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Applications of Environmental Valuation for Determining Externality Costs†

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Analyzing the effectiveness of environmental programs and regulations requires comparing the costs and benefits of reducing different pollutants or further abatement. To make useful comparisons, the various benefits from reduced pollution must be translated into dollars. Unfortunately, estimating the dollar value of environmental damages is complicated, controversial, and generally uncertain. Often these estimates have been misused. This paper identifies the need for benefit estimates, shows how they are constructed, and demonstrates how they can be used to improve environmental policy analysis.

Introduction

The easy environmental problems have been solved. The increasing controversy over new regulations reflects the increased costs and growing uncertainty about benefits from further abatement, e.g., the $PM_{2.5}$ and ozone rules. The U.S. Congress required the U.S. Environmental Protection Agency (EPA) to examine the costs and benefits of the Clean Air Act retrospectively from 1970 to 1990 and then prospectively from 1990 to 2010. Congress has also required the EPA to assess the social benefits and costs of every major new regulation.

Environmental scientists and engineers have made notable progress in assessing the consequences of environmental discharges and in advancing technologies for the prevention or abatement of emissions. Estimating the costs of abatement programs is somewhat uncertain, but environmental engineers and economists have developed acceptable methods. The largest difficulty for federal, state, and local regulators and for companies has been finding ways to monetize the physical consequences of abating discharges to satisfy Congressional requirements and to set abatement priorities.

Without a means of setting priorities among discharges, inefficient or even counterproductive decisions will be made. For example, the uncontrolled emissions of a coal-burning power plant contain huge quantities of fly ash, tiny amounts of small particles ($PM_{2.5}$), and even smaller amounts of toxic metals, such as lead and mercury. Despite their dominant mass, fly ash poses little or no threat to health, in contrast to $PM_{2.5}$ or the toxic metals. Are additional controls required for a modern plant with a precipitator and flue gas desulfurization? If so, is the priority additional removal of particles, of NO_x and SO_x, or of heavy metals?

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A Primer on Valuation

For goods and services purchased in a competitive market (a market in which both buyers and sellers are "price takers" who have no long-term influence on price), the market price represents the economy's best valuation of an additional unit of that good or service. Under some assumptions, this price is also society's best estimate of value. These statements are not correct for markets where a few buyers or sellers have monopoly power or people do not have "reasonable" information or expectations about future supplies and future technologies. Most economists view the U.S. economy as "reasonably" competitive and accept market prices as a measure of social value, except in cases with important externalities.

External effects or externalities are spillovers (positive or negative) from the production of a good or service. For example, air pollution from a coal-fired power plant can present a health hazard to the neighboring community. These neighbors can suffer additional asthma, bronchitis, and even premature mortality as a result of producing electricity by burning coal. The market provides no signal that too much coal is being burned or that the plant ought to control its air emissions. The problem might be solved by centralized command and control regulation where the EPA requires the plant to add precipitators and flue gas desulfurization to reduce emissions. Alternatively, the incentives to the plant could be changed so that it had to pay the social costs of its emissions. A third alternative would have consumers pay the social costs of emissions when they purchased each kilowatt-hour, leading them to buy less electricity. All three approaches would lower pollutant emissions, although the party bearing the initial costs and the efficiency of the solutions would likely differ.

Determining a social value for a good or service is difficult in the absence of a competitive market. One approach is to search for "similar" goods and services that are sold in the market, e.g., valuing camping in public campgrounds by the amount people pay to camp in a private campground, valuing freeway services by willingness to pay (WTP) for toll roads, and valuing a particular aluminum alloy sold only to the Department of Defense by looking at a similar alloy that has a more competitive market.

For goods and services (or bads) not valued in the market, economists have developed a number of approaches to help estimate their social values: damage functions, WTP, measures of damage (lost wages, medical expenditures, jury awards for wrongful injury), and travel cost. We briefly explore the advantages and disadvantages of the most relevant approaches.

