

Energy, Industry and Nitrogen: Strategies for Decreasing Reactive Nitrogen Emissions

Nitrogen oxides are released during atmospheric combustion of fossil fuels and biomass, and during the production of certain chemicals and products. They can react with natural or man-made volatile organic compounds to produce smog, or else can be further oxidized to produce particulate haze, or acid rain that can eutrophy land and water. The reactive nitrogen that begins in the energy sector thus cascades through the atmosphere, the hydrosphere and soils before being eventually partially denitrified to the global warming and stratospheric ozone-depleting gas nitrous oxide or molecular nitrogen. This paper will suggest how an economic analysis of the nitrogen cycle can identify the most cost-effective places to intervene. Nitrogen oxides released during fossil-fuel combustion in vehicles, power plants and heating boilers can either be controlled by add-on emission control technology, or can be eliminated by many of the same technical options that lead to carbon dioxide reduction. These integrated strategies also address sustainability, economic development and national security issues. Similarly in industrial production, it is more effective to focus on redesigning industrial processes rather than on nitrogen oxide pollution elimination from the current system. This paper will suggest which strategies might be utilized to address multiple benefits rather than focusing on single pollutants.

INTRODUCTION

The transportation, electric power and industrial systems that we have developed appear to have been designed to optimize the production of the oxides of carbon, sulfur, and nitrogen. Atmospheric concentrations of carbon dioxide CO₂ have increased by 30% since preindustrial times, while nitrogen and sulfur oxide releases have each more than doubled since then (1). The bulk of reactive nitrogen is intentionally produced as chemical fertilizer for agriculture, but approximately one-fifth is released from the energy and industrial sectors. Living in an oxidizing atmosphere obviously makes the production of oxides easier, but what is striking is the uphill energy path that is required to produce reactive forms of nitrogen from molecular N₂. We shall explore the relationship between the chemistry of nitrogen, its environmental damage, and the economic and policy dimensions of environmental damage reduction and prevention.

While nitrogen is essential for life, the environmental problems associated with reactive nitrogen from energy systems and industrial products are extensive.

- NO_x is a direct precursor of ground-level ozone and photochemical smog.
- NO_x is the second largest contributor to acid precipitation.
- Nitrate deposition is a significant contributor to eutrophication of water bodies.
- Nitrate deposition is decreasing the biodiversity of terrestrial ecosystems.
- Nitrate aerosols diminish atmospheric visibility.
- N₂O is a potent global warming greenhouse gas.
- N₂O is a depleter of the stratospheric ozone layer.

Most of these impacts are recognized and are addressed in a variety of national laws and regulations in North America, Europe and Japan, and in 2 important international treaties. The

Long Range Transport of Air Pollutants Treaty (LRTAP) has a specific NO_x Protocol for reducing acid rain that has been ratified by most of Eastern and Western Europe, the US and Canada. Nitrous oxide is one of the greenhouse gases that may count towards emissions reductions under the Kyoto Protocol should it enter into force. However, as will be demonstrated shortly, there is little coordination among the “different” nitrogen problems, and little recognition of the relationship between the nitrogen problems and other important environmental issues. There is also little attention given to economic costs or benefits or even public preferences in setting priorities for developing policy tools. We will propose an alternative approach that will attempt to address nitrogen emissions in the context of several other environmental pollutants and issues that holds the potential for cost effective reductions in reactive nitrogen.

FOSSIL FUEL COMBUSTION AND NITROGEN OXIDE (NO_x) PRODUCTION

Nitrogen oxides are released during the combustion of fossil fuels and biomass in 2 different ways. The first is called thermal production and arises from the direct reaction of atmospheric nitrogen and oxygen in the high temperature of a flame to produce nitric oxide. (N₂ + O₂ = 2 NO).

The second source of NO_x comes from organically bound nitrogen in the fuel as amines and other organic compounds and from ammonia and other volatile forms of nitrogen compounds released during pyrolysis by the high temperature. An example of one such oxidation may be represented by the following *schematic* reaction.



There is no organic nitrogen in natural gas, but it ranges from zero to nearly 2% in petroleum, and 1 to 2% in coal. Wood contains very little nitrogen, but leaves and stalks of grasslike plants contain 1–2%. Coal is by far the largest producer of NO_x with the ratio of fuel NO_x to thermal NO_x being as much as 2:1 depending upon temperature and other combustion conditions.

NO is rapidly further oxidized by several pathways to nitrogen dioxide, NO₂, in a matter of minutes. It is the mixture of NO and NO₂ that is normally referred to as NO_x. (NO + [O] = NO₂).

The amount of NO_x produced increases with flame temperature, gas pressure (it is worse in high compression internal combustion engines) and with longer flame contact time. Thermal and fuel nitrogen are oxidized by different mechanisms and hence may not respond similarly to all emission reduction technologies.

Additional higher oxidation states of nitrogen are also formed in the atmosphere including N₂O₅ and nitric acid (HNO₃). The formation of nitric acid provides the major route by which these reactive nitrogen oxides are removed from the atmosphere as acidic precipitation.

