Optimal Environmental Policies for Multiple Externalities of Energy: Theoretically Sound Policy Design & Empirical Evidence from the United States

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Abstract

This paper explores the optimal set of environmental policies for multiple externalities related to energy use. A theoretical model is first developed based on a general equilibrium framework where a multiple output technology is assumed and two public bads (greenhouse gases and local air pollutants) are generated through the use of fossil fuels in the consumption and production processes. The policy in this paper is defined as levying Pigouvian taxes on the users of fossil fuels. Jointly implementing a Pigouvian tax on greenhouse gases and a Pigouvian tax on local air pollutants is the theoretically first-best regulatory mean. The empirical work in this paper draws upon the theoretical findings. A computable general equilibrium (CGE) model for the United States is built to illustrate how ignorance of jointly optimal policies affects the overall welfare, energy production and consumption, environmental consequences, and economic activities. Three scenarios on energy taxes, including taxing greenhouse gases alone, taxing local air pollutants alone, and joint implementation of the above two taxes, are analyzed. Our numerical results are consistent with the optimal policy rule: the United States can achieve a higher welfare gains along with lower fuel use and pollution emissions in the scenario where joint taxes on greenhouse gases and local air pollutants are adopted. The estimated overall welfare gains are $12,308 million, where welfare gains of reductions in climate change damage and in adverse health effects make substantial contributions. With respect to the welfare gains from the reductions in the adverse health effects, the monetary health benefits estimates are dominated by the reductions in acute mortality and the chronic bronchitis effects, which represent about 98 percent of the total monetary health benefits.

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Introduction

One area of the heated discussion on environmental externalities in the recent literature relates to energy use (e.g., Krewitt, 2002; Miranda and Hale, 2002; Parry and Williams, 1999; Vehmas *et al*., 1999). Among the various forms of energy use, fossil fuel[1] combustion has long been recognized by scientists and policymakers as a major cause of serious damages to our environment through greenhouse gas (GHG) emissions and toxic air pollutants. The externalities of these pollution emissions are complex in nature because of the multiple emitting sources and the multiple spatial dimensions of the environmental problems. The multiple emitting sources mean that these externalities may be generated through both private consumption and industrial production. The environmental problems caused by the pollution emissions of fossil fuel combustion involve global and local dimensions.

The global environmental externalities, global warming or climate change, are mainly caused by the accumulation of greenhouse gases arising chiefly from burning fossil fuels (IPCC, 1992).[2] The warming-up of the Earth's atmosphere potentially results in economic damage through a number of different pathways, such as extreme weather events, rising sea levels, changes in rainfall patterns, and the spread of communicable diseases. At the local level, toxic air pollutants, such as particulate matter (PM), emitted from fossil fuel combustion can affect local air quality and have potential serious effects on human health. The health impacts, including mortality and morbidity, are probably the most significant portion of the damage costs from air pollution (Navrud, 2001).

[1] Fossil fuels include coal, crude oil, natural gas, and petroleum products.
[2] It has been estimated that global emissions of CO_2 in 1990 amounted to 6.9 Giga tons of carbon (GtC), of which 5.7 GtC were caused by fossil fuel burning.

Despite the substantial efforts to examine the effects of these global and local air quality externalities, a review of the economics literature shows that the vast majority of the studies have treated them individually.[3] This is typical of most standard environmental models that deal with a single pollutant or single polluting source, either implicitly or explicitly assuming other externalities or sources are fixed or are unimportant. For example, Halkos (1993) discusses the case where only a single pollutant (sulphur) is considered; Crawford and Smith (1995) is another example of a single polluting source, road transport. Although some recent economics research has incorporated the ancillary benefits of targeted environmental policy, they have been primarily focused on only one environmental policy, either at local or global level. One example is the recent attention paid to the ancillary benefits, such as improvement of local air quality and health benefits, of technological and policy options aimed at reducing energy use to achieve the target of greenhouse gases mitigation (e.g. Ekins, 1996; Wang and Smith, 1999; Cifuentes *et al*., 2001).

However, these approaches implicitly ignore the fact that these global and local externalities originate from multiple input and multiple output technology where some outputs are traded in organized markets, and others have no markets because of their externality or public-good nature. Furthermore, with no recognition of the interrelation between energy production and use and these multiple externalities, "compartmentalized" single government programs to deal with each externality separately may actually work at cross-purposes. For these reasons, the proper design of the efficient set of internalizing policies where the use of fossil fuels generates several jointly produced externalities

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[3] Likewise, policies aimed at the various externalities from fossil fuel combustion are typically legislated and administered independently.

remains largely unexplored. The goal of this paper is hence to contribute to this policy design.

This paper consists of two parts, one analyzing the optimal policy design from a theoretical perspective and a second examining the theoretical findings by an empirical framework. Specifically a theoretical model is first developed based on a general equilibrium framework where a multiple output technology is assumed and two public bads (greenhouse gases and local air pollutants) are generated through the use of fossil fuels in the consumption and production processes. Among all market-based policy instruments with which the social planners correct the externalities of energy use, we focus on implementing environmental taxes on fossil fuels. The result indicates that the theoretically first-best regulatory mean is joint implementation of a Pigouvian tax on greenhouse gases and a Pigouvian tax on local air pollutants.

We then develop an empirical framework of computable general equilibrium (CGE) model for the United Sates to illustrate how ignorance of jointly optimal policies affects the overall welfare, environmental consequences, economic costs, and energy production and consumption (fuel choices). Three scenarios on energy taxes, including taxing greenhouse gases alone, taxing local air pollutants alone, and joint implementation of the above two taxes, are analyzed. Our numerical results are consistent with the optimal policy rule: the United States can achieve a higher welfare gains along with lower fuel use and pollution emissions in the scenario where joint taxes on greenhouse gases and local air pollutants are adopted.

The remainder of the paper proceeds as follows. Section 2 first derives the optimal environmental policies with a theoretical model based on general equilibrium framework. Section 3 describes the settings of the empirical model and data sources. Section 4 presents the three scenarios and the designs of numerical simulations. Section 5 discusses the empirical results. The conclusions drawn from our findings and their implications for policy recommendations are examined in the final section.

Theoretically First-Best Regulatory Mean

Let X, Z, E_1, and E_2 represent energy-intensive goods, non energy-intensive goods, fossil fuels, and electricity, respectively. These four commodities can be produced from two primary factors, labor L, capital K, and intermediate inputs X, Z, E_1, and E_2. In addition to being used as intermediate inputs, X, Z, E_1, and E_2 are consumed by private individuals. The use of energy E_1 in production and final consumption processes may generate two types of externalities, including greenhouse gases (P_{GA}) and local air pollutants (P_{LA}). To link the externalities to the volume of fossil fuels E_1 used, we denote the emission factors for energy use in consumption processes $\tau_{GA}^{C_i}$ and $\tau_{LA}^{C_i}$ for consumer i, and in production processes $\tau_{GA}^{F_j}$ and $\tau_{LA}^{F_j}$ for firm j. The total emissions can be expressed as the terms summing up the products of emission factors and corresponding volume of fuels E_1 used.

Let I_{vj} denote the amount of primary factor or intermediate input v used by firm j, where $v = L,K,X,Z,E_1,E_2$ and $j = X,Z,E_1,E_2$, to produce output O_j. The technologies for firm j can be represented by

$T^{j}(I_{Lj}, I_{Kj}, I_{Xj}, I_{Zj}, I_{E_1 j}, I_{E_2 j}) \geq O_j$ and $T^{j}_{I_{vj}} > 0$, where the subscripts of T^{j} denote the first order derivatives.[4]

Assume the size of the population of the economy is N. Individual i derives utility from the consumption of final goods X, Z, E_1, and E_2, and experiences direct disutility from greenhouse gases and local air pollutants. The impact of greenhouse gases on the global environment is assumed to depend on its stock, the sum of initial state of P_{GA} ($\overline{P}_{GA}$), and the current accumulations. Conversely, the stock effects of local air pollutants are very short-lived and are negligible since a reduction in emissions is likely to cause a fast recovery of air quality at the local level. Therefore, only the flow effects of local air pollutants are considered.

Given that both greenhouse gas accumulation and local air pollution are non-depletable, the externalities experienced by each individual are the total amount of the externalities generated by consumers and firms. (i.e., $P_{GA} = \overline{P}_{GA} + \sum_{i} P_{GA}{}^{i} + \sum_{j} P_{GA}{}^{j}$ and $P_{LA} = \sum_{i} P_{LA}{}^{i} + \sum_{j} P_{LA}{}^{j}$, where $P_{GA}{}^{i}$, $P_{LA}{}^{i}$, $P_{GA}{}^{j}$, and $P_{LA}{}^{j}$ are the externalities generated during the consumption and production processes and these externalities all depend on the volume of the fossil fuels E_1 used).

