

Relative costs of NO_x emissions reductions by physical controls and environmental dispatch

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1. SYNOPSIS

NO_x emissions reduction from power generation are sought in the San Francisco Bay Area to reduce the severity of intermittent episodes of photochemical smog. The cost of reducing emissions using a variable NO_x tax on electric utility dispatch are compared to the currently favored technology, selective catalytic reduction.

2. ABSTRACT

Like most major industrial areas worldwide, the San Francisco Bay Area, suffers from periodic poor air quality episodes, notably unhealthy concentrations of photochemical smog. Current local regulations require installation of selective catalytic reduction (SCR) emissions control equipment on most electric utility stacks over the next decade. SCR effectively reduces emissions of NO_x, the major photochemical smog precursor pollutant; however, since the fixed cost of SCR is high, since poor air quality episodes are rare, and since many generators are infrequently used, the cost of improving air quality using SCR is high. This paper compares the cost of the current regulatory approach to one that relies on biasing the dispatch of power generation away from the more polluting and towards the less polluting generators available during episodes. The dispatch is biased by the imposition of an intermittent NO_x tax, operations being simulated using a Lagrangian relaxation unit commitment and dispatch model under a Monte Carlo random drawing of outage states. Results show that the taxed dispatch delivers modest levels of NO_x emissions reductions for increased fuel costs lower than the cost of SCR.

3. INTRODUCTION

3.1. Research goal

This work explores the relative costs of two alternative ozone abatement strategies for the power sector in the San Francisco Bay Area, where the goal of the abatement is improved local air quality as measured by surface ozone concentrations during smog episodes. The two alternative strategies are: 1. *selective catalytic reduction* (SCR) as mandated by the current regulatory regime of pollution control equipment requirements established by the Bay Area Air Quality Management District (District), and 2. *an intermittent NO_x tax* on thermal generating resources.¹ Only a two-way comparison is conducted, and no attempt is made here to compare the costs of NO_x emissions reductions in the power sector with control costs in other sectors.

3.2. Smog formation

Ozone is formed in polluted urban air through a complex series of chemical reactions involving many pollutants that are together often referred to as *ozone precursors*. These reactions also give rise to other troublesome pollutants, notably peroxyacetyl nitrate (PAN), nitric acid (HNO₃), nitrous acid (HONO), and many organic compounds, some of which are carcinogens. Ozone is formed when NO_x and reactive non-methane hydrocarbons (NMHC) are mixed together under the influence of incident ultra violet radiation in stagnant, warm air (Finlayson-Pitts and Pitts 1986).² This process supplies virtually all known anthropogenic ozone. In any specific airshed, the relative importance of the two precursor groups, NO_x and NMHC's, in

ozone formation and, consequently, the relative benefits of controlling either one or both of them are always controversial topics. However, greater emphasis is now being placed on NO_x control (National Research Council 1991). Further, NO_x control poses a particularly tough regulatory dilemma because emissions can also have a short-run or local benefit called *NO_x quenching*, which comes about because of the reaction of NO with O_3 .

Ozone is harmful if breathed and is directly hazardous to plant life at low concentrations. Prolonged exposure diminishes lung function and aggravates various pulmonary disorders. The residence time of ozone in polluted urban air is short, no more than a few hours, so the problem of ozone exposure tends to be localized to cities and areas downwind of them. Although ozone concentrations that are elevated above background levels but do not exceed the standards may be harmful, the focus here is on the goal of meeting the standard. It is, therefore, assumed that emissions on days on which there is no danger of an exceedence are harmless. The important issue of pollutant transport is also overlooked in this analysis.

3.3. Bay area smog problem

Despite the generally good air quality in the District relative to the Los Angeles area, the Bay Area remains one of the air basins not in attainment with either the U.S. Federal or the State of California standard for ozone. The Bay Area's ambient ozone concentration typically exceeds the Federal ozone standard on less than 2 days per year, and fails to meet the tighter California standard on about 15-20 days.³

Despite steady improvements in the District's ozone attainment over the last two decades, three factors will tend to tighten its rules over the coming decade. First, growing populations may outstrip the benefits of current control measures. Second, provisions of the 1988 California Clean Air Act and the 1990 Amendments to the Federal Clean Air Act will increase the jurisdiction of State and Federal agencies within the District. And third, fears that relatively low ozone exposures may cause cumulative lung damage may strengthen resolve to limit ozone excursions, to lower exposures more generally defined, or to tighten existing standards.