The average atmospheric lifetime of NO_x is fairly short in the atmosphere; about one day or less in polluted urban atmospheres, and 5 to 10 days in the upper troposphere. Because of their short atmospheric lifetime, NO and NO₂ are not uniformly distributed, and the concentration varies by over 5 orders of magnitude from about 1 ppt over the remote Pacific oceans to more than 100 ppb in urban regions like New York or Beijing (2). In fact, urban

smog and nitric acid rain are concentrated along urban corridors and in the regions downwind from them. One of the most striking aspects of the energy sector nitrogen cascade is the finding that 40% of the nitrogen eutrophication of the Chesapeake Bay comes from nitrate contained in rainfall, with the remainder coming from agricultural and urban runoff.

Fossil fuel use has grown dramatically in the world over the past half century (Fig. 1). From 1950 through 2000, all fossil fuels increased by 4.6-fold on an energy basis. Coal use increased by a factor of 2.0, oil by 7.6-fold and natural gas by 12.2-fold (3). Globally, coal use, began to level off in the 1980s with the amount of coal burned in 2000 less than in any year since 1984. Oil surpassed coal as the dominant fossil fuel in the mid-1960s while gas passed coal only in 1999, and is now second to oil (3). While coal use continues to grow rapidly in many developing countries, it has stabilized in most industrial countries, and declined sharply in the formerly centrally planned economies of Central and Eastern Europe (Fig. 2). Coal is currently producing 55% of electricity in the US, but nearly 90% of new capacity is natural-gas turbines. With the removal of most subsidies, and the closing down of economically inefficient state firms, China's coal use has apparently actually declined by nearly 5% during the latter half of the 1990s, but is expected to rise again as the economy expands further.

The Intergovernmental Panel on Climate Change (IPCC) estimates that global NO_x released in the year 2000 was approximately 52 TgN yr^{-1} from both natural and man-made sources. Of this, an estimated 34 TgN yr^{-1} come from the combustion of fossil and biomass fuels (mostly the former). North America is responsible for nearly one-third of the total fossil-fuel emissions with 10.1 TgN yr^{-1} , followed by Europe with 7.3, East Asia with 5.6, Africa with 2.5, India, 1.7, South America 1.4, Southeast Asia, 1.2, and the rest of the world at 2.8 TgN yr^{-1} (Fig. 3) (1).

The concentrations of NO_2 have declined at US monitoring sites by about 14% between 1980 and 2000 even though NO_x emissions increased 4% primarily from diesel engines (2). NO_x concentrations have also dropped by comparable amounts in central London as the result of regulations that reduce allowable emissions that are described below. UK emissions are projected to drop by 55% from 1990 levels by 2010 (4, 5). Declines of 15% and 17% have been noted in Germany and Spain since the mid-1980s, and Canada has recorded a phenomenal decrease of 32% since 1980 (5). Despite these near-term regional declines, the IPCC estimates that by 2100, fossil-fuel related NO_x emissions could increase more than threefold to 110 TgN yr^{-1} because of the growth of uncontrolled fossil-fuel burning (especially coal) in Asia and elsewhere in the developing world. This scenario also shows US and European emissions doubling over this period if fossil-fuel use continues as the primary energy source (1). Even the introduction of many technologies described by Bradley and Jones in this issue of *Ambio* (6) will not be able to off set the large growth in fossil-fuel use that is potentially possible during the 21st century.

NO_x is involved in a catalytic cycle that converts CO to CO_2 with the assistance of the hydroxyl radical. NO and NO_2 play complex roles in atmospheric chemistry. NO increases the concentration of the hydroxyl radical and thereby shortens the lifetime of CO, CH_4 and HFCs. This clearly benefits air quality and lowers contributions to global warming. But NO_2 drives photo-

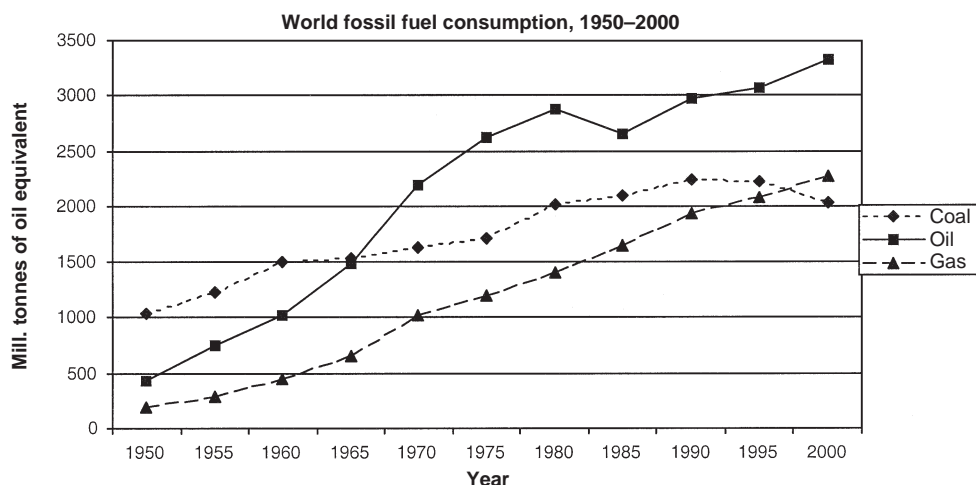


Figure 1. Composition of fossil fuels 1950–2000. 1 Mtoe (million tonnes of oil equivalent which is approximately 30 million GJoules or 30×10^{15} Joules) (3).