In addition, it is assumed that individual i's health status H_i contributes directly to his/her utility level. The level of local air quality (P_{LA}) has an adverse

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[4] Our specifications of the production functions are different from those in chapter 4 of Baumol and Oates (1988) where a netput vector (by convention, the positive numbers denote net outputs, and negative numbers denote the net inputs) is used in describing production technology. Since the externalities are generated by the use of intermediate inputs (fossil fuel), gross input and output in production technology are more appropriate to pursue the goal of linking the externalities to its sources (use of fossil fuels) and making optimal policy interventions to correct the externalities.

impact on H_i, and we assume $H_i = H_i(P_{LA})$, where $\partial H_i / \partial P_{LA} < 0$. The term $\partial H_i / \partial P_{LA}$, defined as ε in this paper, is so-called "dose-response coefficient" in the epidemiological literature. Individual consumer i's preferences are represented by the utility function $U^i(C_{Xi}, C_{Zi}, C_{E_1 i}, C_{E_2 i}, H_i(P_{LA}), P_{GA}, P_{LA})$ and $U^i_{C_{Xi}} > 0$, $U^i_{C_{Zi}} > 0$, $U^i_{C_{E_1 i}} > 0$, $U^i_{C_{E_2 i}} > 0$, $U^i_{H_i} > 0$, $U^i_{P_{GA}} < 0$, $U^i_{P_{LA}} < 0$, where the subscripts of U^i denote the first order derivatives. A consumer chooses his/her consumption bundle $(C_{Xi}, C_{Zi}, C_{E_1 i}, C_{E_2 i})$ based on this preference function, but can not affect the levels of P_{GA} and P_{LA}.

An individual's health status H_i can also influence production through the labor market by affecting the total effective labor force ($\overline{R}_L^{\,*}$). Let individual i's labor endowment be $\overline{R}_{Li}$ and the corresponding ratio of effective labor force to his/her endowment be $\rho(H_i)$, where $\rho'(H_i) > 0$ and $0 \le \rho(H_i) \le 1$. The supply of effective labor can hence be written as $\overline{R}_L^{\,*} = \sum_{i=1}^{N} \rho(H_i) \overline{R}_{Li}$. The model economy and the channels through which the economic activities and the environment can affect the welfare are summarized as Figure 1.

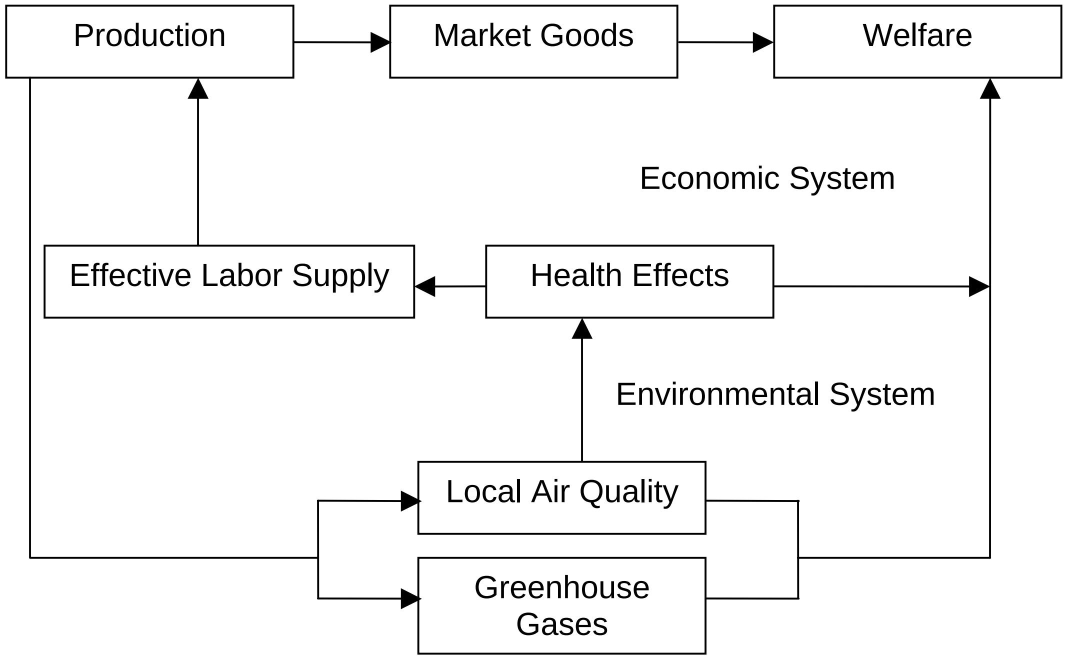

Figure 1 Summary of the Model Economy

We assume that the feasible set of consumption complexes for each consumer is closed, convex, bounded from below in C_{Xi}, C_{Zi}, C_{E_1i}, and C_{E_2i}, and contains the null vector, that the utility function that represents each person's preference is twice differentiable, quasi-concave, increasing in C_{Xi}, C_{Zi}, C_{E_1i}, C_{E_2i}, and H_i, and decreasing in P_{GA} and P_{LA}, and that the feasible production set for each firm is defined by a set of technical constraints that are twice differentiable and define a convex production possibility set. Under these circumstances, as is well known, the solution to the maximization problem exists and is unique.[5]

[5] See chapter 4 in Baumol and Oates (1988) for the conditions required. As noted in Luenberger (1995), in order to firmly tie the result to the underlying economics, the conditions required are stated directly in terms of preferences and production possibility sets, rather than

In the following discussion, we derive the necessary conditions for Pareto optimality and market equilibrium for an economy pursuing domestic welfare maximization. We examine the optimal tax rates and properties for two types of taxes: a Pigouvian tax for externalities on emitters (i.e., both of the producers and the consumers emit greenhouse gases and air pollutants) and a direct tax on emitting inputs (fossil fuel). With this done, we can easily determine the characteristics of the prices (of primary factors and produced goods) and taxes (for externalities generated by firms and consumers) that will induce the behavioral patterns by consumers and firms in a perfectly competitive economy necessary (and sufficient) for the satisfaction of Pareto-optimality conditions.

Pareto Optimality

Following Baumol and Oates (1988), we find a Pareto optimum by maximizing the utility of any arbitrarily chosen individual, say, individual 1, subject to the requirements that there be no consequent loss to any other individuals (equation (2) below), and that the constraints constituted by the production functions (equation (3) below) and the feasibility conditions for primary factors and produced goods are satisfied. The feasibility conditions are grouped into two types. The first type corresponds to the primary factor endowments L and K in the economy, which are not consumed by private individuals but are used in production, as shown in equations (4) and (5). Equation (6), the second type of the feasibility conditions, characterizes the

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indirectly through properties of the excess demand function, as seen in most general equilibrium model.

constraints for the produced good used both in private consumption and production, including X, Z, E_1 and E_2.

The problem of Pareto optimality is then to solve the following system.

(1) Max $U^1(C_{X1}, C_{Z1}, C_{E_1 1}, C_{E_2 1}, H_1(P_{LA}), P_{GA}, P_{LA})$

subject to

(2) $U^i(C_{Xi}, C_{Zi}, C_{E_1 i}, C_{E_2 i}, H_i(P_{LA}), P_{GA}, P_{LA}) \geq \tilde{U}^i$ for $i = 2, \ldots, N$

(3) $T^j(I_{Lj}, I_{Kj}, I_{Xj}, I_{Zj}, I_{E_1 j}, I_{E_2 j}) \geq O_j$ for $j = X, Z, E_1, E_2$

(4) $\sum_j I_{Lj} \leq \sum_{i=1}^{N} \rho(H_i) \overline{R}_{Li}$

(5) $\sum_j I_{Kj} \leq \overline{R}_K$

(6) $\sum_i C_{ti} + \sum_j I_{tj} \leq O_t$ for $t = X, Z, E_1, E_2$

all $C_{ti} \geq 0$, $H_i \geq 0$, ${P_{GA}}^i \geq 0$, ${P_{LA}}^i \geq 0$, $I_{vj} \geq 0$, $O_j \geq 0$, ${P_{GA}}^j \geq 0$, ${P_{LA}}^j \geq 0$, $P_{GA} \geq 0$, and $P_{LA} \geq 0$

Because of the concavity-convexity assumptions, the Kuhn-Tucker theorem is used to characterize the necessary and sufficient conditions for desired maximum. Letting $\lambda_1 = 1$ and $\tilde{U}^1 = 0$, the Lagrangian ƛ can be written as

$$(7)\quad ƛ = \sum_i \lambda_i [U^i(\cdot) - \tilde{U}^i] + \sum_j \mu_j [T^j(\cdot) - O_j] + \varpi_L [\sum_i \rho(H_i)\overline{R}_{Li} - \sum_j I_{Lj}]$$

$$+ \varpi_K [\overline{R}_K - \sum_j I_{Kj}] + \sum_t \varpi_t [O_t - \sum_j I_{tj} - \sum_i C_{ti}]$$

where λ's, μ's and ϖ's are Lagrange multipliers.