The moderate air quality problem of the San Francisco Bay Area actually makes it a more interesting test case than the more frequently studied Los Angeles basin. The total fraction of the U.S. population living in non-compliance areas totals a disturbing 54%; however, only about 23% are exposed to 10 exceedence days per year or more. That is, while the total number of people exposed is huge, actually, over 30% of the U.S. population lives in areas that are only *marginally* out of compliance, that is, 10 days per year, or less. While few consistent data exist, the smog problem is similarly infrequent in most European cities.

3.4. Intermittence

Clearly, the nature of the urban photochemical smog problem is intermittent, and the Bay Area is rather typical of many urban areas. While there may be benefits to reducing ozone concentrations during non-episode times, the focus of U.S. policy since the first Federal Clean Air Act has been to reduce the number and duration of exceedences of air quality standards, both Federal and State. Given this historic focus on the peak of the smog problem, it is surprising that almost no regulations originating from the District, or other agencies, have any intermittent provisions. In the lexicon of the utility industry, a problem that is dramatically *peaking*, that is, one occurring only a few hours per year, has been addressed as a strictly *base load* problem, that is, one that is evenly spread across all times.

It should be emphasized that physical controls on emissions through combustion modification or exhaust clean-up perform poorly with respect to this problem. While the cost of such NO_x control measures, in terms of dollars per avoided kg of NO_x emission may be low, it might be expensive in terms of dollars per avoided *episode day* kg. Or, to look at the problem the other way around, an intermittent control strategy that may be costly in terms of dollars per avoided kg of emissions may still be cost effective in terms of dollars per avoided episode day kg. As jurisdictions inch towards compliance, intermittent controls may look more and more attractive.

Under current power sector regulation, the imposition on generators of specific control equipment is implemented through a permitting system that requires emissions from large point sources be within fixed physical limits, under a specified test condition. This permit condition is usually set such that it will necessitate the installation of certain control equipment. In addition to the existence of the control equipment, other operating constraints, such as daily or annual emission ceilings, are often imposed. Note that an equipment requirement alone assures no emissions reduction because it provides no incentive to use

Table 1. Various Estimates of NO_x Control Costs for Moss Landing 6 using SCR (source: PG&E)

average NO _x reduction (kg/MWh)	capacity factor (%)	365	episode days per year 50 5	
			(\$/kg)	
0,45	0,55	7	48	476
0,15	0,15	65	473	4 729
	0,45	23	170	1 704
	0,75	15	110	1 099
0,60	0,15	16	118	1 182
	0,45	6	43	426
	0,75	4	27	275
2,00	0,15	5	35	355
	0,45	2	13	128
	0,75	1	8	82

assumptions:

- analysis loosely based on Moss Landing 6, a 739 MW super-critical gas-fired unit located ap proximately 110 km south of San Francisco
- levelized capital cost of SCR = 11 \$/kW·a
- fixed maintenance cost of SCR = 1,25 \$/kW·a
- variable maintenance cost of SCR = 0,39 \$/MWh
- fuel cost of heat rate penalty = 0,0045 \$/MWh
- assumed capacity factors are constant on all days

the controlled generator over more polluting ones during episodes. Further, it does not even penalize taking the controlled unit out for maintenance during episodes.

3.5. Bay area power sector

To simulate the effect of imposing a NO_x tax the power generation resources in the Bay Area were isolated from the remainder of the northern California grid and were dispatched as an independent system to meet local load.⁴ The 7146 MW system that results is called here the Bay Area Power System (BAPS). It consists primarily (89 %) of capacity owned by the Pacific Gas and Electric Company (PG&E), the remainder being QF's.⁵ Given the small capacity of gas turbines owned by PG&E and the total dominance of natural gas fuel, it is not surprising that BAPS is fully 83 % natural gas fired steam thermal generation.

