

PRELIMINARY ESTIMATES OF CUMULATIVE PRIVATE  
AND EXTERNAL COSTS OF ENERGY

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# PRELIMINARY ESTIMATES OF CUMULATIVE PRIVATE AND EXTERNAL COSTS OF ENERGY

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*This is a summary comparison and "first rough cut" cumulation of recent estimates regarding private and external costs of energy. The estimates of external costs take into consideration damage to health and property caused by air pollution from coal, oil, and gas; damage caused by acid rain from coal, and costs of reducing acid rain; costs of delaying global warming caused by carbon dioxide from coal, oil, and gas; national security costs of importing oil, and benefits of oil security; national security costs of minimizing damage from terrorist attacks on nuclear power plants; insurance subsidies for nuclear accidents; storage of nuclear waste; loss of nuclear reactors from accidents and safety risks; and benefits from additional nuclear safety requirements. The estimates of private costs focus on nuclear plants, coal, oil, gas, conservation, wind, solar power plants, and geothermal steam.*

## 1. INTRODUCTION

Recent estimates of externalities indicate that the prices of most conventional energy sources are substantially below the social costs. Therefore, if efficiency is a policy goal, the estimates imply that the U.S. economy misdirects substantial investments toward conventional energy sources that should be invested in less polluting alternatives. Presented here is a summary comparison of several analysts' estimates of externalities and a "first rough cut" aggregation of these estimates.

The cumulative estimates of externalities and cost savings effected by implementing the policy recommendations of the various analysts is only a first rough cut for three main reasons. (i) Property rights to pollute are subject to change through the political process and have not been clearly allocated. Changes from present levels of pollution to efficient levels would have large effects on the distribution of wealth within and across generations. (ii) Efficient allocation of resources would have concomitant prices, measures of costs, and values substantially different from those existing today. Thus, the partial equilibrium framework employed here falls somewhat short of encompassing all of these general equilibrium effects. (iii) If prices reflected social costs, the dynamics of technological change would favor energy efficiency and energy sources that pollute less than do conventional energy sources.

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The selection of sources summarized here is primarily from the other articles in the July 1990 *Contemporary Policy Issues* edition and from references in those articles. While the literature on externalities is large, few sources present estimates of damages from pollution, benefits of reducing pollution, or costs of reducing pollution that are attributable to or can be allocated to specific energy sources. Even less frequent are sources that specify the amount of each energy source associated with the damage, benefit, or cost. Also, because estimates that do exist are specific to a particular location and for a specific pollutant, they cannot be added to other estimates to obtain a cumulative estimate of external costs. These constraints limit the remaining sources for this paper and limit the accuracy of the estimates presented below.

In 1986, 18 percent of U.S. gross investment—\$119 billion—was in energy industries (Hall, forthcoming). If a large percentage of these investments are economically inefficient, they represent major annually recurring misallocations of resources resulting from market and regulatory failure.

Holdren (1982) and others charge that analysts in economics and other disciplines continue to under-estimate the external costs of conventional technologies. This charge has several bases, but the critics assert that most analysts habitually make two crucial errors. First, most analysts err by setting at zero external costs that they cannot measure. For example, Nordhaus' (1989) estimates of the damage from global warming assume that the health effects are zero simply because he acknowledges he has omitted these effects. Another example, the 10-year National Acid Precipitation Assessment Program (NAPAP), concludes that the cost of controlling acid rain is not worth the price. The final NAPAP omits the economic valuation of damage to human health—the largest component of total external cost (see note o in table 1)—from the final report. Also omitted is damage to buildings, the second largest category of damage.

The second charge is that most analysts consider one externality at a time. For example, the interim NAPAP study focuses singly on the damage from acid deposition and ignores the damage from precursors to acid rain—e.g., sulfur oxides, ozone—that one must control to reduce acid rain (Callaway and Englin, 1990). In another example, Nordhaus (1989) concludes that most measures to reduce the "greenhouse effect" cost more than the damage to the economy. Nordhaus ignores external costs that also would be avoided by measures to reduce the greenhouse effect, such as damage from acid rain, air pollution, and national security externalities.

The aggregation of estimates presented here also omits some external costs by setting equal to zero various cost categories for which numerical estimates are lacking. One omission is the external cost of the transfer of nuclear weapons technology occurring when nuclear plants are built in countries without nuclear weapons. Another omission is the external cost of the

risk of nuclear material diverted to terrorists—a risk that grows with the nuclear industry. However, this aggregation does include external costs for several important categories. It also presents estimates of private costs of conventional energy sources and alternatives.