Differentiating (7) with respect to variables of consumption, inputs and outputs for production, we can obtain the necessary conditions for Pareto optimality, shown as (8^{O})-(12^{O}), where the subscripts of U^i and T^j denote the first order derivatives.

$$(8^{O})\quad \lambda_i U^i_{C_{ti}} - \varpi_t \leq 0 \ \text{ and } \ C_{ti}[\lambda_i U^i_{C_{ti}} - \varpi_t] = 0 \ \text{ for } \ t = X, Z, E_2; \forall i$$

$$(9^{O})\quad \lambda_{\bar{i}} U^{\bar{i}}_{C_{E_1\bar{i}}} + \sum_i \lambda_i (U^i_{P_{GA}} \cdot \tau^{C_{\bar{i}}}_{GA} + U^i_{P_{LA}} \cdot \tau^{C_{\bar{i}}}_{LA} + U^i_{H_i} \cdot \varepsilon \cdot \tau^{C_{\bar{i}}}_{LA})$$

$$+ \varpi_L (\sum_i \rho'(H_i) \cdot \varepsilon \cdot \tau^{C_{\bar{i}}}_{LA} \cdot \overline{R}_{Li}) - \varpi_{E_1} \leq 0$$

and

$$C_{E_1\bar{i}}[\lambda_{\bar{i}} U^{\bar{i}}_{C_{E_1\bar{i}}} + \sum_i \lambda_i (U^i_{P_{GA}} \cdot \tau^{C_{\bar{i}}}_{GA} + U^i_{P_{LA}} \cdot \tau^{C_{\bar{i}}}_{LA} + U^i_{H_i} \cdot \varepsilon \cdot \tau^{C_{\bar{i}}}_{LA})$$

$$+ \varpi_L (\sum_i \rho'(H_i) \cdot \varepsilon \cdot \tau^{C_{\bar{i}}}_{LA} \cdot \overline{R}_{Li}) - \varpi_{E_1}] = 0 \qquad \text{for } \ \bar{i} = 1, 2, \ldots, N$$

$$(10^{O})\quad \mu_j T^j_{I_{vj}} - \varpi_v \leq 0 \ \text{ and } \ I_{vj}[\mu_j T^j_{I_{vj}} - \varpi_v] = 0 \ \text{ for } \ v = L, K, X, Z, E_2; \forall j$$

$$(11^O)\quad \mu_{\bar{j}}\, T^{\bar{j}}_{I_{E_1\bar{j}}} + \sum_i \lambda_i (U^i_{P_{GA}} \cdot \tau^{F_{\bar{j}}}_{GA} + U^i_{P_{LA}} \cdot \tau^{F_{\bar{j}}}_{LA} + U^i_{H_i} \cdot \varepsilon \cdot \tau^{F_{\bar{j}}}_{LA})$$

$$+ \varpi_L (\sum_i \rho'(H_i) \cdot \varepsilon \cdot \tau^{F_{\bar{j}}}_{LA} \cdot \overline{R}_{Li}) - \varpi_{E_1} \leq 0$$

and

$$I_{E_1\bar{j}} [\mu_{\bar{j}}\, T^{\bar{j}}_{I_{E_1\bar{j}}} + \sum_i \lambda_i (U^i_{P_{GA}} \cdot \tau^{F_{\bar{j}}}_{GA} + U^i_{P_{LA}} \cdot \tau^{F_{\bar{j}}}_{LA} + U^i_{H_i} \cdot \varepsilon \cdot \tau^{F_{\bar{j}}}_{LA})$$

$$+ \varpi_L (\sum_i \rho'(H_i) \cdot \varepsilon \cdot \tau^{F_{\bar{j}}}_{LA} \cdot \overline{R}_{Li}) - \varpi_{E_1}] = 0 \quad \text{for} \quad \bar{j} = X, Z, E_1, E_2$$

$$(12^O)\quad -\mu_t + \varpi_t \leq 0 \quad \text{and} \quad O_t [-\mu_t + \varpi_t] = 0 \quad \text{for} \quad t = X, Z, E_1, E_2$$

For an interior maximum (i.e., choice variables C_{ti}, H_i, ${P_{GA}}^i$, ${P_{LA}}^i$, I_{vj}, O_j, ${P_{GA}}^j$, ${P_{LA}}^j$, P_{GA}, and P_{LA} are strictly positive), the corresponding inequalities in (8^O)-(12^O) must hold as equalities.[6] Equations (8^O) and (10^O), the optimal conditions for using goods which do not generate externalities in consumption and production processes, imply that the marginal benefit from consuming a good or the marginal cost of using a good are equal to the shadow price of that good. The optimal choices of E_1 in consumption and production processes are characterized by equations (9^O) and (11^O), respectively. The first term is the marginal benefits of using E_1 for each individual or firm. The second term corresponds to the sum of total marginal damage of externalities directly experienced by private individuals and through

[6] From Kuhn-Tucker (necessary) theory, the product of each choice variable and corresponding inequality should be equal to zero. For an interior maximum (choice variables are positive), the corresponding inequalities in (8^O)-(12^O) must hold as equalities to ensure that the necessary conditions are satisfied.

the health effects. The third term is the marginal loss in labor force, measured by its shadow price. The last term is the shadow price of E_1. Equation (12^O) implies that the two shadow prices of output O_t (for $t = X, Z, E_1, E_2$) must be equal at the equilibrium.

Competitive Equilibrium

Beginning with the consumers' problem in a competitive market, the objective of the consumer i is to minimize the expenditure on consumption and taxes, and the loss in labor income necessary to achieve the given level of utility $\widetilde{U}^i$, so that in Lagrangian form the problem is to find the saddle value of (13).[7]

$$(13)\quad \lambda_i = \sum_t p_t C_{ti} + t_{GA}^{C_i} \cdot P_{GA}^i + t_{LA}^{C_i} \cdot P_{LA}^i + p_L \cdot [1-\rho(H_i)] \cdot \overline{R}_{Li} + \alpha_i [\widetilde{U}^i - U^i(\cdot)]$$

The Kuhn-Tucker conditions of (13) are shown as (8^C) and (9^C).

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[7] The term "saddle value" originates from Kuhn-Tucker theorem. The individual's problem is a typical nonlinear problem termed *convex programs*. The necessary and sufficient conditions for solution to such problem are named *Kuhn-Tucker conditions* (See chapter 14 in Gass, 1985). The standard convex-programming problem can be represented as follows. Minimize $f(X)$ subject to $g_i(X) \le 0$ (for $i = 1,2,...,m$) and $X \ge 0$, where $f(X)$ and all the $g_i(X)$ are convex, continuously differentiable functions. The *Lagrangian function* for these functions is defined as $F(X,\Pi) = f(X) + \sum_{i=1}^{m} \Pi_i g_i(X)$, where Π_i's are called *Lagrange multipliers*. The *saddle-point problem* is to find the nonnegative vectors (X^O, Π^O) for the Lagrangian function $F(X,\Pi)$, such that $F(X^O,\Pi) \le F(X^O,\Pi^O) \le F(X,\Pi^O)$ for all $X \ge 0$ and $\Pi \ge 0$. Note that $F(X^O,\Pi^O)$ can be interpreted as $F(X^O,\Pi^O) = \max_{\Pi \ge 0}[\min_{X \ge 0} F(X,\Pi)] = \min_{X \ge 0}[\max_{\Pi \ge 0} F(X,\Pi)]$. The Kuhn-Tucker theorem states that X^O is a solution to the convex-programming problem if and only if a vector Π^O exists such that (X^O, Π^O) is a solution to the saddle-point problem.