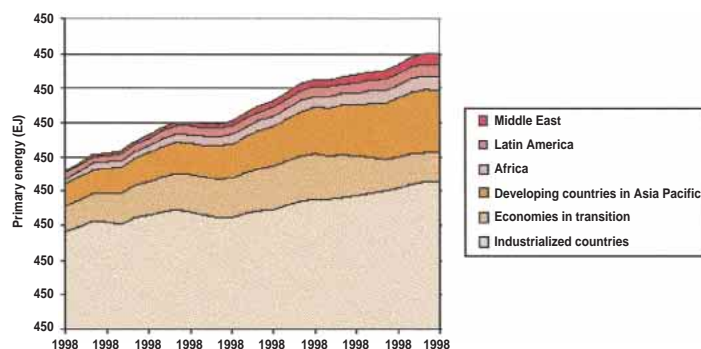


Figure 2. Primary energy use by region, 1971–1998. (1).

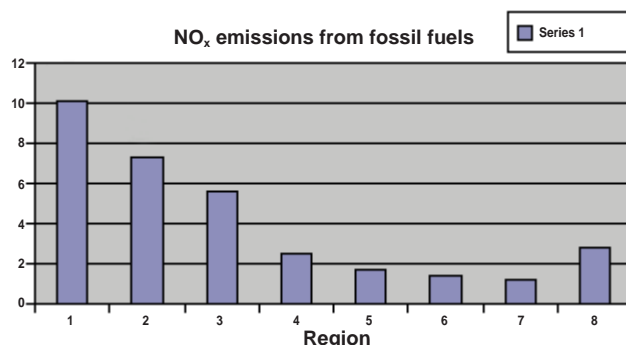


Figure 3. Annual NO_x emissions by region for 2000: 1. North America, 2. Europe, 3. East Asia, 4. Africa, 5. India, 6. South America, 7. South East Asia, 8. Other (1).

chemical smog formation by absorbing sunlight to provide the energy for the smog reactions. NO_2 alone and in the presence of volatile organic compounds, forms ozone, which is a significant absorber of infrared radiation. This creates a perverse feedback loop; ozone is formed more readily in a warm atmosphere, and is itself a greenhouse gas that creates further global warming.

REACTIVE NITROGEN REGULATION IN THE UNITED STATES

Most of the focus of reactive-nitrogen regulation is on the lowering of NO_x emissions. In the United States, it is the Clean Air Act, and in particular, the 1990 Amendments, that form the major regulatory structure. Melillo and Cowling (7) and Bradley and Jones (6) provide a fuller history of the Act and its evolution. Under this legislation NO_2 is considered one of 6 Criteria Pollutants, and is regulated primarily as a precursor to photochemi-

cal smog. The Act sets ambient mean annual concentration limits of $100 \mu\text{g m}^{-3}$ (0.053 ppm) (8). This is a somewhat arbitrary value that is a political compromise based loosely upon scientific estimates and a judgment by legislators as to the availability and cost of technological remedies. It also happens to be a round number. Because the several oxides of nitrogen react rather rapidly in the atmosphere, the total concentration is not well mixed, and values fluctuate by large amounts regionally and through time. For example, in New York City annual average NO_x levels of 0.03 ppm are within the compliance standard, but 1-hr NO_x levels as high as 0.18 ppm, which greatly exceed that standard have been reported as recently as 1999 (9). In order to address the contribution of NO_x to acid rain, the 1990 Amendments set a goal of reducing annual emissions by 2 mill. tonnes (t).

In the US, just over half (55%) of fuel combustion NO_x emissions come from mobile sources. Road transport accounted for 34% of NO_x emissions in 1998, with additional mobile sources and machinery accounting for an additional 21% (7). To achieve the ambient concentration standard, specific emission rates are set for each source. For example, the 1990 Clean Air standard for automobiles is $0.4 \text{ NO}_x \text{ mile}^{-1}$. California has specified even tighter regulations for the future. Light trucks are permitted to emit higher levels, and since these vehicles now have replaced half of auto sales, the rate of NO_x concentration decreases from the transport sector has slowed. As is discussed later, the use of 3 way catalysts reduces most of the nitric oxide in the exhaust stream to molecular nitrogen, but a small fraction is released as nitrous oxide. N_2O is not regulated domestically, but is a source of concern for its global warming and stratospheric ozone depleting potential. Globally, about 2% of NO_x comes from air transport (1).

