Environmental Accounting for Pollution: Methods with an Application to the United States Economy

Nicholas Muller, Robert Mendelsohn, and William Nordhaus

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Abstract

The present study presents a framework to include environmental externalities into a system of national accounts. The paper develops estimates of air pollution damages for each industry in the United States. The first section proposes a framework for national economic accounting that values pollution using marginal damages. An integrated-assessment model (the Air Pollution Emission Experiments and Policy analysis model) is used to quantify the marginal damages of air-pollution emissions for the U.S. The empirical estimates indicate that stone quarrying, solid waste combustion, sewage treatment plants, and fossil fuel based power generation have pollution damages larger than their conventionally measured value added. The largest single industrial contributor to external costs is coal-fired electric generation, whose damages range from 1.4 to 3.5 times value added depending upon modeling assumptions.

I. Introduction

An important and enduring issue in environmental economics has been to develop both appropriate accounting systems and reliable estimates of environmental damages. There is now an extensive literature on environmental accounting (Leontief, 1970, Ahmed et al. 1989, Aronsson et al. 1997, Nordhaus and Kokkelenberg 1999, Uno and Bartemus 1998). Some of this literature has focused on valuing natural resources such as water resources, forests and minerals (Peskin 1989, Repetto 1989, World Bank 1997, Cairns 2000, Gundimeda et al., 2007, Vardon et al., 2007). Other studies have focused on including pollution. For example, the earliest literature on pollution used material flows analysis to calculate the tons of emissions per unit of production for various industries (Ayres and Kneese 1969). This has been formalized in several European accounts (for example, in the Netherlands, see Keuning 1993, and in Sweden, see Palm and Larsson, 2007). Although empirical, this approach can be misleading because emissions cause different levels of damages depending upon where they are released and upon the impacts per unit of exposure.

In principle, one wants to value emissions by the damage they cause. Several studies have measured national pollution damages (Freeman 2002, Muller and Mendelsohn 2007, USEPA 1999). There have been proposals to integrate economic impacts of pollution into satellite accounts (Bureau of Economic Affairs 1994, de Boo et al. 1991). However, to date, there have been no actual damage estimates included by any national statistical agency.

This paper contributes to this literature in two ways. First, we present a framework to integrate external damages into national economic accounts. The Gross External Damages (GEDs) from pollution caused by each industry are included into the national accounts as both a cost and an (unwanted) output. Second, we use empirical estimates of the marginal damages (in effect, the prices) associated with each emission and calculate the national damages from air pollution damages by industry for the U.S., demonstrating that the methodology can be applied in practice.

In the next section, we develop the framework for integrating external effects into national economic accounts. We add external effects both as an input and as an output in the accounting framework. Effectively, air pollution becomes another cost of doing business. With regulations there are abatement costs by each industry but there are also remaining GEDs incurred by society. Abatement costs are already included as a cost by industry in traditional accounts, but GEDs are not. We should note some conventions that we use in constructing our estimates. First, as is standard in national accounting, we do not assume that the observed transactions represent an economic optimum. Rather, as is the norm, both market and environmental quantities are valued at market or imputed prices. A similar imputation occurs, for example, for owner occupied housing, where rent-equivalent prices are used. This study measures only the externalities from air pollution and omits other external effects that take place through water, soils, noise, and other media.

In the subsequent section, we provide empirical estimates of the marginal damages and the economic impacts of air pollution damages by industry. We briefly introduce an integrated assessment model that is used to calculate the marginal damages or shadow prices of emissions (from Muller and Mendelsohn 2007). The model first calculates the total damages from the 2002 levels of emissions across the U.S. Numerical experiments, undertaken by adding one ton to baseline emissions from each source, provide estimates of the marginal damages from emissions. This calculation captures the effects of secondary pollutants and pollution interaction effects. We then repeat this process for the remaining 10,000 sources in the U.S. and for each of six primary pollutants.[1] Multiplying the shadow price times the quantity of emissions by industry yields the GEDs caused by that source[2]. Summing GEDs from all sources within an industry yields the GEDs for that industry. Summing GEDs across industries within a sector yields the GEDs for that sector.

In Section IV, we compare GED to value added (VA). The purpose is to determine whether correcting for external costs has a substantial effect on the net economic impact of different industries. We find that the ratio of GED/VA is greater than one for four industries (stone quarrying, solid waste incineration, sewage treatment plants, and fossil fuel power plants). This indicates that the air pollution damages are greater than their net contribution to output of these industries. Several other industries also have high GED/VA ratios.

For some purposes, we are also interested in the overall size of GED for an industry. Five industries stand out as large air polluters: fossil fuel power plants, crop production, truck transportation, livestock production, and highway, street, and bridge construction. Finally, we examine the results by sectors of the economy. The GED/VA ratio for the utility and agriculture sectors are by far the largest in the economy, whereas this ratio is low for manufacturing. We also conduct a sensitivity analysis that shows how sensitive the results are to assumptions about the methodology for valuing pollution-related fatalities and

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[1] The pollutants tracked in this paper include sulfur dioxide, nitrogen oxides, two measures of particulate matter ($PM_{2.5}$ and PM_{10}), ammonia, volatile organic compounds, and carbon dioxide emissions from the electric power generation sector.

[2] GED is equivalent to Gross Annual Damages (GAD) in Muller and Mendelsohn 2007.

the mortality dose-response function. The paper concludes by reviewing key results, discussing implications for regulation, and raising promising future research opportunities.

II. Economic Accounting for the Environment

This section reviews the analytical and accounting questions involved in designing and estimating environmental accounts. While much has been written on the general topic, there appears to be no consensus about how to redesign the standard national accounts to incorporate externalities. We address several important analytical questions in this section.

A. Treatment in the Standard National Accounts

National economic accounts are based on the principle that they cover those activities that are included in market activities. For simplicity, we will discuss only the current-price accounts, as issues of price and quantity raise no major accounting issues. External effects are activities that are by definition excluded from market transactions, and they are therefore *by definition and in principle* excluded from the market accounts.

There is by now a vast literature on environmental accounting, but there are few attempts to incorporate such accounts in the standard national accounts framework. The National Academy of Sciences described the principles of augmented national accounts in a report on non-market accounting as follows (Abraham, Mackie 2005):

> [A] conceptual framework must be adopted on which to develop an economic account. For a number of reasons, the panel believes that experimental satellite accounts will be most useful if their structure is as consistent as possible with the NIPAs [national income and product accounts]. Because the national accounts have undergone extensive scrutiny, reflecting a long history of research and policy use, the underlying principles are well tested and practice shows they can be implemented. Moreover, researchers are interested in developing augmented measures of output that are compatible with GDP. These considerations argue for pursuing an approach that uses dollar prices as the metric for relative value and, wherever possible, values inputs and outputs using analogous observable market transactions.

The closest thing to an international consensus is the approach known as SEEA (United Nations 2003, Palm and Larsson, 2007). This approach has an input-output matrix of physical quantities, but no value accounts (see particularly p. 98 and Chapters 3 and 9). SEEA designates an "environment industry" as the new analytical construct, but it is unclear whether a valuation framework is also envisioned or how a valuation framework would be introduced. The SEEA is also unclear about whether to use damage-based pricing or cost-based pricing, although it seems conceptually clear that damage-based pricing is necessary to implement a welfare-based concept of output.[3]

Some of the issues discussed here were developed in Nordhaus and Tobin (1972). The major effort of the U.S. Bureau of Economic Analysis was contained in its IEESA (Integrated Economic and Environmental Satellite Accounts), which is an accounting framework that covers the interactions of the economy and the environment (Bureau of Economic Analysis 1994). The BEA effort was derailed by the Congress and has not yet gotten back on track. The National Academy of Sciences reviewed the IEESA and other accounting efforts, as well as the substantial literature on environmental accounting, in a report on environmental accounting (Nordhaus and Kokklenberg 1999).

The theoretical background for environmental accounting is discussed in Hamilton (1996). The staff of the World Bank has made a series of estimates of "genuine savings rates" that include a number of corrections for investments that are excluded from the standard national accounts, including human capital and depletion of sub-soil assets (Hamilton 2000). Several important issues are reviewed in the contributions in Musu and Siniscalco (1996). Overall, it seems fair to conclude that there has been little progress in developing a practical accounting system that can be integrated with the national economic accounts.

One important exception is the recent work of Ho and Jorgensen (2007) that computes air pollution damages by sector in China. This work reports emissions (tonnage) for total suspended particulates (TSP) and sulfur dioxide (SO_2) for 33 sectors of the Chinese economy in 1997. Additionally, Ho and Jorgensen tabulate the human exposures and health damages due to emissions from each of these sectors. Further, these authors report damages per unit of gross output by sector, by pollutant, and they determine the percentage share of total damages attributable to emissions from each sector (Ho and Jorgensen, 2007).

B. National accounts with pollution

For the present discussion, we present the accounts that would apply in an economy in which there is a pollution externality that is subject to regulation.

[3] Only if regulations were allocatively efficient would cost-based and damage-based accounting systems be identical.

We begin with a description of an example and then provide a graphical interpretation of the appropriate accounting.

Suppose for concreteness that the economy contains two industries. In the first industry, farmers produce market berries. The second industry is power, which produces electricity, earning returns from capital after payments to labor and other inputs. We assume that power production causes damages to market berry production. Because of a failure from high transaction costs, the berry farmers are not compensated for the loss (hence, there is an externality).

If the externalities affect other market sectors, the externalities do not get lost in the current accounting system even though they are not explicitly recognized. The accounts measure the reduction in net output arising from the externality – there are fewer berries. As long as the externality is entirely within the market, net national output is correctly measured. However, the standard accounts do not measure industry output correctly because they do not include the (external) costs to the berry industry of the operations of the power industry. In practice, the bulk of the externalities are to nonmarket sectors such as health, visibility, and ecosystems, which are not measured. The traditional national accounts do not measure these losses and overestimate net national output.

