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Environmental Accounting for Pollution in the United States Economy†

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This study presents a framework to include environmental externalities into a system of national accounts. The paper estimates the air pollution damages for each industry in the United States. An integrated-assessment model quantifies the marginal damages of air pollution emissions for the US which are multiplied times the quantity of emissions by industry to compute gross damages. Solid waste combustion, sewage treatment, stone quarrying, marinas, and oil and coal-fired power plants have air pollution damages larger than their value added. The largest industrial contributor to external costs is coal-fired electric generation, whose damages range from 0.8 to 5.6 times value added. (*JEL* E01, L94, Q53, Q56)

An important and enduring issue in environmental economics has been to develop both appropriate accounting systems and reliable estimates of environmental damages (Wassily Leontief 1970; Yusuf J. Ahmad, Salah El Serafay, and Ernst Lutz 1989; Nordhaus and Edward Charles Kokkelenberg 1999; Kimio Uno and Peter Bartelmus 1998).

Some of this literature has focused on valuing natural resources such as water resources, forests, and minerals (Henry M. Peskin 1989; World Bank 1997; Robert D. Cairns 2000; Haripriya Gundimeda et al. 2007; Michael Vardon et al. 2007). Other studies have focused on including pollution. For example, the earliest papers that focused on pollution relied on material flows analysis to calculate the tons of emissions per unit of production by industry (Robert U. Ayres and Allen V. Kneese 1969). This has been formalized in the Netherlands (Steven J. Keuning 1993) and in Sweden (Viveka Palm and Maja Larsson 2007). The materials-flow approach is useful for tracking physical flows, but it is inappropriate for national economic accounts because it does not contain values and because the damages associated with different source locations and toxicity are not included.

This paper contributes to this literature in two ways. First, we present a framework to integrate external damages into national economic accounts. The gross

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external damages (GED) from pollution caused by each industry are included in the national accounts as both a cost and an (unwanted) output. Second, we demonstrate that the methodology can be applied in practice. Using empirical estimates of the marginal damages (in effect, the prices) associated with each emission in every county, we calculate the national damages from air pollution damages by industry for the United States.

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. Air pollution becomes another cost of doing business. In regulated industries, firms already engage in some abatement, and such costs are already included as a cost in the existing national accounts. However, GED from the remaining emissions is not incorporated into the accounts.

This paper argues that emissions should be valued by the damage they cause. Several studies have measured national pollution damages (A. Myrick Freeman III 2002; Muller and Mendelsohn 2007; United States Environmental Protection Agency (USEPA) 1999). There have been proposals to integrate economic impacts of pollution into satellite accounts (Bureau of Economic Analysis (BEA)1994; Abram J. de Boo et al. 1991). To date, no national statistical agency has linked pollution damages to industries.

We should note some conventions that we use in constructing our estimates. First, as is standard in national accounting, we rely on market prices to value quantities. That is, marginal values are applied to both marginal and inframarginal units. This implies that GDP estimates do not reflect consumer surplus. Second, we do not assume that the observed prices represent an economic optimum. Rather, market prices may reflect a number of distortions such as taxes or markets that are not perfectly competitive. Third, when the necessary prices are not available, they must be imputed. For example, the national accounts impute a rent for owner occupied housing. This study imputes a price on air pollution emissions equal to marginal damages in order to measure the externalities from air pollution. Finally, the damages due to air pollution are included in this study, but other external effects such as those that take place through water, soils, noise, and other media are not. For example, this paper quantifies the damages due to air pollution emissions from sewage treatment facilities, but it does not report the benefits stemming from water pollution control.

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 (Muller and Mendelsohn 2007, 2009). The model first calculates the total baseline damages from the 2002 levels of emissions across the United States. Next, one ton of a particular air pollutant is then added to baseline emissions at one source and the total (national) damages are recalculated. The change in the total damage is the marginal damage, or the shadow price, of the additional ton emitted from the selected source (Muller and Mendelsohn 2007). This calculation captures the effects of secondary pollutants and pollution interaction effects. We then repeat this process for each of the 10,000 sources in the United States and for each of six primary pollutants.[1] Multiplying the estimated shadow price times the quantity of emissions by source yields GED caused by that source (Muller and Mendelsohn 2007). Summing GED from all sources within an industry yields GED for that industry. Summing GED across industries within a sector yields GED for that sector. GED reported in this study is the annual damages from emissions in the year 2002. The only exception is the analysis of greenhouse gases, which evaluates the present value of future damages from 2002 emissions. Because we do not evaluate emissions over multiple years, this study does not address either conceptual or methodological issues associated with deflation of GED. Using GED as an index of pollution is a promising subject of further inquiry.

In Section III, we first examine the economy from a sectoral perspective. This provides a broad picture of the sectoral sources of air pollution in the United States economy. The utility sector is by far the largest polluter in the economy, accounting for one-third of air pollution damages. Agriculture, transportation, and manufacturing are also large sources of air pollution damages. Throughout the paper, we compare GED to value added (VA). The purpose of this comparison is to determine whether correcting for external costs has a substantial effect on the net economic impact of different industries. From this perspective, the agriculture and utility sectors yield the largest GED/VA ratio; both sectors generated GED that constitute over one-third of their VA.

We then turn to the estimation of damages by industry. We find that the ratio of GED/VA is greater than one for seven industries (stone quarrying, solid waste incineration, sewage treatment plants, oil- and coal-fired power plants, marinas, and petroleum-coal product manufacturing). This indicates that the air pollution damages from these industries are greater than their net contribution to output. Several other industries also have high GED/VA ratios. We also present the overall size of GED by industry. Five industries stand out as large air polluters: coal-fired power plants, crop production, truck transportation, livestock production, and highway-street-bridge construction.

In order to explore the robustness of our results to certain assumptions in the integrated assessment model, we conduct a sensitivity analysis. The analysis shows that the level of GED is sensitive to assumptions about the value of mortality risks, how this value varies by age, and the adult mortality dose-response function for particulate matter. A final analysis examines the fossil fuel electric generating industry in detail. It presents a more detailed calculation of GED for coal-fired power plants and it includes the impact of carbon dioxide (CO_2). The paper concludes by reviewing key results, and raising promising future research opportunities.

I. 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

[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.

national accounts to incorporate externalities. We address several important analytical questions in this section.

A. *Treatment of the Environment in the Standard National Accounts*

National economic accounts are based on the principle that they cover those activities that are included in market activities. 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. For simplicity, we will discuss only the current-price accounts, and our empirical application is for a single year. Constructing a constant-price time series would require both time series for all values and defining price indexes for each of the environmental variables, which is beyond the scope of the present study.

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 nonmarket accounting as follows (Katharine G. Abraham and Christopher 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.*

One widely discussed set of accounts is the Satellite Economic and Environmental Accounts (SEEA) (United Nations 2003; Palm and Larsson 2007). SEEA attempts to bring together economic and environmental data in a common framework to measure the contribution of the environment to the economy and the impact of the economy on the environment. There are four different categories of accounts in SEEA, including flow accounts, environmental expenditures, natural resource accounts, and valuation accounts. At present, however, SEEA does not include a full treatment of how to incorporate environmental flows into the national economic accounts.