The majority of transport emissions now come from heavy diesel trucks and to a lesser extent buses and trains. This is in part because of diesel's higher operating temperature and compression ratios that favor NO formation from air. Because of the strict NO_x standards on automobiles, and the lack of stringent controls on heavy diesel trucks, buses and trains, these latter vehicles constitute a growing fraction of emissions. In the Northeast US, which is an important nonattainment area for ozone, 33% of NO_x that is an ozone precursor is estimated to come from heavy diesel trucks alone. This is equivalent to the total emissions for all light- vehicles and electric power generators in the region (9). These vehicles also are responsible for major amounts of the most toxic particulates. Technologies that would meet stricter regulatory standards are currently tied up in debates over the need to reduce sulfur in diesel fuel in order to have effective catalysts and lower particulate emissions.

Stationary sources such as fossil-fuel power plants, stationary diesel engines and industrial, commercial and residential boilers account for 41% of emissions of NO_x . Industrial boiler and power plant emissions are regulated under the Clean Air Act. Coal is the largest sector emitter of NO_x , and coal-burning power plants are responsible for nearly one-fourth of total US NO_x emissions. Because of the high content of organic nitrogen in coal, approximately twice as much NO_x comes from the fuel nitrogen as from the thermal formation of NO from nitrogen and oxygen in air. Industrial processes are estimated to release an additional 3% of US emissions (mostly from nitric acid synthesis and from cement production), and agriculture and waste treatment add about 1% more (2).

INTERNATIONAL AGREEMENTS

Internationally, over 30 countries in Europe and North America are parties to the Long Range Transport of Air Pollutants (LRTAP) and its 6 Protocols. The Treaty was negotiated in 1979, by the UN Economic Commission for Europe to which both the US and Canada are members along with every country of East-

ern and Western Europe. The first substantive Protocol addressed sulfur dioxide emissions (1985) while the second to control transboundary emissions of NO_x was negotiated in 1988 and entered into force in 1991. The motivation for these Protocols is to reduce acid deposition, but they do not preclude addressing other effects of NO_x on human health or ecosystems. The U.S. is a party to the NO_x agreement, but not to the Sulfur Protocol (10).

The approach to setting standards under LRTAP is; "*based on critical loads methods to integrate scientific, technical and economic data in order to determine appropriate control strategies, ... and at deciding on further internationally agreed measures to limit and reduce emissions of nitrogen oxides or their transboundary fluxes.*" (10).

In other words, the extent of control is based upon the capacity of particular regions to sustain deposition or atmospheric concentrations of nitrogen compounds. The treaty specifically endorses the use of models to determine the relationship between sources and sinks. It also calls for an ongoing process of assessing technological options and developing lower cost economic strategies. While standards that are adopted do not necessarily protect all areas from damage because of cost or technological limitations, the scale of the effects remain the basis from which the political judgments are made. This scientifically based approach is quite different from that of the US where political compromises dominate the legislative process.

The only other oxide of nitrogen that is subject to international regulation is nitrous oxide. N_2O is a highly stable gas (120 year average lifetime) that is broken down primarily by ultraviolet photolysis in the stratosphere. There, the resulting NO catalyzes the chemical destruction of the ozone layer. Despite this well-established effect, N_2O is not regulated or even mentioned under the Montreal Protocol on Substances that Deplete the Ozone Layer. Instead, because of its long atmospheric lifetime and strong infrared absorption, it is listed specifically as a greenhouse gas that should be regulated under the Kyoto Protocol of the UN Framework Convention on Climate Change (10). The Kyoto Protocol was finally approved in November 2001, but has not been ratified by enough nations to enter into force. The US has announced that it will not be bound by this agreement.

While approximately half the N_2O comes from agriculture and forestry, 25–30% is released in industrial chemical processes. The remainder is nearly equally divided between electric-power production and fuel combustion for heating and transport (1).

Production of HNO_3 , much of it for nitrogen fertilizer synthesis, and adipic acid mostly used for nylon manufacture are the major industrial sources. DuPont, for example, has taken on a major responsibility to reduce its greenhouse gases by 65% below 1990 levels, mostly by eliminating N_2O and other industrial waste gases. Between 1990 and 1999, DuPont's N_2O emissions have dropped by nearly 90% worldwide (11). The cost is not known, but they are undertaking these reductions even without a regulatory mandate. Even as industrial emissions drop, and as more vehicles utilize 3 way catalysts, the relative and absolute emissions from fossil fuel combustion in vehicles and stationary sources will grow. This illustrates the problems with focusing on one sector or one mode of emissions, as regulatory efforts tend to do.

