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Dynamic Management of NO_x and SO_2 Emissions in the Texas and Mid-Atlantic Electric Power Systems and Implications for Air Quality

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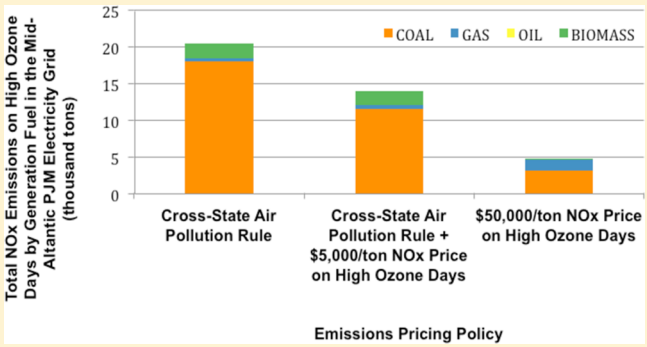
Supporting Information

ABSTRACT: Cap and trade programs have historically been designed to achieve annual or seasonal reductions in emissions of nitrogen oxides and sulfur dioxide from power plants. Emissions reductions may not be temporally coincident with meteorological conditions conducive to the formation of peak ozone and fine particulate matter concentrations. Integrated power system and air quality modeling methods were developed to evaluate time-differentiated emissions price signals on high ozone days in the Mid-Atlantic portion of the Pennsylvania−New Jersey−Maryland (PJM) Interconnection and Electric Reliability Council of Texas (ERCOT) grids. Sufficient flexibility exists in the two grids with marked differences in demand and fuel generation mix to accommodate time-differentiated emissions pricing alone or in combination with a season-wide program. System-wide emissions reductions and production costs from time-differentiated pricing are shown to be competitive with those of a season-wide program on high ozone days and would be more cost-effective if the primary policy goal was to target emissions reductions on these days. Time-differentiated pricing layered as a complement to the Cross-State Air Pollution Rule had particularly pronounced benefits for the Mid-Atlantic PJM system that relies heavily on coal-fired generation. Time-differentiated pricing aimed at reducing ozone concentrations had particulate matter reduction co-benefits, but if particulate matter reductions are the primary objective, other approaches to time-differentiated pricing may lead to greater benefits.



1. INTRODUCTION

Emissions cap and trade programs have been the preferred federal policy instruments for achieving reductions in emissions of nitrogen oxides (NO_x) and sulfur dioxide (SO_2) from electric-generating units (EGUs). The emissions reductions are designed to reduce acid deposition and regional ozone and fine particulate matter concentrations. A cap or limit is placed on total emissions from all regulated sources and tightened over time; affected sources are issued emission allowances that can be purchased or sold on an open market or banked in accordance with individual objectives and program rules as long as compliance is maintained at the reconciliation period.[1] Two of the largest programs, the Acid Rain Program (ARP) established by Title IV of the 1990 Clean Air Act Amendments (CAAA) and the Clean Air Interstate Rule (CAIR), have collectively reduced annual (2014) NO_x and SO_2 emissions by 53 and 68%, respectively, relative to 2005 levels.[2] Such programs have also demonstrated economic efficiency relative to command-and-control approaches and incentivized technology and process improvements.[2−9] The Cross-State Air Pollution Rule (CSAPR), the proposed successor to CAIR, is designed to continue the application of cap and trade policy to the electric power sector to achieve further reductions of NO_x and SO_2 emissions in the eastern half of the United States.[10]

These programs have been designed with limited time differentiation for emissions reductions. For example, CAIR consists of three multi-state cap and trade rules; two are aimed at reducing interstate contributions to fine particulate matter by reducing annual emissions of NO_x and SO_2, while a third has the objective of reducing interstate contributions to ozone formation through seasonal NO_x emissions reductions.[10]