## II. THEORY OF ESTIMATION

A market economy allocates resources efficiently only if all the costs of production and consumption are reflected in market prices. Externalities, public goods, and common property prohibit market prices from reflecting all of these costs. Externalities occur when all costs of production or consumption are not borne by the producer or consumer. Public goods, unlike private goods, are not depleted by consumption. Common property does not have exclusive rights for use. Depleting public goods and destroying common property cause negative externalities. National security is an example of a public good that can be adversely affected by oil consumption and the nuclear power industry. Global warming, acid rain, and air pollution are examples of fossil fuel consumption's adversely affecting public goods and common property. Private insurers are unwilling to insure owners and operators of nuclear power facilities for attacks by terrorists and are unwilling to provide complete coverage in the case of nuclear meltdowns. Thus, the nuclear industry lacks the incentive to provide the optimal amount of safety in the production of nuclear power. The public living near nuclear power plants bears the external cost from the risk of radiation.

Recent findings suggest that economists err when claiming that the optimal amount of pollution control occurs where the marginal benefit (MB) of a cleaner environment equals the marginal cost (MC) of providing it. In figure 1, MB equals MC at a level of emission reduction equal to RA. The MB curve shows the amount people would be willing to pay to reduce pollution. The MB curve assumes that polluters hold the property right to pollute. The marginal damage (MD) from pollution shows the amount people would have to be compensated if they are to accept pollution. The MD curve assumes people hold the property right for a clean environment.

Knetsch (1990) reviews empirical evidence that the MD curve is above and to the right of the MB curve. Standard utility theory dictates that the income effect of allocating the property rights explains the difference between the MB and MD curves. Utility depends on wealth in the more sophisticated von Neumann-Morgenstern model, used in the context of health and other risks. Viscusi and Evans (1990) extend that model so that marginal utility is higher when we are healthy and lower when we are ill—for example, from air pollution.

Solutions proposed by economists imply different allocations of property rights. Pollution taxes retain the right for the public. Tradable permits allocate the right to the polluter. Tradable permits that depreciate the amount of

**TABLE 1**  
Cumulative Estimates of External and Total Social Costs of Energy  
(dollars/unit of energy)

Source of Energy Service	Conservation Efficiency	Wind	Solar	Geothermal	Natural Gas	Oil	Coal	Nuclear
Water Pollution	-0-	-0-	-0-	Minor	-0-	Omitted	Omitted	Omitted
Solid Waste <sup>a</sup>	-0-	-0-	-0-	-0-	-0-	Omitted	Omitted	1988 \$ AC: 0.07¢/kWh
Air Pollution and Acid Rain	-0-	-0-	-0-	Minor <sup>k</sup>	1988 \$ IB: <sup>m</sup> \$0.286/ MMBTU	1985 \$ IB: <sup>m</sup> \$11.59/ BBL	1985 \$ IB: <sup>o</sup> \$16.80-\$18.77/ Ton MC: <sup>p</sup> \$7.23-\$7.67/ Ton	
Green House <sup>b</sup>	-0-	-0-	-0-	-0-	1988 \$ MC: <sup>n</sup> \$0-\$2.56/ MMBTU	1988 \$ MC: \$0-\$3.48/ BBL	1988 \$ MC: \$0-\$4.50/ MMBTU	
National Security <sup>c</sup>	-0-	-0-	-0-	-0-	Substantial Reserves: Soviet Union and Iran	1985 \$ AC: \$5.79/ BBL AB: \$4.20-\$7.07/ BBL	-0-	1986 \$ AC: 0.85¢/kWh
Nuclear								
Insurance Subsidy <sup>d</sup>	-0-	-0-	-0-	-0-	-0-	-0-	-0-	1985 \$ AC: 0.49¢/kWh