In order to value pollution emissions, one could employ either marginal abatement costs or marginal damages (Nordhaus and James Tobin 1972). Of course, if regulations are perfectly efficient, these two measures would be identical. But if pollutants are underregulated (overregulated), marginal damages will exceed (be less than) marginal costs. From a conceptual point of view, damage-based pricing is necessary to implement a welfare-based measure of pollution output.

The BEA made an effort to build a system of environmental accounts; the IEESA (Integrated Economic and Environmental Satellite Accounts) were developed in 1994 but this effort was derailed by the Congress. The National Academy of Sciences reviewed the IEESA and other accounting efforts in a major report on environmental accounting (Nordhaus and Kokkelenberg 1999). Other contributors to the theory of environmental accounts include Kirk Hamilton (1996, 2000) and Ignazio Musu and Domenico Siniscalco (1996). There has been little progress, however, in developing a practical environmental accounting system that can be integrated with the national economic accounts.

One important empirical study to note is the recent work of Mun S. Ho and Dale W. Jorgenson (2007) that computes air pollution damages by sector in China. This work reports the health damages from emissions of total suspended particulates (TSP), nitrogen oxides (NO_x), and sulfur dioxide (SO_2) for 33 sectors of the Chinese economy. The study makes the important step of estimating the value of air pollution emissions, rather than simply reporting the quantity of emissions as prior research has done. The values reported by Ho and Jorgensen, however, are based on the average impact of emissions within industries, rather than the preferred marginal damage of each emission. This paper improves upon the Ho-Jorgenson study by using source-specific marginal damages, and by reporting both industry and sector damages.

B. *National Accounts with Pollution*

Our discussion focuses primarily on the "production accounts." It is important to develop the accounts further to include a full or integrated set of accounts. The gold standard for integrated accounts has been laid out by Jorgenson and J. Steven Landefeld (2006). An integrated set of accounts includes not only the production accounts developed here but also the income or receipts accounts, the balance sheet with assets and capital, as well as international accounts. The most important next steps would be income and asset accounts. Nordhaus (2008a) discusses environmental income accounts, while the BEA (1994) discusses environmental asset accounts. Developing these further steps in a complete set of environmental accounts is on the agenda for future research.

We begin our discussion of the fundamentals of environmental accounts with an example, and then provide a graphical interpretation of the appropriate accounting. 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. 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 market failure due to the public good nature of pollution, the power industry does not take into account its effect on the berry farmers when choosing inputs, outputs, and technology and, hence, there is an externality.

If the externalities exclusively 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. Net national output is correctly measured. The standard accounts do not, however, measure industry output correctly because they do not include the (external) costs to the berry industry of the operations of the power industry. From the national accounts perspective, the power industry has no external costs, but the berry industry is smaller than it would be if pollution did not exist.

In practice, most of the externalities are to nonmarket sectors such as health, visibility, and recreation, which are not measured in the accounts. The traditional national accounts do not measure these losses and, therefore, they 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 allocated 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. If the polluter receives the permits without cost, GED is the correct measure of the omitted environmental costs of that industry.

If, however, the polluter pays for the pollution (either by buying permits or through pollution taxes), the costs of the pollution would be part of the firm's cost of production under standard accounting principles. To avoid double counting, the costs of the permits should be subtracted from GED to obtain *net external damages*, or NED. In most cases today, firms receive permits free of charge, in which case NED equals GED, so environmental accounts can use GED as the correct measure. In the future, however, if the volume of trade increases, if pollution allowances are subject to auction, or if pollution taxes become prominent, one would need to adjust GED by subtracting permit costs or taxes. In the very unlikely case where the permit price is exactly equal to marginal damages, NED is equal to zero and no adjustment would be necessary to include environmental damages in the economic accounts.[2]

Note that the adjustment to output depends therefore on the institutional arrangement concerning how pollution is regulated (for example, how initial permits are allocated in a cap-and-trade system). The adjustment is conceptually separate from the

[2] If the marginal damage exceeds the permit price, NED is still positive and traditional accounts continue to overestimate the industry's VA. If, however, the permit price exceeds marginal damage, NED is negative. In this case, the correct VA for the industry is higher than the traditional accounts suggest because the pollution regulation is overly strict.

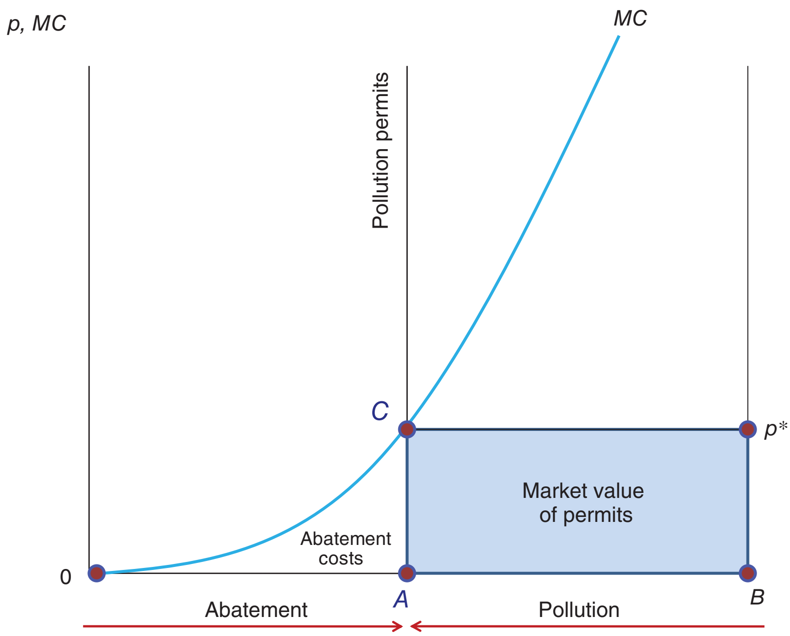

FIGURE 1. ABATEMENT COSTS

Notes: This figure shows the marginal cost of abatement function for a typical pollutant. Pollution is limited by regulation to the vertical line marked "pollution permits." The area *OAC* is the total cost of abatement, which is captured by traditional national accounts. The area $BACp^*$ is the market value of pollution permits if firms had to buy all of their permits at market prices.

property-rights question of whether the polluter must compensate the affected parties—whether the polluter-pays principle applies (Nordhaus 2008a). 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. Whether a firm should obtain pollution permits at zero cost, however, or pay for them is a property rights issue.