From the point of view of NO_x taxed dispatch, BAPS is a challenging system because the homogeneity of BAPS limits the potential of a NO_x dispatch to reduce overall emissions. That is, flexibility to move generation from more polluting to less polluting units is limited. Clearly, a system that had a more

diversified fuel mix would pose more opportunities for lowering emissions. On the plus side, BAPS provides a good opportunity to study the dispatch in some detail, and the pure dispatch effects should be clearly identifiable.

3.6. Intermittent NO_x tax

The intermittent NO_x tax regime imposes no restrictions on generators during periods when the risk of smog formation is negligible, but encourages operation of generators in a less polluting manner under smog episode conditions. Unlike most proposed emissions taxes, this tax is nonuniform over time, depending on the amenability of ambient weather conditions to smog formation. The tax stands at zero most of the time and peaks during those hours of episode days when emissions are most detrimental, typically the few hours before an exceedence. The viability of such a scheme is not nearly as unlikely as it might seem because the nature of the utility industry has required the development of sophisticated methods for coping with operating restrictions that vary over time. The influence of the tax on system operations can be readily estimated within the traditional framework of fuel cost minimization. Since the standard operating rule for the power system is fuel cost minimization, this alternative mode of operating the generation system will result in higher generation costs, and, almost certainly, higher fuel use.

By conducting comparative runs, using a Lagrangian relaxation electric utility production cost model, the costs of imposing a penalized dispatch are found and a cost per avoided mass of NO_x calculated. Additionally, an atmospheric chemistry model is used to estimate the ozone improvements that could result from the reduced NO_x emissions achievable through an intermittently penalized dispatch.

3.7. Acid deposition

Another complication of NO_x emissions is that they also serve as precursors to acid deposition, which is much less clearly an intermittent problem. That is, while acid deposition may have some regional and seasonal aspects, the NO_x emissions do more consistent damage over time and space through acid deposition than through smog. In this analysis, it is implicitly assumed that acid rain control regulation is separable from smog control regulation. If, for example, NO_x control for acid rain abatement were in the form of flat emissions tax, this tax would be levied at the national, or even international, level, whereas the intermittent NO_x tax for ozone abatement would be levied at the local level. The total tax bill faced by an electric generator would be the sum of these two taxes. Fortunately, such a formulation does not change the mathematics of dispatch. Indeed, fuel taxes are currently levied by multiple levels of government.

3.8. EEUCM

The BAPS simulation is conducted using the Lagrangian Relaxation Environmental Economic Unit Commitment Model (EEUCM) (Gjengedal, Johansen, and Hansen 1992). EEUCM was extended for the purposes of this work by the addition of a Monte Carlo drawing of outage states of the system.

4. COST OF SCR

The California Air Resources Board's (CARB) Best Available Retrofit Control Technology for utility boilers is selective catalytic reduction (SCR), and this technology will likely become mandated for most utility boilers in the District. Clearly, the designation *best* available technology defies economic reason because cost is simply not a factor in the choice. In the case of SCR, apart from its high overall cost, the structure of its cost poses a special problem. The nature of this problem is simply that SCR is capital intensive. In other words, it is a baseload technology whereas photochemical smog is a peaking problem.

Table 1 demonstrates the effect of intermittence on the cost of capital intensive control technologies. This table is a simple spreadsheet used for estimating the control cost of SCR. The data are loosely based on appropriate numbers for Moss Landing 6, which is one of the best SCR candidates among BAPS units. Consider the first line, which shows reasonable assumptions for this unit, an annual 55 % capacity factor,

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and an average SCR NO_x reduction of 0,45 kg/MWh, or about 90 %. The three right-hand columns show the actual \$/kg NO_x control cost assuming three different lengths of smog season, 5, 50, and 365 days.⁶ The 365-day column treats the whole year as evenly important, which is the traditional assumption. Under this assumption, plus the basic assumptions mentioned above, the cost of control that emerges is 7 \$/kg. This figure reflects the attractiveness of this unit for SCR, primarily because of its high capacity factor. The two far right columns show the cost of control if only 50 and 5 days are considered of high enough smog danger to warrant NO_x control. This shortening of the smog season, not surprisingly, drives up the control costs dramatically to 48 and 476 \$/kg.