**TABLE 1 continued**

Reactor Loss <sup>c</sup>	-0-	-0-	-0-	-0-	-0-	-0-	-0-	1987 \$ AB: 0.14¢/kWh
Additional Safety	-0-	-0-	-0-	-0-	-0-	-0-	-0-	1988 \$ AB: 0.16¢-0.94¢/ kWh
Cumulative External Cost (1989 \$) <sup>g</sup>	-0-	-0-	-0-	Minor <sup>k</sup>	\$0.30-\$2.85/ MMBTU	\$16.85-\$22.14/ BBL	\$13.68-\$124.75/ Ton	1.9¢-2.7¢/ kWh
Private Cost (1989 \$)	0.5¢-2¢/ kWh <sup>h</sup>	8¢-10¢/ kWh <sup>j</sup>	9¢-12¢/ kWh <sup>j</sup>	5¢-11¢/ kWh <sup>i</sup>	\$2.50-\$3.00/ MMBTU	\$15-\$18/ BBL	\$35-\$45/ Ton	14¢-16¢/ kWh
Total Social Cost (1989 \$)	0.5¢-2¢/ kWh 36¢/Gallon Gasoline	8¢-10¢/ kWh	9¢-12¢/ kWh	5¢-11¢/ kWh	\$2.80-\$5.85/ MMBTU	\$32-\$40/ BBL	\$49-\$170/ Ton	16¢-19¢/ kWh

Notes: IB = Incremental Benefit; AB = Average Benefit; AC = Average Cost; MC = Marginal Cost; BBL = Barrels of Oil, 42 gallons or 6 MMBTU; Tons of Coal = 2,000 pounds or 24.7 MMBTU; MMBTU = Million British Thermal Units; ¢/kWh = cents per kilowatt hour levelized over the life of a typical unit; M-Ton = Metric Ton = 2,200 pounds.

<sup>a</sup>Nuclear from Chapman (1990). Omits decommissioning costs.

<sup>b</sup>The lower bound, \$0/MMBTU, assumes no cost of global warming. The upper bound assumes cost of reducing CO<sub>2</sub> equal to \$49/M-Ton, equivalent to implementing measures for energy efficiency, cogeneration, fuel switching, solar; wind and geothermal (see table 3, column (4)). Assumes CO<sub>2</sub> emission rates: 202 pounds/MMBTU, coal; 156 pounds/MMBTU, oil; 115 pounds/MMBTU, gas (Dudek and LeBlanc, 1990).

<sup>c</sup>For oil: the AC is from Hall (1990 forthcoming); the AB is from Broadman and Hogan (1988). For nuclear: the AC is calculated from Pilarski (1986) for bunkering against terrorist attack, assuming  $i = 10\%$ , 35 year life, 57.4% capacity factor (DOE, 1988). For nuclear, omissions include materials diversion to terrorists and weapons technology transfer.

<sup>d</sup>Calculated from Dubin and Rothwell (1990), subsidy of \$21.72 million per reactor year, assuming 93,700 MW/107 reactors = 875 MW per reactor (DOE, 1988), and 57.4% capacity factor (DOE, 1988).

TABLE 1 continued

<sup>c</sup>Out of 110 reactors, two shut down (Three Mile Island and Rancho Seco). Levelized cost of nuclear in 1987: 7.5¢/kWh (Bemis and DeAngelis, 1990).  $7.5 \times 2/110 = 0.14\text{¢/kWh}$ .

<sup>d</sup>Calculated from Harding's (1990) estimates ranging from \$70 million to \$400 million per reactor, assuming 875 MW/reactor (DOE, 1988), 35 year life,  $i = 10\%$ , and 57.4% capacity factor (DOE, 1988).

<sup>e</sup>Inflated to 1989 dollars with the Implicit Price Deflator (IPD) for GNP (CEA, 1990). This row sums all the above rows. The lower-bound estimate for fossil fuels assumes no cost from global warming. The upper-bound estimate includes a cost of reducing CO<sub>2</sub> equal to \$49/M-Ton (see note b above and table 3).

<sup>f</sup>Energy efficiency investments from Akbari et al. (1989) and Akbari and Rosenfeld (1990):

Shade trees/light surfaces save yearly—0.51 QUADS at 0.5¢/kWh

Appliance efficiency annual savings—50 billion kWh at 2¢/kWh

Additional efficiency annual savings—800 billion kWh at 2¢/kWh

<sup>g</sup>Increased gas mileage for cars, from 27 mpg to 35 mpg, cost \$370/vehicle (Akbari and Rosenfeld, 1990). Assuming 18,000 miles/year, calculate 153 gallons (23%) saved per year. At \$1.00/gallon, \$153/year saved. Assuming 5-year life and 10% interest, the present value equals \$580. Net savings:  $580 - 370 = 210$ , for an annual savings of \$55.39 (at 10% interest, 5 years), or \$0.36/gallon.

<sup>h</sup>From Hall and Walton (1990).

<sup>i</sup>Assuming emission controls.

<sup>j</sup>From Bemis and DeAngelis (1990).