NITROGEN ECONOMICS

Cost-benefit analysis is often advocated by members of the economics profession and by some policy makers and potentially regulated industries. In principle, this sounds like a fairly straightforward exercise. One determines the environmental and public health damage, and decides upon an appropriate level of emissions reductions that would lower concentrations to a *politically acceptable* level. The cost of reaching that level is then determined by identifying technological, implementation, and

transaction costs, and compares them to the damage costs mitigated. In practice, there are many difficult issues that often revolve around the value of a human life or loss of fish or wildlife, or the decreased value of degraded ecosystems and their lower level of ecosystem services. Since the costs and benefits extend outward into the future at differing rates, there is also the question of what discount rate to use in determining the net present value of the costs and benefits.

Another problem with this traditional economic analysis is that following consumption, the material and energy embedded in economic goods disappears from the universe of economic analysis, even though the laws of thermodynamics and the conservation of mass guarantee their environmental persistence. An alternative approach would be to value *specific fluxes* of nitrogen flows, in and out of a particular geographical region or ecosystem. So, in contrast to static cost-benefit analysis, an industrial ecology approach is concerned with the full life cycle of materials and energy and recognizes that economic wastes still need to be accounted for following consumption of goods. In a limited way, economic cost-benefit analysis can account for post-consumption wastes as *negative environmental externalities* by subtracting costs of environmental damages from the total benefits. However, industrial ecology recognizes that nitrogen incorporated in fertilizer does not disappear after fuel is burned to produce smog, but continues to cascade through the biosphere. The degraded ecosystem continues to provide fewer ecosystem services for the indefinite future. Some of the nitric acid may rain down on crops or forests providing nutrients, in some degraded, higher entropy form. This diluted nitrogen has the economic equivalent of "scrap value", even if humans do not find it expedient to recover it given present techniques.

The economic value of N-fluxes may be determined in 3 ways: *i*) direct economic benefits or costs; *ii*) the residual economic value of post-consumption wastes; *iii*) costs of remediating nitrogen-induced environmental damage and/or the costs of replacing lost ecosystem services. One can begin by estimating the value of the nitrogen in its various chemical forms and concentrations. In general, nitrogen enters the economic system in a higher-value, low-entropy form and exits in a lower-value, higher-entropy form. In short, while only parts of this analysis have been conducted to date, one can in principle create an economic nitrogen cycle that parallels the more familiar biogeochemical nitrogen cycle. This economic cycle may be of greater relevance to policy makers by identifying the points where the greatest environmental damage and least cost interventions can occur.

INTEGRATED NITROGEN REGULATORY STRATEGIES

The current regulatory strategy often fails to make cost effective policies to reduce reactive nitrogen emissions on 2 levels. First, the environmental regulatory system usually treats pollutants one-at-a-time, and if a pollutant has more than one environmental consequence in the nitrogen cascade, it is treated differently under problem-specific environmental regulatory regimes. Second, the electric power sector is often regulated economically so as to increase pollutants by ignoring multipollutant strategies and by discriminating against combined heat and power systems that would gain the maximum energy and lowest emissions from each ton of fuel. Furthermore, much of the regulatory system eschews economically more effective options for more expensive solutions.

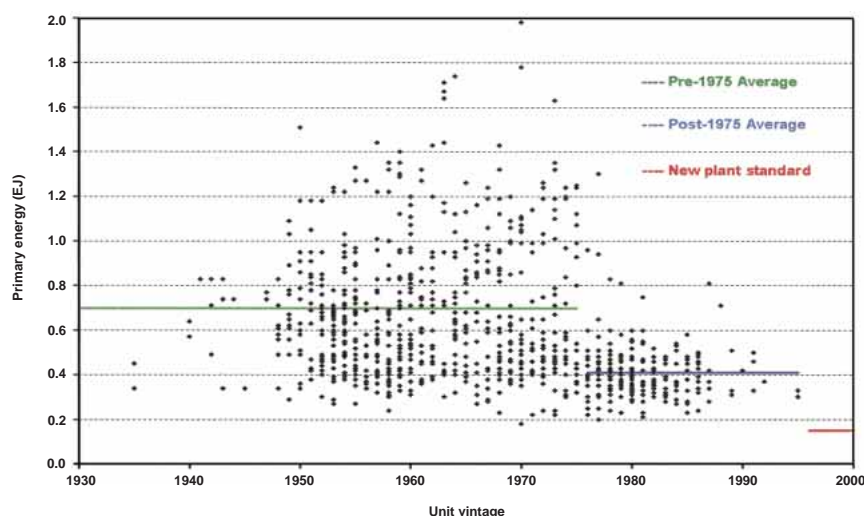
Let us examine the effects of utilizing a multipollutant control strategy. In the United

States, older electric-power plants are permitted to continue polluting at the much higher levels allowed prior to passage of the latest regulations. Their emissions were "grandfathered" under the rules of the Clean Air Act on the assumption that they will eventually be phased out. New power plants, by contrast, must meet stringent new source performance standards that are established separately for each pollutant. The economic incentive is therefore to keep older power plants in use for as long as possible in order to avoid the much higher pollution control costs of new plants. As a result, the average electric power plant in the US was constructed in 1964 using even older technological designs. Half of coal plant capacity was built before 1975, a quarter before 1965. More than half of all sulfur emissions nationwide and a large part of nitrogen emissions come from pre-1975 coal plants. Coal plants, of which there are 886 in the US, generate approximately 55% of electricity. In the northeast, it is estimated that 91% of power plant NO_x can be attributed to coal-burning facilities (12).