A 50-day smog season assumption is reasonable for the District because potential smog creating conditions exist on about this number of days, suggesting that one of the best candidates for SCR, Moss Landing 6, can deliver NO_x emissions reductions for about 46 \$/kg. Hence, the number of approximately 50 \$/kg control cost for SCR can be used as a basis of comparison between SCR and a NO_x tax dispatch. Note, however, two aspects of the 50-day assumption. First, it is somewhat conservative to begin with, given that the District experiences only 15-20 State non-compliance days per year. Second, assuming steady progress towards meeting the standard, which is clearly the District's aim, implies steadily escalating control costs. For the sake of argument, assume the District manages to reduce the number of days of exceedence danger from 50 today to 5. Now, the 50 \$/kg control cost looks quite conservative, and 500 \$/kg becomes credible. Although playing with the numbers like this might sound simplistic, most analyses of control costs being done in the regulatory arena today will follow the procedure that results in the 7 \$/kg estimate and proceed no further.

5. COST OF NO_x TAXED DISPATCH

5.1. The NO_x tax

The tax is implemented in a simple manner. Historic ozone concentrations for 1989 at one of the monitoring stations in the District reporting almost the worst air quality, Livermore, were used as the basis for the tax. Analysis of the historic emissions data for the Bay Area focuses on the episode of mid September, 1989. The District studies this episode in policymaking.

Figure 1 shows the O_3 concentration at Livermore during the 11-17 September 1989 episode, and also the tax based on this concentration data. The O_3 concentration curve shows the diurnal cycle of O_3 formation and dissipation. On most evenings O_3 disappeared completely from the air, yet the afternoon peaks

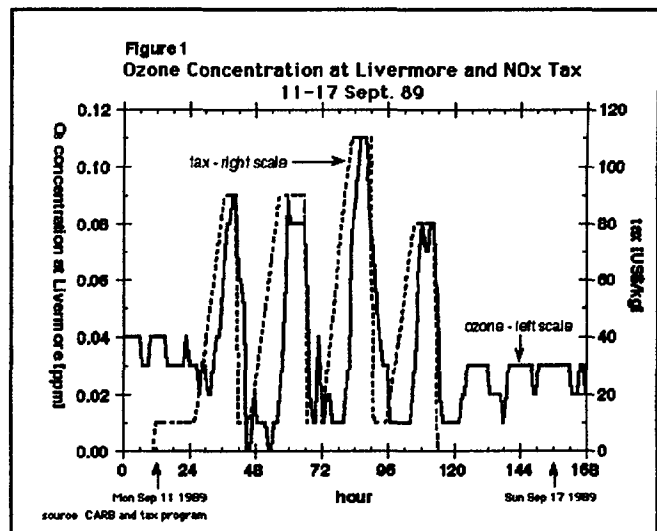


Figure 1.

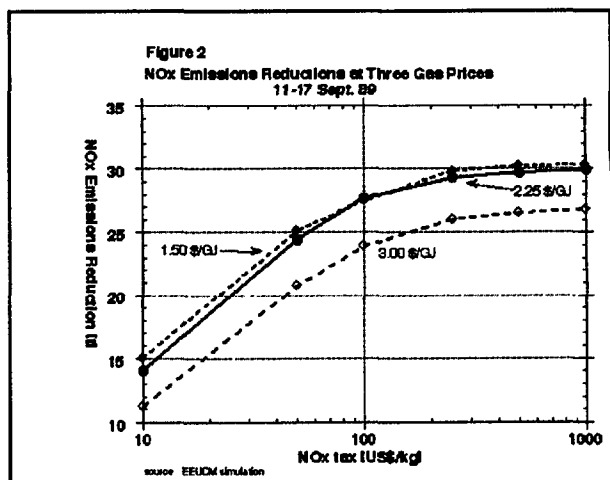


Figure 2

exceeded the State standard on Thursday. The Federal standard was never exceeded during the week. The data for the 14th show clearly that this was the worst day of the episode, the maximum reported concentration being 0,11 ppm. Since the tax is variable, the designation of it in terms of \$/kg must be fixed at some marker concentration. In this work, that concentration is 0.10 ppm. The value of the tax is set by a simple algorithm at all other times.