Damage Function Models

The first step in evaluating the benefits of pollution abatement is to estimate the effect of pollution emissions on things we care about, e.g., health, visibility, materials deterioration, and damage to the natural environment. The next step is monetizing these estimated damages, e.g., the costs of preventing or repairing materials deterioration. Suppose, an additional 100 000 ton of SO_2 emissions might be estimated to increase the deterioration of steel structures in the region by 1% per year. Furthermore, the cost of earlier replacement, repair, or preventing corrosion might be $1 million. If so, the value of abating SO_2 emissions is $10/ton in terms of preventing materials corrosion.

Damage functions must be estimated for the most important effects of environmental pollution. In particular,

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human health effects from air pollution include restricted activity days, increases in incidence of cases of asthma and bronchitis, and even premature deaths. Additional effects include damages to aquatic and terrestrial ecosystems and from reduced visibility.

Each of these physical effects is modeled to determine the quantitative effects of changes in ambient levels of pollution. For example, how does the incidence of asthma or bronchitis change as air pollution levels change? The next step is to ascribe a dollar value to each change in the physical damages, e.g., the costs of replacing a steel structure earlier, of repairing corrosion, or of preventing corrosion by painting. These steps estimate the type and the extent of physical damage that results from increased air pollution as well as a dollar measure of this damage.

Despite decades of damage research, both the qualitative and quantitative effects of environmental pollution are uncertain. For example, the EPA's benefit−cost analysis of the $PM_{2.5}$ and ozone standards ascribed all premature mortality associated with air pollution to $PM_{2.5}$, assuming that the contribution of other pollutants was negligible (*1*). A further uncertainty is the extent of life shortening associated with a premature death due to $PM_{2.5}$. Estimating damage functions is complicated by interactions with other factors and the changing nature of air pollution across areas and over time. Uncertainties in the damage functions are more important than uncertainties in monetizing and estimating the benefits of abatement.

WTP Studies

Valuing the cost of painting or replacing a steel structure is straightforward. The materials and labor are valued in reasonably competitive markets, and so the bill for replacement or repair is a good estimate of the monetary damage. In contrast, it is more difficult to monetize the value of fewer asthma attacks or being able to see a landmark 30 mi away rather than 10 mi away. A prospective buyer scrutinizes the attributes of available products and their prices before making a choice. Products that are less desirable or more expensive than their competitors suffer in markets, eventually being eliminated. Thus, market prices reflect consumer evaluations. But there are no markets for asthma attacks or visibility.

Economists construct a surrogate market by asking people what they would be willing to pay for these improvements. Many questions have been raised about whether people can give accurate answers or are motivated to give honest answers to the questions. Some studies indicate that there is a reasonable level of validity for these responses. However, the answers are controversial and uncertain, particularly where the good or service is outside the experience of the people doing the evaluation, e.g., WTP to protect sea otters in Prince William Sound. Such methods are called contingent valuation (CV).

In the EPA's benefit−cost analyses of air pollution abatement, the category responsible for more than 90% of the benefits was premature mortality (*2, 3*). We will focus on this category. Here we ignore uncertainty about the damage (dose−response) function for each pollutant.

Economists confuse readers, and even themselves, by using the term "value of life". This term calls to mind the value of your American birthright or perhaps the deliberate sacrifice of an individual. Neither interpretation is relevant here. What is being monetized is a small change in the likelihood that individuals at risk will experience a premature death. With 100% certainty, we know that everyone will die eventually. We are discussing premature death. What is being valued is, for example, an increased chance of 1 in 10 000 that an individual will die this year prematurely. Economists ask for the social WTP to lower this chance of dying from, for example, 1 in 10 000 to 1 in 20 000. No information is given about which individual would die prematurely. Indeed, we cannot identify those individuals who died prematurely last year due to air pollution.

Initial attempts at monetizing this small chance of premature death looked at the earnings that that individual would have had over the rest of his life (*4*). Earnings are not a socially acceptable measure of the social WTP to prevent premature death. In accordance with society's practices, an earning measure values women less than men and blacks less than whites. It values retired persons at zero.