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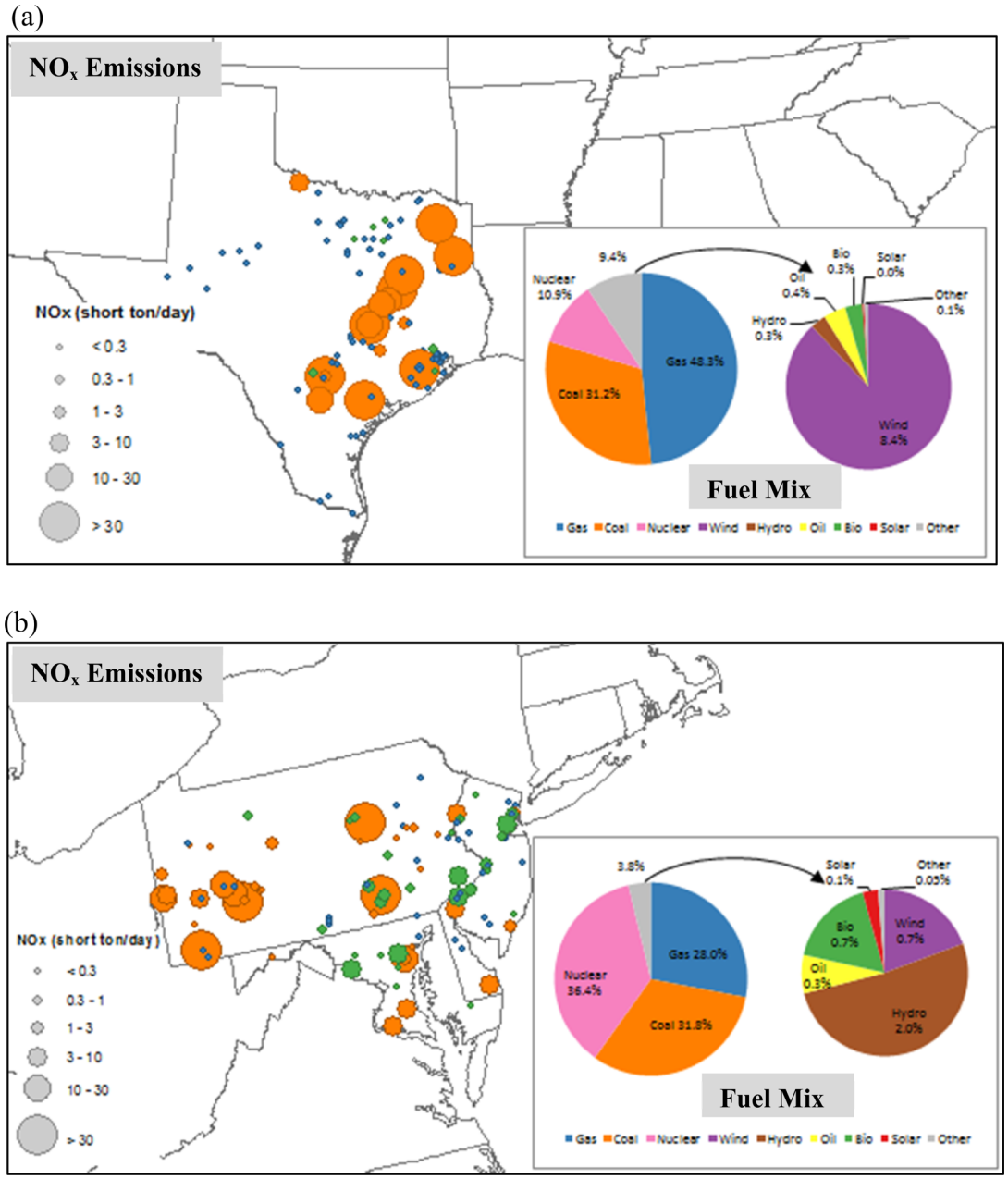

Figure 1. NO_x emissions (tons per day) in 2012 and generation fuel mix in the (a) ERCOT and (b) Mid-Atlantic PJM power systems. Generators in the map are color-coded by fuel type.

Although CAIR has contributed to significant season-wide and annual emissions reductions,[2] previous studies have demonstrated that NO_x emissions have variable damages depending on when they occur during the summer ozone season.[11−14] The timing of the emissions reductions induced by these rules may not be temporally coincident with meteorological conditions conducive to the formation of peak ozone concentrations.[15−17] Consequently, dynamic air quality management approaches that leverage capabilities in air quality forecasting and near real-time operational decisions may provide incentives for achieving emissions reductions during the periods that are most conducive to ozone and fine particulate matter formation and accumulation.

The concept of time-differentiated emissions reductions is routinely applied in U.S. communities through regulatory measures on days forecasted to have high ozone levels and/or voluntary "ozone action day" initiatives in which organizations and individuals voluntarily contribute to emission reductions that are not mandated. Previous studies have suggested the utility and feasibility of time-differentiated emissions reduction strategies for the electric power sector. Farkas et al.[18] found strong correlations between electricity demand and associated NO_x emissions and the occurrence of high ozone days in New England. Yun et al.[19] have developed energy load-adjusted emissions estimates and methodologies for their inclusion in air quality forecasting models to eventually facilitate dynamic intervention strategies. Bharvirkar et al.[20] and Sun et al.[21] simulated the use of time-differentiated pricing signals on high ozone days to reduce NO_x emissions from EGUs in the eastern United States. Together, these studies suggested that time-differentiated pricing could achieve significant NO_x reductions, sufficient flexibility in the systems exists to meet demand during