5.2. Dispatch results

Figure 2 shows some basic results for the same episode week. The x-axis shows the tax rate at the marker concentration, and the y-axis the tons of NO_x emissions avoided for the week. The three curves represent three natural gas prices. The 2,25 \$/GJ curve serves as the base case. Emissions reductions are quite dramatic at low tax rates, but the elasticity of emissions to the tax rate falls off sharply and over 90 % of the potential Emissions reduction is captured by a tax of 100 \$/kg. Total base emissions for this week are 530 t, so the maximum emissions reduction is approximately 6 %. The sensitivity using a lower fuel price of 1,50 \$/GJ produces similar results, but the higher fuel price results in lower emissions reductions across the board. The reason for this effect is that the higher fuel price case results in lower base case emissions, and therefore, the potential of taxes to further reduce emissions is restricted. In other words, if the BAPS system were faced with higher gas prices, emissions would fall simply due to the changed dispatch of the system.

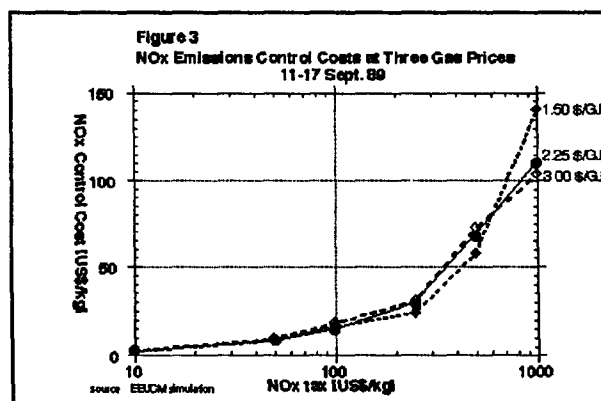


Figure 3

Figure 3 relates these emissions reductions to the increased fuel cost incurred. Again the three fuel price cases are shown. The y-axis now shows the NO_x control cost implied by the previous results. The notable feature of these results is that modest reductions are achieved at low control cost, but control costs increase dramatically at higher tax levels. Noting that in Table 1 a realistic low estimate for SCR is in the 50 \$/kg range, all of the control below the 50 \$/kg line could be interpreted as *prima facie* cost effective relative to SCR. This preliminary evidence, then, suggests that a modest variable episode NO_x tax in the 100-500 \$/kg range may make good economic sense, although the impact of such a tax on total emissions and, therefore, air quality would not be dramatic by any means.⁷ In other words, in the case of the Bay Area at its current state of air quality, some physical control of NO_x emissions would be necessary in addition to the imposition of an intermittent NO_x tax.

Figure 4 shows emissions hour-by-hour during the Thursday of the episode week for two tax schemes. The dashed line shows the results of applying a variable 250 \$/kg tax, as described above, whereas the solid line shows the outcome of imposing a fixed 100 \$/kg tax during the same period. The patterns of emissions reductions are surprisingly similar. Emissions are clearly reduced most during the nighttime hours. In fact, the nighttime period contains two reductions peaks, one around midnight, and the other during the morning hours. Reductions in the afternoons are low, falling to a minimum that is only one third of the maximum. The most encouraging