C. Measurement of Gross External Damage and Net External Damage

From an analytical point of view, we interpret externalities as uncompensated transactions. In other words, the externalities are treated as flows of services from the industry damaged by pollution to the polluting industry. In our example above, the damages caused by the power industry to the berry industry are treated as flows of inputs or negative outputs. For a given level of pollution, we can estimate the marginal damage from emitting an extra unit of pollution and use this as the imputed price.

The approach can be illustrated by considering a simple example of a polluting industry. Suppose the government limits the amount of emissions of a pollutant, such as sulfur dioxide. The government might use command and control regulations, tradable emissions permits, or taxes on pollution. In our example, we assume that the government creates property rights for pollution using tradable emission permits, and that the permits are freely traded with a uniform price. We examine the tradable permit system in this discussion because it leads to a single price of pollution and simplifies the accounting. (The results apply to a command-and-control system as well, but the concepts and measurements are more complex since each polluter is likely to face a different marginal abatement cost. Alternatively, the government might set a price on pollution as an emissions fee and let the market determine the quantity of pollution, but that case also introduces no new analytical issues.)

We define the *gross external damages* (GED) as equal to the marginal damages of emissions (the price) times the total quantity of emissions. However, it is important to avoid double counting. If the polluter pays for permits or incurs pollution taxes, these costs should in principle already be counted in the accounts as flows of costs and incomes. From an accounting point of view, therefore, we should only include *net external damages* (NED), which are equal to gross external damages minus the costs of pollution permits. This implies that when we adjust the national or industry accounts, we should only adjust for NED, that is, for the difference between GED and the cost of permits. Only in the case where there is zero accounting cost of the permits would NED equal GED.

Note that the adjustment to output is conceptually separate from the property-rights question of whether or not the polluter must compensate the affected parties – whether or not the polluter pays principle applies (Nordhaus 2008). From the point of view of production accounting, the measurement of the flow of services from an asset does not depend upon who actually owns that asset.

D. Graphical Treatment of Accounting

We can use a set of figures to illustrate these points. We take the case of a single pollutant, such as sulfur dioxide. Figure 1 shows the marginal costs of abatement. For this purpose, we have taken all the pollution sources and have ranked them from lowest marginal abatement cost at the left to highest marginal abatement cost at the right. This ranking produces the *MC* curve of monotonically increasing marginal abatement costs. Additionally, we assume that the government has issued a given quantity of pollution allowances, as indicated by the vertical line labeled "Pollution permits," and as shown by the arrow on the horizontal axis.

With these costs and quantities, under a tradable permit system, the price of permits will be at the level indicated by *p*.* Abatement is shown by the arrow marked "Abatement." Additionally, for the regulated pollution level, the market value of the pollution is indicated by the shaded blue area, *ACp*B.* This equals the pollution quantity times the market value of permits.

We have also shown total abatement cost as the area *0AC,* marked "Abatement costs." These costs are incurred by firms and would already be included in the costs of production. We therefore need not make any further adjustment for abatement costs in our environmental accounts.

Figure 2 shows the accounting for pollution damages in our framework. We have shown as a dashed line the marginal external damages of pollution. We estimate the marginal damages from pollution at the regulated level to be v^*. Using the standard conventions of national accounting, the value of pollution is the marginal value of pollution times the quantity of pollution, which is shown by the shaded rectangle ADv^*B, marked "Gross external damages." This is gross because the firm may pay some fraction (less than or equal to one) of the damages in its purchases of pollution permits.

Finally, we show the proposed accounting framework in Figure 3. Gross external damages are the same as in Figure 2. We need, however, to calculate net external damages. That is, we need to calculate the total damages caused by firms minus their payments for pollution permits. This is easily seen to be the upper rectangle in Figure 3, shown as "Net external damages." This is equal to gross external damages minus the market value of permits. Recall that abatement costs are already included in the accounts and need no further adjustments.

Figure 3 illustrates the case, which corresponds to our empirical results below, that regulated pollution levels are inefficiently high. Then, as shown in Figure 3, there are additional damages incurred by the berry industry that the power industry does not have to pay. If pollution limits were too restrictive, such as may be the case with urban ground-level nitrogen oxide emissions (Tong et al. 2006), NED might be negative.

E. Current Accounting Treatment of Pollution Permits

In order to complete our estimates, we need to determine the way that the cost to the polluter of permits or other instruments is treated under current tax, financial, and national accounting. Under standard principles of national accounting, the inputs of pollution would be valued at their current or replacement cost.[4] For the present case, this means that pollution permits should be valued at their market value. However, the tax and financial accounting for permits do not generally use market-value pricing.

For the U. S., tax accounting is well-defined for the sulfur dioxide allowances governed by the Acid-Rain Program. According to Internal Revenue

[4] The U.N. System of National Account states the convention as follows: "Current cost accounting is a valuation method whereby assets and goods used in production are valued at their actual or estimated current market prices at the time the production takes place (it is sometimes described as 'replacement cost accounting')." See http://unstats.un.org/unsd/sna1993/toctop.asp, section 1.60.

guidelines, there are three important points. First, the allowances are capitalized. They are thereby an asset when bought by or allocated to a polluting source. Allocation does not cause a taxable event. The tax basis is the historical cost, which is zero for units that receive allowances by allocation, and is actual cost if purchased. Second, the allowances are not depreciated. Instead, the cost of the allowances is deductible in the year in which the sulfur dioxide is emitted, that is, when they are used. At that point, if the entire allowance is used, the tax deduction is equal to the cost basis. The deduction would be zero for allocations, and would be historical cost for purchases of allowances. Finally, any cost would be included as a depreciation charge rather than a current charge. The tax treatment has the anomalous feature that the charge against income would differ depending upon whether permits were purchased or allocated (U.S. Department of the Treasury 2000).[5]

The treatment of permits under financial accounting is currently under review by U.S. and international accounting groups. For utilities regulated by the Federal Energy Regulatory Commission (FERC), the historical-cost principle is used. This leads to the same results as those described for tax accounting.

We have been unable to determine if there are any specific adjustments made for the purchase and sale of emissions permits in the U.S. or other national income and product accounts. However, we suspect that the costs of permits are buried in the income accounts and are treated according to the tax guidelines just described.

In the empirical estimates below, we assume that the costs of any pollution allowances included in the national accounts and in the input-output estimates are very small, and the costs are therefore taken to be zero. While the appropriate treatment of permits is evolving, our judgment is that the actual costs of permits are a small fraction of the replacement cost of those permits. This judgment is primarily based on the presumption that most emissions are not controlled by purchased allowances either because they are not in an allowance program or because most permits are used by those who were allocated them at zero cost. Moreover, in the case of permit purchases, a purchase triggers both income and expense, may also involve several intervening counterparties, and may be treated either as income or capital items in the accounts; we therefore cannot even judge whether the sign of the error is positive or negative. We have displayed this conclusion in Figure 3 by inserting the dashed line, which shows that the accounting cost of permits is well below their market value. It should be emphasized that this assumption needs further investigation.

[5] See Revenue Procedure No. 1992-91, Rev. Proc. 1992-91.

III. Modeling Methods

In this section, we estimate the gross external damages from different kinds of air pollution by industry. To the extent that industries purchase permits, those costs should be subtracted from gross external damages to obtain net external damages. Our best judgment is that the dollar value of that subtraction in the actual national accounts is very small, and that the net external damages are therefore very close to the gross external damages. First, pollution permits are currently allocated across polluting industries at zero cost. Permits are only purchased when a firm's emissions exceed its permit allocation. Second, the market price for permits tends to be far less than marginal damages. Figure 4 shows that the marginal damages of sulfur dioxide emissions are generally greater than the permit price. Both of these factors imply that NED is generally positive and probably a large fraction of GED.

A. The APEEP Model

This paper uses the Air Pollution Emission Experiments and Policy analysis model (APEEP), which is an integrated assessment economic model of air pollution for the United States (Muller and Mendelsohn 2007).[6] The APEEP model connects emissions of six major pollutants (sulfur dioxide (SO_2), nitrogen oxides (NO_x), volatile organic compounds (VOC's), ammonia (NH_3), fine particulate matter ($PM_{2.5}$), and coarse particulate matter (PM_{10} -$PM_{2.5}$) to the physical and economic consequences of these discharges on society. The effects included in the model calculations are adverse consequences for human health, decreased timber and agriculture yields, reduced visibility, accelerated depreciation of materials, and reductions in recreation services. In addition, for the electric power generation sector, we include the damages from carbon dioxide emissions.

APEEP generates national results quite similar to other integrated assessment models. For example, it estimates a baseline level of damages similar to models used by USEPA (Muller and Mendelsohn 2007). We use APEEP to measure the marginal damage of emissions from each source location in the U.S. (Muller and Mendelsohn 2008). This is accomplished by first estimating an aggregate level of damages given baseline emissions (USEPA 2006). We then calculate marginal damages numerically by estimating the impact of adding one additional ton of each pollutant in each source location. The change in total damages between the baseline and the incremental run is the marginal damage

[6] For earlier examples of integrated assessment models, see Mendelsohn 1980; Nordhaus 1992; USEPA 1999.

of that emission *($MD_{s,j}$)* where *s* is the pollutant and *j* is the source location. For example, we would calculate the increment to total national damages across all counties and daughter products of an additional unit of SO_2 emissions from a source located in Grant County, New Mexico. This would be calculated by comparing a base case and an incremented case by running both cases through the air quality model, calculating the change in concentrations in each receptor county, calculating the change in impacts, valuing each change, and then taking the difference.

This experiment is repeated for each of the six pollutants covered in this study and for each of the 10,000 different sources in the U.S. This leads to a marginal damage for all anthropogenic emissions of these 6 air pollutants in the U.S. In estimating total damages from air pollution, this study uses the national accounting (NIPA) methodology described in section II. That is, pollution damages are valued using the total emissions times the marginal damages of an additional unit of pollution.