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Table 1. Time-Differentiated and Season-wide NO_x and SO_2 Pricing Policies Considered for Each System[a]

policy	NO_x price ($/ton)	SO_2 price ($/ton)	notes
baseline	20	1.50	2011 allowance prices;[31] applied daily
CSAPR	500	500	applied daily
season-wide NO_x			
1K	1000	1.50	applied daily
5K	5000	1.50	applied daily
season-wide SO_2			
1K	20	1000	applied daily
5K	20	5000	applied daily
time-differentiated NO_x			
1K	1000	1.50	high ozone days
5K	2000	1.50	high ozone days
20K	20000	1.50	high ozone days
50K	50000	1.50	high ozone days
100K	100000	1.50	high ozone days
150K	150000	1.50	high ozone days
time-differentiated SO_2			
1K	20	1000	high ozone days
5K	20	5000	high ozone days
20K	20	20000	high ozone days
50K	20	50000	high ozone days
100K	20	100000	high ozone days
150K	20	150000	high ozone days
layered policies			
CSAPR and 5K time-differentiated NO_x	500 (CSAPR), 5000 (time-differentiated)	500 (CSAPR)	CSAPR price applied daily, time-differentiated price layered only on high ozone days
CSAPR and 5K time-differentiated SO_2	500 (CSAPR)	500 (CSAPR), 5000 (time-differentiated)	CSAPR price applied daily, time-differentiated price layered only on high ozone days
CSAPR and 5K time-differentiated NO_x and SO_2	500 (CSAPR), 5000 (time-differentiated)	500 (CSAPR), 5000 (time-differentiated)	CSAPR price applied daily, time-differentiated price layered only on high ozone days

[a]All prices are expressed as U.S. dollars (USD).

peak hours, and costs could be competitive with conventional post-combustion control technologies. Sun et al.[21] found that air quality forecasting capabilities were sufficiently accurate to allow EGUs to adapt their power generation strategies in ways that reduce peak ozone.

The work presented here evaluates the air quality implications and cost effectiveness of time-differentiated pricing of NO_x and SO_2 emissions from power plants alone and in combination with other technology and season-wide market-based approaches. Dispatching algorithms account for real-world operational constraints, such as minimum load and ramping, and include endogenous decision capabilities regarding control technology installation, which were not components of earlier studies. Two power systems are considered, the Electric Reliability Council of Texas (ERCOT) and a portion of the Pennsylvania–New Jersey–Maryland Interconnection known as Mid-Atlantic or Classic PJM, which includes the states of Pennsylvania, New Jersey, Maryland, and Delaware, as well as the District of Columbia; these systems, shown in Figure 1, differ in generation fuel mix and the number of states included. The contributions of this study are (1) to compare time-differentiated, season-wide, and combined regulatory designs, (2) to explore the resulting emissions reductions considering realistic constraints on EGUs and endogenous technology adoption, (3) to demonstrate the implications for predicted regional ozone and fine particulate matter concentrations, and (4) to investigate opportunities for joint abatement of NO_x and SO_2 emissions through single-pollutant or multipollutant time-differentiated price signals.

2. METHODS

2.1. Two-Stage Unit Commitment Power System Model. A novel two-stage method, the Control Technology Investment at Nash Equilibrium with Unit Commitment (CONTINU) model, has been developed to explore short- and long-term generator responses to time-differentiated policies, season-wide policies, or combinations of these policies and the effects on emissions and producer costs within the Mid-Atlantic PJM and ERCOT systems during 2012.[22] The model minimizes total system dispatch cost, including the sum of operational and start-up costs across all generators and nonserved energy costs. Real-world operational constraints on power plants were enforced, including ramping limitations, minimum load, and minimum uptime or downtime, but did not include the transmission network beyond zonal transmission;[22−24] assumptions for these parameters are given in Table S1 of the Supporting Information. Mean monthly demand profiles during 2012 are shown in Figure S1 of the Supporting Information. Representations of the grids in 2012 were based on the Emissions and Generation Resource Database (eGRID)[25] and Energy Information Administration Form 860 and Form 923 databases.[26,27] Average emission rates for most generators were based on 2012 Continuous Emissions Monitoring System (CEMS) data.[28] The Supporting Information provides further details about the model and its assumptions.

In the first stage of the two-stage CONTINU model, coal-fired generators were simulated both with and without a post-combustion control technology if it was not already installed by 2012 (see the Supporting Information). Because of its

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computational intensity, the unit commitment model was run for two noncontiguous summer weeks that best approximated the entire summer demand profile in each power system using the approach of de Sisternes and Webster.[29] Two technologies were considered as "dispatchable" strategies",[30] such that generators could choose to operate or not, either Selective Catalytic Reduction (SCR) for NO_x emissions control and/or Flue-Gas Desulfurization (FGD) for SO_2 control.[31] Generators first unilaterally examined their individual profit maximization under a given pricing policy as the difference between electricity generation revenues and the sum of generation costs [i.e., variable operation/maintenance (O&M) and fuel costs], fixed capital, fixed and variable O&M associated with the adopted technology, and emission costs (see the Supporting Information). Once individual adoption decisions were established, dependencies associated with market dynamics that impacted a given generator's decision to install a control technology were determined using open-loop Nash Equilibrium.[22] This approach specifically allowed each generator to re-evaluate technology adoption given the decisions of all other generators in the system.[22] This is a necessary consideration because each unit's decision may change the system electricity price, potentially altering another unit's decision.