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." Complete abatement is marked as B. If firms must buy the permits in an auction, 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 show the total abatement cost as the area *0AC*, marked "Abatement costs." These

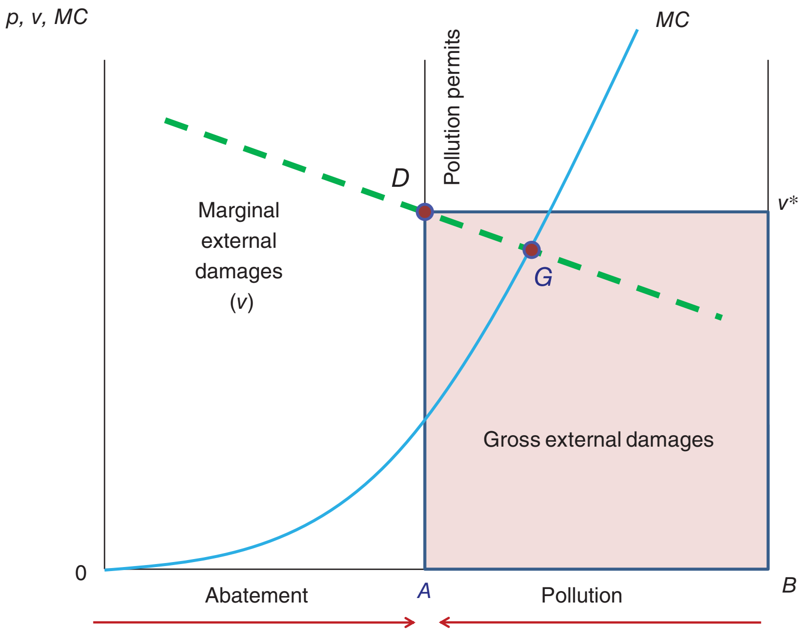

Figure 2. Damages from Pollution

Notes: This figure shows the accounting treatment if firms are freely allocated pollution permits. The marginal damage function of pollution is the dashed line. GED is the shaded rectangle $BADv^*$ that represents the product of emissions times marginal damage.

costs are incurred by firms and are already included in the measured costs of production. Because permits are freely allocated, we need not make any further adjustment for abatement costs in the environmental accounts.

Figure 2 shows the accounting for pollution damages in our framework. We show as a dashed line the marginal damage function of pollution. In the diagram, marginal damages fall with increased abatement (rise with increased 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." Figure 2 illustrates an important point: the accounting rule should be valid whether or not regulations are optimal. Point G is at the optimal regulation, where the marginal costs equal marginal damages. The example shown in Figure 2 assumes that the regulations are not optimal, so the equilibrium is at point D, not at point G.

Finally, if firms must buy all of their permits, we show how the accounting framework in Figure 2 must be modified in Figure 3. GED is the same as in Figure 2. We need to subtract the cost of the permits, however, to calculate net external damages. NED is GED minus the payments for permits, which is the upper rectangle in Figure 3.

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 and financial

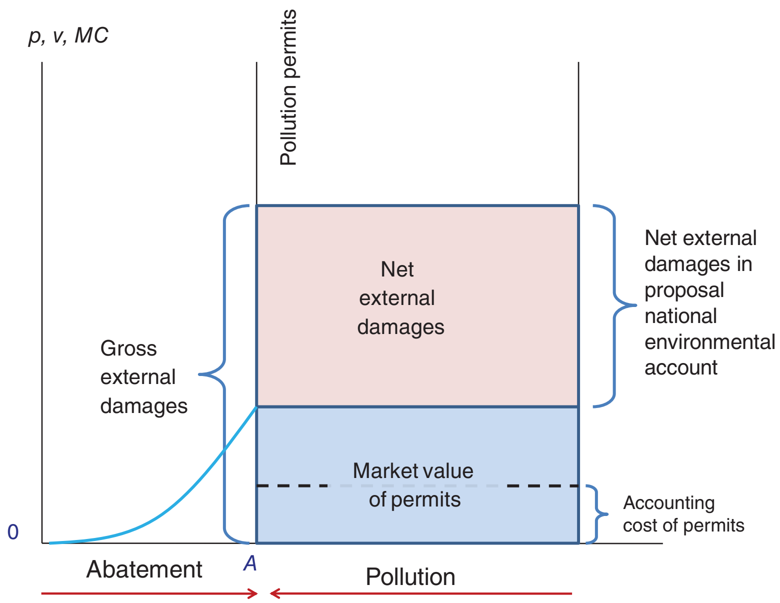

Figure 3. Net External Damages

Notes: This figure shows the accounting treatment if firms must buy all permits (or make emission tax payments) at market prices. 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. Net external damages do not have to be positive.

accounts and in the National Income and Product Accounts (NIPAs) of the United States.[3] From an economic point of view, we would expect that the inputs of pollution would be valued at their current or replacement cost.[4] This means that pollution permits should be valued at their market value. The tax and financial accounting for permits, however, do not generally use market-value pricing, and the structure of the NIPAs excludes the value of permits under the current US regulatory regime and accounting conventions.

For the United States, tax accounting is well defined for the sulfur dioxide allowances governed by the Acid Rain Program. According to Internal Revenue Service guidelines, there are three important points. First, virtually all allowances are allocated to firms based on their historical emissions. When allowances are allocated to utilities, this does not involve a financial transaction and is therefore not recorded in the books of either the firms or the government. On the corporation's books, the allowances are capitalized as an intangible asset at zero cost. 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.

[3] This description has benefited from information from the staff of the BEA.

[4] The United Nations 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.

Second, the allowances are not depreciated or amortized. 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 is included as a depreciation charge for an intangible asset 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 (US Department of the Treasury 2000).

Third, under accounting principles used in the United States, the NIPAs remove depreciation or amortization of intangible assets that are not capitalized in the national accounts. Because allowances are not currently capitalized, they will not be depreciated. This implies therefore that, in principle, none of the transactions associated with the SO_2 allowance program is currently recorded as transactions in the NIPAs.

The treatment of permits under financial accounting is currently under review by US 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.

While the appropriate treatment of permits is evolving, our judgment is that the accounting costs of permits in the NIPAs are a negligible fraction of the replacement cost of those permits. This judgment is primarily based on two observations concerning the current accounting and regulatory regime in the United States. First, most industries are governed by command-and-control regulations, which allow emissions without payment up to the specified standard. Second, those industries regulated by cap-and-trade programs obtain allowances through allocation at zero cost. Current treatment in the national accounts would in principle exclude any costs both because it is a zero-cost basis and because it involves an uncapitalized intangible asset. In principle, therefore, the national accounts would treat NED as equal to GED.

In summary, the empirical estimates below assume that the accounting costs of pollution allowances included in the national accounts and in the input-output estimates are zero. We consequently rely on the analysis in Figure 2 for our estimates of the cost of air pollution in the United States. That is, we assume that NED equals GED. This assumption must be reviewed as institutions or regulations change because the future accounting cost of permits may not be zero, particularly if future allowances are auctioned by the government.

II. Modeling Methods

In this section, we describe the methods that are employed to estimate the GED from different kinds of air pollution by sector and industry. We begin with an exploration of the integrated assessment model that is used to compute the marginal damage estimates. The discussion focuses, in particular, on how the impacts on human health are modeled. Next, we discuss the values that are employed to characterize the impact of CO_2 emissions. Finally, we show how GED is computed for specific sources and by industry.