A second valuation was taken to be the amounts that juries awarded plaintiffs in suits for wrongful death. Juries awarded a wide range of amounts, and many people were given no award at all. In addition, a premature death due to air pollution does not have the same emotional connotation as a death due to a drunk driver or other negligent action.

There is now a substantial base of literature related to the social WTP to avert statistical premature mortality. The EPA's Retrospective Analysis of the Clean Air Act used 26 individual WTP studies as the basis of its distribution on health effects from premature mortality. Of these 26 studies, five were based on CV methods that sought the WTP of individuals to avoid the risk of premature death. The remaining studies were straightforward economic studies that estimated the additional wages paid to workers for increases in risk of premature death. For example, it is assumed that workers on high-rise construction sites must be paid a "risk premium" as compared to other laborers to incur the additional risk associated with performing the same jobs 40 stories above the ground.

The literature on medical procedures and devices uses a different metric. Here analysts estimate the number of "quality adjusted life-years" that a patient would be expected to gain by a medical procedure. If the cost of a quality-adjusted life-year is less than $30 000, there is general consensus that society benefits from going ahead. If the cost is greater than $50 000 or $100 000, the general recommendation is that society does not benefit.

In the end, the Retrospective Analysis used a distribution for WTP estimates, with a median estimate of $4.8 million per life (and a standard deviation of $3.2 million). Although not used explicitly in the analysis, the estimated value per life-year was approximately $300 000. Of course, the uncertainty associated with using either of these estimates is significant.

Externality Adders

Another example of using economic valuation studies to support decision making are "externality adder" studies completed by several states in the 1990s to guide selection of new electricity generation capacity. In these studies, states explicitly sought estimates of the social damage from different types of power generation plants. These states recognized that utilities made investment decisions on the basis of their cost per kilowatt-hour. The state regulatory commissions saw that a utility might choose a polluting plant because it was cheaper to the utility, even though emissions would impose large social costs. They sought externality adders that would recognize the social costs of these emissions. They would then order the utilities to select the technology that had the lowest costs, including both the utility's private costs and these externality adders. Thus, when building a new coal-fired power plant, the company would need to consider not only the stream of discounted net benefits including construction and maintenance costs offset by revenues but also the sulfur dioxide and other conventional pollutant releases generated by the facility over its lifetime. If the plant was expected to produce 10 000 ton of SO_2/year, and the externality adder set by the state was $2000/ton, then $20 million/year of "environmental externality costs" had to be

TABLE 1. Unit Social Damage Estimates ($1992) from Air Emissions of Environmental Externalities[a]

species	no. of studies	estimated external costs ($/t of air emissions) min	median	mean	max
carbon monoxide (CO)	2	1	520	520	1050
nitrogen oxides (NO_x)	9	220	1060	2800	9500
sulfur dioxide (SO_2)	10	770	1800	2000	4700
particulate matter (PM_{10})	12	950	2800	4300	16200
volatile organic compounds (VOC)	5	160	1400	1600	4400
global warming potential (in CO_2 equiv)	4	2	14	13	23

[a] Sources: refs *5*−*12*.

included in the investment analysis to determine which technology was most desirable. The adders were to be used to decide, for example, among coal, oil, natural gas turbines, windmills, and other technologies. One immediate difficulty is that these externality adders were not to be used in the dispatch decisions. Thus, new plants would have the lowest social costs; however the day-to-day management of generation sources would depend on private costs, so that the new plants might not be used. California, Massachusetts, Nevada, and New York estimated externality adders (as referenced below).

A Statistical Look at Existing Damage Valuation Studies

Using a sample of the existing economic valuation literature for conventional pollutant and greenhouse gas emissions, we provide the following summary of estimates (in $1992/t) for these releases in Table 1.

Note that the existing body of literature (including, as discussed above, state-level externality adders) presents a wide range of estimates of the damage resulting from an additional ton of pollution. Uncertainty is evident, since the maximum estimates are 6−1000 times greater than the minimum estimates.