After technology adoption decisions were determined in the first stage, the unit commitment was simulated for all weeks from May through October in the second stage. System-wide emissions and producer costs on high ozone days and season-wide were calculated at hourly time steps. Averaged across all monitoring site locations, days with predicted maximum daily average 8 h ozone concentrations of >60 ppb were defined as high ozone days. The numbers of predicted high ozone days in the Mid-Atlantic PJM and ERCOT systems were 51 and 29, respectively. Total emissions were calculated as the sum of emissions from power generation and start-ups. Total system producer costs equaled the sum of dispatching costs and capital costs for any control technology, if installed (see the Supporting Information). Unlike the case for the calculation of generator profits in the first stage of the model, the second stage did not include the cost of emissions.[22]

Table 1 presents a summary of the policies considered. Time-differentiated pricing was implemented as a cost per ton of emissions applied over the entire 24 h period on high ozone days. Season-wide pricing polices in which a flat price is assessed for each ton of pollutant emitted over the entire summer were evaluated for comparison, including those representing allowance prices reported at the end of 2011[31] and anticipated prices under CSAPR.[32] Note that the range of prices considered is significantly wider than observed prices to date; this is intended to explore the resulting emissions and reductions and air quality impacts of possible future regulations.

2.2. Emissions Processing and Air Quality Model Configuration. Emissions from each policy scenario were processed with the Sparse Matrix Operator Kernel Emissions (SMOKE) system and used within the Comprehensive Air Quality Model with Extensions (CAMx) to evaluate metrics for ozone and fine particulate matter concentrations. The basis for the air quality modeling was an annual CAMx configuration for 2005 (2005as_05b) that was developed to support the assessments of the Environmental Protection Agency (EPA) of the Transport Rule and CSAPR;[32] the Supporting Information describes additional updates that were made to this configuration along with an evaluation of model performance.

For the purposes of this study, a 2012 baseline simulation was developed by replacing anthropogenic emissions of the 2005 base year model configuration to reflect more recent emissions inventories; all other inputs remained the same, and the relationship between 2005 demand and meteorological conditions was maintained. Inventories for nonpoint anthropogenic sources and stationary sources other than those in the Mid-Atlantic PJM and ERCOT systems in the baseline simulation were obtained from the 2011v6 Emission Modeling Platform of the EPA and Lake Michigan Area Director's Consortium (LADCO).[33,34] Emission rates for stationary power generation sources within the ERCOT and Mid-Atlantic PJM systems were generated by the CONTINU model that represented 2012 grid characteristics. The 2012 baseline simulation applied emissions estimates from the CONTINU model reflecting season-wide NO_x and SO_2 allowance prices of \$20/ton and \$1.50/ton daily (Table 1). Full descriptions of the CAMx configuration as well as the matching and processing of hourly emissions generated by the CONTINU model to the SMOKE framework are provided in the Supporting Information. All differences in emissions, production costs, and air quality metrics described below for each policy under consideration are relative to the 2012 baseline policy and reflect only changes in emissions to stationary power generation sources within the Mid-Atlantic PJM or ERCOT systems.

3. RESULTS

3.1. System-wide Emissions and Production Costs. *3.1.1. Time-Differentiated NO_x Price Signals: Effects on High Ozone Day NO_x Emissions.* Figure 2 illustrates the effects of time-differentiated NO_x pricing policies on NO_x emissions on high ozone days in the ERCOT and Mid-Atlantic PJM systems. NO_x emissions declined by as much as 57% in the ERCOT and 85% in the Mid-Atlantic PJM systems with a time-differentiated NO_x price of \$150000/ton. Substantial reductions were evident at lower time-differentiated price signals. For example, a \$5000/ton NO_x price provided Mid-Atlantic PJM system-wide average NO_x reductions of 38% on high ozone days. Sufficient flexibility existed in both grids to meet demand without incurring nonserved energy regardless of the time-differentiated NO_x price signal.

The two systems differed in their baseline NO_x emissions, as well as the levels of reductions achieved, technology installations, and escalation of production costs with the time-differentiated policies. These differences reflected their generation fuel mixes. In ERCOT, emissions reductions obtained through time-differentiated pricing of NO_x emissions were primarily driven by the substitution of gas- for coal-fired generation (Figure 2). NO_x emissions from coal-fired generation declined by more than half on high ozone days with a time-differentiated NO_x price of \$50000/ton. Additional reductions were minimal for prices above \$50000/ton with significantly higher production costs. No SCR installations were observed in ERCOT with any of the time-differentiated NO_x prices considered.