The 10,000 emission sources represent a complete inventory of all anthropogenic sources of these six pollutants in the U.S. (USEPA 2006). The inventory reported in 2006 is the most recent inventory of the USEPA. It measures emissions in 2002. The fact that this inventory is not more frequently updated is a serious deficiency from both a research and a regulatory perspective. The 2002 inventory includes 656 large point sources (individually documented facilities). The inventory also includes area sources from vehicles and stationary ground sources aggregated by county for the entire contiguous US.[7] The area sources are distinguished by height as well as location. The emissions are also identified by a six-digit industry code (*i*) from the North American Industry Classification System (NAICS).

APEEP uses an air quality model based on the Gaussian plume model to calculate concentrations in all destination counties from each emission. This step entails modeling dispersion from wind patterns at each source location and modeling important chemical reactions which cause the emitted substances to change into other pollutants. For instance, emissions of NO_x are transformed into concentrations of tropospheric ozone (O_3) and into constituents of fine particulate matter ($PM_{2.5}$); both of these daughter products are tracked in the APEEP model. The output from the air quality models in APEEP is a set of annual average ambient concentration estimates for each county in the lower 48 states for each of the pollutants and daughter products included in the model. The accuracy of the predicted pollution levels produced by these models has been statistically tested and documented (see Muller and Mendelsohn 2007).

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[7] The data are provided by the USEPA's 2002 National Emission Inventory, USEPA, 2006.

B. Impacts on Health and Other Damages

Using the modeling approach described in the last section, we then computes exposures and the physical effects of the predicted exposures. Exposures are determined by first calculating the size of sensitive "populations" in each county: populations include numbers of people, as well as crops, timber, materials, visibility, and recreation resources. County exposures to each pollutant including secondary pollutants are calculated by multiplying each county's population of each kind times that county's ambient pollution concentration.

The exposures are translated into physical effects using peer-reviewed dose-response relationships from the literature in the relevant scientific disciplines.[8] These include human health impacts (both fatalities and illnesses), reduced agricultural and timber yields, impaired visibility in recreation and residential settings, reduced recreation uses, and increased depreciation of materials in the capital stock (especially materials on buildings). Finally, APEEP converts the physical effects into economic impacts using the results of valuation studies (such as dollars per unit of impaired visibility or per case of a specific disease). The resulting dollar damage per ton of emission can then be compared with abatement costs. In this study, the marginal damages are used to estimate GED by industry and for the overall economy.

One of the important results of the estimates is that most of the damages due to exposures to air pollution result from human health effects, specifically premature fatalities (USEPA 1999, Muller and Mendelsohn 2007). We next describe how human mortality effects are modeled in APEEP (Muller and Mendelsohn 2007). To count exposures, APEEP contains an inventory of populations in each county which are subdivided into 19 age groups.[9] The population is divided by age because age is a key determinant of human health effects. To measure the effect of chronic (long-term) exposures to fine particulate matter ($PM_{2.5}$) on adult mortality rates, APEEP uses the results from the ongoing study by Pope et al., (2002) which tracks a large sample of individuals distributed across nearly 200 cities in the U.S. In order to capture the effect of $PM_{2.5}$ on infant mortality rates, we employ results from the recent Woodruff et al., (2006) study. APEEP also calculates the relationship between exposures to tropospheric ozone (O_3) and adult mortality rates using the study by Bell et al. (2004). In addition to

[8] The full list of dose-response functions used in APEEP is found in Muller and Mendelsohn, 2007.

[9] This approach is in accordance with how the U.S. Census Bureau reports its age-specific population estimates.

mortality effects, APEEP accounts for the relationship between exposures to air pollution and a collection of acute and chronic illnesses, including chronic bronchitis and chronic asthma (see Muller and Mendelsohn 2007).

Translating the health effects into economic losses requires placing an economic value of premature mortality. Our preference is to treat premature mortality in terms of the life-years of loss rather than just in terms of premature mortalities. The primary reason for our preference is that we would expect that the social value of early mortality would differ as to whether it was a death in the prime of life, with many years of life foregone, as compared with an ill person whose mortality might be shortened by days or weeks because of a complication from an environmental exposure. We recognize that this assumption is not universally shared, and that some would prefer either affixing a uniform value to all early mortalities, or perhaps some non-linear function of age and years. We will show the impact on our estimates of the uniform valuation approach below. The non-linear approach becomes too complicated for the present purposes because it involves the selection of functional forms and alternative methodologies and loses the transparency that is useful in a study that is already quite elaborate.

This study values mortality risks using evidence from both revealed preference studies and stated preference studies in the literature. The revealed preference studies generally estimate the premium required by workers to assume additional mortality risks in the workplace. Stated preference studies ask people about their willingness to pay to avoid additional mortality risks in a survey format. In both contexts, the methodology calculates the value of a statistical life as the marginal willingness to pay for an incremental risk reduction (R) divided by the risk increment ($\Delta\gamma$); hence $R/\Delta\gamma = VSL$.[10] We take a VSL of $6 million (in 2000 dollars) per premature mortality as the central estimate in this study. This figure is used by the USEPA in their analyses of the benefits and costs of the Clean Air Act (USEPA 1999). This VSL is the mean of 28 studies from both the revealed preference and the stated preference literatures that have been selected based on their methodological merits (USEPA 1999).

To obtain the value of a life-year from the VSL, we undertake the following calculations. First, we estimate the impact of pollution on the overall distribution of life expectancy of the population; estimate the change in the life expectancy of each member of the population; and then value premature fatalities by multiplying the change in life expectancy by the value per life-year. The value of a life-year is calculated by multiplying the VSL times the discount rate applicable to human health (δ), which we take to be 3 percent per year in real

[10] See particularly Viscusi and Aldy, 2003 for a discussion.

terms. The economic cost of mortality risks for each age group is determined by computing the discounted value of their remaining years of life weighted by the probability of each age group surviving to the next time period. This computation is shown in equation (1).

$$V_{a,c} = \sum_{t=0}^{\infty} \left[(VSL)\, \delta\, \Gamma_{T,a,c} \,(1+\delta)^{-t} \right] \qquad (1)$$

where:

$V_{a,c}$ = present value of a premature mortality of person in age-cohort *(a)* in county *(c),*
VSL = value of statistical life,
$T_{a,c}$ = the number of life-years remaining for persons in age-cohort *(a),* in county (c).
$\Gamma_{T,a,c}$ = cumulative probability of survival to period *(T)* for age-cohort *(a),* living in county *(c).*
δ = discount rate on life-years.

The life-years approach places a relatively large value on young relative to old persons because young people have a much higher life expectancy. This difference is important for air pollution because air pollution has a much larger impact on the mortality rate of older people than young people. An alternative valuation approach is to use VSL directly regardless of age. We estimate the damages assuming both life-year and constant VSL.

Global warming externality

A final computation added here is a calculation for the potential damages from emissions of greenhouse gases. Our estimates measure only the emissions of carbon dioxide from fossil fuels. Carbon dioxide emissions contribute to global warming, which in turn cause damages far into the future. Several studies have estimated the global damages per ton of emissions (see Tol 2005; IPCC 2007; Nordhaus 2008). We rely on these estimates to place a value on carbon emissions by industry. As a central estimate, we use the estimate from Nordhaus 2008 of \$27/tC in 2000 U.S dollars. We then use \$6/tC as a lower bound and \$65/tC as an upper bound based on a careful survey of results from other studies (Tol 2005).

C. Gross External Damages (GED)

The USEPA's National Emission Inventory (USEPA, 2006) identifies the volume (E) and location (j) of every emission of the air pollutants of each pollutant (s) tracked in this study in the U.S. Each source is assigned to a six-digit industry code (i) from the North American Industry Classification System (NAICS). As discussed above, the APEEP model estimates the marginal damage of an emission of pollutant (s) from each location (j), $MD_{s,j}$. The Gross External Damages (GED) are calculated by multiplying the emissions ($E_{s,i,j}$) times the location and pollutant-specific marginal damage ($MD_{s,j}$). The $GED_{s,i,j}$ attributed to source (j) in industry (i) emitting pollutant (s) is shown in the following equation.

$$GED_{s,i,j} = MD_{s,j} \times E_{s,i,j} \tag{2}$$

The total GED attributed to industry (i) is the sum of damages across the six emitted pollutants covered by APEEP and across all source locations.

$$GED_i = \sum_{j,s} MD_{s,j} \times E_{s,i,j} \tag{3}$$

For each six-digit NAICS industry, we measure the ratio of GED_i to value added (VA_i). The value-added data are gathered from the Bureau of Economic Analysis and from the U.S. Census Department's Economic Census.[11] All monetary values are expressed in base year 2000 dollars. Carbon damages are calculated in a similar fashion using the social cost of carbon, which does not vary by (j).

IV. Results

Overall Results

We now present the estimates of air pollution damages by industry. The first set of results reports the ratio of the GED to value added (VA) by six-digit NAICS code. The 900 industries in the U.S. are ranked according to the GED/VA ratio (the complete table is available in Appendix A-1). Table 1 presents the 12 industries with the highest ratio of GED/VA. The table does not include the value of carbon dioxide emissions. All results are in 2000 prices.

[11] The sources of data used in this analysis are shown in the accompanying data appendix (pp. 38-39).

Five industries have environmental damages that are actually larger than their value added. These five are solid waste combustion, petroleum-fired electric power generation, sewage treatment, coal-fired electric power generation, and stone mining. The ratios of damages to value added across these five industries range from 4.1 for solid waste combustion to 1.2 for stone mining. The fact that the GED exceeds the value added implies that if the national accounts included environmental costs, the true value added of these industries would actually be negative.

Most of the harmful emissions of firms engaged in (nonhazardous) solid waste combustion are nitrogen oxides (NO_x). These facilities have a large GED because they are often located in cities near large populations. Petroleum-fired power generators emit relatively large quantities of sulfur dioxide (SO_2), and NO_x as well as substantial amounts of fine particulates ($PM_{2.5}$). Sewage treatment facilities produce NO_x, SO_2, and ammonia (NH_4); each of which combines with other compounds to form $PM_{2.5}$. Like solid waste incinerators these facilities produce a large GED since they are frequently located in or near large cities. Although often located away from urban centers, coal-fired power generators produce large quantities of emissions of SO_2, NO_x, and $PM_{2.5}$. Most of the air pollution produced by the stone mining industry is particulate matter (both $PM_{2.5}$ and PM_{10}). This is produced during site preparation and in the quarrying and mining of stone.