(8^C) $p_t - \alpha_i U^i_{C_{ti}} \geq 0$ and $C_{ti}(p_t - \alpha_i U^i_{C_{ti}}) = 0$ for $t = X, Z, E_2; \forall i$

(9^C) $$p_{E_1} + t^{C_{\bar{i}}}_{GA} \cdot \tau^{C_{\bar{i}}}_{GA} + t^{C_{\bar{i}}}_{LA} \cdot \tau^{C_{\bar{i}}}_{LA} - \alpha_{\bar{i}} U^{\bar{i}}_{C_{E_1 \bar{i}}}$$

$$- \alpha_{\bar{i}} (U^{\bar{i}}_{P_{GA}} \cdot \tau^{C_{\bar{i}}}_{GA} + U^{\bar{i}}_{P_{LA}} \cdot \tau^{C_{\bar{i}}}_{LA} + U^{\bar{i}}_{H_{\bar{i}}} \cdot \varepsilon \cdot \tau^{C_{\bar{i}}}_{LA}) - p_L \cdot \rho'(H_{\bar{i}}) \cdot \varepsilon \cdot \tau^{C_{\bar{i}}}_{LA} \cdot \overline{R}_{L\bar{i}} \geq 0$$

and

$$C_{E_1 \bar{i}} [p_{E_1} + t^{C_{\bar{i}}}_{GA} \cdot \tau^{C_{\bar{i}}}_{GA} + t^{C_{\bar{i}}}_{LA} \cdot \tau^{C_{\bar{i}}}_{LA} - \alpha_{\bar{i}} U^{\bar{i}}_{C_{E_1 \bar{i}}}$$

$$- \alpha_{\bar{i}} (U^{\bar{i}}_{P_{GA}} \cdot \tau^{C_{\bar{i}}}_{GA} + U^{\bar{i}}_{P_{LA}} \cdot \tau^{C_{\bar{i}}}_{LA} + U^{\bar{i}}_{H_{\bar{i}}} \cdot \varepsilon \cdot \tau^{C_{\bar{i}}}_{LA}) - p_L \cdot \rho'(H_{\bar{i}}) \cdot \varepsilon \cdot \tau^{C_{\bar{i}}}_{LA} \cdot \overline{R}_{L\bar{i}}] = 0$$

for $\bar{i} = 1, 2, ..., N$

For an interior maximum (i.e., choice variables C_{ti}, H_i, P^i_{GA}, and P^i_{LA} are strictly positive), the corresponding inequalities in (8^C), and (9^C) must be equations. The optimal conditions for consuming goods which do not generate externalities are characterized by equation (2.8^C), implying that the individual's marginal rate of substitution between any two goods must be equal to their price ratio, the marginal rate of exchange between them. Equation (9^C) determines the optimal choices of E_1 by setting to zero the sum of total marginal financial costs, and net marginal benefits of using E_1. The financial costs include expenditures on purchasing E_1, taxes on externalities, and losses in labor income. The net marginal benefits are equal to marginal utility from consuming E_1 minus marginal disutility caused by one's own consumption. For the case in which there are no taxes levied on the consumption externalities (i.e., $t_{GA}^{C_i} = 0$ and $t_{LA}^{C_i} = 0$), the emissions will exceed the socially optimal level by the assumption of concave utility function.

Firm j pursues the goal of maximizing profits after taxes subject to the constraints given by its production relation, $T^j(\cdot) \geq O_j$. Its Lagrangian problem is to find the saddle value of (14).

$$(14) \quad \hat{\lambda}_j = p_j O_j - \sum_v p_v I_{vj} - t_{GA}^{F_j} \cdot P_{GA}^j - t_{LA}^{F_j} \cdot P_{LA}^j + \beta_j [T^j(\cdot) - O_j]$$

The Kuhn-Tucker conditions of (14) are shown as (10^C), (11^C) and (12^C).

$$(10^C) \quad -p_v + \beta_j T_{I_{vj}}^j \leq 0 \text{ and } I_{vj}[-p_v + \beta_j T_{I_{vj}}^j] = 0 \text{ for } v = L, K, X, Z, E_2; \forall j$$

$$(11^C) \quad -p_{E_1} - t_{GA}^{F_{\bar{j}}} \cdot \tau_{GA}^{F_{\bar{j}}} - t_{LA}^{F_{\bar{j}}} \cdot \tau_{LA}^{F_{\bar{j}}} + \beta_{\bar{j}} T_{I_{E_1 \bar{j}}}^{\bar{j}} \leq 0 \text{ and}$$

$$I_{E_1 \bar{j}}[-p_{E_1} - t_{GA}^{F_{\bar{j}}} \cdot \tau_{GA}^{F_{\bar{j}}} - t_{LA}^{F_{\bar{j}}} \cdot \tau_{LA}^{F_{\bar{j}}} + \beta_{\bar{j}} T_{I_{E_1 \bar{j}}}^{\bar{j}}] = 0 \text{ for } \bar{j} = X, Z, E_1, E_2$$

$$(12^C) \quad p_t - \beta_t \leq 0 \text{ and } O_t [p_t - \beta_t] = 0 \text{ for } t = X, Z, E_1, E_2$$

For an interior maximum (i.e., choice variables I_{vj}, O_j, P_{GA}^j, and P_{LA}^j are strictly positive), the corresponding inequalities in (10^C), (11^C), and (12^C) must hold as equalities. Equations (10^C), determining the optimal levels of primary factors and intermediate inputs which do not generate externalities in production process, implies that market price of one input must be equal to its marginal value of products. The optimal condition for choosing input E_1, shown in equation (11^C), indicates that financial expenditure on using E_1, including market price of E_1 and taxes on corresponding externalities, must be equal to its marginal value of products. Equation (12^C) implies that the market price of produced good O_t (for $t = X, Z, E_1, E_2$) must be equal to its shadow price at the equilibrium. For the case in which there are no taxes levied on the production externalities (i.e., $t_{GA}^{F_j} = 0$ and $t_{LA}^{F_j} = 0$), the emissions will exceed the socially optimal level by the assumption of concave production function.

Proposition 1 (*Price-Tax Solution)*

The tax structure sustaining a competitive equilibrium that is a Pareto optimality is

(15) $t_{GA}^{C_{\bar{i}}} = -\sum_{i \neq \bar{i}} \lambda_i \, U_{P_{GA}}^i$ *for taxing on* P_{GA} *generated by individual* $\bar{i}$

(16) $t_{LA}^{C_{\bar{i}}} = -\sum_{i \neq \bar{i}} \lambda_i (U_{P_{LA}}^i + U_{H_i}^i \cdot \varepsilon) - \varpi_L (\sum_{i \neq \bar{i}} \rho'(H_i) \cdot \varepsilon \cdot \overline{R}_{Li})$ *for taxing on* P_{LA} *generated by individual* $\bar{i}$

(17) $t_{GA}^{F_{\bar{j}}} = -\sum_{i} \lambda_i \, U_{P_{GA}}^i$ *for taxing on* P_{GA} *generated by firm* $\bar{j}$

(18) $t_{LA}^{F_{\bar{j}}} = -\sum_{i} \lambda_i (U_{P_{LA}}^i + U_{H_i}^i \cdot \varepsilon) - \varpi_L (\sum_{i} \rho'(H_i) \cdot \varepsilon \cdot \overline{R}_{Li})$ *for taxing on* P_{LA} *generated by firm* $\bar{j}$

and the corresponding price structure is

(19) $\varpi_v = p_v$ *for* $v = L, K$

(20) $\mu_j = \beta_j = \varpi_j = p_j$ *for* $j = X, Z, E_1, E_2$

(21) $\lambda_i = \alpha_i \quad \forall i$

The Pigouviam taxes levied on externalities are based on their social costs. The tax rates on firms are uniform. To keep the tax rates on all individuals the same further requires identical preferences for P_{GA} *and for* P_{LA} *across individuals.*[8] *Furthermore, taxing only one of the externalities (local or global) or one of the sources (consumption or production) can not lead the competitive equilibrium to Pareto optimality. In other words, the four policy instruments, as shown in (15)-(18), have to be imposed jointly to attain the social welfare maximization.*

Proof

Substituting the values of $t_{GA}^{C_i}$, $t_{LA}^{C_i}$, $t_{GA}^{F_j}$, and $t_{LA}^{F_j}$ from (15) - (18) into (8^C) - (12^C), we see that the system of inequalities and equations determining the competitive equilibrium coincides with the system of inequalities and equations (8^O)-(12^O) determining Pareto optimality if the price structure conditions hold. The tax rates on externalities are equal to the net marginal damages to others.

[8] Both theoretical and empirical evidences suggest that the preferences for environmental quality depend on income levels (e.g. Copeland and Taylor, 1994; Grossman and Krueger, 1993). If environmental quality is a normal good, we would expect that wealthier individuals would want to “buy” more of it. In addition, the consumer’s valuation of marginal disutility caused by the pollution is higher for the wealthier individuals than that for the poorer individuals.