NO_x emissions in the Mid-Atlantic PJM system originated primarily from coal-fired generation, with approximately 10% attributed to biomass. Reductions obtained through time-differentiated pricing of NO_x emissions were driven by substantial declines in coal-fired generation at all price levels and declines in biomass-fired generation and the substitution of gas-fired generation at time-differentiated NO_x prices of

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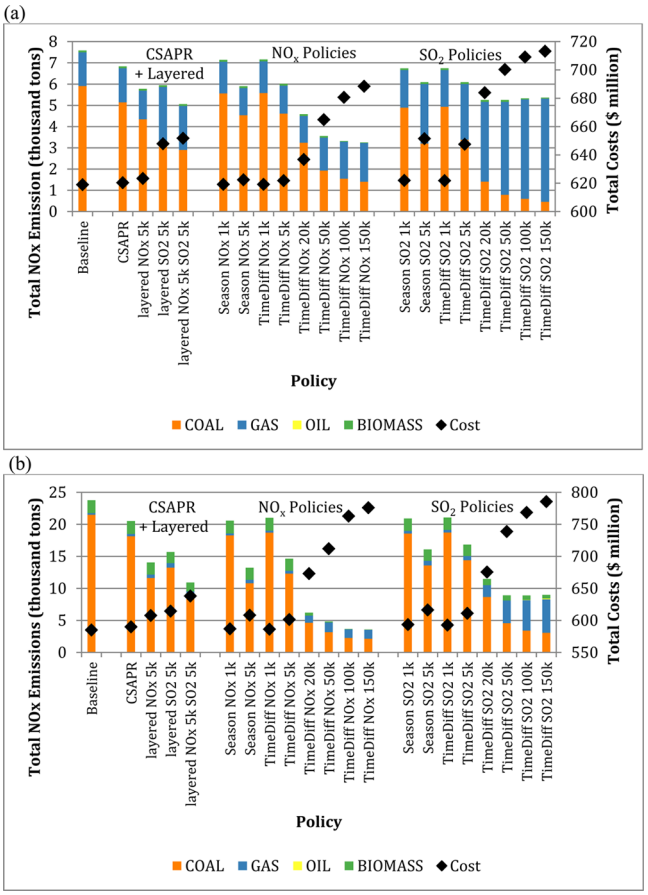

Figure 2. Total NO_x emissions (thousand tons; columns) and producer costs (millions of dollars; diamonds) by policy in the (a) ERCOT and (b) Mid-Atlantic PJM systems on high ozone days summed over the ozone season. The generation fuel is coded by color. All prices are expressed as U.S. dollars. Note differences in scales between plots.

$20000/ton and higher. Ten coal-fired generators, with a cumulative capacity of installed SCR of 4.99 GW, selected to install SCR at a time-differentiated NO_x price of $100000/ton in the Mid-Atlantic PJM system; 15 generators, with a cumulative capacity of installed SCR of 5.46 GW, selected SCR installation at a time-differentiated NO_x price of $150000/ton.

Redispatching was the driver for emissions reductions even with the SCR installations at higher price signals. Increases in production costs with time-differentiated NO_x prices were almost entirely due to the energy costs of redispatching with small shares (<5%) for startup costs and SCR installation.

Figure S5 of the Supporting Information illustrates that NO_x emissions reductions were more costly, on average, in ERCOT than in the Mid-Atlantic PJM system. Coal-fired generators in the Mid-Atlantic PJM system provided a higher share of less expensive baseload power generation than in ERCOT. The average NO_x emissions rate (2.9 lb/MWh) of coal-fired generators in the Mid-Atlantic PJM system was also considerably higher than in ERCOT (1.3 lb/MWh). A greater reduction in emissions was obtained from displacement of coal-fired generation in the Mid-Atlantic PJM system than in ERCOT. The incremental costs per ton of NO_x emissions reductions (calculated on the basis of the amount of NO_x reduced and the system-wide cost increase for a given policy relative to the baseline) were higher in ERCOT than in the Mid-Atlantic PJM system, reflecting differences in the reliance on coal for base load power generation and the higher average NO_x emission rate of generators within the Mid-Atlantic PJM system.

3.1.2. Co-Benefits of Single-Pollutant Time-Differentiated Price Signals on High Ozone Days. SO_2 price signals implemented alone on high ozone days resulted in a co-benefit of reduced NO_x emissions (Figure 2) but of a magnitude lower than and a cost per ton higher than those of a comparable NO_x price signal (Figure 2 and Tables S7 and S8 of the Supporting Information). Collectively, the findings indicated that single-pollutant time-differentiated pricing policies had multifaceted environmental benefits. In the Mid-Atlantic PJM system, a $50000/ton SO_2 price yielded NO_x reductions of 63% ($10350/ton NO_x reduced) on high ozone days; in contrast, a $50000/ton NO_x price yielded reductions of 80% ($6710/ton of NO_x reduced). Demand met by generators with relatively higher SO_2 emissions must be replaced by an increased reliance on natural gas-fired generation, especially within ERCOT, which had higher associated energy costs. The incremental costs associated with NO_x reductions achieved by SO_2 policies alone were more pronounced in ERCOT; a SO_2 price of $50000/ton yielded a 31% ($34910/ton for NO_x) reduction in NO_x emissions relative to a 53% ($11410/ton for NO_x) reduction at the comparable NO_x price. SO_2 prices of greater than $50000/ton yielded additional reductions in NO_x emissions of less than 5% in both systems. Time-differentiated SO_2 policies achieved greater reductions in SO_2 emissions than NO_x policies with generally comparable or higher production costs (Figure S6 of the Supporting Information). On high ozone days, SO_2 emissions were reduced by 50% in ERCOT and 75% within the Mid-Atlantic PJM system under a time-differentiated NO_x price of $50000/ton, because of reductions in coal-fired (and biomass-fired in Mid-Atlantic PJM) generation.