A. *The APEEP Model*

This paper uses the Air Pollution Emission Experiments and Policy (APEEP) analysis model, which is an integrated assessment economic model of air pollution for the United States (Muller and Mendelsohn 2007).[5] The APEEP model connects emissions of six major pollutants (sulfur dioxide (SO_2), nitrogen oxides (NO_x), volatile organic compounds (VOCs), 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 is an integrated assessment model that employs the USEPA national emission inventory of air pollution emissions in the United States, along with an air quality model to calculate the resulting air pollution concentrations across the country. Using detailed, county-level inventories of sensitive receptors, the model determines exposures to these emitted pollutants, and APEEP computes the resulting physical consequences by relying on peer-reviewed dose-response functions. Finally, the model expresses these physical effects in monetary terms using standard estimates of the value of mortality and morbidity risks. APEEP generates national concentrations, exposures, and damages quite similar to other integrated assessment models. For example, it estimates a baseline level of damages similar to models used by the USEPA (Muller and Mendelsohn 2007).

The important advance from using the APEEP model is that we can measure the marginal damage of emissions from each source location in the United States rather than the average damages (Muller and Mendelsohn 2009). This is accomplished by first estimating an aggregate level of damages given baseline emissions (USEPA 2006). We then add one ton of each pollutant in each source location (one pollutant and source for each calculation) and recalculate the total damages of all emissions. The change in total damages between the baseline and the incremental run is the marginal damage 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. Further, in this application each emission source is attributed to a particular industry in the US economy.

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 United States. This leads to a marginal damage for all anthropogenic emissions of the six air pollutants listed above in the US; hence, 60,000 marginal damages are produced by the analysis. In estimating total damages from air pollution, this study uses the national accounting (NIPA) methodology described in Section I. That is, pollution damages are valued using the total emissions times the marginal damages of an additional unit of pollution.

[5] For earlier examples of integrated assessment models, see Mendelsohn (1980), Nordhaus (1992), USEPA (1999).

The 10,000 emission sources represent a complete inventory of all anthropogenic sources of these six pollutants in the United States (USEPA 2006). The inventory reported in 2006 is the most recent USEPA inventory, and measures emissions in 2002.[6] 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 United States.[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 annual concentrations in all destination counties from each emission. This step entails modeling dispersion from wind patterns at each source location. The model is enhanced to include atmospheric chemistry as well. The model approximates important chemical reactions which cause the emitted substances to change into different pollutants that produce large damages. For instance, SO_2 is transformed into sulfate ($PM_{2.5}$) and emissions of NO_x, and VOC are transformed into concentrations of tropospheric ozone (O_3) and nitrate ($PM_{2.5}$). These daughter products are then 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 predicted annual pollution concentrations of APEEP are highly correlated with the results from a state-of-the-art air quality model (see Muller and Mendelsohn 2007). APEEP consequently does a reasonable job of capturing chronic exposures. However, it is not designed to capture daily fluctuations in concentrations and so cannot capture acute events.

We then compute exposures and the physical effects of the predicted exposures. Exposures are determined by first calculating the size of sensitive "populations" in each county. The populations include numbers of people by age, 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 concentration-response relationships from the peer-reviewed literature in the relevant scientific disciplines.[8] Prior studies that have explored air pollution damages suggest that the single most critical concentration-response function is the relationship between (adult) human mortality and chronic exposures to small particulates ($PM_{2.5}$), (USEPA 1999; Muller and Mendelsohn 2007, 2009). The model also includes concentration-response functions governing the relationship between mortality rates and ozone exposures, as well as various functions capturing morbidity impacts, agricultural and timber yield effects, 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

[6] Since the analysis in this paper was completed, the 2005 inventory was released.
[7] The data are provided by the USEPA 2002 National Emission Inventory (USEPA 2006).
[8] The full list of dose-response functions used in APEEP is found in Muller and Mendelsohn (2007).

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 damage 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). To count human exposures, APEEP contains an inventory of populations in each county 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 C. Arden Pope III et al. (2002), which tracks a large sample of individuals distributed across nearly 200 cities in the United States. Because mortality effects are subject to considerable uncertainty and are also so important to total GED, we estimate results using both the Pope et al. (2002) study and another analysis (Francine Laden et al. 2006) in the sensitivity analysis. In order to capture the effect of $PM_{2.5}$ on infant mortality rates, we employ results from the recent study by Tracey J. Woodruff, Jennifer D. Parker, and Kenneth C. Schoendorf (2006). APEEP also calculates the relationship between exposures to tropospheric ozone (O_3) and adult mortality rates using the study by Michael L. Bell et al. (2004). In addition to mortality effects, APEEP accounts for the relationship between exposures to air pollution and a collection of acute and chronic illnesses, such as chronic bronchitis and chronic asthma (see Muller and Mendelsohn 2007).

Translating the health effects into economic losses requires determining an economic value for premature mortality. The baseline analysis, referred to as Case I, treats premature mortality in terms of the life-years lost rather than just a death. The value attributed to premature mortality among persons in age cohort (a) in county (c), denoted ($V_{a,c}$), is the sum of the annual mortality risk premium (R) times the expected number of life-years remaining. In addition, the value affixed to future years of life are discounted and weighted by the probability of each age group surviving to the next time period. This computation is shown in equation (1):

$$V_{a,c} = \sum_{t=0,\ldots,Ta,c} \left[R\Gamma_{Ta,c}(1 + \delta)^{-t} \right], \quad (1)$$

where

$V_{a,c}$ = present value of a premature mortality of person in age-cohort (a) in county (c),

R = annual mortality risk premium, (\$/life-year),

$T_{a,c}$ = the number of life-years remaining for persons in age-cohort (a), in county (c),

[9] APEEP has been updated to include more detailed mortality rate data for people over 65. This improvement leads to higher mortality rates than reported in Muller and Mendelsohn (2007, 2009).

$\Gamma_{T,a,c} =$ cumulative probability of survival to period (T) for age-cohort (a), living in county (c), *and*

$\delta =$ discount rate.

The annual mortality risk premium (R) is determined by calculating a value of R such that the present value of the expected life-years remaining equals the value of a statistical life (VSL) for an average worker. For example, with a VSL of \$6 million (USEPA 1999) and a discount rate of 3 percent, for an average 35-year-old male worker, R is approximately \$265,000 (\$/life-year).

This approach leads to a social value of early mortality that is higher for younger people and lower for the elderly. This is a controversial assumption. As a result, we also employ an alternative approach in the sensitivity analysis in which the value $(V_{a,c})$ is held constant regardless of the age of the exposed population. The relationship between mortality valuation and age could also follow alternative patterns (W. Kip Viscusi and Joseph E. Aldy 2003).

Another key assumption is the magnitude of the value placed on mortality risks. This study values mortality risks using evidence from both revealed preference studies and stated preference studies in the literature. Specifically, we employ a value of a statistical life (VSL) of \$6 million per premature mortality. This figure represents the mean of 28 studies reviewed by the USEPA and it is used by the agency in their analyses of the benefits and costs of the Clean Air Act (USEPA 1999). In order to explore the impact that different VSLs have on GED, we explore two alternative values of \$2 million and \$10 million in the sensitivity analysis. The lower value stems from a meta-analysis of revealed-preference methods (Janusz R. Mrozek and Laura O. Taylor 2002) and the upper value comes from Viscusi and Michael J. Moore (1989). Further, the \$10 million and \$2 million values reflect a range of one standard deviation above and below the mean value of \$6 million from the distribution of studies reviewed by the USEPA (USEPA 1999).