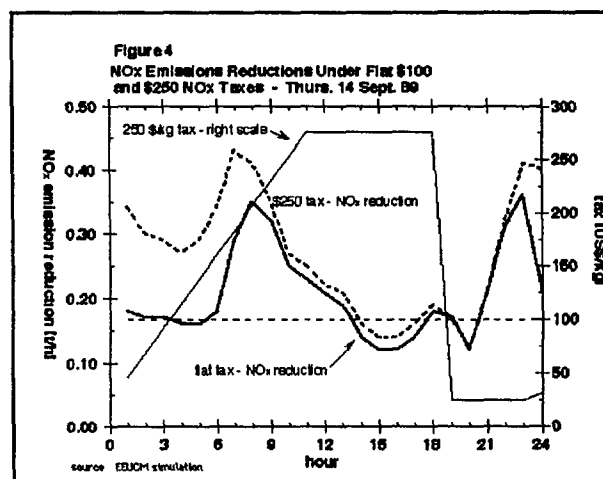


Figure 4

aspect of these results is the morning hour reductions. Given the lag in the atmospheric chemistry, reducing emissions during the morning hours should have a beneficial impact on afternoon ozone concentrations. Low emissions reductions are achieved in the afternoon hours because the high electrical loads leave little flexibility in the system. In fact, the similarity of NO_x emissions reductions under the two tax structures shows that the flexibility in the system really determines the outcome. The higher reductions at night under the \$250 tax show the effect on unit commitment of the existence of the tax.

6. CONCLUSION

This project set out to determine whether biasing the dispatch away from the more polluting units in the Bay Area could result in reduced NO_x emissions during its intermittent smog episodes, and, if so, at what cost in terms of increased fuel burn. Imposition of an assumed tax lowers NO_x emissions modestly, but at low increased fuel cost. The cost of modest NO_x emissions reductions are low compared to SCR, if the benefits of SCR are calculated over similar periods. However, in the homogeneous BAPS system, the NO_x emissions reductions were small, approximately 6 % of the total during an historic episode week. The biased dispatch alone, therefore, is unlikely to provide enough emissions reductions to meet air quality goals. Results so far have shown that an intermittent NO_x tax dispatch is a viable policy to improve air quality, although the overall effect is modest, and incorporation of such a tax into current dispatch simulation is straightforward.

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ENDNOTES

1. Nitric oxide (NO) and nitrogen dioxide (NO₂) are together referred to as NO_x.
2. The name Non-Methane Hydro-Carbons (NMHC's) derives from the practice of reporting hydro-carbon concentrations as two numbers, one for methane (CH₄), and another for all others. A large number of diverse species are covered by NMHC's and other names, such as reactive organic gases (ROG's) are common.
3. Compliance with the Federal standard requires that the fourth highest daily peak concentration over a rolling 3-year period not exceed 0,12 ppm mole fraction. The State of California standard requires no exceedences whatsoever of a 0,09 ppm concentration.
4. While it is not within the confines of the District, Moss Landing is included in the analysis. Data on 16 non-PG&E generators were entered explicitly and the other large (> 1 MW) within the District were included as two general resources.
5. QF's are qualifying independent generating facilities that sell power to the local utility under the terms of the Federal 1978 Public Utilities Regulatory Policies Act.
6. All costs are in U.S. dollars, trading at ECU 0,83 at time of writing.
7. This is not to say that choosing between SCR and the taxed dispatch results in the minimum control cost because other technologies may be economic for certain units.

GLOSSARY

BAPS	Bay Area Power System - BAPS is a fictitious utility consisting of the major power generation in the Bay Area plus the large Moss Landing station, which is just outside the District. BAPS demand is assumed to be all electricity consumption within the District.
CARB	California Air Resources Board District Bay Area Air Quality Management District
EEUCM	Economic and Environmental Unit Commitment Model - EEUCM is a computer model that simulates the operations of an electric utility during time periods of up to a month.
ppm	parts per million by volume - pollutant concentration as mole fraction
QF	see endnote 5
NO _x	see endnote 1.
PG&E	Pacific Gas and Electric Company - PG&E is a large investor-owned electric utility company that serves most of northern California.
SCR	selective catalytic reduction - A method of reducing NO _x emissions by injecting ammonia into the exhaust gas in the presence of oxygen and a catalyst. Within a narrow temperature range, NO is reduced to harmless molecular nitrogen and water, as follows (Flagen and Seinfeld 1987): $4\text{NO} + 4\text{NH}_3 \Rightarrow 4\text{N}_2 + 6\text{H}_2\text{O}$

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