Sources of Uncertainty

The wide range in values comes from several sources. The principal source is variation in the underlying damage function. A second source is the air chemistry and diffusion modeling, transforming point emissions to ambient concentrations at the receptor. A third source is that some studies considered only health effects while others accounted for visibility and other effects. While monetization is responsible for some of the variation, it is not the principal source.

In addition, the states did not specify a uniform basis for their damage functions and valuations. However, the values emerged in a political process through hearings and public comment. Thus, these figures have a reasonable claim to be the social valuations that should be used in making social decisions.

Policy Applications of Damage Estimates

Despite their shortcomings, economic valuations of environmental releases can assist in estimating environmental benefits. Many different classes of policies and projects can be studied, but we focus on a few for illustration: first, policies that attempt to adjust aggregate governmental accounting measures; second, policies that attempt to bring product and process prices in line with the social costs of production; finally, benefit−cost analysis of environmental regulations.

The United States is currently in the midst of its longest peacetime economic expansion. When the inevitable recession comes, political leaders will scramble to find policies to renew growth. In our judgment, national policies and optimism about the economy would have been quite different if measured national output had declined each year in the 1990s. Macroeconomic activity is typically measured by Gross Domestic Product (GDP), the total value of final goods and services produced and sold in the economy. With the exception of a few years during severe recessions, GDP and GDP per capita have risen almost every year for 60 years, which is usually interpreted to mean that Americans have been made better off every year. In economic terms, this suggests that social welfare has consistently increased.

However, has social welfare really improved as much as indicated by the traditional GDP per capita measure? What if the externality costs of environmental pollution are included in the account? GDP is not a good measure of welfare because, along with other reasons, it does not attempt to correct for changes in environmental quality or the depletion of natural resources. Thus, each year Americans consume more goods and services but may be living in a despoiled environment and simultaneously eroding the ability of future generations to produce goods and services in the future. Recognizing this problem, researchers and policy-makers have been working on ways to transform GDP into a better indication of human welfare.

The United Nations' System of National Accounts (SNA) guides countries toward collecting and measuring macroeconomic data like GDP. The SNA measures consumption, exports, etc. that show the value of the transactions in an economy. Using data on the social costs of production, attempts have been made to make integrated "green" national accounts by adjusting them for environmental (and other) costs. For example, early work by Nordhaus and Tobin (*13*) developed a measure of economic welfare (MEW) accounting for household and volunteer work, leisure, and pollution discharges. However, they concluded that GDP and MEW did not significantly differ over time and that both were increasing. They also found that adjusting GDP for the amount of leisure time or involuntary unemployment dominated the environmental contribution. Daly and Cobb's Index of Sustainable Economic Welfare (ISEW) makes more radical adjustments to GDP, correcting for distributional inequity, resource depletion, land loss, and pollution costs (*14*). Instead of the reported 2% annual increase in per capita GDP in the 1970s and 1980s, per capita ISEW increased by only 0.7% in the 1970s and decreased by 0.8% in the 1980s.

A more recent method, the Genuine Progress Indicator further adjusts GDP by adding the economic value of roadways and subtracting costs for crime, accidents, deforestation, and family breakdown (*15*). It also shows per capita increases in GDP in the early 1970s and a steady decline of about 2.5% per year from 1976 to the present.

The three studies are controversial because the authors had to make subjective judgments concerning the dollar value of changes in environmental quality. The controversy should not obscure the agreement that GDP would be a better measure of welfare if it included corrections for changes in environmental quality and resource depletion. It is especially striking that research can conclude that, although GDP has been rising, the public has been made worse off.

Note that environmental measures are not completely absent from measured GDP. For example, activities such as waste management, pollution controls, and environmental consulting services add to GDP. Thus, in a perverse way, as more pollution is generated, pollution control efforts are more likely; even though they generally fail to restore the initial level of environmental quality, the control expenditures cause GDP to increase. The point of these exercises is not just that GDP is mismeasured. Rather, GDP as measured and reported leads society to focus on economic growth and to neglect the need for environmental quality and sustainability. The result is decisions by business, government, consumers, and voters that worsen these problems.

