fired EGUs; results would likely vary for SCR installed on a different subset.

Initially, the increased NO_x cost for reducing 1 ppb of daily 8-h maximum ozone (Δcost/ΔO_3 in $ million/ppb) was considered as the criterion for comparison of the cost-effectiveness of time-differentiated NO_x pricing against SNCR with uncertainty in ozone forecasts. However, both Δcost and ΔO_3 decreased as the false negative rate (q) increased. Thus, focusing exclusively on the ratio Δcost/ΔO_3 could lead to an erroneous conclusion that a time-differentiated approach was more cost-effective than the SNCR case even with a small ozone reduction. Consequently, a modified criterion was developed, in which a time-differentiated scenario was considered to be more cost-effective than SNCR if it had both a lower Δcost/ΔO_3 and achieved an ozone reduction of at least 70% of that achieved by SNCR.

The modified mean Δcost/ΔO_3 for SNCR and the three time-differentiated NO_x pricing policies are shown in Figure 4 and in Section S6, Supporting Information, for different rates of false positive and false negative errors under a 75 ppb threshold concentration for high ozone days. An approximate frontier where Δcost/ΔO_3 is equal for time-differentiated NO_x pricing and SNCR is shown as a black diagonal line. As the NO_x price increased, so too did the threshold false negative error rate that was required to prefer a time-differentiated policy, and the more sensitive its cost-effectiveness was to the required level of ozone forecast accuracy. Regardless of NO_x price, the higher the false negative rate, the lower the required rate of false positives for time-differentiated policies to be preferred. As shown in Figure 4a, the threshold false negative rate, q, for a time-differentiated policy with a $50k/ton NO_x price to be more cost-effective than the SNCR case was approximately 0.36; if q was 0.3, the values of p for which this scenario was more cost-effective than the SNCR scenario range from 0 to 0.25. The region of high false negative values (above approximately 0.4) is shaded in black because little ozone reduction (<70% of that achieved by SNCR) was achieved.

As an estimate of the accuracy in ozone forecasting, the observed daily maximum 8-h ozone concentrations at 37 ozone monitoring sites during the summer of 2002 in the Philadelphia/Baltimore region were compared with the predicted daily maximum 8-h ozone concentrations for the same grid cells. The rates of false positives, p, and false negatives, q, were calculated as 0.087 and 0.28. In addition, the local agency responsible for creating the Philadelphia ozone forecast utilized a variety of tools in their forecasting process, including, among others, in-house regression models and the NOAA Air Quality Forecast Guidance model. The agency provided output from these models used in Philadelphia from 2006 to 2008[42] as well as the human forecast. Analysis of each model and the human forecast yielded six different combinations of p and q, shown in Figure 4. Figure 4a indicates that a time-differentiated policy with NO_x pricing of $50k/ton could be more cost-effective than the SNCR case. For example, in the case of $p = 0.20$, $q = 0.4$, as provided by one forecast model for the Philadelphia area, time-differentiated NO_x pricing at $50k/ton was more cost-effective than the SNCR case while resulting in slightly greater ozone reduction. These results suggested that uncertainty in ozone forecasting may not be a major limiting factor for the feasibility of a time-differentiated NO_x cap-and-trade program. The results for the time-differentiated $30K/ton and $100K/ton pricing policies are described in Section S6, Supporting Information. Although there existed a range of false positive and false negative errors within which time-differentiated NO_x pricing $100k case was more cost-effective than installing SNCRs, the required ozone forecast accuracy was at the limits of current capabilities. The ozone reduction amount under the $30k/ton policy was less than 70% of the reduction achieved in the SNCR scenario.