3.1.3. Time-Differentiated versus Season-wide Policies: High-Ozone Day and Seasonal Comparisons. Figure 2 compares the costs and emissions reductions of time-differentiated NO_x pricing with season-wide NO_x pricing policies, including those based on average allowance prices reported at the end of 2011[31] (baseline), the expected marginal cost of reducing annual and ozone-season NO_x and SO_2 emissions of $500/ton from CSAPR,[32] and prices of $1000/ton or $5000/ton. Figure S6 of the Supporting Information shows similar results for SO_2 emissions. On high ozone days, emissions reductions and production costs incurred from time-differentiated pricing were competitive with those of a season-wide program at the same price level. The primary differences arose in the consideration of the benefits achieved season-wide relative to those on high ozone days, shown in Tables S7 (ERCOT) and S8 (Mid-Atlantic PJM) of the Supporting Information. In contrast to high ozone days, season-wide pricing achieved greater cumulative emissions reductions over the entire summer season at a comparable cost per ton than those of time-differentiated NO_x pricing at the same level. For example, summer-wide NO_x emissions reductions under a season-wide price of $1000 per ton reduced NO_x emissions by 13870 tons (19%) at an average cost of $460/ton; a time-differentiated price of $1000 per ton resulted in a reduction of 3250 tons (4.5%) at a cost of $400/ton. If the objective is to reduce emissions on days where high pollution levels are anticipated, these findings suggested the utility of considering

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time-differentiated pricing as a complement to a season-wide program, such as CSAPR.

3.1.4. Layered Single-Pollutant and Joint-Pollutant Pricing. Additional scenarios considered layered time-differentiated NO_x and SO_2 prices of \$5000/ton as single- or joint-pollutant policies along with the implementation of CSAPR. The benefits of such an approach were evident in both systems; with a layered time-differentiated single-pollutant policy, NO_x emissions were reduced by an additional 10−15% in ERCOT and 20−25% in the Mid-Atlantic PJM system relative to CSAPR alone on high ozone days (Tables S7 and S8 of the Supporting Information). A layered joint pricing strategy enhanced reductions of NO_x emissions achieved by CSAPR alone (by approximately 25% in ERCOT and 30% in the Mid-Atlantic PJM system) or the layered single-pollutant pricing strategies.

3.2. MDA8 Ozone Concentrations. *3.2.1. Ambient Monitoring Locations.* Attainment with the National Ambient Air Quality Standard (NAAQS) for ozone is determined as a three-year average of the annual 4th-highest maximum daily average 8 h (MDA8) concentration. The CAMx episode spanned May through October encompassing an ozone season in both the Mid-Atlantic PJM and ERCOT regions of the United States. Table S9 of the Supporting Information shows the locations of monitors in the U.S. Environmental Protection Agency's Air Quality System (AQS). Figure S7 of the Supporting Information shows predicted differences in the 4th-highest MDA8 ozone concentration during the episode relative to the baseline policy. Differences in daily MDA8 ozone concentrations across all high ozone days are shown in Figure S8 of the Supporting Information. Tables S10 and S11 of the Supporting Information show predicted differences in the 4th-highest MDA8 ozone concentrations and mean differences in MDA8 ozone concentrations at 20 AQS sites within the Mid-Atlantic PJM system, respectively.

Single-pollutant season-wide and time-differentiated policies at the same price level had similar impacts on MDA8 ozone concentrations on high ozone days. Within the Mid-Atlantic PJM system, median reductions in the seasonal 4th-highest MDA8 ozone concentration were −1 to −1.3 ppb with time-differentiated NO_x prices of \$20000/ton or higher. Individual locations had reductions exceeding −4 ppb in the 4th-highest MDA8 ozone concentration and in daily MDA8 ozone concentrations of almost −15 ppb. The median difference in the seasonal 4th-highest MDA8 ozone concentration due to the implementation of CSAPR alone was −0.13 ppb; layering CSAPR with a joint price of \$5000/ton on both NO_x and SO_2 emissions resulted in a reduction of −0.6 ppb.

Median reductions in the 4th-highest MDA8 ozone concentrations within ERCOT were markedly smaller than in the Mid-Atlantic PJM system (less than −0.05 ppb for all policies considered). Individual locations had reductions in the 4th-highest MDA8 ozone concentration that exceeded −1 ppb and in daily MDA8 ozone concentrations of nearly −2 ppb. Disbenefits, or increases in 4th-highest MDA8 ozone or daily MDA8 ozone concentrations, were evident at individual sites in both systems; these occurred with both season-wide (e.g., CSAPR) and time-differentiated policies but were more common with SO_2 pricing policies.

3.2.2. Regional Impacts. Figure 3 shows mean differences in MDA8 ozone concentrations for selected policies relative to the baseline policy on high ozone days in the ERCOT and Mid-Atlantic PJM systems. Similar results for the full suite of policies considered are presented in Figures S9 and S10 of the Supporting Information.