As an initial step toward improving national accounting methods to reflect environmental damage, the Bureau of Economic Analysis began to calculate Integrated Economic and Environmental Satellite Accounts (*16*) as part of President Clinton's 1993 call for green GDP measures. Unfortunately, Congress decided these accounts were not helpful and banned them in 1994. However, the Department of Commerce and the National Research Council are reconsidering their place in government (*17*).

Other adjustments to governmental aggregate measures are also possible. Matthews (*18*) shows that green price indices could be calculated using the estimates in Table 1 and that the necessary Consumer Price Index adjustment would be about 3%, and Producer Price Indices would range between 9% (for crude materials) and 5% (for finished goods). In particular, if industrial emissions of the air pollutants in Table 1 are considered and multiplied by the valuation range, the annual external cost ranges from $40 to $615 billion, with a median estimate of $178 billion per year in $1992—about 5% of 1992 GDP. This is a significant adjustment despite almost 30 years of clean air legislation. The estimate includes only air pollution externalities of conventional and global warming pollutants. It could be seen as a minimum or lower bound estimate of the air pollution externality since it does not include airborne toxic substances or discharges to land and water. However, even this limited measure can be useful in adjusting national environmental performance.

Seemingly the greatest difficulty in greening national accounts is in gathering appropriate data and agreeing upon accepted valuations and indicators. For example, to adjust GDP for damages from natural resource depletion, estimates must be available both for the quantity of resources depleted and the social value per unit of resource lost. Data on the relevant quantities are hard to come by for many environmental effects in most countries in the world (with the United States, Europe, and parts of Asia being exceptions). Also, the economic valuation literature is only well developed for a handful of specific environmental criteria (e.g., mostly releases of criteria air pollutants). As the number of adjustment criteria increases, availability of data across countries to measure those criteria decreases, and so many adjusted metrics are based on relatively few criteria.

The Department of Commerce gathers data from firms to calculate GDP. To create environmental or sustainability measures, the firms' accounting systems must be capable of supplying the necessary environmental data, which is not generally possible today.

Full Cost Pricing of Products and Processes

One way to support improved corporate environmental accounting systems is to make product or process-level social costs more widely available. This would entail estimating the external costs of environmental releases associated with a firm's production technologies. Ideally, these external cost estimates would be based on product or process life cycles, including emissions from extraction of raw materials, component fabrication, manufacture, use, and disposal (*19*−*21*).

TABLE 2. EIO−LCA Supply Chain Effects of Producing $1 Million of Electricity in the United States, 1992

sector	economic $mill
total	1.671088
electric services (utilities)	1.007134
coal	0.102573
other repair and maintenance construction	0.087334
crude petroleum and natural gas	0.041535
natural gas distribution	0.037961
railroads and related services	0.032541
wholesale trade	0.024300
petroleum refining	0.023054
real estate agents, managers, operators, and lessors	0.021044
banking	0.017472
all other sectors	0.276140

With such an idea in mind, an alternative method of valuing the environmental externalities of production has been created. It is based on the Economic Input−Output Life Cycle Assessment (EIO−LCA) method (*22*−*24*). This method uses the 485-sector 1992 U.S. Department of Commerce input−output table of the economy combined with a variety of environmental effects to link the total supply chain requirements of production with the resulting environmental damages. The model considers emissions through the production stage in commodity life cycles (i.e., does not include use or disposition). For example, the EIO−LCA model would show the economic and environmental effects of mining, producing, and transporting the coal to a power plant in addition to the actual effects of burning the coal to make electricity. Table 2 shows the total economic supply chain requirements for producing $1 million worth of electricity in the U.S. economy (in 1992). More detail on the calculations used to produce Table 2 is found on the Internet (at http://www.eiolca.net/).