NO_x is controlled primarily to reduce its contribution to ozone and photochemical smog production, and only secondarily for acid-rain reduction. Costs to retrofit existing systems can be very expensive. Most of the technologies designed to reduce NO_x require some combination of low NO_x burners, recirculating exhaust gases, fluidized beds, or other techniques for lowering the flame temperature. Also, post-combustion catalytic or chemical treatment of the gas stream can also lower emissions. See Bradley and Jones (6) for a description of particular technologies for reducing NO_x emissions. Under separate rules, power generators must reduce particulate emissions and SO₂ emissions. These technologies all reduce efficiency of the generation process by several percent. Even before emission reduction requirements for NO_x, SO₂ and particulates were implemented, the electric efficiency of power plants reached an average of 33% around 1960, and has remained at that level almost to the present time. With increased concern over the contribution of CO₂ to global warming, the low efficiency from older plants creates a conflict among potential regulatory goals.

Ackerman and co-workers (12) have examined a cost-effective strategy for assessing these pollutants simultaneously. They explore the implications of a multipollutant strategy for NO_x, SO₂ and CO₂. Figure 4 shows the NO_x emissions by year of completion of power plants. Also shown by the horizontal lines are the averages for pre-1975 plants, (0.7 lbs million⁻¹ BTU), average for post 1975 plants (0.41 lbs million⁻¹ BTU), and current requirements of the 1990 Clean Air Act Amendments (0.15 lbs million⁻¹ BTU). Note that no coal power plants have been built that meet the 1990 standard for NO_x.

Figure 4. NO_x emissions by vintage of US coal-burning power plants (12).



They compare the fuel, operation, and maintenance costs of existing coal-burning power plants with the capital, fuel, operation and maintenance costs of new efficient combined-cycle gas turbines. It is assumed that since the coal plants are on average so old, that their capital costs have been fully depreciated. Because costs vary so strongly with capacity factor, they produce a scatter plot of the unit cost of electric power from all US coal power plants relative to capacity factor. They then plot on the same diagram the cost curve for new combined-cycle gas turbines. As can be seen in Figure 5 less than 1% of the coal capacity is more expensive than natural gas under these assumptions so that only these few coal plants might be economically displaced by gas plants.

If all of the coal plants, including those that are grandfathered to operate under less strict emission rules, were brought up to current NO_x and SO₂ standards utilizing a combination of pre- and post-combustion emissions reduction technologies, the cost of coal plants and their operation would be increased. These new costs are plotted in Figure 6 and compared to the cost of combined-cycle gas turbines. Under these assumptions, 6% of the coal capacity would no longer be economically competitive with new gas facilities that meet NO_x and SO₂ standards. Most coal plants meet particulate standards, but the gas plants would be even cleaner.

The net effect of requiring grandfathered coal plants to meet current standards would reduce SO₂ emissions by 7.3 mill. t or 40% of US total emissions, and would lower NO_x by 3.3 mill. t or 15% of total US emissions. Using the cost of a known backstop technology, namely combined-cycle gas turbines, only 6% of the coal plants would be replaced by them rather than retrofitted with known emission-control technology. This is because of the assumption that the capital cost of all of the coal plants has been fully depreciated while capital costs of gas plants would need to be accounted for in full. Put another way, the cost of owning and operating existing coal burning plants is so low that it is still economically competitive to put on quite expensive emission-control technology. The estimated cost of achieving the Clean Air Act nitrogen and sulfur goals for the industry as a whole is USD 9.6 thousand mill. on an annual basis. An expenditure of USD 0.4 of this is for plants that are better retired and replaced with new facilities. Only one-third of this cost is explicitly for nitrogen controls. Since total retail cost of electricity in 1996 was USD 212 thousand million, this expenditure amounts to an increase of just 4.3% in utility bills.

Next, these authors assume that a tax of USD 10 t⁻¹ CO₂ is placed on all fossil fuels. This is equivalent to USD 37 t⁻¹ carbon. This represents a relatively modest increase that amounts to approximately USD 30 t⁻¹ of coal or roughly a doubling of coal prices. To put this in more familiar terms, this is equivalent to raising the price of gasoline 10 cents gallon⁻¹. Because natural gas is a lower carbon fuel per unit of heat produced than is coal, and because gas turbines are substantially more efficient, the costs of coal plants increase more than those that operate on gas. Figure 7 now shows that when all 3 criteria are applied simultaneously, then fully one-third of coal capacity would not be cost competitive with gas-turbine facilities under the stated assumptions. If electric generation were an economically competitive market, then ultimately, according to this analysis, one-third of US coal capacity would eventually be displaced by gas because of a 3-pollutant strategy at the stated levels of reduction. Introducing a fourth regulated pollutant, mercury, would raise the cost of coal-plant operations even further.