Figure 5 displays the VA, GED, and the net value added (VA minus GED) of the top five industries in Table 1. The figure clearly shows that if the GED were included, the net value added for these industries would be negative. Figure 5 also emphasizes the difference in the value added of sewage treatment, solid waste combustion, dimension stone mining, and oil-fired electric power generation relative to the coal-fired power generation. Coal-fired power generation has a value added of $24.3 billion while the value added of the other four industries is each less than $1 billion.

The marina industry and the manufacturing of assorted petroleum and coal products are also in Table 1. Most of the air pollution emissions from marinas come from burning gasoline and diesel by recreational watercraft. The GED/VA ratios for these two industries are 0.93 and 0.84, respectively. Two of the remaining 5 industries listed in Table 1 produce GED that is nearly two-thirds of their value added. These are the water transportation sector and firms in the utility sector that supply steam heat and air conditioning to commercial facilities. The remaining three industries in Table 1 have GED that are between 35 and 50 percent of their value added. They include sugarcane mills, manufacturers of carbon black (a dye used in tire manufacturing), and livestock producers.

It is also interesting to note that two of the industries with the highest GED/VA ratios include firms engaged in different aspects of waste management, one-quarter of the high GED/VA industries are in the utility sector, and only one-quarter of these industries are in the manufacturing sector.

Results for Electric Power Generation

Perhaps the most important sector in terms of air pollution damages is electric power generation. Table 2 decomposes the electric power generation sector by fuel type. The first three columns estimate GED excluding the damages from CO_2 emissions. This shows that coal-fired facilities account for 95 percent of the Gross External Damages of the electric generating sector. The GED/VA ratio is 1.41 for coal-fired units. Petroleum-fired electric power generation displays the largest ratio of GED to value-added: 3.36. Although oil fired power plants are cleaner than coal fired power plants, they have a much lower VA because oil is so much more expensive than coal. Natural gas facilities show much smaller GED, $600 million, annually, and a significantly smaller GED to VA ratio of 0.28. Nuclear-powered electric generation facilities yield even lower total GED although this estimate does not include the cost of radioactive waste disposal (Nordhaus, 1997). Table 2 also shows the GED per kilowatt-hour (kwh) of electricity produced for each of the fuel types. Coal and petroleum-fired generators produce the highest costs of 1.8 cents and 1.3 cents per kwh, respectively.

The last three columns of Table 2 display estimates of GED^+, which we define as Gross External Damages plus the damages from carbon dioxide emissions.[12] The central estimate of the damages from carbon dioxide uses a value of $27 per ton of carbon ($7.4 per ton of CO_2) (Nordhaus 2008). When climate-change effects are included, the damages caused by fossil-fuel power plants are much higher. The annual GED^+ for coal-fired generators increases by 50 percent to $49.4 billion and the associated GED^+/VA increases to 2.03. Petroleum-fired generators have an annual GED^+ of $1.7 billion and a GED^+/VA of 4.80. Finally, the annual GED^+ for natural gas-fired power producers is $3.08 billion and the GED^+/VA for natural gas facilities is 1.19.

Table 2 also displays a range for the GED^+ and the GED^+/VA based on different estimates of the social cost of carbon reported in Nordhaus (2008). Specifically, we employ a lower bound ($6/tC) and an upper bound ($65/tC) to form the range of values shown in parentheses in Table 2. The GED^+ for coal-fired generators ranges from $37.5 billion to $70.8 billion. The range of GED^+ for

[12] The estimates of CO_2 emissions for electric power generators are provided by the Energy Information Agency (http://www.eia.gov).

petroleum-fired facilities is \$1.3 billion to \$2.4 billion. The $GED^{+}$for natural gas-powered generators is between \$1.1 billion and \$6.6 billion.

Table 2 then reports the GED^{+}/kwh, representing the external costs per kilowatt-hour when the damages due to CO_2 are included. The GED^{+}/kwh for coal, oil, and natural gas facilities are 2.6 cents, 1.8 cents, and 0.5 cents, respectively. Note that the range of GED^{+}/kwh depending on the social cost of carbon estimate used is also reported in Table 2. In 2002, residential consumers of electricity faced an average market price of 8.4 cents per kwh. Hence, using the central GED^{+}estimate, the external costs associated with electric power generation using coal, oil, and natural gas represent 31, 22, and 6 percent of the average residential retail price of electricity in 2002. Note that residential electricity prices vary by the primary fuel type used in electricity production. In states that primarily rely on coal-fired power, residential electricity prices averaged 6 cents per kwh. External costs of coal-generated electricity represent 43 percent of the average residential retail price of electricity in a "coal state". In states that rely on natural gas, residential electricity prices averaged 11 cents per kwh. External costs of natural gas-generated electricity represent just 4.5 percent of the average residential retail price of electricity in a "natural gas state" (U.S. Department of Energy, 2008).

Figure 6 shows the share of GED^{+} that is due to emissions of CO_2 for fossil fuel electric power generators. This figure shows the relative value of emissions of the criteria air pollutants and emissions of CO_2. The figure employs the three different estimates of the social cost of carbon that are used in Table 2. For all values of the social cost of carbon, emissions of CO_2 have the largest percent impact on the damages from natural gas-fired power plants (40 percent to 90 percent). This is because natural gas-fired power plants generate very small amounts of the criteria pollutants. In contrast, the CO_2 share of GED^{+} for both coal-fired and oil-fired power generators is between 10 percent and 50 percent. Although coal plants generate a great deal of CO_2, they generate greater damages due to other pollutants.

Our estimates of the air pollution damages from nuclear power and hydroelectric power are much lower than those for fossil-fuel plants. For nuclear energy, normal emissions of radioactive material are quite low. We also include the expected value of an accident. Whereas the damages of a meltdown are very high, the probability of such an event are quite low given the safety measures in American power plants. The expected value of radioactive air emissions from nuclear power plants is therefore quite low. There is also a small risk of air emissions associated transport and storage of waste materials. However, most of the risk of storage concerns long term soil and water pollution. Hydropower may cause small emissions of carbon as reservoirs require forests to be cleared and methane is released from lake ecosystems (Fearnside 2004) but these effects are small compared to the damages generated by fossil-fuel plants.

Other industries and sectors

Table 3 ranks industries according to the magnitude of the GED due to their emissions of air pollution (not counting CO_2). Coal-fired electric power generators produce the largest GED of $34.1 billion, annually. The damages attributed to this sub-sector are over three times larger than the GED due to the three next most polluting industries: farms engaged in agricultural crop production, $9.8 billion/year, livestock production, $9.4 billion/year, and construction of roadways and bridges, $8.6 billion/year. The truck transportation sector produces $7.2 billion in damages and the GED is equal to 8 percent of its value added.

The water transportation sector produces damages equal to $5.1 billion, while petroleum refineries cause GED of $3.2 billion. Firms that burn solid waste generate GED equal to $3.0 billion. Bulk stations and terminals that distribute petroleum products on a wholesale basis cause damages of $2.7 billion. These damages are primarily due to emissions of volatile organic compounds from the evaporation of gasoline spilled during filling of the terminal or in filling vehicles used to transport the fuels. Food service contractors produce GED of $2.7 billion annually. Landscape contractors generate annual GED of $2.4 billion. Finally, railroads produce damages of $1.8 billion.

Table 4 shows the GED and the GED to VA ratio for the entire market economy by two-digit sector codes. The utility sector generates the largest GED, roughly $40 billion, and this sector's GED is 23 percent of the value added. The agriculture and forestry sector generates the next largest GED ($20 billion) and the GED produced by this sector comprises 24 percent of the VA for agricultural and forestry production. The transportation sector and the manufacturing sector produce GED of $16.9 billion and $16.7 billion, respectively. The administration and waste management and construction sectors also generate substantial GED of $6.7 billion and $9.7 billion, annually. The bottom row in Table 4 indicates that the total GED across all market sectors of the economy in 2002 is $121.7 billion. One-third of the total damages are due to emissions from the utility sector. The agricultural sector contributes 17 percent of the total market GED.

Sensitivity Analysis

Studies of environmental accounting have many uncertainties embedded in the analysis. We highlight two particularly important sources of uncertainty in the following sensitivity analysis: the link between exposures to $PM_{2.5}$ and human mortality and the dollar value to place on mortality risks; specifically whether to value mortality risks faced by all age groups equally or to use age-specific values. We vary each of these assumptions in Table 5 and compare the results to the findings in Table 1 on GED/VA for the top 12 industries.

In our baseline case in Table 5, we estimate damages based on the number of life-years remaining for each age group and rely on the findings from Pope et al. (2002) for the dose-response relationship between exposures to $PM_{2.5}$ and adult mortality rates. In the first sensitivity analysis, we use a dose-response function for adult mortality from $PM_{2.5}$ which is about twice as sensitive (Laden et al. 2006). In the second sensitivity analysis, we apply the VSL uniformly across all ages. This replicates the strategy that the USEPA used when analyzing the costs and benefits of the Clean Air Act (USEPA, 1999). Most of the fatalities due to exposures to air pollution occur in elderly populations, so this alternative places a relatively higher value on mortality.

Employing the mortality dose-response function reported in Laden et al., (2006) increases GED/VA by a factor of approximately 2.5. This change is not proportional across all industries. The industries that are most sensitive to the mortality dose-response function emit pollutants that lead to small particulates (especially $PM_{2.5}$, SO_2, and NH_3). Table 5 suggests that the GED/VA ratio for solid waste combustion is greater than ten in this scenario. The industries that are least sensitive to this alternative approach emit pollutants that have lower mortality impacts and higher morbidity effects (especially through emissions of PM_{10-}).