Therefore, there are slight differences in tax rates between consumers and producers since consumer i has to pay a tax rate which excludes his/her disutility caused by his/her own consumption for one unit of the externalities. Additionally, the tax rates for per unit of consumption externalities are the same across consumers only when the preferences of every consumer (U^i) are the same. However, the uniformity of the tax rates for production externalities holds without any restrictions on consumer's preference.

By summing and discounting the potential long-term feedback of greenhouse gas accumulation into one term, the tax rate for P_{GA} is equal to sum of individual i's marginal direct disutility from global air pollution. On the other hand, to address the health feedback from local air pollution, the tax rate for P_{LA} can be decomposed into three parts, including the sum of individual i's marginal direct disutility from local air pollution, the sum of individual i's marginal utility of health due to change in air pollution, and the sum of total value of lost labor productivity. The second and third terms result from health feedback of local air pollution.

From Kuhn-Tucker theory, we know that the product of each shadow price (ϖ) and its corresponding feasibility conditions (i.e., (4)-(6)) should be equal to zero. From the price structure equations (19) and (20), the equilibrium market price of the good (p) should be equal to its shadow price (ϖ) (i.e., $p_v = \varpi_v$ for $v = L, K, X, Z, E_1, E_2$). Therefore, $p_v > 0$ holds only when the items are used up completely (market clearance). In other words, any item not utilized fully in an optimal solution must be assigned a zero market price.

The result of this theoretical work indicates that taxing only one of the externalities (local or global) or one of the sources (consumption or production) can not lead the competitive equilibrium to Pareto optimality. In other words, the theoretically first-best regulatory mean is joint implementation of a Pigouvian tax on local air pollution and a Pigouvian tax on greenhouse gases.

Empirical Model

To examine the theoretical finding by an empirical framework, we need a model that captures all mechanisms linking fossil fuel use, greenhouse gas accumulation, local air pollution, and health feedback. Specifically we need a framework which (1) captures the interaction between the economy, the energy system, and the environment; (2) has an explicit treatment of energy substitution, physical energy use and corresponding global and local air pollution emissions; (3) explicitly incorporates market goods, direct damage of greenhouse gas and local air quality into consumers' utility functions; (4) estimates changes in adverse health effects and their impacts on effective labor supply.

For this reason, we follow the lead of Burniaux and Troung (2002), and employ an applied general equilibrium model with energy substitution. The model by Burniaux and Troung (2002), namely, GTAP-E, is a modified version of the Global Trade Analysis Project (GTAP) framework (Hertel and Tsigas, 1997), built on the version 5 GTAP database. Since GTAP-E does not include local externalities of fossil fuel combustion and corresponding effects such as direct disutility, health feedback and its effects on labor productivity, we develop an extended version of GTAP-E, namely, GTAP-EAH (i.e., a model that further incorporates local air pollution and health feedback) in order to make it appropriate for our analysis.

Specifically the modifications and extensions we made to GTAP-E include incorporation of local air pollutants from fossil fuel combustion in production and consumption processes, and the addition of a wide range of different effects such as direct welfare effects, adverse health effects, and productivity effects. This entails the addition of both theory (assumption) and data, which are summarized as Figure 2.

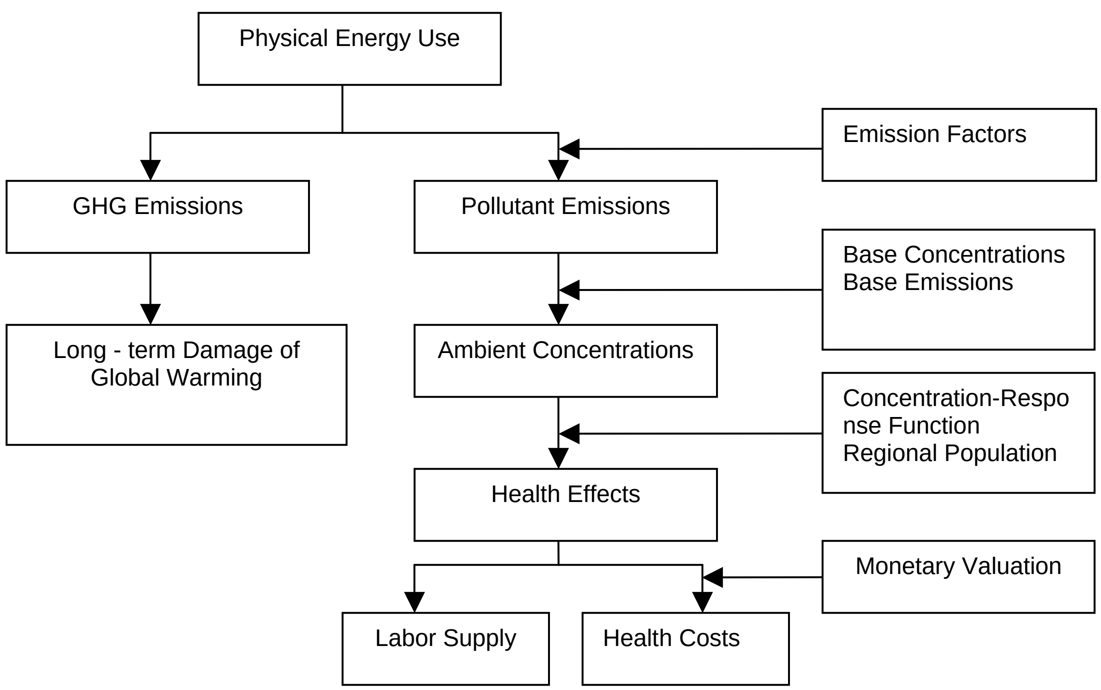

Figure 2 Empirical Framework

Based on Figure 2, the extensions of GTAP-E can be broadly classified into two categories. The first category is related to global externalities. In addition to incorporating CO_2 emissions as GTAP-E did, this model incorporates the direct damage costs caused by global warming. The second category relates to the linkages between local air pollutants and corresponding health and productivity effects. Several steps are developed to characterize the overall impacts. First, based on a review of current epidemiological literature, we recognize PM_{10} as the major local air pollutants that have significant health impacts.[9] The emissions of PM_{10} from fuel combustion are computed by summing the products of sectoral and private households' physical energy use and corresponding emission factors. By the assumption of linear emissions scaling,[10] the changes in yearly average concentration level for PM_{10} as a result of changes in fuel use is the product of the baseline mean annual ambient concentration level and the ratio of post-simulation minus baseline emissions to the total baseline emissions. Finally, the resulting changes in region-wide yearly average concentration levels,

[9] Epidemiological studies typically involve estimation of a statistical relationship between the frequency of specific health effects observed in a study population in its normal environment and some specific air pollutant measured at stationary outdoor monitors in the study area. These studies are therefore able to provide "concentration-response" functions that can be used to estimate the change in the frequency of health effects for a population in its normal environment that would be expected to occur with specific changes in ambient outdoor concentration of the air pollutant. As noted in Dockery and Pope (1994), many studies, over a period of two decades, have reported an association with some form of particulate and adverse health effects ranging from increased rates of respiratory infections to death. The most recent research has sought to sort out whether observed effects are directly related to particulate, *per se*, or to some closely correlated factor such as sulphur or an acidic species. The convergence of results suggests a clear role for particulate, especially PM_{10}, in triggering a number of health effects.

[10] The assumption of linear emissions scaling is common practice in empirical studies (e.g. U.S. EPA, 1999; EC, 1995; ORNL/REF, 1994). A possible objection is that acute health damage may only arise with episodes of high pollution over several days, and that pollution levels are otherwise of little significance. Whether or not this is correct is somewhat unclear. However, since the approximately linear functions seem to correspond well with the observations in concentration-response studies, it is reasonable to use them. Moreover, although this technique does not take into account pollutant transport or atmospheric chemistry, it is believed that episodes of heavy pollution are strongly correlated with the annual mean concentration (Rosendahl, 1998) and that linear scaling generates reasonable approximations of ambient concentrations.

together with the concentration-response coefficients and regional population size, determine the changes in regional adverse health effects. These adverse health effects then have impacts on effective labor supply and welfare levels.

Additional data are required to fulfill our goal of incorporating a wide range of global and local externalities of fossil fuel combustion. These data include direct damage of global warming; coefficients related to estimation of adverse health effects: three dimensional emission factors for local air pollutants, baseline ambient concentration level, concentration-response coefficients, death rate and regional population; monetary valuation of the adverse health effects; and relationships between adverse health effects and effective labor supply. For detailed discussion of these extensions and data, we refer the reader to Lee (2003).