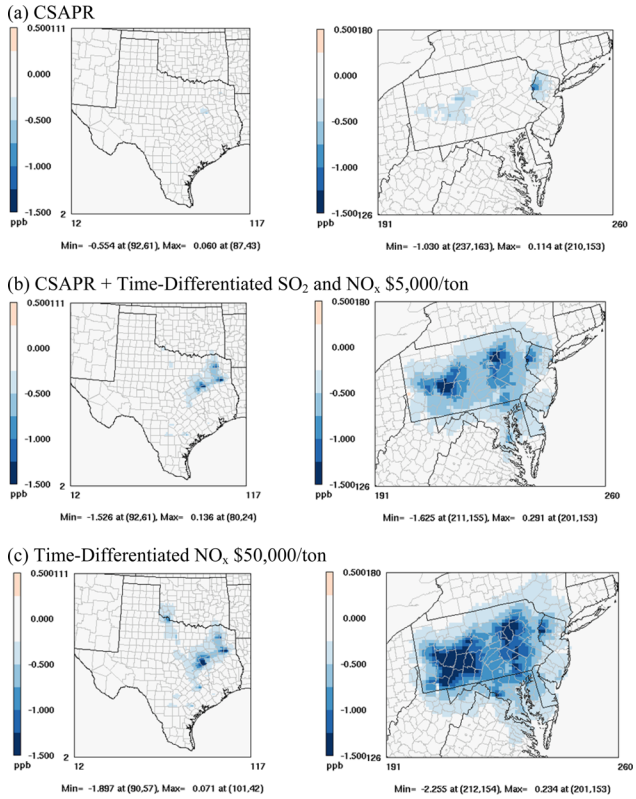

Figure 3. Mean differences in MDA8 ozone concentrations relative to the baseline policy on high ozone days in the ERCOT (left) and Mid-Atlantic PJM (right) systems for the following policies: (a) CSAPR, (b) layered CSAPR and time-differentiated NO_x and SO_2 prices of \$5000/ton, and (c) time-differentiated NO_x price of \$50000/ton. Negative values indicate reductions in MDA8 ozone concentrations relative to the baseline policy and vice versa.

Within the Mid-Atlantic PJM system, relatively modest joint time-differentiated prices of \$5000/ton of NO_x and SO_2 emissions on high ozone days layered with CSAPR led to widespread reductions in mean MDA8 ozone concentrations across the region; the spatial extent and magnitude of these reductions and the number of high ozone days affected exceeded those of CSAPR implemented alone. Maximum reductions in mean MDA8 ozone concentrations with the season-wide and time-differentiated policies at NO_x or SO_2 prices of at least \$5000/ton occurred in eastern and southwestern Pennsylvania. Season-wide policies produced spatial benefits in neighboring states slightly greater than those produced by the comparably priced time-differentiated policies. At a time-differentiated NO_x price of \$50000/ton, the maximum number of days on which reductions in mean MDA8 ozone concentrations exceeded −0.5 ppb was 42 and the magnitude of the maximum reduction was −2.3 ppb in southwestern Pennsylvania; these values increased slightly, but the spatial patterns of effects were quite similar at higher price points. Time-differentiated SO_2 policies were generally as effective as NO_x policies for reducing mean MDA8 ozone concentrations over much of the region on high ozone days.

Effects of policies on regional mean MDA8 ozone concentrations within ERCOT exhibited several commonalities with the Mid-Atlantic PJM system. Layering single- or joint-pollutant time-differentiated policies provided additional

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benefits on high ozone days above what could be achieved by CSAPR alone; time-differentiated NO_x or SO_2 policies both produced reductions in mean MDA8 ozone concentrations, and the maximum number of days (25) on which reductions exceeded −0.5 ppb encompassed most high ozone days of the season at price levels of at least $50000/ton. An important distinction between the two systems was the considerably greater spatial heterogeneity in the locations of benefits as well as their proximity to existing ambient monitors within the ERCOT region, regardless of the policy implemented. Reductions in MDA8 ozone concentrations primarily occurred in northeastern Texas coincident with the location of much of the coal-fired generation in the state (Figure 1). Increasing the levels of time-differentiated prices reduced emissions from these generators and, in particular for the SO_2 policies, shifted emissions to other areas within ERCOT where natural gas-fired generation predominated.