The second sensitivity analysis examines the importance of using a constant VSL across all ages. Uniform VSLs increase the GED/VA by about 60 percent to 100 percent. Since this parameter only affects mortality impacts, this second sensitivity analysis is similar to the first analysis. The GED/VA ratio for solid waste combustion is 6.7 and the GED/VA for petroleum-fired power generation is now 5.4.

Table 6 shows the impact of the sensitivity analyses on industries with the largest GED. The GED of the coal-fired electric power generation industry is \$34.1 billion in the baseline, \$85.4 billion in the first sensitivity analysis, and \$53.8 billion in the second analysis (excluding CO_2 damages). If we include CO_2 emissions, the GED^+ of coal-fired power plants is \$49.4 billion in the baseline, \$101 billion in the first sensitivity analysis, and \$69 billion in the second analysis. Table 6 also reports that firms engaged in crop production generate GED of \$10 billion, \$25 billion and \$16 billion, in the baseline and two sensitivity cases respectively.

V. Conclusions

This study develops an accounting framework and presents empirical estimates of the external costs of pollution in the framework of the national economic accounts. The analytical section shows that there is a natural extension of current national-accounting principles to include pollution. The suggested approach measures the environmental damages caused by each industry. Specifically, the national accounting system should measure the gross external damages caused by each industry and subtract any costs for permits or pollution taxes incurred by firms. The gross external damages would be measured by multiplying emissions times the marginal damage of emissions at each location. This proposed framework would capture the full costs of production to society of each industry. Because pollution damages per unit of value added vary a great deal from one industry to the next, the integrated accounting framework provides a more accurate accounting of each industry's net contribution to augmented GDP.

We note several qualifications about the results. First, our estimates are accounting measures and not measures of economic welfare. The economy has many pre-existing distortions other than those from air pollution – such as taxes, market distortions, and other externalities – and existing accounts do not attempt to incorporate those. Second, we note that the finding of a negative adjusted value added does not imply that an industry should be shut down. Rather, it indicates that a one-unit increase in output of that industry has additional costs that are higher than the revenues. This cannot be extrapolated to infra-marginal adjustments. Third, our estimates of net external damage do not include an adjustment for the accounting costs of emissions permits. Given the flawed accounting treatment of these costs, we suspect that this assumption introduces a small error, but in fact we cannot even judge the sign of the error. Fourth, this study includes only the impact of air pollution and excludes other effects, including those of water, soil, and radiation. Fifth, we note that the uncertainties are particularly large for three elements: the treatment of the value of life or life-years, the value of CO_2 emissions, and the dose-impact effect of small particulates. Sensitivity analyses using alternative values can change the magnitude of the results significantly.

In the empirical section of the paper, we apply the framework to major air pollutants in the United States for the year 2002. We employ a newly developed computerized integrated-assessment model that combines emissions, dispersion, chemical transformations, exposures, health and other impacts, and economic valuation of impacts. The paper follows standard national-accounting principles in applying the marginal valuations to the quantities-emitted of each pollutant. Emissions by industry at each source are multiplied by the estimated marginal damage by location to obtain a total damage. The damages are added across sources to estimate industry damages and across industries to estimate sectoral damages.

The study estimates that aggregate pollution damages, GED, from the market sector for all industries in 2002 were $121.7 billion. Pollution from households (homes and cars), which reflects non-market activity, is not counted in this amount. The ratio of GED to value added (GED/VA) varies greatly across industries. For some industries, (sewage treatment plants, solid waste combustion, stone quarrying, petroleum-fired and coal-fired power generation) GED actually exceeds conventionally measured VA.

The results also reveal that there are a number of other industries with relatively high GED/VA ratios. Crop and livestock production have high GED/VA ratio, which is surprising given that these activities generally occur in rural (low marginal damage) areas. Other industries with high GED/VA ratios include water transportation, marinas, steam heat and air conditioning supply, and sugar cane mills.

Summing up the GED across two-digit sectors provides a profile of those sectors of the economy which are contributing most to damages due to air pollution. The two sectors with the highest GED/VA ratio are utilities (23 percent) and agriculture (24 percent). They are responsible for $40 billion and $20 billion of damages, or 33 percent and 17 percent of the total damages produced by market activity, respectively. The sector with the next highest GED/VA ratio is transportation (8 percent), with air pollution damages of about $16.9 billion. The waste management sector produces GED equivalent to 3 percent of its VA ($14 billion). Interestingly, while manufacturing is responsible for $16.7 billion of damages, its GED is equal to only 1 percent of its VA. The GED/VA ratio of manufacturing is surprisingly low.

There are many parameters in the integrated-assessment model that are important for damage assessment. These include the parameters governing physical dispersion of emissions, chemical transformation rates of airborne pollutants, human exposures, dose-response relationships, and the values attributed to mortality risks. Previous sensitivity analyses identified the mortality dose-response function and the valuation methodology for mortality risk as two of the most important assumptions (Muller and Mendelsohn 2007). In order to determine how these assumptions affect the results, we explore alternative values from the literature for both parameters. The estimates of GED are sensitive to these assumptions. The assumptions change the estimated impacts of some industries more than others because the mix of pollution emitted varies by industry. However, the assumptions largely have an across the board effect. For example, a more sensitive dose-response function for mortalities caused by exposure to $PM_{2.5}$ increases the damages from solid waste incinerators by 2.7 times and increases the damages from coal-fired power plants by 2.5 times.

The case study of air pollution damages in the U.S. reveals that it is possible to estimate the pollution damages caused by each industry. The results suggest it would be desirable to extend the findings to water pollution, solid waste, and hazardous waste pollution. Integrated-assessment models of watersheds and land use could capture these remaining sources of damage. Another important extension is to consumers. In this study, emissions from the different sectors of the economy caused $121.7 billion of annual damage. Consumption of final goods is also an important source of air pollution damages. For example, residential combustion of fossil fuels and wood generated $8.1 billion in damages in 2002.

There are major implications of the results of this study. To begin with, this study shows that it is possible to undertake empirically-based environmental national accounts for the United States. The Bureau of Economic Analysis began to construct integrated environmental accounts in 1994, but these efforts were stopped by the Congress. Given the size and distribution of damages, it is important that these efforts be restarted. While private scholars can make provisional estimates of the present kind, a full set of accounts needs the full-time staff, professional expertise, and access to proprietary information that only a government agency possesses.

Additionally, we believe that the results of this study, when confirmed by additional estimates of other scholars or government agencies, can give direction to regulatory efforts. We have found that a number of industries actually have a *negative value added* when external effects are included. For example, the ratio of pollution damages to conventionally measured value added ranges from 1.4 to 3.5 for coal-fired electricity generation. A well-constructed set of environmental accounts can help ensure that regulatory efforts, such as those aimed at slowing climate change, are well targeted. It is instructive that many of the current efforts at climate-change mitigation are aimed at automobiles, while the largest damages are likely to be in the area of coal-fired generation. Without careful measures of costs and impacts, best undertaken in the framework of environmental accounting, our regulatory policies may turn out to be wasteful and ineffective.

Table 1. Industries with Largest Gross External Damage (GED) to Value-Added (VA) Ratio
[Value added (VA) in $billion per year, 2000 prices]

Industry	GED/VA	VA
Solid Waste Combustion and Incineration	4.09	0.73
Petroleum-fired Electric Power Generation	3.36	0.36
Sewage Treatment Facilities	2.95	0.45
Coal-fired Electric Power Generation	1.41	24.30
Dimension Stone Mining and Quarrying	1.17	0.24
Marinas	0.93	1.48
Other Petroleum and Coal Product Mfg.	0.84	0.49
Water Transportation	0.65	7.78
Steam & Air Conditioning Supply	0.65	0.29
Sugarcane Mills	0.43	0.39
Carbon Black Mfg.	0.43	0.50
Livestock Production	0.36	26.40

Table 2. Electric Power Generation Sector Breakdown, Including Carbon Dioxide Emissions.

[GED in $billion per year, 2000 prices]

Fuel Type	GED/VA	GED	($GED)/kwh	GED*/VA	GED*	($GED*)/kwh
Coal	1.41	34.1	0.0176	2.0 (1.6, 2.9)	49.4 (37.5, 70.8)	0.0255 (0.0194, 0.0366)
Petroleum	3.36	1.2	0.0126	4.8 (3.7, 6.8)	1.7 (1.3, 2.4)	0.0179 (0.0138, 0.0253)
Natural Gas	0.28	0.6	0.0010	1.2 (0.4, 2.6)	3.1 (1.1, 6.6)	0.0045 (0.0016, 0.0096)
Nuclear	0.04	0.4	0.0005	0.04	0.4	0.0005
Hydroelectric	0.00	0.0	0.0000	0.00	0.0	0.0000

GED* = gross external damages including CO_2 emissions. Numbers in parenthesis represent using lower bound ($6/tC) and upper bound ($65t/C) estimates for social cost of carbon.