Scenario Descriptions

The environmental taxes in this paper relate to two categories of social costs – costs of climate change damage and costs of air pollution. We compute the low, central, and high estimates for social costs of the global and local externalities from per unit fuel use based on GTAP-EAH data and assumptions.[11] The social costs are then expressed as a percentage of fuel prices. The computed results of the low, central, and high estimates of social costs and social costs as a percentage of fuel prices are summarized in Table 1. The social costs of fossil fuels are measured in $ per ton of coal, $ per thousand gallon of oil and oil products, and $ per thousand cubic feet of natural gas. For example, the central estimate of the climate change costs of coal

[11] The low, central, and high estimates for social costs of the global externalities from per unit fuel use are computed based on available low (US$5 per ton of carbon), central (US$20 per ton of carbon), and high (US$45 per ton of carbon) estimates of marginal costs of present CO_2 emissions.

used in the sector of electricity generation is $13.85 per ton of coal. Given the price of $27.16 per ton of coal, the tax rates based on climate change costs is equal to 50.99%. The social costs of energy vary substantially by fuel type and by sector. Coal has by far the highest costs associated with its use. The damage from oil and oil products and natural gas are both much lower than the social costs associated with coal.

The central estimates of social costs as a percentage of fuel prices serve as the optimal tax rates for internalizing the externalities of climate change and air pollution applied in our simulations, and they are added to existing excise taxes on the fuels in the United States. For comparison purpose, the tax rates applied in our analysis and those applied in Norland and Kim (1998) are listed in Table 2.

Table 1 Social Costs of Climate Change and Air Pollution[a]

Fuels	Climate Change			Air Pollution		
	Low	Central	High	Low	Central	High
Coal						
Electric Utilities	3.46	13.85	31.16	26.45	41.42	56.09
	12.75	*50.99*	*114.74*	*97.37*	*152.51*	*206.51*
En_Int_ind[b]	3.46	13.85	31.16	26.45	41.42	56.09
	12.75	*50.99*	*114.74*	*97.37*	*152.51*	*206.51*
Other Sectors	3.46	13.85	31.16			
	12.75	*50.99*	*114.74*			
Private Household	3.46	13.85	31.16			
	12.75	*50.99*	*114.74*			
Oil and Oil products[c]						
Electric Utilities	12.36	49.45	111.27	14.26	22.33	30.24
	2.88	*11.53*	*25.94*	*3.32*	*5.21*	*7.05*
En_Int_ind	12.36	49.45	111.27	45.06	70.57	95.56
	2.88	*11.53*	*25.94*	*10.50*	*16.45*	*22.27*
Other Sectors	12.36	49.45	111.27	22.36	35.03	47.43
	1.49	*5.95*	*13.39*	*2.69*	*4.22*	*5.71*
Private Household	12.36	49.45	111.27	22.36	35.03	47.43
	1.49	*5.95*	*13.39*	*2.69*	*4.22*	*5.71*
Natural Gas						
Electric Utilities	0.07	0.28	0.62	0.14	0.22	0.29
	2.48	*9.93*	*22.35*	*4.97*	*7.78*	*10.53*
En_Int_ind	0.07	0.28	0.62	0.14	0.22	0.29
	1.92	*7.69*	*17.31*	*3.85*	*6.02*	*8.16*
Other Sectors	0.07	0.28	0.62			
	1.92	*7.69*	*17.31*			
Private Household	0.07	0.28	0.62			
	0.99	*3.98*	*8.95*			

a. The social costs are measured in $ per ton of coal, $ per thousand gallon of oil and oil products, and $ per thousand cubic feet of natural gas. Numbers in italics are social costs as a percentage of fuel prices.
b. Energy Intensive Industries.
c. We assume that oil and oil products used by electric utilities and energy intensive industries are residual oil (as fuel oil). Oil and oil products used by other sectors (including transportation) and private household are gasoline.

Table 2 External Costs as a Percentage of Fuel Prices

Fuel	Our Simulation		Norland and Kim (1998)[a]	
	Climate Change	Air Pollution	Climate Change	Air Pollution
Coal			35.34	260.85
Electric Utilities	50.99	152.51		
En_Int_ind[b]	50.99	152.51		
Other Sectors	50.99			
Private Household	50.99			
Oil and Oil Products			9.32	13.37
Electric Utilities	11.53	5.21		
En_Int_ind	11.53	16.45		
Other Sectors	5.95	4.22		
Private Household	5.95	4.22		
Natural Gas			6.26	0.47
Electric Utilities	9.93	7.78		
En_Int_ind	7.69	6.02		
Other Sectors	7.69			
Private Household	3.98			

a. The tax rates in Norland and Kim (1998) are based on medium estimates of climate change and air pollution damages, and they are expressed as percentage of fuel prices for 1996.
b. Energy Intensive Industries.

Our estimates of the social costs as a percentage of fuel prices vary substantially by fuel type and by sector for two reasons. First, as mentioned before, the pollutant emissions are primarily dependent on the fuel types and the industrial or private activity processes. Differences in emission factors constitute diverse social costs. Second, the fuel prices are different for different end users. Even in the case where two sectors have the same emission factors, the social costs as a percentage of fuel prices for these two sectors are different if the fuel prices for these two sectors are different (i.e., different fuel prices represent different denominators in computing the percentage of fuel prices). Without identifying the sectoral differences, Norland and Kim (1998) apply the same tax rates on each type of fuel to all sectors.

Our simulation scenarios are designed to illustrate how ignorance of jointly optimal policies affects the overall welfare, environmental consequences, economic costs, energy production and consumption (fuel choices). In particular, we consider three scenarios for the United States. The first scenario (S-1) represents the case where only the global externalities are internalized. Only the local externalities are corrected in the second scenario (S-2). The third scenario (S-3), a scenario combining S-1 and S-2, serves as the benchmark under which jointly optimal policies are implemented.

Simulation Results

This section presents the quantitative results of the three simulation scenarios for the United States and for the other regions. We first compare the welfare impacts for the United States in the three policy scenarios. The results of energy production and consumption, environmental consequences, impacts on adverse health effects and labor market are then presented in turn.

Welfare Impacts

There are three variables related to welfare evaluations in our model, including equivalent variations, welfare effects of climate change (global externalities), and welfare effects of adverse health effects (local externalities). Equivalent variations evaluate the welfare impacts of the distortions on the economy (i.e., taxes on fuels). The results of equivalent variations tell us the direct economic costs / welfare losses, mostly arising from allocative inefficiency, due to higher fuel prices. The welfare effects of reducing climate change damage (global externalities) and those of adverse health effects (local externalities) reflect the welfare gains as a result of reductions in fuels use.

Table 3 presents the results of welfare impacts of internalizing social costs of fuels for the United States. The first two scenarios represent the cases which have been primarily focused on only one environmental policy, either at global (S-1) or local (S-2) level. The results of these two cases show the existence of ancillary benefits of targeted environmental policy. For example, taxing only global externalities (S-1) has ancillary benefits of reductions in the adverse health effects because reducing carbon emissions also reduces air pollution simultaneously. In addition to the primary welfare gains of reducing climate change damage ($3,490 million), there are also welfare gains from ancillary benefits of reductions in the adverse health effects ($7,111 million).

Table 3 Welfare Impacts of Internalizing Social Costs of Fuels

Welfare Impacts[a]	S-1 Global	S-2 Local	S-3 Joint
Equivalent Variation	-1,140	-7,766	-16,193
Reduction in Climate Change Damage	3,490	5,041	7,566
Reduction in Adverse Health Effects	7,111	14,440	20,935
Sum	9,461	11,715	12,308

a. Welfare impacts are measured in US$ million.

By correctly pricing fuels through the environmental taxes to reflect their social costs of global and local externalities, the United States can achieve the maximal welfare gains (S-3). The estimated welfare gains are $12,308 million. Due to the highest tax rates of fossil fuels in S-3, the economic costs / welfare losses in this scenario ($-16,193 million) are largest among the three scenarios. However, the reductions in fuels use make substantial contributions to the overall welfare through the welfare gains of reductions in climate change damage ($7,566 million) and in adverse health effects ($20,935 million).

GDP

GDP in the base data and in the post-simulation equilibrium for the United States are reported in Table 4. GDP in the base data is $7,945,197 million. GDP rises slightly in each of the three scenarios. The estimated increases in GDP are $11,552 million (0.15%) for S-1, $3,442 million (0.04%) for S-2, and $7,665 million (0.10%) for S-3, respectively. Taxing fossil fuels raises the agents' prices and nominal value of output, and, therefore, we have higher GDP in all of the three scenarios.