Figure 5. Comparison of capital, fuel, and operating costs of new gas plants relative to the operating costs of existing coal plants (12).

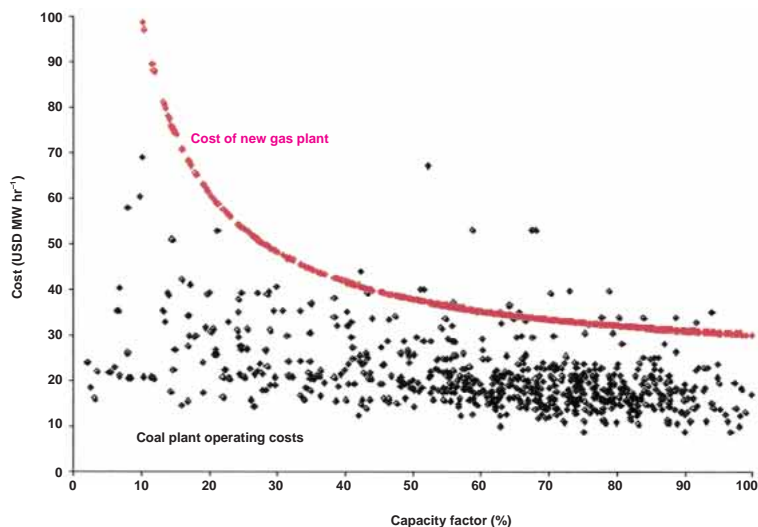


Figure 6. Cost of new gas plants relative to requiring all existing US coal plants to meet existing NO_x and SO₂ emissions standards (12).

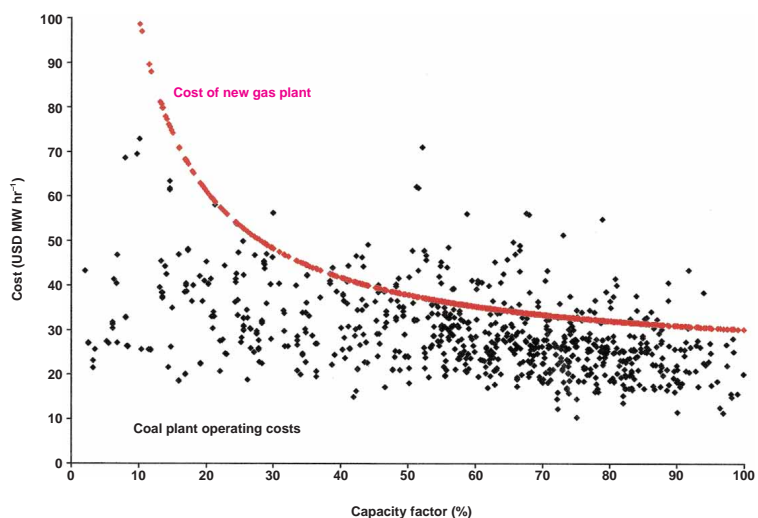
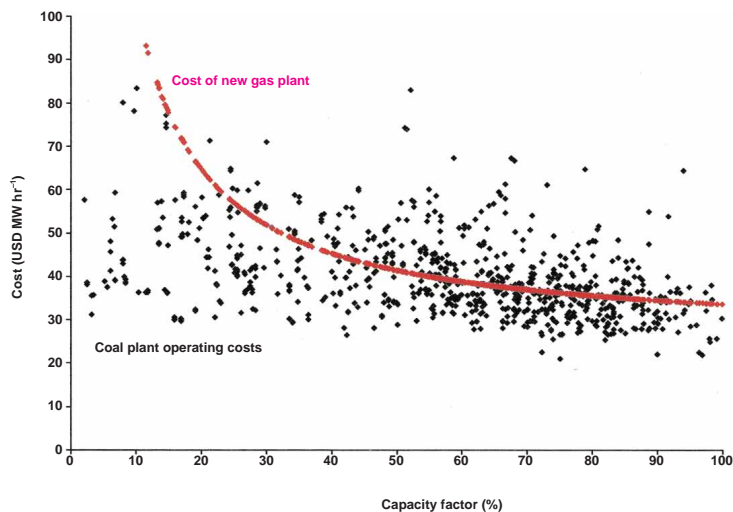


Figure 7. Cost of new gas plants relative to requiring all existing US coal plants to meet existing NO_x and SO₂ emissions standards plus a USD 10 ton⁻¹ CO₂ tax (12).



But the reality is that despite utility deregulation in some states, there remain many policies in place that insulate existing power plants from new competition. An additional strategy that would address all of these pollutants simultaneously would be to require as many thermal-power plants as possible to be built or retrofitted as combined heat and power (CHP). There are substantial industrial and densely developed parts of the US such as the northeast and upper midwest that are well suited to this option. Again a market price test should be performed to determine the least cost option for meeting multipollutant goals. In numerous cases, CHP proves to be the most viable solution (13).