For the electric power industry, we make one final calculation by including the damages from CO_2 emissions. Although we were interested in making this analysis across all industries, estimates of CO_2 emissions are not yet available for all industries. However, CO_2 emissions have been calculated for the fossil fuel electric power generators (United States Energy Information Administration 2008). CO_2 contributes to global warming, causing a stream of damages far into the future. Several studies have estimated the global damages per ton, also referred to as the social cost of carbon, of emissions (see Richard S. J. Tol 2005; IPCC 2007; Nordhaus 2008b). We rely on these estimates to place a value on carbon (C) emissions by industry. As a central estimate, we use the estimate from Nordhaus (2008b) of $\$27/tC$.[10] 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). Note that these values apply to emissions in 2002. As concentrations of CO_2 increase in the atmosphere, the social cost of carbon is expected to rise over time (Nordhaus 2008b).

[10] Note that these values are expressed in terms of 2000 USD per ton of carbon. The $\$27/tC$ is equivalent to \$7.4 per ton of carbon dioxide.

B. *Gross External Damages*

The USEPA 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 United States. Each source is assigned to a six-digit industry code (i) from NAICS. As discussed above, the APEEP model estimates the marginal damage of an emission of pollutant (s) from each location (j), $MD_{s,j}$. GED is calculated by multiplying the emissions $(E_{s,i,j})$ times the location and pollutant-specific marginal damage $(MD_{s,j})$. $GED_{s,i,j}$ attributed to source (j) in industry (i) emitting pollutant (s) as shown in equation (2):

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

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:

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

For each six-digit NAICS industry, we measure the ratio of GED_i to value added (VA_i). The VA of an industry is the market value of output minus the market value of inputs, not including the factors of production—labor, land, and capital. The VA data are gathered from the BEA and from the US Census Department 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 location (j).

III. Results

The following section begins by exploring GED for each sector of the US economy. We then move to an analysis of GED by industry. Next, we present the results from our sensitivity analysis. Finally, we examine, in detail, GED for the electric power generation sector as well as the damages due to CO_2 emissions from this sector.

A. *Gross External Damages by Sector*

We begin by presenting estimates of air pollution damages by sector to see what parts of the US economy are responsible for the predicted air pollution damages. Table 1 shows GED and the GED to VA ratio for the market economy by two-digit sector codes. The bottom row in Table 1 indicates that the total GED across all market sectors of the economy in 2002 is $184 billion. The utility and agriculture-forestry sectors stand out as the largest polluters, generating 50 percent of this

[11] The sources of data used in this analysis are shown in the online Data Appendix (see Appendix A3 in supplementary materials).

Table 1—Gross External Damages and GED/VA Ratio by Sector

Sector	GED	GED/VA
Agriculture and forestry	32.0	0.38
Utilities	62.6	0.34
Transportation	23.2	0.10
Administrative, waste management, and remediation services	10.7	0.08
Construction	14.7	0.03
Arts, entertainment, and recreation	2.2	0.03
Accommodation and food services	4.2	0.02
Mining	3.3	0.02
Manufacturing	26.4	0.01
Other services	1.0	0.01
Wholesale trade	1.2	0.00
Retail trade	1.7	0.00
Information	0.0	0.00
Finance and insurance	0.0	0.00
Real estate services	0.0	0.00
Professional, scientific, and technical services	0.0	0.00
Management	0.0	0.00
Educational services	0.0	0.00
Health care services	0.7	0.00
Total all sectors	184.0	

Note: GED in $ billion per year, 2000 prices.

GED. The utility sector generates the largest GED of all sectors, roughly $63 billion/year, which is 34 percent of its value added. One-third of the total GED is due to emissions from the utility sector. The agriculture-forestry sector generates $32 billion of GED with a GED/VA ratio of 38 percent. The transportation sector generates another $23 billion of GED. This sector produces a GED that is equivalent to 10 percent of its VA. The GED/VA ratios for all of the remaining sectors indicate that GED is less than 10 percent of VA. Nonetheless, a few of the other sectors do contribute sizable GED. For example, the manufacturing sector generates GED of $26 billion, the construction sector produces GED of nearly $15 billion, and the administrative-waste management sector yields GED of close to $11 billion.

B. *Gross External Damages by Industry*

We now turn to a more detailed accounting of the economy by industry. Table 2 reports GED and the ratio of GED to VA by six-digit NAICS code for industries that meet the following two criteria: either GED/VA ratios above 45 percent or GED above $4 billion. The 820 industries in the United States are ranked according to GED and GED/VA ratio (the complete table is available in online Appendix A-1). Conceptually, GED represents an additional set of costs (predominantly costs to nonmarket sectors such as human health) associated with production. Therefore, incorporating GED into a measure of *net* VA provides a more complete assessment of industry VA than when these costs are omitted from the current accounts. The table does not include the value of carbon dioxide emissions. All results are in year 2000 prices. Also, note that the values reported in Table 2 do not reflect any nonmarket services or costs aside from GED.

Table 2—Gross External Damages and GED/VA Ratio by Industry

Industry	GED/VA	GED
Solid waste combustion and incineration	6.72	4.9
Petroleum-fired electric power generation	5.13	1.8
Sewage treatment facilities	4.69	2.1
Coal-fired electric power generation	2.20	53.4
Dimension stone mining and quarrying	1.89	0.5
Marinas	1.51	2.2
Other petroleum and coal product manufacturing	1.35	0.7
Steam and air conditioning supply	1.02	0.3
Water transportation	1.00	7.7
Sugarcane mills	0.70	0.3
Carbon black manufacturing	0.70	0.4
Livestock production	0.56	14.8
Highway, street, and bridge construction	0.37	13.0
Crop production	0.34	15.3
Food service contractors	0.34	4.2
Petroleum refineries	0.18	4.9
Truck transportation	0.10	9.2

Notes: GED in $ billion per year, 2000 prices. Industries included in Table 2 have either a GED/VA ratio above 45 percent or a GED above $4 billion/year.

Table 2 shows that of the 17 industries meeting the criteria above, four (or nearly one-quarter) belong to the manufacturing sector, while three of the industries are in the utility sector. Agriculture, waste management, and the transportation sectors each contribute two industries.

Seven industries have air pollution damages that are clearly larger than their VA. These seven are solid waste combustion, petroleum-fired electric power generation, sewage treatment, coal-fired electric power generation, stone mining and quarrying, marinas, and petroleum and coal products. The ratios of damages to VA across these five industries range from 6.7 for solid waste combustion to 1.4 for petroleum and coal products. The fact that GED exceeds VA implies that if the national accounts included the external costs due to air pollution emissions, the augmented measure of VA for these industries would actually be negative. If these external costs were fully internalized, either through purchases of pollution allowances or emission tax payments valued at the marginal ton, and if output and input prices did not change, the magnitude of the external costs would exceed the market VA for these seven industries. Of course, if the external costs were fully internalized, prices would change, so the results do not imply that the US economy would be better off not having these industries at all.