Table 4 GDP: Base Data and Simulation Results

	Base Data	S-1 Global	S-2 Local	S-3 Joint
GDP[a]	7,945,197	7,956,749	7,948,639	7,952,862
Change		11,552	3,442	7,665
%		*0.15*	*0.04*	*0.10*

a. GDP and changes in GDP are measured in US$ million. Numbers in italics are percentage changes from base value.

Energy Use

Table 5 presents the energy use in the base data and post-simulation equilibrium for the United States. According to the base data, firms' production relies heavily on oil products (612.59 million toe), coal (514.02 million toe), and natural gas (448.73 million toe). Private households are also major consumers of oil products (264.42 million toe). Oil products consumed by firms and by private household account for 70% and 30% of the total volume, respectively. The total volumes of energy consumption, from the highest to the lowest, are oil products (877.01 million toe), coal (514.78 million toe), natural gas (509.36 million toe), and oil (0.26 million toe).[12]

[12] Oil used in the sector of oil products is for refined processes, rather than for end use. The volume of oil used in the sector of oil products is excluded.

Table 5 Energy Use: Base Data and Simulation Results[a]

	Base Data	S-1 Global	S-2 Local	S-3 Joint
Total	1,901.41	1,705.83	1,643.08	1,495.67
		-10.29	*-13.59*	*-21.34*
Coal	514.78	407.14	307.80	243.09
		-20.91	*-40.21*	*-52.78*
Oil	0.26	0.24	0.25	0.24
		-7.69	*-3.85*	*-7.69*
Gas	509.36	485.89	501.33	478.71
		-4.61	*-1.58*	*-6.02*
Oil_Pcts	877.01	812.56	833.70	773.63
		-7.35	*-4.94*	*-11.79*
Firm				
Coal	514.02	406.58	307.01	242.50
		-20.90	*-40.27*	*-52.82*
Oil	0.26	0.24	0.25	0.24
		-7.69	*-3.85*	*-7.69*
Gas	448.73	426.83	440.43	419.50
		-4.88	*-1.85*	*-6.51*
Oil_Pcts	612.59	570.94	586.16	547.90
		-6.80	*-4.31*	*-10.56*
Private Household				
Coal	0.76	0.56	0.79	0.59
		-26.32	*3.95*	*-22.37*
Oil	0.00	0.00	0.00	0.00
		0.00	*0.00*	*0.00*
Gas	60.63	59.06	60.90	59.21
		-2.59	*0.45*	*-2.34*
Oil_Pcts	264.42	241.62	247.54	225.73
		-8.62	*-6.38*	*-14.63*

a. Energy use is measured in million tons of oil equivalent (Mtoe). Numbers in italics are percentage changes from base value.

The post-simulation results suggest that energy taxes substantially influence agents' behavior- raising costs does induce major reductions in energy consumption. Among the three scenarios, the total use of fossil fuels falls most in the scenario where the global and local environmental taxes are jointly implemented (S-3). The estimated reductions in the total use of fossil fuels are 405.74 million toe (21.34%). Among the fossil fuels, the reduction in coal use in response to environmental taxes is largest because of its highest social costs. The estimated reductions in total coal use are 107.64 million toe (20.91%) for S-1, 206.98 million toe (40.21%) for S-2, and 271.69 million toe (52.78%) for S-3.

For all of the three scenarios, reductions in firms' fuels use make great contributions to the overall reductions in fuels use. To get better understanding of the whole story, we further decompose the total changes in firms' fuel use into sectoral levels. The sectoral fuel use in the base data and the changes in sectoral fuel use for the three scenarios are reported in Table 6. Again, all of the numbers are measured in million tons of oil equivalent (million toe). According to the base data, around 95% of firms' coal use (488.82 million toe) is utilized in electricity generation. Two-thirds of the natural gas is used in the two sectors: electricity and other industries and services, and each of them accounts for one-third of the total. The majority of oil products is used in the sector of other industries and services (404.46 million toe, 66% of the total).

Table 6 Sectoral Energy Use: Base Data and Simulation Results[a]

BASE									
	Ag	Coal	Oil	Gas	Oil_Pcts	Elec	En_Int	Oth_ind	Total
Coal	0.61	0.08	0.00	0.00	0.00	488.82	5.73	18.79	514.02
Oil	0.00	0.00	0.00	0.19	0.00	0.00	0.04	0.02	0.26
Gas	52.81	0.00	0.00	23.95	0.32	149.88	58.07	163.69	448.73
Oil_Pcts	16.27	0.00	0.00	0.00	52.14	19.07	120.64	404.46	612.59

S-1 Global									
	Ag	Coal	Oil	Gas	Oil_Pcts	Elec	En_Int	Oth_ind	Total
Coal	0.50	0.06	0.00	0.00	0.00	386.10	4.60	15.33	406.58
Oil	0.00	0.00	0.00	0.18	0.00	0.00	0.03	0.02	0.24
Gas	51.41	0.00	0.00	22.86	0.30	138.10	56.19	157.97	426.83
Oil_Pcts	15.50	0.00	0.00	0.00	47.83	16.68	108.78	382.14	570.94

S-2 Local									
	Ag	Coal	Oil	Gas	Oil_Pcts	Elec	En_Int	Oth_ind	Total
Coal	0.65	0.04	0.00	0.00	0.00	282.94	3.62	19.76	307.01
Oil	0.00	0.00	0.00	0.19	0.00	0.00	0.03	0.02	0.25
Gas	56.12	0.00	0.00	23.64	0.31	129.58	57.94	172.84	440.43
Oil_Pcts	16.09	0.00	0.00	0.00	49.21	16.39	106.73	397.73	586.16

S-3 Joint									
	Ag	Coal	Oil	Gas	Oil_Pcts	Elec	En_Int	Oth_ind	Total
Coal	0.54	0.03	0.00	0.00	0.00	222.77	2.92	16.23	242.50
Oil	0.00	0.00	0.00	0.18	0.00	0.00	0.03	0.02	0.24
Gas	54.88	0.00	0.00	22.59	0.28	118.46	56.08	167.22	419.50
Oil_Pcts	15.40	0.00	0.00	0.00	45.20	14.23	96.24	376.82	547.90

a. The sectoral fuel use in the base data and the post simulation results are measured in million tons of oil equivalent (Mtoe).

The post-simulation results show that imposing energy taxes has substantial impacts on sectoral fuel use. For all of the three scenarios, the electricity generation contributes most to the reductions in firms' use of coal and natural gas. The estimated reductions of coal use by electricity generation are 102.72 million toe for S-1, 205.88 million toe for S-2, and 266.05 million toe for S-3, respectively. In terms of percentage change, the reduced volume of coal use by electricity generation explains above 95% of the total reductions for all of the three scenarios.

The estimated reductions of natural gas use by electricity generation are 11.78 million toe for S-1, 20.30 million toe for S-2, and 31.42 million toe for S-3, respectively. Note that the sector for other industries and services increases its use of natural gas through inter-fuel switching as the tax rates of other types of fuels are relatively high. However, the increases in the total volume of natural gas are modest. For all of the three scenarios, the energy intensive industries and other industries and services account for most of the reductions in the use of oil products. The estimated reductions of oil products by the sectors of energy intensive industries / other industries and services are 11.86 / 22.32 million toe for S-1, 13.91 / 6.73 million toe for S-2, and 24.40 / 27.64 million toe for S-3, respectively.

Fossil Fuel Intensity

Fossil fuel intensity is defined as the volume of fossil fuels use (Table 5) divided by GDP (Table 4), which is measured in tons of oil equivalent (toe) per million dollars of gross domestic products. The computed results of fossil fuel intensity in the base data and the post-simulation equilibrium for the United States are reported in Table 7. According to the base data, the fossil fuel intensity, from the highest to the lowest, are oil products (110.38 toe / US $ million), coal (64.79 toe / US $ million), natural gas (64.11 toe / US $ million), and oil (0.03 toe / US $ million). The overall fossil fuel intensity, the sum of the above four terms, is 239.32 toe / US $ million. The post-simulation results of fossil fuel intensity decrease for all of the three scenarios. This is an inherent consequences following on the results of fossil fuel use (Table 5). As a result of slight change in GDP in all of the three scenarios, the patterns of percentage changes in fuel intensity (Table 7) are almost parallel to those in fuel use (Table 5).

Table 7 Fossil Fuel Intensity[a]

	Base Data	S-1 Global	S-2 Local	S-3 Joint
Total	239.32	214.39	206.71	188.07
		-10.42	*-13.62*	*-21.41*
Coal	64.79	51.17	38.72	30.57
		-21.02	*-40.23*	*-52.82*
Oil	0.03	0.03	0.03	0.03
		-7.83	*-3.89*	*-7.78*
Gas	64.11	61.07	63.07	60.19
		-4.75	*-1.62*	*-6.11*
Oil_Pcts	110.38	102.12	104.89	97.28
		-7.48	*-4.98*	*-11.87*

a. Fossil fuel intensity is measured in toe / US $ million. Numbers in italics are percentage changes from base value.