<sup>k</sup>Estimates for California derived from Hall et al. (1989), SCAQMD (1988, 1989a,b), and CEC (1989a,b). From Hall et al. (1989): \$6.7 billion benefit to meet PM-10 standard in Los Angeles air basin (L.A. basin), \$2.4 billion benefit to meet ozone standard in L.A. basin. Calculations assume: for ozone (15% from natural, gas, 75% from oil); for PM-10 (1% from natural gas, 71% from oil and product production, refining, and consumption). From CEC: 1988 oil consumption in California, 565.8 million BBL; 1988 natural gas consumption in California, 14,935 million therms. Estimates:

Oil ( $\$6.7 \text{ Billion} \times 0.71 = + \$2.4 \text{ billion} \times 0.75$ )/565.8 MMBBL = \$11.59/BBL;

Gas ( $\$6.7 \text{ billion} \times 0.01 + \$2.4 \text{ billion} \times 0.15$ )/14,935 million therms = \$0.286/MMBTU.

Estimates conservatively omit: acid fog from oil and gas, benefits of reduced air pollution within California outside of L.A. basin, non-health-related benefits within L.A. basin, non-criteria pollutants within L.A. basin, benefits of reducing criteria pollutants (NO<sub>x</sub>, ROG, SO<sub>x</sub>, CO) in L.A. basin, ozone damage to pulmonary function.

<sup>l</sup>Omits methane, CO<sub>2</sub> only.

TABLE 1 continued

<sup>o</sup>Summary of damage in descending order of magnitude for acid rain (1985 \$):

1. Human health (in 1985 \$) (Lave, 1986)	
Incremental benefit from SO <sub>2</sub> reduction of 12.9 million tons	\$5.6 billion
2. Materials (inflated to 1985 \$)	
a. 17 midwestern and northeastern states (Adams, 1986), Total Damages	\$2 billion (in 1984 \$)
b. 117 cities, reduction in acid deposition (Callaway and Englin, 1990), Total Damages	\$2.279 billion (in 1984 \$)
c. a. and b. inflated to 1985 \$	\$2.1 billion-\$2.4 billion
d. Emissions of SO <sub>2</sub> (Dowlatabadi and Harrington, 1990)	
(1) Ohio Valley emissions: 6.2 million tons	
(2) Reduction of 6.2 - 4.5 = 1.7. New level for Ohio Valley is equivalent to national goal of reducing U.S. emissions by 10 million tons.	
(3) Reduction of 6.2 - 6.1 = 0.93. New level for Ohio Valley is equivalent to national goal of reducing U.S. emissions by 12 million tons.	
(4) Percentage reduction of SO <sub>2</sub> :	
10 M-Ton reduction: $1.7/6.2 = 27.6\%$	
12 M-Ton reduction: $0.93/6.2 = 15\%$	
e. Incremental benefit from reducing acid deposition, assuming linear damage function (in 1985 \$):	
10 M-Ton reduction: $0.726 \times \$2.1 \text{ billion}$ and $0.726 \times \$2.4 \text{ billion} =$	\$1.5 billion-\$1.7 billion
12 M-Ton reduction: $0.85 \times \$2.1 \text{ billion}$ and $0.85 \times \$2.4 \text{ billion} =$	\$1.8 billion-\$2.0 billion
3. Visibility (Adams, 1986)	
Eastern U.S. visibility improvement from reductions of 8-12 million tons SO <sub>2</sub>	\$1.4 billion -\$1.9 billion (in 1984 \$)
Incremental benefit of visibility (inflated to billions 1985 \$)	\$1.5 billion-\$2 billion
4. Agriculture (deflated to 1985 \$)	
a. Adams (1986)	
(1) 5 U.S. crops, 20-25% ozone reduction	\$1.2 billion (in 1978 \$)
(2) 6 U.S. crops, 25% ozone reduction	\$1.7 billion (in 1980 \$)
(3) Soybeans in 31 eastern states, 50% acid deposition reduction, \$1.4 billion (in 1980 \$), cancelled by NO <sub>x</sub> fertilization: zero net effect.	
b. Callaway and Englin (1990)	
Soybeans in 31 states, total damage from acid deposition, excludes damage from ozone and SO <sub>2</sub> but includes benefit from nutrient NO <sub>3</sub> , benefit from nutrient greater than damage	-\$51.5 million (in 1984 \$)