An impact of concern is the creation of disbenefits or increases in ozone concentrations in response to a given policy scenario, particularly if the effects are manifested in ozone nonattainment areas. Disbenefits were evident but were not widespread in the two systems. Each instance of a disbenefit that occurred at a location of an AQS monitoring site with the implementation of selected time-differentiated pricing policies on high ozone days was investigated (Table S12 of the Supporting Information). These results indicated that disbenefits were more prevalent under time-differentiated SO_2 policies than under comparable NO_x policies and arose because of two different circumstances: (1) a reduction in NO_x emissions that resulted in less titration of ozone or (2) a shift or increase in NO_x emissions that contributed to an increase in ozone formation. Under time-differentiated SO_2 policies within the ERCOT system, the strong incentive to reduce SO_2 emissions from coal-fired generation in northeastern Texas drove the substitution of gas-fired generation that shifted NO_x emissions (Figure S11 of the Supporting Information) and resulted in isolated instances of increased ozone concentrations in other areas of the state (Figure S12 of the Supporting Information). The magnitudes of disbenefits associated with time-differentiated NO_x policies were smaller than those of comparable SO_2 policies and primarily occurred in the Houston−Galveston area due to NO_x titration. Instances of disbenefits under a time-differentiated SO_2 pricing policy within the Mid-Atlantic PJM system were associated with shifts in generation that increased NO_x emissions, similar to ERCOT, but also reductions in NO_x emissions and titration of ozone (Figure S12 and Table S12 of the Supporting Information). Disbenefits of a relatively larger magnitude under time-differentiated SO_2 or NO_x policies occurred primarily in Pennsylvania associated with reductions in NO_x titration. The findings for the two systems suggested the potential utility of evaluating the spatial differentiation of time-differentiated pricing policies for ozone nonattainment areas as well as the relative benefits of joint time-differentiated pricing pollutant pricing policies to mitigate unintended consequences of comparable single-pollutant pricing policies.

3.3. Co-Benefits for $PM_{2.5}$ Reductions. Figure S13 of the Supporting Information shows regional mean differences in 24 h average $PM_{2.5}$ concentrations in the ERCOT and Mid-Atlantic PJM systems for selected policies. Although time-differentiated price signals were triggered on the basis of an ozone concentration threshold in this study, widespread regional reductions in $PM_{2.5}$ concentrations were evident for all policies in the Mid-Atlantic PJM system on high ozone days, as well. Table S13 of the Supporting Information shows the locations of ambient $PM_{2.5}$ monitoring sites in the two systems. Attainment with the NAAQS for 24 h average $PM_{2.5}$ concentrations is based on the three-year average of the 98th percentile concentrations at ambient monitoring sites. Median reductions in 98th percentile 24 h $PM_{2.5}$ concentrations at the locations of ambient monitors in the Mid-Atlantic PJM system shown in Figure S14 ranged from 0.1 to 0.4 $\mu g/m^3$ with time-differentiated NO_x or SO_2 prices of at least $5000/ton over the May to October season considered. Regional reductions in $PM_{2.5}$ concentrations were in general spatially coincident with those for ozone, with the most pronounced reductions occurring in southeastern and southwestern Pennsylvania. Within ERCOT, reductions in 24 h average $PM_{2.5}$ concentrations in response to time-differentiated pricing policies occurred over northeastern Texas and were similar to but more spatially distributed than the effects on ozone concentrations. Median reductions in 98th percentile 24 h $PM_{2.5}$ concentrations at the locations of ambient monitors within ERCOT ranged from 0.01 to 0.05 $\mu g/m^3$ under time-differentiated NO_x or SO_2 prices of at least $5000/ton. The spatial extent and magnitude of $PM_{2.5}$ reductions were greater under time-differentiated SO_2 than NO_x policies, although both resulted in benefits on high ozone days in the two systems. Layering of single- or joint-pollutant time-differentiated policies provided additional benefits above those achieved by CSAPR alone. Figure S15 of the Supporting Information indicates that during the episode period, measured 95th percentile 24 h average $PM_{2.5}$ concentrations at the location of AQS sites were frequently but not always correlated with MDA8 ozone concentrations in the two systems. Conditions of conducive regional meteorology and common sources of precursor emissions affect both ozone and $PM_{2.5}$ concentrations, but distinctly targeted time-differentiated price signals may be required to fully address peak concentrations of both.

3.4. Implications. These findings suggest that policy goals must be carefully considered. Season-wide market-based programs have the overall goal of reducing continental-scale pollution and transport to downwind areas. If an objective is to specifically achieve reductions in emissions on days conducive to the formation of high pollution levels, a season-wide program is less cost-effective than a time-differentiated program because of its untargeted application. In this study, time-differentiated pricing incurred costs only on high ozone days, although some "carryover" benefits were evident on days subsequent to those identified as high ozone days. Co-benefits of reductions in 24 h $PM_{2.5}$ concentrations were evident with the implementation of time-differentiated price signals for NO_x and/or SO_2 on high ozone days, but full realization of reductions in peak concentrations may require distinct time differentiation. Sufficient flexibility to accommodate such an approach existed in two electricity grids with marked differences in demand and fuel generation mix. The utility of considering time-differentiated pricing as a complement to a season-wide program such as CSAPR is particularly pronounced for the Mid-Atlantic PJM system, which relies more heavily on coal-fired rather than natural gas-fired generation such as in ERCOT. A time-differentiated scheme could be implemented as a higher redemption ratio of emissions permits on high ozone days or as an entirely separate trading program layered with a season-wide policy.

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■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.5b04175.

Descriptions of the CONTINU model, CAMx configuration and performance, and effects of pricing policies on emissions reductions and predicted air quality (PDF)

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Notes

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