The values in Table 2 indicate that to make the average $1 million of electricity, there is some electricity needed ($7134) as well as about $102 000 of coal, $87 000 of construction, etc. Note that the 1992 U.S. input−output table used as the basis of the model (the most recent available) does not disaggregate electricity production into coal-fired, hydroelectric, nuclear, etc. Thus, the supply chain above represents the average purchases at the national level to make $1 million of average national generation source electricity. The input−output model assumes that all relationships are proportional. Thus, producing $10 million of electricity could be done by multiplying each of the values in Table 2 by 10.

The EIO−LCA model uses Department of Commerce data on fuel consumption per sector (*25*), AIRS data from the U.S. EPA (*26*), and greenhouse gas emissions factors by sector to determine the relationship between purchases and emissions within the IO model. Using the IO production function, sectoral emissions are calculated based on fractions of overall demand. Table 3 shows the top 10 contributing sectors in terms of conventional pollutant and global warming potential (GWP) releases for producing $1 million of electricity. GWP releases in carbon dioxide equivalents were calculated via the 1993 IPPC weighting guidelines (*27*).

As stated above, such information is not very useful in determining environmental strategies since 1 ton of sulfur dioxide is not worth the same as 1 ton of suspended particles. Using the minimum, median, and maximum external cost valuation statistics in Table 1, the emissions in Table 3 were dollar-weighted and are summarized in Table 4.

As Table 4 shows, the total supply chain external costs for producing $1 million of electricity range from $86 000 to $947 000, with a median estimate of $339 000. This estimates a median external cost of 34% of the price of electricity. Of

TABLE 3. Top 10 Contributing Sectors to Conventional Pollutant and Global Warming Releases Associated with Producing $1 Million of Electricity in the United States[a]

sector	t of releases					
	SO_2	CO	NO_2	VOC	PM_{10}	GWP
total	67.1	3.43	32.0	0.539	2.00	12,600
electric services (utilities)	66.5	2.09	30.4	0.238	1.37	11,000
coal	0.017	0.013	0.018	0.004	0.071	1,100
crude petroleum and natural gas	0.078	0.134	0.134	0.033	0.001	210
other repair and maintenance construction	0.000	0.104	0.130	0.001	0.436	4
natural gas distribution	0.080	0.071	0.039	0.001	0.000	150
railroads and related services	0.104	0.219	0.785	0.045	0.045	30
petroleum refining	0.074	0.040	0.049	0.038	0.004	15
blast furnaces and steel mills	0.025	0.107	0.015	0.005	0.004	20
water transportation	0.046	0.014	0.041	0.009	0.006	4
trucking & courier services, except air	0.005	0.198	0.084	0.037	0.000	9
all other sectors	0.137	0.441	0.277	0.128	.062	43

[a] Totals do not sum due to rounding.

TABLE 4. Top 10 External Cost-Generating Sectors in the Supply Chain Associated with Producing $1 Million of Electricity in the United States[a]

sector	external cost ($thousands)		
	low	median	high
total	85.8	338.8	946.9
electric services (utilities)	81.3	311.2	880.3
coal	2.2	15.4	26.4
crude petroleum and natural gas	0.5	3.4	6.8
other repair & maintenance construction	0.5	1.5	8.5
natural gas distribution	0.4	2.3	4.3
railroads and related services	0.4	1.8	9.8
petroleum refining	0.1	0.5	1.4
blast furnaces and steel mills	0.1	0.4	0.9
water transportation	0.1	0.2	0.8
trucking and courier services, except air	0.0	0.4	1.4
all other sectors	0.3	1.7	6.3

[a] Conventional pollutants and GWP only, using min, median, and max externality costs from Table 1. Totals do not sum due to rounding.

this, the majority of the externality ($311 000 out of $339 000 or 92%) comes directly from the production of electricity, and the remainder of the supply chain is not so important. Levy et al. (*28*) estimated median external costs of an oil and gas-fired power plant at 9% but noted that the complete supply chain effects would be nearly double. In a similar fashion, Matthews (*18*) shows that the average total external air pollution cost per sector is about 3%. This analysis can be done for all of the 485 commodity sectors in the U.S. economy to yield an assessment of the air pollution damage from industrial production.