How should these high GED/VA ratios be interpreted? One interpretation is that the air pollution from these industries is not efficiently regulated—that the marginal damages exceed the marginal cost of abatement. We can work through the implications of inefficient pricing for a specific example. The sulfur dioxide (SO_2) from coal-fired electric power generators is currently regulated by a cap-and-trade program under the Clean Air Act. A recent analysis suggests that the cap on SO_2 is far too high (Muller and Mendelsohn 2009). The marginal damages of emissions from most plants exceed the marginal cost of abatement as measured by the market price of permits (see Figure 4).

To equate the marginal cost of abatement with marginal damages, the quantity of allowances should be sharply reduced. At the efficient level of emissions, the cost

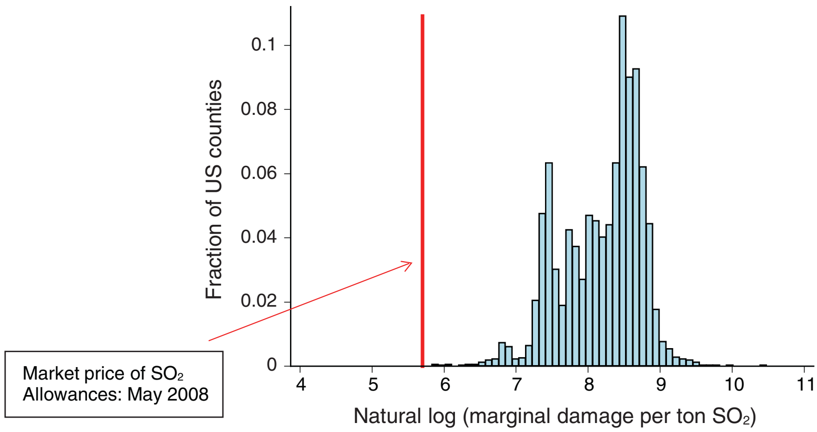

Figure 4. Calculated Marginal Damages from SO_2 and the Market Price of SO_2 Permits by County

of abatement would increase slightly, but GED would fall substantially (Muller and Mendelsohn 2009). An efficient regulatory program that equated marginal damage to marginal cost would lower GED to less than 20 percent of current levels.[12] Additionally, the higher abatement costs would probably be partially offset by higher prices for electricity from these plants. Thus, for coal-fired power plants, the current GED/VA ratio of 2.2 stems primarily from inefficiently high levels of emissions, as well as electricity prices that do not reflect social costs.

A second explanation concerning why some of these industries have high GED/VA ratios is that the VA as measured in the current national accounts may not accurately capture the value of their services. Solid waste combustion facilities, sewage treatment plants, and marinas all provide valuable nonmarket services that are not correctly measured by prices in the national accounts. The national accounts measure the value of these nonmarket services by the cost of production such as sewage fees, tipping fees, and landing costs. However, if the value of these services exceeds the fees, the VA would be undervalued. It is clearly beyond the scope of this study to provide adequate measures of the nonmarket services for these sectors, although a complete set of environmental accounts would include them. It is important to note, however, that the external costs should be included in the decisions about the proper level of nonmarket services, just as they should be for market services. For example, suppose that the output of sewage treatment plants were set to balance marginal costs with marginal benefits. If the marginal costs exclude the external costs, then the output level of sewage treatment would be inefficiently high in just the way that those of coal-fired electric power generators are excessively high as described in the last paragraph.

There are several other industries with relatively high GED/VA ratios. Water transportation and steam heat and air conditioning suppliers have GED/VA ratios close to one. The GED/VA ratios of sugarcane mills, and manufacturers of carbon black (a dye used in tire manufacturing) are 70 percent, livestock producers are

[12] Note that the results reported in Muller and Mendelsohn (2009) employ a $2 million VSL. With the $6 million VSL used in this study, the reduction in GED from an efficient cap is approximately equal to $30 billion.

56 percent and highway, street, and bridge construction, crop production, and food service contractors are more than one-third. The remaining industries have GED/VA ratios that are 20 percent or less.

Table 2 also reports the magnitude of GED from each industry (not counting CO_2). Coal-fired electric power generators produce the largest GED of \$53 billion annually. Coal plants are responsible for more than one-fourth of GED from the entire US economy. The damages attributed to this industry are larger than the combined GED due to the three next most polluting industries: crop production, \$15 billion/year, livestock production, \$15 billion/year, and construction of roadways and bridges, \$13 billion/year. In declining magnitude of GED, the next two industries are the truck transportation sector which produces GED of \$9.2 billion, and the water transportation sector, generating GED equal to \$7.7 billion. Oil refineries, solid waste combustion, and food service contractors are also large sources of damages.

C. *Sensitivity Analysis*

The GED results described above depend on several assumptions embedded in the integrated assessment model that could be viewed as controversial and uncertain. One potential source of uncertainty is the air quality model that connects emissions to ambient concentrations. In separate analyses, the results of the air quality model used in this paper have been compared to the predictions of a state-of-the-art atmospheric transport and chemistry model, Community Multiscale Air Quality (CMAQ) (Daewon Byun and Kenneth L. Schere 2006).[13] Given the same emissions inventory, both models produce very similar predicted concentrations of $PM_{2.5}$ and O_3 across the United States. That is, the APEEP model has comparable predictive capabilities as the state-of-the-art atmospheric transport model. Of course, that does not mean the air quality model is perfectly accurate across space. Both air quality models are not able to predict the high ambient concentrations observed at some pollution monitoring stations. This may reflect a bias in the model predictions or it may reflect a bias in the locations of the monitors.

In addition to air quality modeling, the results are sensitive to three other assumptions in the integrated assessment model. First, the results are sensitive to the link between exposures to $PM_{2.5}$ and adult mortality rates. Second, the results are sensitive to whether the value of mortality risks varies by the age of the exposed population. Third, the results are sensitive to the dollar value placed on mortality risks. We vary each of these assumptions in a sensitivity analysis. Table 3 reports the results of the sensitivity analysis and we then compare the GED/VA for each perturbation to the findings in Table 2.

The $PM_{2.5}$-mortality dose-response function reported in Laden et al. (2006) suggests that adult mortality rates are almost three times more sensitive to $PM_{2.5}$ exposure than the function reported in Pope et al. (2002). Using this more sensitive dose-response function more than doubles GED/VA. However, the GED/VA ranking of each industry with respect to each other remains very close to the ranking in Case I.

[13] See Muller and Mendelsohn (2007) for a comparison of APEEP and CMAQ.