Environmental Consequences

The carbon emissions and PM_{10} emissions in the base data and the post-simulation equilibrium for the United States are reported in Table 8. In the base year, carbon emissions and PM_{10} emissions in the United Sates are

1,499.78 million tons of carbon and 1,522.67 million lbs, respectively. The impact on emissions follows the impacts on fossil fuel energy use. Taxing only global externalities (S-1) also helps to reduce the local externalities at the same time, and *vice versa*. The emission reductions achieve the maximum in the scenario where the fuels are priced based on their social costs (S-3). The estimated reductions of carbon emissions and PM_{10} emissions are 378.24 million tons of carbon (25.22%) and 643.48 million lbs (42.26%).

Table 8 Pollution Emissions: Base Data and Simulation Results[a]

	Base Data	S-1 Global	S-2 Local	S-3 Joint
Carbon Emissions	1,499.78	1,325.36	1,247.67	1,121.54
		-11.63	*-16.81*	*-25.22*
PM_{10}	1,522.67	1,263.51	1,042.57	879.19
		-17.02	*-31.53*	*-42.26*

a. Carbon emissions and PM_{10} are measured in million tons of carbon and million lbs, respectively. Numbers in italics are percentage changes from base value.

Reductions in Adverse Health Effects

As noted above, the changes in regional adverse health effects are the products of the changes in mean annual ambient concentration levels of air pollution, the concentration-response coefficients and regional population size. Reductions in pollution emissions prevent the occurrence of the illness. The results of the estimated annual health benefits and their monetary values are reported in Table 9.

Table 9 Estimates of Annual Health Benefits

Adverse Health Effects	Annual Number of Cases Prevented			Annual Monetary Value[a]		
	S-1 Global	S-2 Local	S-3 Joint	S-1 Global	S-2 Local	S-3 Joint
Acute Mortality	302	613	889	1,092	2,217	3,214
Chronic Bronchitis	23,354	47,422	68,752	5,913	12,007	17,408
Hospital Admission	62	127	184	1	2	3
RAD	1,664,787	3,380,485	4,901,015	100	203	294
Symptom day	155,136	315,015	456,708	6	11	16
Sum				7,111	14,440	20,935

a. Monetary value of adverse health effects are measured in US$ million.

The estimated annual monetary health benefits in the United States are $7,111 million for S-1, $14,440 million for S-2, and $20,935 million for S-3, respectively. For all three scenarios, the monetary health benefit estimates are dominated by the acute mortality and the chronic bronchitis effects. The numbers of cases prevented of these two adverse health effects are relatively small as compared with the restricted activity days and the symptom days, but the high monetary values per case of these two adverse health effects result in large monetary benefits. The combination of the acute mortality reductions and the chronic bronchitis reductions represent about 98 percent of the total monetary health benefits. The largest numbers of cases reduced are restricted activity days and symptom days. As a result of low monetary values per case, these two adverse health effects represent about 1.5 percent of the total monetary health benefits.

Labor Market

The effective labor supply hinges on one of the adverse health effects: restricted activity days (RAD). According to ORNL/REF (1994), 62 percent of all RAD are bed-disability days and work loss day, while the reminder are described as minor restricted activity days (MRAD). Following Rosendahl (1998), we assume that RAD and MRAD reduce the labor productivity by 100 percent and 10 percent, respectively. The increase in labor supply, as shown in Table 10, is computed by annual number of RAD prevented (Table 9) multiplied by the corresponding weights. The estimated annual increases in labor supply in the United States are 1.10 million of work days for S-1, 2.22 million of work days for S-2, and 3.22 million of work days for S-3, respectively. In terms of percentage change, the increase in effective labor supply make only small contributions to total labor supply. The percentage changes in effective labor supply are 0.002% for S-1, 0.005% for S-2, and 0.007% for S-3, respectively.

Table 10 Impacts on Effective Labor Supply

	S-1 Global	S-2 Local	S-3 Joint
Increase in Labor Supply[a]	1.100	2.220	3.220
	0.002	*0.005*	*0.007*

a. The increase in labor supply is measured in million of work days. The total labor supply in the base data is 44,854.14 million of work days. Numbers in italics are percentage changes from base value.

Implications for Policy Recommendations

The goal of this paper is to contribute the proper design of optimal environmental policies where energy use generates several jointly produced and consumption externalities. A theoretical model is first developed based on general equilibrium framework where a multiple output technology is assumed and two public bads (global and local externalities) are generated through the use of fossil fuels in the consumption and the production processes. Though other regulatory instruments are available, we concentrate on the use of environmental taxes. To achieve welfare maximization of a closed economy, a Pigouvian tax on local air pollution and a Pigouvian tax on greenhouse gases have to be jointly implemented.

We then examine our theoretical finding by an empirical framework. The manner we model the interactions between economic activities, fuel use, and environmental consequences is distinct form the existing studies in two ways. First, to reflect the fact that energy use in different sectors has different emission factors, detailed data of sectoral energy use and three-dimensional emission factors (pollutants by fuel type by private consumption or production processes) are incorporated into our empirical model. The incorporation of this feature provides not only more precise estimations of pollution emissions, but also the impacts of energy taxes on the fuel use at sectoral levels. Second, the value-added of this study is the addition of a wide range of different effects such as direct welfare effects, adverse health effects, and productivity effects within an empirical framework intended for analysis of fuel use and its externalities. With a comprehensive description of multiple externalities of fuel use, our empirical model explicitly brings together the jointly produced global and local externalities, and the trade-offs between the global and local environmental policies.

Three scenarios on energy taxes, including internalization of global externalities alone, internalization of local externalities alone, and joint implementation of the above two policies, are analyzed. The tax rates are set equal to each fuel's estimated external costs of global and/or local environmental externalities, and they vary substantially by fuel type and by sector because of differences in sectoral emission factors and fuel prices. The design of the simulation scenarios can be interpreted as implementing energy taxes at three different levels, and the focus of this study is to explore how well the taxes correspond to actual environmental costs and the impacts of the taxes on the economy and environment. Internalizing the multiple externalities generated by a single input through combined taxes is equivalent to adding up all of the external costs, and, therefore, the tax rates in the third scenario are highest. Consequently, the simulation results from the three scenarios are of quasi-linearity.

According to the original theoretical principles of environmental taxation of A.C. Pigou (1920), the welfare of society will be increased if external environmental costs of energy use are internalized as fuel taxes are paid by the fuel users. Correctly pricing fuels through joint global and local environmental taxes to ensure that all environmental externalities of fossil fuel combustion are accounted for in market mechanisms is theoretically first-best regulatory means. Our numerical results are consistent with this optimal policy rule of "full social costs pricing of energy": the United States can achieve a higher welfare gains along with lower fuel use and pollution emissions in the third scenario, as compared with the first two scenarios where only global or only local externalities are internalized. The estimated overall welfare gains are $12,308 million, where welfare gains of reductions in climate change damages and in adverse health effects make substantial contributions. Adopting joint global and local environmental taxes leads the highest tax rates on fuel use in the third scenario, which procures substantial reductions in fossil fuels use, and emissions of carbon and air pollutants (PM_{10}), and improvement in fossil fuels intensity. The estimated reductions in the total use of fossil fuels are 405.74 million toe (21.34%). The emissions of carbon and PM_{10} reduce by 25.22% (378.24 million tons of carbon) and 42.26% (643.48 million lbs), respectively. With respect to the welfare gains from the reductions in adverse health effects, the monetary health benefits estimates are dominated by the acute mortality and the chronic bronchitis effects. The combination of the acute mortality reductions and the chronic bronchitis reductions represent about 98 percent of the total monetary health benefits.

In practice, however, there is a regulatory gap between economists who know theoretical virtues of Pigouvian taxes and political decision-makers who are aware of practical difficulties in the legislation. Public resistance of the new taxes arises from concerns about the possible negative impacts of Pigouvian taxes, such as losses of efficiency or competitiveness. Given the enormous uncertainties surrounding the effects of future climate change, internalizing local air pollution alone is more acceptable since the welfare gains from reductions in adverse health effects and increases in labor productivity are more apparent. Moreover, reducing local air pollution also accompanies ancillary benefits of reductions in carbon emissions and future climate change damages. It should be noted that the benefits from reductions in adverse health effects and increases in labor productivity is of highly geographical sensitivity, and the distribution of the welfare gains within the United States is beyond the scope of this study but is worthy of future research.

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