Table 3. Industries with Largest Gross External Damages
[GED in $billion per year, 2000 prices]

Industry	GED/VA	GED
Coal-fired Electric Power Generation	1.41	34.1
Crop Production	0.22	9.8
Livestock Production	0.36	9.4
Highway, Street, & Bridge Construction	0.25	8.6
Truck Transportation	0.08	7.2
Water Transportation	0.65	5.1
Petroleum Refineries	0.12	3.2
Solid Waste Combustion & Incinerators	4.10	3.0
Petroleum Bulk Stations & Terminals	0.10	2.7
Food Service Contractors	0.22	2.7
Landscaping Services	0.10	2.4
Rail Transportation	0.09	1.8

Table 4. Gross External Damages and GED/VA Ratio by Sector
[GED in $billion per year, 2000 prices]

Sector	GED	GED/VA
Agriculture & Forestry	20.4	0.24
Utilities	40.2	0.23
Transportation	16.9	0.08
Administrative, Waste Management & Remediation Services	6.7	0.03
Arts, Entertainment, & Recreation	1.4	0.03
Construction	9.7	0.02
Accommodation & Food Services	2.7	0.01
Manufacturing	16.7	0.01
Mining	2.0	0.01
Wholesale Trade	2.8	0.01
Other Services	0.6	0.00
Retail Trade	1.0	0.00
Information	0.0	0.00
Finance & Insurance	0.0	0.00
Real Estate Services	0.0	0.00
Professional, Scientific, Technical Services	0.0	0.00
Management	0.0	0.00
Educational Services	0.0	0.00
Health Care Services	0.4	0.00
Total All Sectors	121.7	

Table 5. Sensitivity Analysis: Industries with Largest GED/VA
[All values are in 2000 prices]

Industry	GED/VA	GED/VA	GED/VA
	Baseline	Case I	Case II
Solid Waste Combustion and Incineration	4.10	11.07	6.72
Petroleum-fired Electric Power Generation	3.36	8.66	5.42
Sewage Treatment Facilities	2.95	8.45	5.23
Coal-fired Electric Power Generation	1.41	3.52	2.21
Dimension Stone Mining and Quarrying	1.17	2.92	1.85
Marinas	0.93	2.48	1.58
Other Petroleum and Coal Product Mfg.	0.84	2.22	1.71
Water Transportation	0.65	1.78	1.05
Steam & Air Conditioning Supply	0.65	1.78	1.70
Sugarcane Mills	0.43	1.13	0.83
Carbon Black Mfg.	0.43	1.12	0.75
Livestock Production	0.36	0.97	0.60

Case I uses a more sensitive dose-response function (Laden et al., 2006), and Case II applies a uniform VSL to all ages.

Table 6. Sensitivity Analysis: Industries with Largest GED
[All values are in 2000 prices; GEC in billions of $]

Industry	GED/VA	GED	GED/VA	GED	GED/VA	GED
	Baseline		Case I		Case II	
Coal-fired Electric Power Generation	1.41	34.1	3.5	85.4	2.2	53.8
Crop Production	0.22	9.8	0.57	25.2	0.36	16.1
Livestock Production	0.36	9.4	0.97	25.5	0.59	15.7
Highway, Street, & Bridge Construction	0.25	8.6	0.63	21.8	0.39	13.5
Truck Transportation	0.08	7.2	0.20	17.7	0.13	11.9
Water Transportation	0.65	5.1	1.78	13.9	1.05	8.2
Petroleum Refineries	0.12	3.2	0.32	8.6	0.22	5.9
Solid Waste Combustion & Incinerators	4.1	3.0	11.07	8.1	6.72	4.9
Petroleum Bulk Stations & Terminals	0.10	2.7	0.28	7.7	0.16	4.4
Food Service Contractors	0.22	2.7	0.61	7.6	0.36	4.4
Landscaping Services	0.10	2.4	0.29	7.0	0.18	4.2
Rail Transportation	0.09	1.8	0.21	4.3	0.14	3.0

Case I uses a more sensitive dose-response function (Laden et al., 2006) and Case II applies uniform VSLs across all ages.

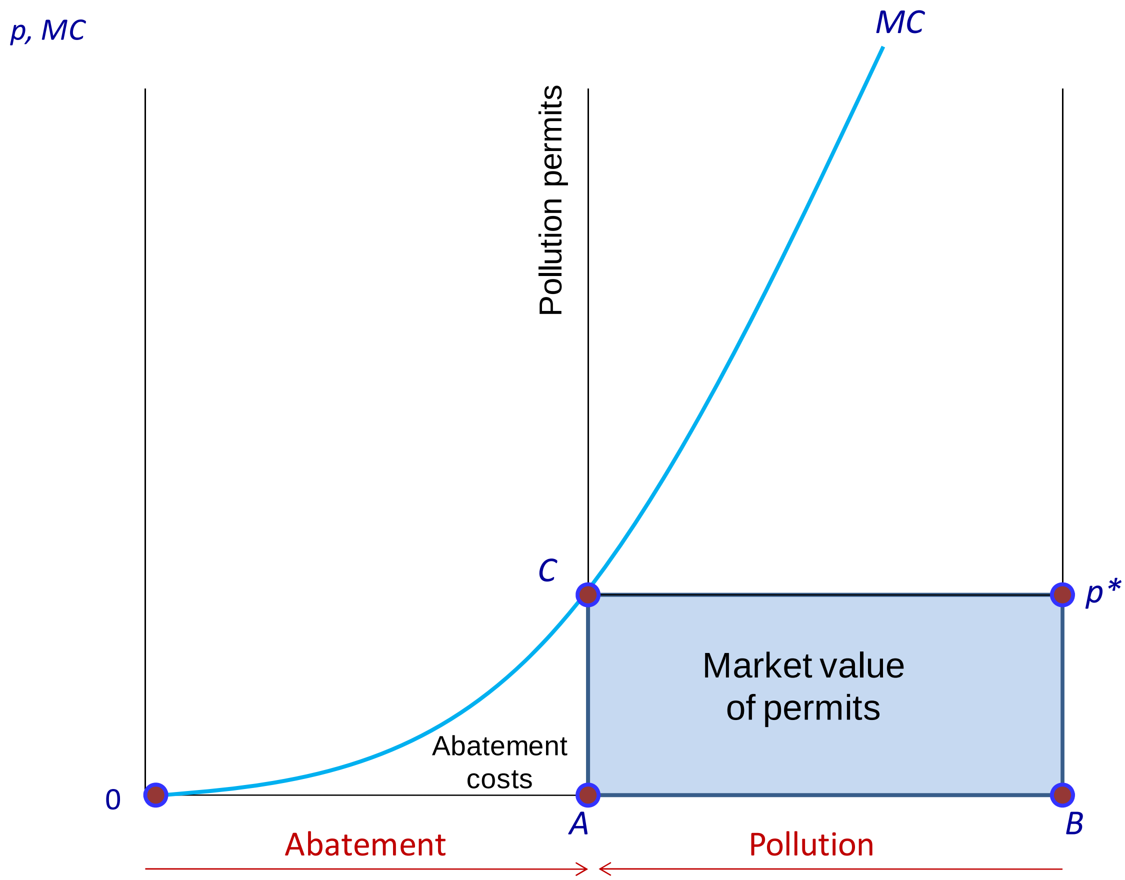

Figure 1. Abatement costs

This figure shows the marginal cost of abatement for a typical pollutant. Pollution is limited by regulation to the vertical line market "Pollution permits." The area *OAC* is the resource cost of abatement, while *BACp** is the market value of pollution permits under a tradable permit program.

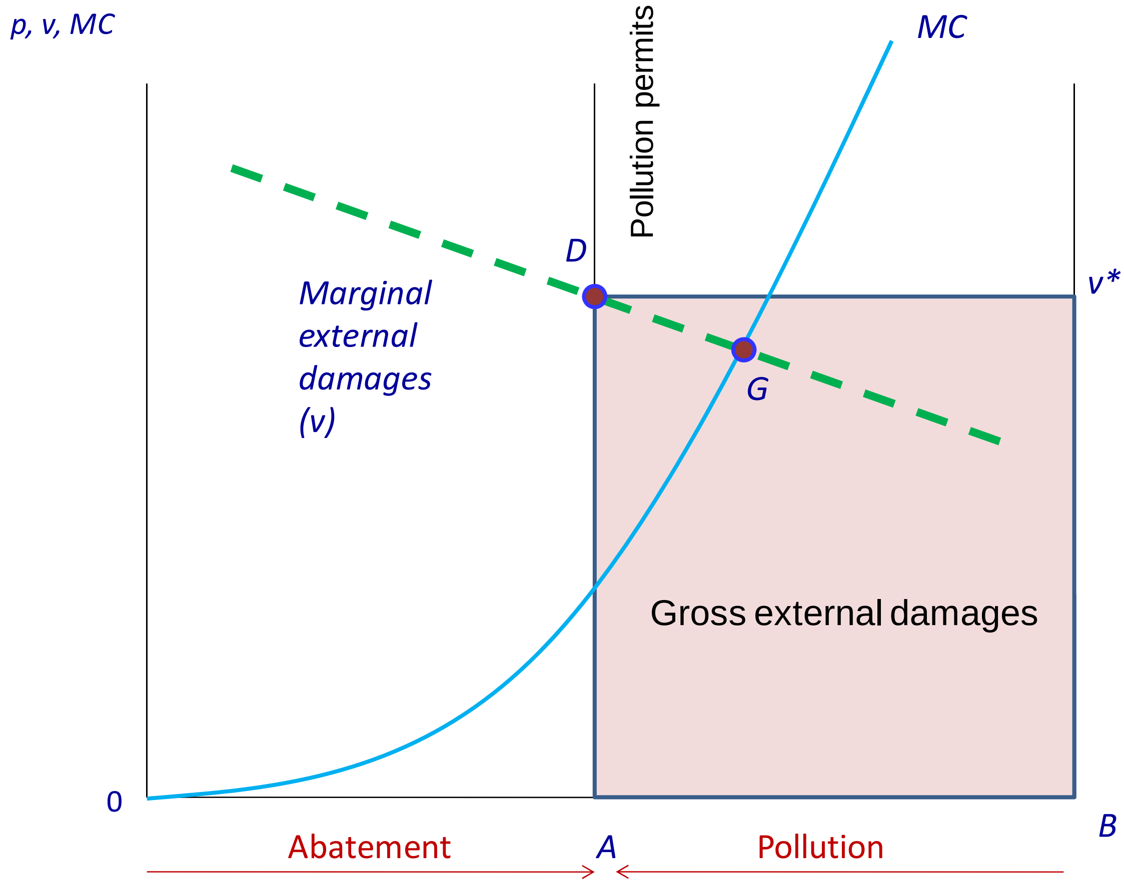

Figure 2. Damages from pollution

This figure shows the same *MC* of abatement as Figure 1, but adds the marginal external damages curve as the dashed line. Marginal damages at the regulated level of pollution is v^*, which then implies that the accounting costs of pollution are $BADv^*$. This shaded rectangle corresponds to our estimate of gross external damages.