Table 3—Sensitivity Analysis of Ratio of GED/VA

Industry	GED/VA Case I	GED/VA Case II	GED/VA Case III	GED/VA Case IV	GED/VA Case V
Solid waste combustion and incineration	6.72	14.66	16.75	2.31	11.01
Petroleum-fired electric power generation	5.13	10.97	13.06	1.77	8.25
Sewage treatment facilities	4.69	9.55	12.09	1.64	7.63
Coal-fired electric power generation	2.20	4.83	5.63	0.78	3.63
Dimension stone mining and quarrying	1.89	3.92	4.47	0.76	2.98
Marinas	1.51	3.27	3.84	0.53	2.46
Other petroleum and coal product mfg.	1.35	2.93	3.34	0.48	2.20
Steam and air conditioning supply	1.02	2.18	2.65	0.35	1.68
Water transport	1.00	2.08	2.43	0.35	1.62
Sugarcane mills	0.70	1.59	1.88	0.24	1.15
Carbon black mfg.	0.70	1.55	1.71	0.25	1.15
Livestock production	0.56	1.22	1.41	0.20	0.92
Highway, street, and bridge construction	0.37	0.77	0.90	0.15	0.60
Crop production	0.34	0.73	0.85	0.13	0.55
Food service contractors	0.34	0.72	0.86	0.12	0.56
Petroleum refineries	0.18	0.38	0.44	0.06	0.30
Truck transportation	0.10	0.24	0.28	0.03	0.18

Notes: Case I = baseline assumptions. Case II = employs the adult mortality dose-response function for $PM_{2.5}$ in Laden et al. (2006). Case III = employs the $6 million VSL, applied uniformly to all ages (USEPA 1999). Case IV = changes the VSL to $2 million (Mrozek and Taylor 2002). Case V = changes the VSL to $10 million VSL (Viscusi and Moore 1989). Cases IV and V employ the VSLY methodology used in Case I.

In the second sensitivity analysis, Case III, we apply the same value for mortality risks to populations of all ages. In this case, the GED/VA ratio increases on average by 2.5 times. This occurs because most of the deaths caused by air pollution fall on the elderly. Using a uniform VSL places a higher value on mortality risks faced by this age cohort, relative to the age-variant approach reflected in Case I. This raises the overall GED but again has a limited effect on relative rankings.

In a third sensitivity analysis, we vary the magnitude of the VSL. Relative to the default scenario in which the VSL is $6 million, the GED/VA ratio falls across the board by two-thirds when we employ a VSL of $2 million in Case IV. A similar

Table 4—GED for Coal-Fired Power Plants by Pollutant and Type of Damage

Pollutant/welfare endpoint	SO_2	$PM_{2.5}$	PM_{10}	NO_x	VOC	NH_3	Total
Mortality	44.20	3.53	0.00	2.75	0.03	0.09	50.6
Morbidity	1.64	0.03	0.12	0.18	0.00	0.00	1.97
Agriculture	0.00	0.00	0.00	0.37	0.00	0.00	0.37
Timber	0.00	0.00	0.00	0.02	0.00	0.00	0.02
Materials	0.06	0.00	0.00	0.00	0.00	0.00	0.06
Visibility	0.22	0.01	0.02	0.02	0.00	0.00	0.26
Recreation	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	46.12	3.57	0.14	3.34	0.03	0.09	53.4

Note: GED in $ billion per year, 2000 prices.

experiment with a VSL of $10 million suggests that the GED/VA ratios increase by about 60 percent relative to the default case. Again, the relative rankings of each industry remain largely the same. The sensitivity analyses reveal that the magnitude of the GED/VA ratios is very sensitive to assumptions about the dose-response functions, the magnitude of the VSL, and how the VSL varies by age. However, these assumptions have almost no effect on the relative rankings across industries. There are a few cases where the ranking of industries according to the GED/VA ratio changes. This is caused by the different mix of pollutants emitted by such industries and the resulting differential impact of the modeling assumptions tested in the sensitivity on their GED.

D. *Gross External Damages from Electric Power Generation*

In order to get a better sense of how GED results in each industry are calculated, we explore GED produced by coal-fired power plants in more detail. For each power plant that burns coal, we compute GED using the formula in (2). We then sum GED across pollutants and sources (as shown in expression (3)), which yields industry estimates of damages.

Table 4 reports the results by pollutant and damage type for coal-fired power plants. The table reveals that emissions of SO_2 are responsible for the bulk of the damages (87 percent). Direct emissions of $PM_{2.5}$ and NO_X cause most of the remaining damages. Increased mortality is by far the largest component of the GED from coal-fired facilities, explaining 94 percent of the damages. Most of the mortality impacts are caused by SO_2 emissions with a smaller amount due to discharges of $PM_{2.5}$ and NO_X. Morbidity effects account for another 4 percent of damages. The damages to crops, timber, material, visibility, and recreation services account for the remaining 2 percent of damages.

Table 5 explores GED due to coal-fired, oil-fired, and natural gas power plants. The first three columns estimate GED/VA, GED, and GED per kwh. Coal-fired facilities account for 95 percent of GED of this sector. The electricity produced by coal-fired facilities also has the highest GED per kwh of 2.8 cents. Oil-fired plants have the highest GED/VA ratio (5.13) and a GED/kwh of 2 cents. The GED for natural gas plants is much smaller, $900 million, and these plants have a much lower GED/VA ratio. The GED/kwh for natural gas is just 0.1 cents.

Table 5—Electric Power Generation with Carbon Dioxide Damages

Fuel type	GED/VA	GED	GED/kwh	GED*/VA	GED*	GED*/kwh
Coal	2.20	53.4	0.0280	2.83 (2.3, 3.7)	68.7 (56.8, 90.1)	0.0359 (0.0297, 0.0472)
Petroleum	5.13	1.8	0.0203	6.93 (5.5, 4.5)	2.5 (2.0, 3.4)	0.0274 (0.0219, 0.0374)
Natural gas	0.34	0.9	0.0085	1.30 (0.6, 2.7)	3.4 (1.4, 6.9)	0.0056 (0.0024, 0.0113)

Notes: GED in \$ billion per year, 2000 prices. GED* is GED plus damages from CO_2 emissions using a social cost of carbon of \$27/*tC*. Numbers in parentheses use a lower (\$6/*tC*) and upper (\$65/*tC*) bound estimate for the social cost of carbon (Nordhaus 2008b). GED/kwh and GED*/kwh expressed in \$/kwh.

We also compute the damages from CO_2 emissions for fossil fuel–based electric power generation. Although it would be desirable to make this computation for all industries in the economy, we have data only for CO_2 emissions from the electric power generation sector (USEIA 2008). The last three columns of Table 5 display estimates of GED^*, which we define as gross external damages plus the damages from CO_2 emissions. The damages from CO_2 were estimated by multiplying the tonnage of CO_2 times the social cost of carbon, which is the present value of the stream of additional damages that one more ton of emission will cause over time. We use the social cost of carbon for the year 2000. This cost will rise over time as greenhouse gases accumulate and marginal damages increase. We assume that the central estimate of the social cost of carbon is \$27 per ton of carbon (Nordhaus 2008b).

When climate-change effects from CO_2 are included, the damages caused by oil- and coal-fired power plants are between 30 and 40 percent higher. The damage per kwh increases proportionally. This implies that for coal-fired generators, the GED^*/kwh increases to 3.6 cents. For electricity produced by oil-fired plants, the GED^*/kwh rises to 2.7 cents. These estimates suggest that, when using the central social cost of carbon estimate, CO_2 emissions are responsible for about one-fourth of the total air pollution damages produced by these two industries. Although the damages from CO_2 are large, they are not as large as GED. For the case of coal-fired power plants, CO_2 causes an additional \$15 billion of damage, which is relatively small compared to the GED of \$53 billion.