The numbers above can be useful within firms to assess the relative merits of various materials, product, and process design choices. For example, a process designer could see that the price of electricity was 34% higher than the price quoted by the firm's electricity provider and choose a design that required less electricity to produce (though the estimates above provide no insight as to which available local electricity generation types would be better or worse). Making such decisions would lower the social costs of a product or process. This could be implemented as an information system presenting the true private costs of the two materials along with additional information on the external costs of each. Since the IO model contains all commodities in the economy, almost all firm-level choices could be evaluated using the type of external cost data summarized above. If implemented, results of such a system could be inputs to broader national environmental accounting efforts and could support more advanced measures of GDP and national welfare.

Regulatory Analysis

A final example of the use of economic valuation studies is illustrated by examining the overall net benefits of regulation. Two recent examples of valuation-based regulatory analysis are the Retrospective and Prospective reports carried out by the EPA to show the net benefits of the Clean Air Act (*2, 3*), as required by Section 812. Each study suggests that the benefits of cleaner air have far exceeded the costs.

Each report relied on extensive modeling to estimate both the emissions that have occurred since passage of the Clean Air Act as well as the emissions that would have occurred had the Act never been passed. The difference between the two estimates is found for each year since 1970 and is assumed to be the "emissions avoided" as a result of the regulation. Separately, the health effect benefits from the reduced emissions (including lead) are estimated using the damage function methods discussed above. In the end, the EPA summed all of the health benefits and calculated net benefits (including control costs) that were more than $22 trillion (in $1990) in the retrospective study of the period 1970−1990.

More than 80% of the health effect benefits came from all avoided mortality (using the WTP valuations above), and 75% came from reducing mortality just from suspended particles. [The EPA made a judgment as to which pollutant caused premature mortality that was not reflective in the full range of available epidemiological studies. Using the EPA's assumptions, not a single American died in the last 25 years as a result of sulfur dioxide emission.]

Discussion

As future accounting, management, and policy tools are developed to consider the effectiveness of environmental programs, significant improvements will need to be made in the models used to value environmental damage. Such models will need to encompass geographic differences and rely less on mortality and WTP estimates. As atmospheric concentrations decrease and the population ages, the morbidity effects may become increasingly important. In addition, more local, state, and federal studies on externality costs will help guide corporate and governmental decision-makers to develop environmental strategies that are socially accepted and less costly.

Future work in this area should be expected to consider the entire life cycle of products and processes, not just the direct emissions easily seen and reported. Improved data can focus regulatory and industry efforts toward meeting national emissions reduction goals. If there is social consensus on the goals and firms use common reference measures, then companies that meet the goals can be rewarded—and vice versa. A large improvement will result from linking the enterprise resource planning (ERP) systems of firms with the tracking and monitoring databases of government environmental protection agencies. Although environmental effects are not generally part of today's ERP systems, companies should be encouraged to move toward fully integrated corporate−government information systems that track, report, and reduce emissions.

Armed with better valuations and more reliable emissions data by source, future policies could make much more cost-effective improvements in the quality of the energy we produce, the products we buy, and the air we breathe.

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Literature Cited

(1) Appeals Court ruling that EPA exceeded its authority in setting the 1998 PM2.5 and Ozone Standards.

(2) U.S. Environmental Protection Agency. *Final Report to Congress on Benefits and Costs of the Clean Air Act, 1970−1990*; U.S. Government Printing Office: Washington, DC, 1997; EPA 410-R-97-002.

(3) U.S. Environmental Protection Agency. *Final Report to Congress on Benefits and Costs of the Clean Air Act, 1990−2010*; U.S. Government Printing Office: Washington, DC, 1997; EPA-410-R-99-01.

(4) Viscusi, W. K. *Risk by Choice*; Harvard University Press: Cambridge, MA, 1983.

(5) Commission of the European Communities. *Externalities of the Fuel Cycle: Externe Project*; Working Documents 1, 2, 5, and 9; European Commission: Brussels, 1993.