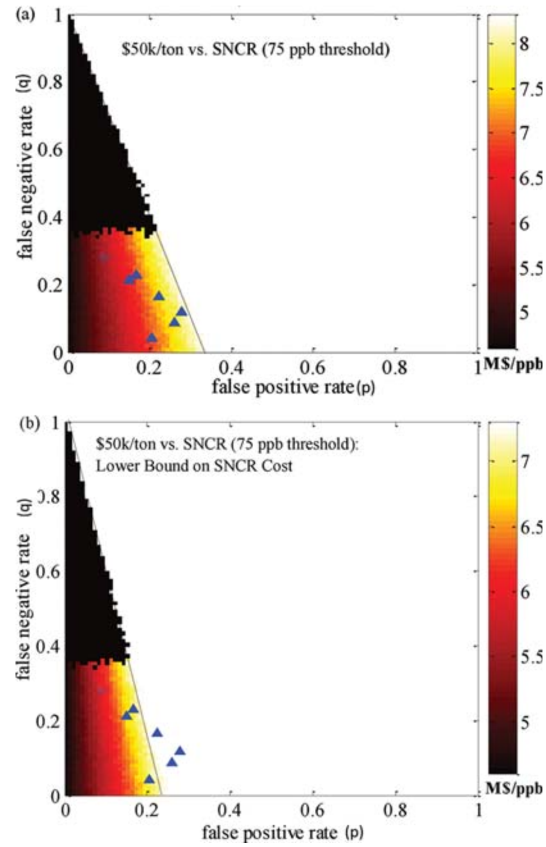

Figure 4. Δcost/ΔO_3 ($M/ppb) for time-differentiated NO_x pricing policies of $50k/ton relative to SNCR as a function of false positive (p) and false negative (q) rates. Note that darker colors on the scale indicate lower values of Δcost/ΔO_3 and that scales differ between plots. The area in white indicates the forecast accuracy rates for which the SNCR scenario is more cost-effective. The assumed daily Δcost for SNCR was (a) the mean, $0.98 M, and (b) the lower bound, $0.86M, of the uncertainty range considered in this work. An approximate frontier where Δcost/ΔO_3 is equal for time-differentiated NO_x pricing and SNCR is shown as a black diagonal line. Note that the cost-effectiveness for error rates of (0,0) are the central estimates shown in Figure 3. The region of high false negative values is shaded in black because little ozone reduction (<70% of that by SNCR) is achieved. As an estimate of the accuracy in ozone forecasting, the observed daily maximum 8-h ozone concentrations at 37 ozone monitoring sites during the summer of 2002 in the Philadelphia/Baltimore region were compared with the predicted daily maximum 8-h ozone concentrations for the same grid cells. The rates of false positives, p, and false negatives, q, were calculated as 0.087 and 0.28 (blue asterisk), respectively. Ozone forecasting models used in Philadelphia from 2006 to 2008[42] yielded six different combinations of p and q (solid blue triangles).

In practice, the cost of installing SNCR controls depends on a multitude of EGU physical and operational characteristics, including size, boiler type, fuel type, and NO_x emission rate. The uncertainty range for the average daily SNCR cost during the 4-month ozone season ranged from \$0.86 to \$1.1 M.[43] A sensitivity analysis explored the modified mean Δcost/ΔO_3 for the time-differentiated NO_x pricing policy of \$50k/ton under a 75 ppb threshold concentration for high ozone days relative to SNCR, assuming the daily cost was \$0.86 M or the lower end of the uncertainty range in this work. The results for different rates of false positive and false negative errors are shown in Figure 4b. The threshold value of q, which approximately equals 0.36, did not change with SNCR cost (reference Figure 4a). From Figure 4b, the threshold values for p assuming a daily SNCR cost of \$0.86 M is approximately 0.15, given a q value of 0.36. Assuming the SNCR cost is at the lower end of the uncertainty range, with the currently achievable ozone forecasting accuracy obtained in this work (p = 0.087, q = 0.28), the cost-effectiveness of time-differentiated NO_x pricing of \$50k/ton would remain competitive with SNCR.

The analysis above was repeated for threshold ozone concentrations of 65 and 85 ppb, and the results are given in Sections S7 and S8, Supporting Information. Under a 65 ppb threshold, time-differentiated policies of \$30k/ton or \$50k/ton were only preferred over the SNCR scenario under very low false positive and false negative rates that were beyond the capabilities of current ozone forecasting. There was no combination of false positive and false negative forecast rates for which a time-differentiated policy of \$100k/ton was preferred over the SNCR scenario. Similarly, there were no combinations of false positive and false negative forecast rates for which any time-differentiated strategy (i.e., \$30k/ton, \$50k/ton, or \$100k/ton) was preferred over the SCR scenario. Under an 85 ppb threshold, a time-differentiated policy of \$50k/ton or \$100k/ton was preferred over the SNCR scenario under current ozone forecasting accuracy, while a time-differentiated policy of \$30k/ton was not preferred over the SNCR scenario because the ozone reduction amount was less than 70% of the SNCR scenario.

Overall, the results from a model of day-specific NO_x pricing applied to the Pennsylvania–New Jersey–Maryland (PJM) portion of the northeastern U.S. electrical grid demonstrate (i) that sufficient flexibility in electricity generation is available to allow power production to be switched from high to low NO_x emitting facilities, (ii) that the emission price required to induce EGUs to change their strategies for power generation are competitive with other control costs, (iii) that dispatching strategies, which can change the spatial and temporal distribution of emissions, lead to ozone concentration reductions comparable to other control technologies, and (iv) that air quality forecasting is sufficiently accurate to allow EGUs to adapt their power generation strategies. The objective is not to design the specific strategy for PJM but rather to demonstrate an alternative approach to consider alongside traditional regulatory strategies in any region. The costs of the time-differentiated strategy could be lower than reported here for several reasons, including lower electricity demand to higher prices on high ozone days, or individual generators opting to install emissions control systems rather than repeatedly not operating on high ozone days. A central consideration is that as air quality improves, but ozone exceedances still exist, the costs of reducing annual or average emissions are likely to become increasingly expensive. Time-differentiated strategies offer expanded options and increased flexibility in the system to target emissions reductions.

■ ASSOCIATED CONTENT

Supporting Information

Classic PJM facilities, cost calculations for SCR and SNCR, and ozone abatement and costs for time-differentiated NO_x pricing policies under various ozone threshold concentrations are described. This material is available free of charge via the Internet at http://pubs.acs.org/

■ AUTHOR INFORMATION

Corresponding Author

*Phone: 512-471-2891; fax: 512-471-1720; e-mail: ecmb@mail.utexas.edu.

Notes

The authors declare no competing financial interest.

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