Using the central social cost of carbon estimate, the GED^*/VA ratio for coal-fired generators is 2.8, and for oil-fired generators the GED^*/VA increases to 6.9. CO_2 has a relatively bigger effect on GED^* for natural gas plants because GED (without CO_2) for natural gas is relatively low. The GED^*/VA ratio for natural gas plants is 1.3, compared to just 0.3 when damages due to CO_2 emissions are not counted.

Table 5 also displays a range for GED^* and GED^*/VA based on the following estimates of the social cost of carbon: \$6/*tC* and \$65/*tC* (Nordhaus 2008b; Tol 2005). Employing these values, GED^* for coal-fired generators ranges from \$56.8 billion to \$90.1 billion given these lower and upper values. The range of GED^* for oil-fired facilities is \$2 billion to \$3.4 billion. GED^* for natural gas plants is between \$1.4 billion and \$6.9 billion.

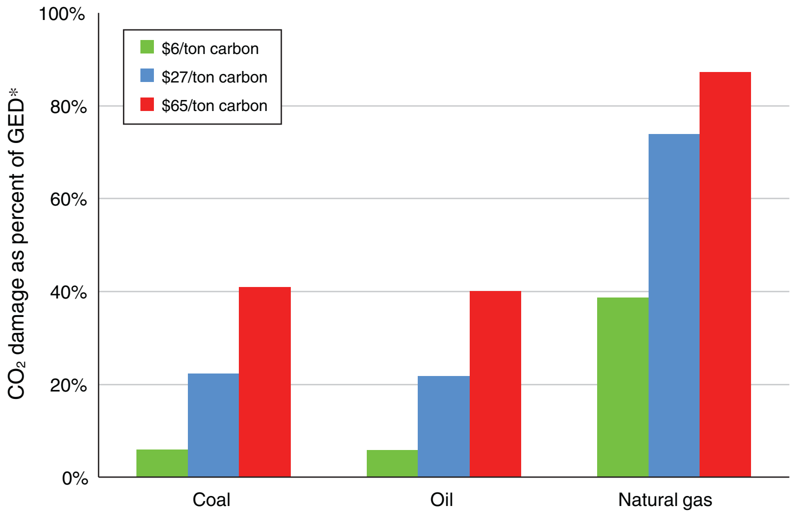

FIGURE 5. PERCENT SHARE OF GED* DUE TO EMISSIONS OF CO_2, FOSSIL FUEL ELECTRIC POWER GENERATORS BY FUEL TYPE

Figure 5 shows the share of GED* that is due to emissions of CO_2 for fossil fuel–based electric power generators. This figure shows the relative value of emissions of the local air pollutants (which comprise GED) and emissions of CO_2. The figure employs the three different estimates of the social cost of carbon that are used in Table 5.

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 local pollutants. In contrast, the CO_2 share of GED* for both coal-fired and oil-fired power generators is between 5 percent and 40 percent. Although coal-fired plants generate a great deal of CO_2, they generate greater damages due to other pollutants.

In 2002, residential consumers of electricity faced an average market price of 8.4 cents per kwh. Hence, the GED*/kwh associated with electric power generation using coal, oil, and natural gas represents 43, 33, and 7 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. The average GED*/kwh of coal-generated electricity is 60 percent of the average residential retail price of electricity in a state relying entirely on coal. In states that rely primarily on natural gas, residential electricity prices averaged 11 cents per kwh. The average GED*/kwh of natural gas–generated electricity is 5 percent of the average residential retail price of electricity in natural-gas states (USEIA 2008).

IV. Conclusions

The present study develops an accounting framework and presents empirical estimates of the external costs of air 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 gross external damages caused by each industry as the marginal external damages times the quantity of pollution at each source location. The accounts would require an adjustment of VA by industry by subtracting net external damages, which equals GED minus the cost of pollution permits or any effluent charges. Under the current regulatory context, where permits tend to have zero cost to firms, NED equals GED. The proposed framework captures the full costs of production to society of each industry. We estimate GED from air pollution for each industry in the United States. Because pollution damages per unit of VA 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 national output.

We note several qualifications. First, our estimates are accounting measures and not measures of economic welfare. The economy has many existing distortions other than those from air pollution—such as taxes, distortions from market power, and other externalities—and existing accounts do not attempt to incorporate those. Second, we note that although GED exceeds VA for some industries, this does not necessarily imply that these industries should be shut down. On a formal level, it signifies that a one-unit increase in output of that industry has additional social costs that are higher than the incremental revenues. At an intuitive level, it indicates that the regulated levels of emissions from the industry are too high. Third, our estimates of GED do not include any accounting costs of emission allowances. We suspect that this assumption introduces a small error, but in fact we cannot determine the sign of the error. Fourth, this study includes only the impact of air pollution and excludes other externalities such as those involving water, soil, and radiation. Fifth, we note that the uncertainties are particularly large for four elements: the value of mortality risks, the relationship of this value to age, the mortality effect of fine particulates, and the social cost of CO_2 emissions. Sensitivity analyses using alternative values for these parameters 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 \$184 billion. Summing up GED across two-digit sectors provides a profile of those sectors of the economy that are the heaviest polluters. The two sectors with the highest GED/VA ratio are agriculture (38 percent) and utilities (34 percent). They are responsible for \$32 billion and \$63 billion of damages, or 17 percent and 34 percent of the total damages produced by market activity, respectively. The sector with the next highest GED/VA ratio is transportation (10 percent), with air pollution damages of \$23 billion. The waste management sector produces GED equivalent to 8 percent of its VA (\$11 billion). Interestingly, while manufacturing is responsible for $26 billion of damages, the GED/VA ratio of manufacturing is low (1 percent).

The GED/VA ratio varies greatly across industries. For some industries (sewage treatment plants, solid waste combustion, stone quarrying, marinas, and petroleum-fired and coal-fired power generation), GED actually exceeds conventionally measured VA. Crop and livestock production also have high GED/VA ratios, 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, carbon black manufacturing, steam heat and air conditioning supply, and sugarcane mills. It is likely that many of these sources are underregulated.

Pollution from households (homes and cars), which reflects nonmarket activity, is not counted in the $184 billion, even though it is an important source of air pollution damages. For example, emissions from light duty cars and trucks produced over $37 billion in air pollution damage and residential combustion of fossil fuels, and wood generated $17 billion in damages in the year 2002.

There are many parameters in the integrated-assessment model that are important for damage assessment. As noted above, the mortality dose-response function, the value of mortality risks, and the relationship between mortality values and age are three particularly important assumptions (Muller and Mendelsohn 2007). We explore alternative values from the literature for these assumptions in a sensitivity analysis. The overall level of GED is sensitive to these assumptions. Further, the assumptions change the estimated impacts of some industries more than others because the mix of pollution emitted varies by industry. However, changing these three central assumptions tends to have a uniform effect on all industries.

There are also broader implications about environmental accounting. The present study shows that it is possible to develop national accounts that include pollution. Moreover, the source data are sufficient to include pollution accounts for detailed industries. While the present study has developed methods and estimates only for air pollution, we believe that it would be feasible to extend the analysis to water pollution, solid waste, and hazardous waste pollution. Given the size and distribution of damages found in this study, the development by national statistical agencies of a full set of environmental accounts embedded in the national economic accounts is clearly warranted. 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 source data that only a government agency possesses.

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