(6) Cifuentes, L.; Lave, L. B. *Annu. Rev. Energy Environ.* **1993**, *18*, 319.

(7) Desvousges, W. H.; Johnson, F. R.; Banzhaf, H. S. *Assessing Environmental Costs for Electricity Generation*; Triangle Economic Research General Working Paper No. G-9402; 1994.

(8) Fankhauser, S. *Energy J.* **1994**, *15* (2).

(9) Koomey, J. *Comparative Analysis of Monetary Estimates of External Environmental Costs Associated with Combustion of Fossil Fuels*; Electric Power Research Institute and Lawrence Berkeley Laboratory: Berkeley: CA, 1990.

(10) U.S. Congress, Office of Technology Assessment. *Studies of the Environmental Costs of Electricity;* U.S. Government Printing Office: Washington, DC, 1994; OTA ETI-134.

(11) Ottinger, R. L. In *Social Costs of Energy, Proceedings of an International Conference held at Racine, WI, Sept. 8−11*; Hohmeyer, O., Ottinger, R. L., Eds.; Springer-Verlag: Berlin, 1992.

(12) Zuckerman, B.; Ackerman, F. *The 1994 Update of the Tellus Institute Packaging Study Impact Assessment Method*; SETAC Impact Assessment Working Group Conference: Washington, DC, 1995.

(13) Nordhaus, W.; Tobin, J. In *Economic Growth*; National Bureau of Economic Research General Series 96E; Columbia University Press: New York, 1972.

(14) Daly, H. E.; Cobb, J. B. *For the Common Good: redirecting the economy toward community, the environment, and a sustainable future*; Beacon Press: Boston, MA, 1989.

(15) Cobb, C.; Halstead, T.; Rowe, J. *The Genuine Progress Indicator: Summary of Data and Methodology*; Redefining Progress Publication: San Francisco, 1995.

(16) Landsfeld, J. S.; Carson, C. S. *Surv. Curr. Business* **1994**, *74* (4).

(17) Nordhaus, W. D.; Kokkelenberg, E. C. *Nature's Numbers: Expanding the National Economic Accounts to Include the Environment*; Panel on Integrated Environmental and Economic Accounting, Committee on National Statistics, Commission on Behavioral and Social Sciences and Education, National Research Council: Washington, DC, 1999.

(18) Matthews, H. S. Ph.D. Dissertation, Carnegie Mellon University, 1999.

(19) *A Technical Framework for Life-Cycle Assessments*; Society of Environmental Toxicology and Chemistry, SETAC Foundation: Washington, DC, 1991.

(20) Curran, M. A. *Environmental Life Cycle Assessment*; McGraw-Hill: New York, 1996.

(21) *Life Cycle Assessment: Inventory Guidelines and Principles*; U.S. Environmental Protection Agency; Cincinnati, OH, 1993; EPA-600-R-92-245.

(22) Lave, L.; Cobas, E.; Hendrickson, C. T.; McMichael, F. *Environ. Sci. Technol.* **1995**, *29*, 420A.

(23) Cobas-Flores, E. Ph.D. Dissertation, Carnegie Mellon University, 1996.

(24) Hendrickson, C. T.; Horvath, A.; Joshi, S.; Lave, L. B. *Environ. Sci. Technol.* **1998**, *32*, 184A.

(25) *Input-Output Accounts of the U.S. Economy, 1992 Benchmark*; U.S. Department of Commerce, Interindustry Economics Division, Computer Diskettes: Washington, DC, 1997.

(26) *AIRS Database.* U.S. Environmental Protection Agency, http://www.epa.gov/airsweb/.

(27) Adriaanse, A. *Environmental Policy Performance Indicators−A Study on the Development of Indicators for Environmental Policy in The Netherlands*; Sdu Uitgeverij Koninginnegracht: 1993.

(28) Levy, J. I.; Hammitt, J. K.; Yangisawa, Y.; Spengler, J. D. *Environ. Sci. Technol.* **1999**, *33*, 4364.

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