Figure 3. Accounting for Pollution

This figure shows the accounting treatment in the study. The bottom rectangle is the market value of permits from Figure 1. If this value is subtracted from the gross external damages in Figure 2, we obtain net external damages. Current accounting does not include the market value of permits but the accounting cost of permits, shown as the small area under the dashed line.

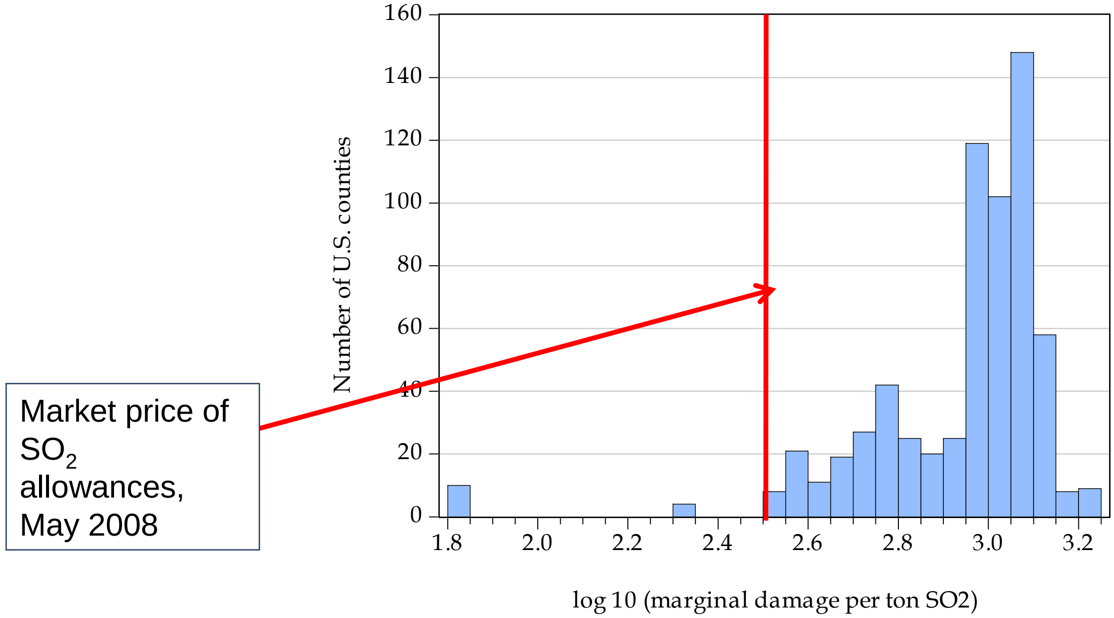

Figure 4. Log of SO_2 Marginal Damages and the Market Price of SO_2 Permits.

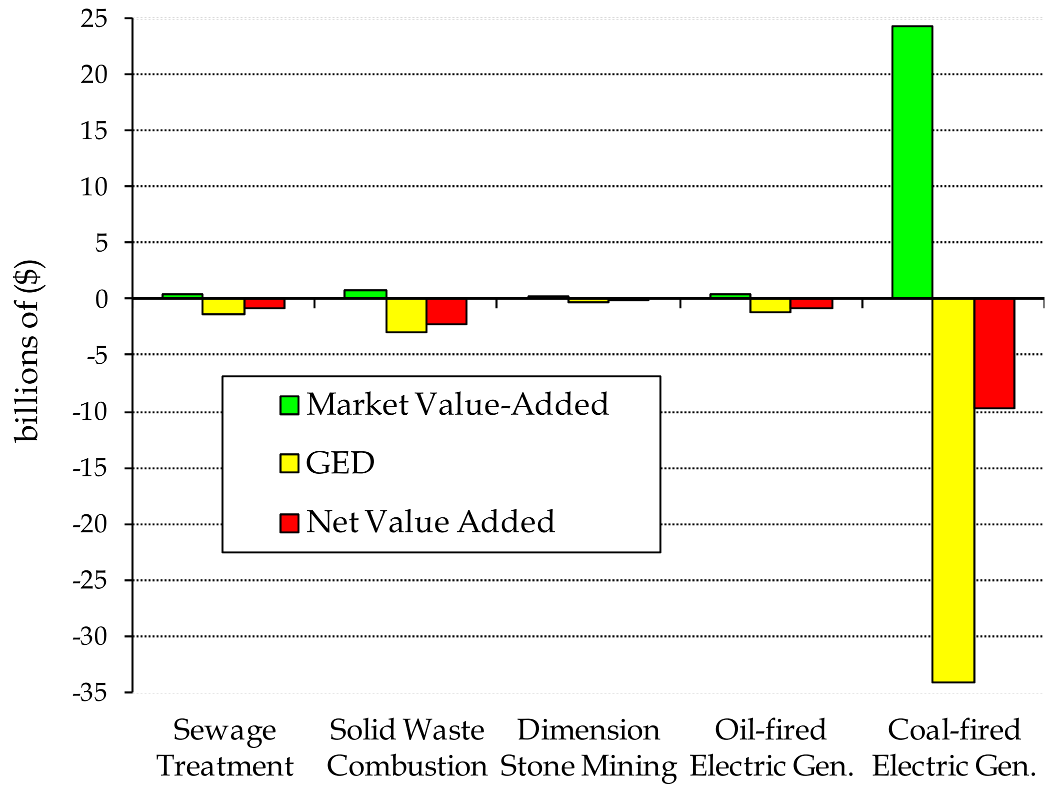

Figure 5. Market Value-Added, Pollution Damages (GED), and Net Value-Added for Five Industries with Largest GED/VA.

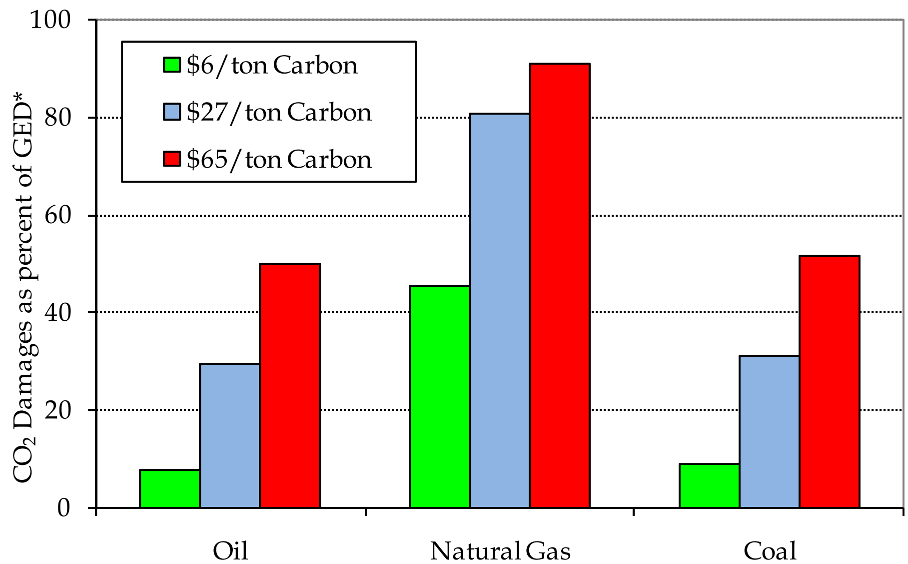

Figure 6. Percent Share of Pollution Damages (GED) Due to Emissions of CO_2, Fossil Fuel Electric Power Generators by Fuel Type.

Technical Appendix

The Air Pollution Emission Experiments and Policy analysis model (APEEP) computes the marginal damage of emissions for specific sources within particular industrial sectors for six different pollutants. Equation (A.1) denotes emissions (E) of pollution species (s), emitted by a source in industry (i), in location (j), at time (t).

(A.1) $E_{s,i,j,t}$ = exogenously determined from data

Equation (A.2) describes the ground-level concentration (C) of pollutant species (s), in location (j) that are due to emissions from a source in industry (i), in location (j), at time (t). The relationship between emissions and concentrations is proportional (except for NOx and O3) and a function of the distance between source and recipient locations as well as meteorological factors and chemical processes in the atmosphere. The different factors are captured in (A.2) by the function ($f_{s,j}$), which is dependent both on the pollution species (s) and location (j).

(A.2) $C_{s,i,j,t} = f_{s,j}(E_{s,i,j,t})$

The model computes exposures (X) to species (s) by multiplying the population in location (j) at time t ($P_{j,t}$) times concentrations.

(A.3) $X_{s,i,j,t} = P_{j,t}\, C_{s,i,j,t}$

The response (R) to exposures (X) are determined by the coefficient (β^s_k), which is distinct for pollutant species (s), due to varying levels of toxicity, and for different health outcomes (k), such as premature mortality and acute illness. The relative mortality or morbidity risk β^s_k is proportional to the baseline concentrations.

(A.4) $R_{k,s,i,j,t} = \beta^s_k\, X_{s,i,j,t}$

The monetary value (V) due to the emissions from industry (i) in time (t) is shown equation (A.5). This is the sum, across locations (j), species (s), and health outcomes (k), of the response (R) to exposures times the coefficient $\alpha_{k,t}$, which translates responses from physical effects into dollar values.

(A.5) $V_{i,t} = \sum_{s,k,t} \left(\alpha_{k,t} R_{k,s,i,j,t} \right)$

Data Appendix

Value-added data for 6-digit NAICS for the year 2002 codes were gathered from the U.S. Census Bureau's 2002 Economic Census. These data are available for the following sectors: mining, construction, and manufacturing (21,23,31,32,33). The data are found at http://factfinder.census.gov/servlet/DatasetMainPageServlet?_program=ECN&_submenuId=datasets_4&_lang=en.

Value-added data for 2-digit and 3-digit sectors and subsectors for the year 2002 were gathered from the Bureau of Economic Analysis' 2002 Benchmark Input-Output Tables. These data are available for the remaining sectors: agriculture and forestry, utilities, wholesale and retail trade, transportation and warehousing, information, finance and insurance, real estate, rental, and leasing, management of companies, administrative support and waste management and remediation services, educational services, health care and social assistance, arts, entertainment, and recreation, accommodation and food services, and other services. These data are found at http://www.bea.gov/industry/iotables/table_list.cfm?anon=69672

For those without value-added data for 6-digit NAICS industries, the industries listed in the above paragraph, we gather total output data, also available at the U.S. Census Bureau's 2002 Economic Census site at http://factfinder.census.gov/servlet/DatasetMainPageServlet?_program=ECN&_submenuId=datasets_4&_lang=en.