CHP would dramatically lower all pollutants by a factor of 2 to 2.5 by utilizing the currently wasted heat from the electrical generation process to displace industrial, commercial, and residential needs for space, water, and industrial heating or cooling. In cities such as Hartford, Connecticut, and St. Paul Minnesota where gas-turbine CHP systems now heat and cool much of the central city, there have been major reductions in NO_x and other pollutants as hundreds of individual unregulated boilers were shut-down. Even though the largest cogeneration facility in the world is at the Dow Chemical Plant in Midland Michigan where a 1000 MWe power plant provides steam and heat to a vast chemical complex, the DOE estimates that at most 7% of US thermal-power plants are CHP. The EU average for CHP is twice that of the US and a goal to double the current levels by 2020 has been set. Denmark, where all of the thermal-power plants rely on coal has a 50% CHP capacity.

A century of American regulatory policy has blocked CHP even where it was economically preferable by assuring monopoly power to generators. Unfortunately, many states still prevent or make it very difficult for a manufacturing company that needs both electricity and steam to sell any surplus power to the utility. As recently as the summer of 2001, 10 000 MW of new gas capacity was proposed for New England, and not a single MW was designed as a combined heat and power system. This means that twice as much natural gas will be used because half of the heat from burning it will simply be dumped into the environment at considerable expense. An unanticipated additional problem this will create is to raise the price of natural gas, which in recent years has been seen to be highly vulnerable to price spikes because of the tight relationship between supply and demand (13).

Finally, if costs were ascribed to NO_x and other pollutants, then alternatives such as wind turbines might become economic alternatives in appropriate sites. The cost of very large wind turbines has dropped below 5 cents kWh⁻¹, and some projects are proposed that approach 4 cents. Even as these prices continue to fall, these zero emission generating sources with zero fuel costs may not be able to compete with unregulated coal plants that are allowed to continue to emit large quantities of pollutants. Even, "clean coal" technology such as coal gasification and lower temperature fluidized-bed technology can not compete with grandfathered coal plants.

An additional benefit of this multipollutant economic costing of pollutants as a strategy for a reformed electric-power industry is that it does not lock-in existing pollution intensive power plants. It also substantially reduces hundreds of additional pollutants from coal including toxic metals such as mercury and lead, radioactive elements such as thorium, particulates, and toxic organic chemicals. In addition, visibility would improve by reducing nitrogen and sulfur-based aerosols as well as emissions of organic particles and inorganic ash.

It would also be more cost effective if it were possible to trade across technologies and sectors for specific pollutants and even among smog pollutants. For example, it is found that it costs anywhere from USD 1300 to USD 7000 to remove 1 t NO_x from the exhaust stream of industrial boilers or power plants. However, it costs only a few hundred dollars to remove 1 t NO_x by

using a specially designed combustor in a replacement gas turbine. It also costs only about USD 550 to remove 1 t NO_x from a heavy diesel truck (12), and this catalytic technology will also remove significant non-methane hydrocarbons that also contribute to smog. However, it is difficult to cross over between transportation standards and fixed source emissions from a regulatory perspective.

CONCLUSIONS

The energy, transportation, and industrial sectors contribute substantially to the production of very large amounts of highly mobile reactive nitrogen. The regulatory system within the United States has focused on one-at-a-time pollutant regulation. And the standards that have been set have been based mostly upon political compromise rather than on any scientific or economic analysis. It also seems that utilizing the European system of critical loads could add a scientific basis for NO_x and other emission standards that is often lacking in the American environmental protection system. This paper demonstrates that consideration of multiple sources and pollutants simultaneously can produce multiple benefits in not only the nitrogen cascade, but also with additional pollutants as well. An economic analysis can also inform decisions about where in the nitrogen cycle it is most effective and economical to intervene. There are many technological options for reducing the environmental damage from reactive nitrogen, and the use of appropriate economic analysis can inform choices among them.

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William R. Moomaw is professor of international environmental policy at the Fletcher School of Law and Diplomacy at Tufts University where he also directs the Tufts Institute of the Environment. Professor Moomaw is a chemist, who works as a policy scientist incorporating science, technology and economics into policy strategies for addressing domestic and international environmental issues. He has served as a lead author on the industry chapters of the 1996 Intergovernmental Panel on Climate Change Report, and was coordinating lead author of the 2001 IPCC Report Chapter on Technological and Economic Potential for Greenhouse Gas Emissions Reductions. He consults for the Dutch government and for the energy industry. He has also published articles on corporate environmental policy, environmental conditions in Eastern Europe and has written on negotiations for multilateral environmental agreements. In addition to his interests in energy and environmental issues, he also works on the protection of biological resources. His address: The Fletcher School of Law and Diplomacy, Tufts University, Medford, MA 02155 USA. E-mail: wmoomaw@attbi.com