In order to allocate the 2-digit and 3-digit value-added among the 6-digit NAICS industries, we compute the share of total output for each 6-digit industry and then multiply the sector value-added times the share of total output.

Air pollution emission data is provided by the U.S. Environmental Protection Agency's National Emission Inventory for 2002, available at http://www.epa.gov/ttn/chief/net/2002inventory.html

Emission estimates for carbon dioxide are available from the greenhouse gas emission inventory produced by the U.S. Department of Energy, Energy Information Agency, available at http://www.eia.doe.gov/oiaf/1605/ggrpt/carbon.html

For stationary point sources, the U.S. EPA codes each source according to the 6-digit NAICS to which the source belongs. The emission inventory also identifies the county in which the stationary point source is located. For mobile sources, the U.S. EPA’s inventory distinguishes only between vehicle weight and fuel type. As a result, we cannot differentiate, for example, between light-duty trucks driven for commercial purposes and those driven by consumers. Only those mobile sources that can clearly be attributed to a NAICS industry or sector (railroads, marine vessels, heavy-duty highways diesel trucks, e.g.) are included in the analysis.

References

Abraham, K. and C. Mackie. 2005 (eds.). *Beyond the Market: Designing Nonmarket Accounts for the United States*, Washington, D.C: National Academy Press.

Ahmed, Y.J., El Serafy, S., Lutz, E. (eds). 1989. *Environmental Accounting for Sustainability.* Washington D.C: World Bank.

Aronsson, T., P.O. Johansson, K.G. Lofgren. 1997 *Welfare Measurement, Sustainability, and Green Accounting.* Cheltenham, UK.

Ayres, R.U. and A.V. Knesse. 1969. "Production, Consumption, and Externalities." *American Economic Review*, 59: 282-297.

Bell, M.L., A. McDermott, S.L. Zeger, J.M. Samet, F. Domenici. 2004. "Ozone and Short-Term Mortality in 95 US Urban Communities, 1987-2000." *J. of the Amer. Medical Association,* 17: 2372-2378.

Bureau of Economic Analysis. 1994. Integrated Economic and Environmental Satellite Accounts. Survey of Current Business. p 50-72.

Cairns, R. D. 2000. "Accounting for Resource Depletion: A Microeconomic Approach." *Review of Income and Wealth,* 46(1): 21-31.

de Boo, A. J., P.R. Bosch, C.N. Garter, S. J. Keuning. 1991. An environmental module and the complete system of national accounts. Number NA-046. Netherlands Central Bureau of Statistics.

Dockery, D.W., C.A. Pope, X. Nu, J.D. Spengler, J.H. Ware, M.E. Fay, B.G. Ferris, F.E. Seizer. 1993. "An association between air pollution and mortality in six U.S. cities." *New England J. of Medicine*, 329: 1753-1759.

Fearnside, P.M. 2004. Greenhouse gas emissions from hydroelectric dams: Controversies provide a springboard for rethinking a supposedly "clean" energy source, Climatic Change 66(1-2): 1-8.

Freeman, A.M. 2002. "Environmental policy since Earth day I: what have we gained?" *J. Econ. Perspectives*, 16: 125-146.

Gundimeda, H., Sukhdev, P., Sinha, R.K., Sanyal, S. 2007. "Natural resource accounting for Indian states – Illustrating the case for forest resources." *Ecological Economics.* 61: 635-649.

Hamilton, K. 1996 "Pollution and Pollution Abatement in the National Accounts." *Review of Income and Wealth,* 42: 13–33.

Hamilton, K. 2000. "Genuine Saving as a Sustainability Indicator." World Bank discussion paper, October 2000.

IPCC (Intergovernmental Panel Climate Change). 2007. *Impacts, Adaptation and Vulnerability*. Cambridge, UK: Cambridge Univ. Press

Jorgenson, D., M. S. Ho, and D. H. Perkins. 1998 "China's Economic Growth and Carbon Emissions" in M. B. McElroy, C. P. Nielsen, and P. Lydon (eds.), *Energizing China* , Cambridge, Harvard University Press pp. 301-342.

Ho, M. S., Jorgenson, D. 2007. "Sector Allocation of Emissions and Damage." in Mun S. Ho and Chris P. Nielsen (eds.), *Clearing the Air: The Health and Economic Damages of Air Pollution in China,* Cambridge, The MIT Press, pp. 279-330.

Keuning, S.J. 1993. "An information system for environmental indicators in relation to the national accounts." In *The Value Added of National Accounting.* (eds.) W.F.M. deVries, G.B. Bakker, M.G. Gircour, S.J. Keuning, and A . Lenson . Voorburg/Heerlen, Netherlands: Netherland Central Bureau of Statistics.

Laden, F., J. Schwartz, F.E. Speizer, D.W. Dockery. 2006. "Reduction in Fine Particulate Air Pollution and Mortality: Extended Follow-up of the Harvard Six Cities Study." *Amer. J. of Respiratory and Critical Care Medicine*, 173: 667-672.

Leontief, W. 1970. "Environmental Repercussions and the Economic Structure: An Input-Output Approach" *Review of Economics and Statistics,* 52(3): 262-271.

Mendelsohn, R.O. 1980. "An Economic Analysis of Air Pollution from Coal-Fired Power Plants" *J. of Environmental Economics and Management*, 7: 30-43.

Muller, N. and R. Mendelsohn, 2007. "Measuring The Damages of Air Pollution in the United States" *J. of Environmental Economics and Management*, 54: 1-14.

Musu, I. and D. Siniscalco. 1996. *National Accounts and the Environment,* London: Kluwer Academic Publishers.

Nordhaus, W.D. and J. Tobin, 1972. "Is Growth Obsolete?" *Fiftieth Anniversary Colloquium V*, New York: National Bureau of Economic Research, Columbia University Press.

Nordhaus, W.D. 1992. "An Optimal Transition Path for Controlling Greenhouse Gases." *Science*, 258: 1315-1319.

Nordhaus, W.D. 1997. *The Swedish Nuclear Dilemma.* Washington D.C: Resources for the Future.

Nordhaus, W.D. and Kokkelenberg, E. (eds). 1999. *Nature's Numbers.* Washington D.C: National Academy Press.

Nordhaus, W.D. 2008. "Issues in non-market accounting: Pollution accounting in theory and practice." in *Measuring Capital – Beyond the Traditional Measures,* Proceedings of the Seminar Session of the 2007 Conference of European Statisticians, United Nations, New York and Geneva, pp. 25-36.

Palm, V., Larsson, M. 2007. "Economic instruments and the environmental accounts." *Ecological Economics.* 61: 684-692.

Peskin, H.M. 1989. "A proposed environmental accounts framework." in *Environmental Accounting for Sustainability*. (eds.) Ahmed, Y.J., El Serafy, S., Lutz, E. Washington D.C: World Bank.

Pope, C.A., R.T. Burnett, M.J. Thun, E.E. Calle, D. Krewski, K. Ito, G.D. Thurston. 2002. "Lung Cancer, Cardiopulmonary Mortality, and Long-Term Exposure to Fine Particulate Air Pollution." *J. of the Amer. Medical Association*, 287 (9): 1132-1141.

Repetto, R. 1989. *Wasting Assets: Natural Resources in the National Income Accounts.* Washington, D.C: World Resources Institute.

Stewart, R.L., J.B. Stone, and M. L. Streitwieser. 2007. "U.S. Benchmark Input-Output Accounts, 2002." *Survey of Current Business*.

Tol, R.S.J. 2005. "The marginal damage costs of carbon dioxide emissions: an assessment of the uncertainties." *Energy Policy*, 33:2064-2074.

Tong, D., N. Muller, D. Mauzerall, and R Mendelsohn. 2006. "An Integrated Assessment of the Spatial Variability of Ozone Impacts from Emissions of Nitrogen Oxides" *Environmental Science and Technology* **40**: 1395-1400.

United Nations. 2003. *Handbook of National Accounting: Integrated Environmental and Economic Accounting*, Series F, No.61, Rev.1 (ST/ESA/STAT/SER.F/61/Rev.1), New York, United Nations.

United States Environmental Protection Agency. 1999. *The Benefits and Costs of the Clean Air Act: 1990--2010.* EPA Report to Congress. EPA 410-R-99-001, Office of Air and Radiation, Office of Policy, Washington, D.C.

United States Environmental Protection Agency. 2006. *National Emissions Inventory (NEI), 2002*. Washington, DC: Office of Air Quality Planning and Standards, Emissions Inventory Group; Emissions, Monitoring, and Analysis Division.

United States Department of Energy, Energy Information Agency, 2008.

United States Department of the Treasury, Internal Revenue Service, 2000. Revenue Procedure No. 1992-91 (Rev. Proc. 1992-91).

Uno, K. and Bartelmus, P. (eds) 1998. "Environmental Accounting in Theory and Practice." Dordrecht: Kluwer Academic Publishers.

Vardon, M., Lenzen, M., Peevor, S., Creaser, M. 2007. "Water accounting in Australia." *Ecological Economics.* 61: 650-659.

Viscusi, W.K., J.E. Aldy. 2003. "The Value of a Statistical Life: A Critical Review of Market Estimates Throughout the World." *J. of Risk and Uncertainty.* 27(1): 5-76.

Woodruff, J.D. Parker, K.C. Schoendorf. 2006. "Fine Particulates Matter ($PM_{2.5}$) Air Pollution and Selected Causes of Post neonatal Infant Mortality in California." *Environmental Health Perspectives,* 114(5): 786-790.

World Bank. 1997. *Expanding the Measure of Wealth: Indicators of Environmentally Sustainable Development.* World Bank. Washington DC.