TABLE 1 continued

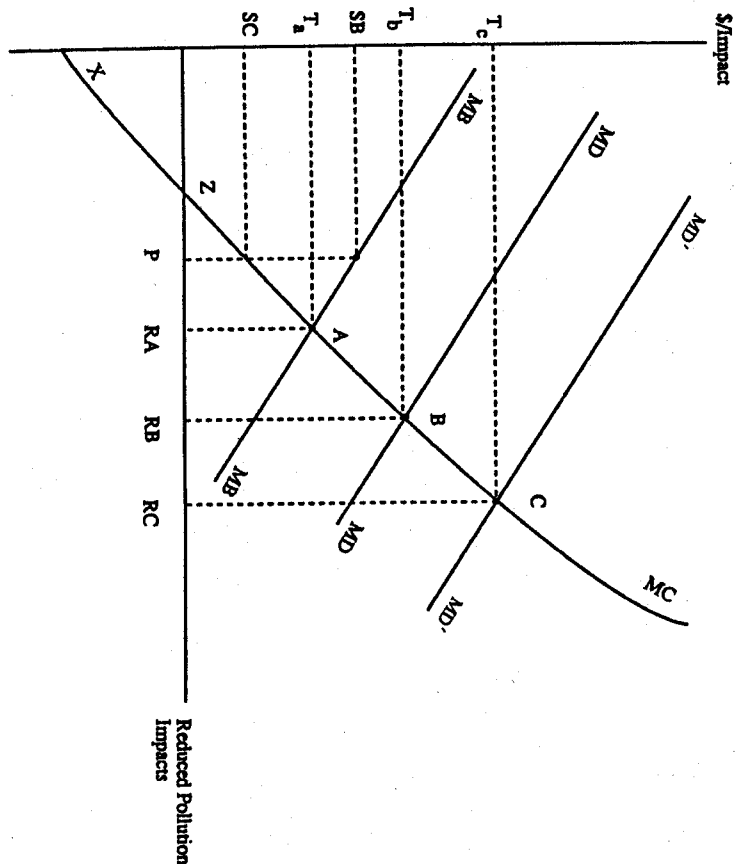
<sup>a</sup>Summary of damage in descending order of magnitude for acid rain (1985 \$) — continued:

c. Deflation to 1985 \$ using the Producer Price Index for farm products (CEA, 1988, table B-65)	
(1) Incremental benefit from ozone reduction	\$1.3 billion-\$1.6 billion
(2) Total loss from elimination of acid deposition and NO <sub>3</sub>	-\$46 million
(3) Incremental loss using 2.d.(4)	-\$33 million-\$39 million
5. Forests	
a. Eastern U.S. wood products, assumed growth reduction of 10%-20% (Callaway and Englin, 1990)	\$.3424 billion-\$0.5101 billion (in 1984 \$)
b. Fishing in Adirondack Lakes (excludes tributaries) (Callaway and Englin, 1990)	\$0.7-\$12 million (in 1984 \$)
c. Total U.S. eastern forests, wood products and fishing deflated to 1985 \$ with Producer Price Index for lumber and wood products (CEA, 1988, table B-65)	\$.034 billion to \$.050 billion
d. Eastern Canadian forests (Adams, 1986) \$1.5 billion (in 1981 \$), inflated to 1985 \$	\$.155 billion
6. Sum total (1-5) incremental benefits (in 1985 \$)	\$11.8 billion-\$13.3 billion
7. 1985 total U.S. consumption of coal (DOE, 1988)	17.48 QUADS
8. Incremental benefits of reducing acid rain and precursors from U.S. coal consumption (6 divided by 7)	\$.068-\$0.76/MMBTU
9. Assuming 24.7 MMBTU/Ton, incremental benefits of reducing acid rain and precursors per ton of coal	\$16.80-\$18.77/Ton

<sup>P</sup>Marginal cost per ton of coal for reducing acid rain precursors (Dowlatabadi and Harrington, 1990; Dowlatabadi, 1990). (1985 \$)

1. Expected total capacity for coal-fired generators	100 GW
2. Expected coal consumption	200 M-Tons
3. Expected SO <sub>2</sub> emissions for \$850/Ton SO <sub>2</sub>	1.7 M-Tons SO <sub>2</sub>
4. Fees collected at \$850/Ton SO <sub>2</sub>	\$1.445 billion
5. Fees per ton of coal	\$7.23/Ton
6. Expected SO <sub>2</sub> emissions for \$1,650/Ton SO <sub>2</sub>	0.93 M-Tons SO <sub>2</sub>
7. Fees collected at \$1,650/Ton SO <sub>2</sub>	\$1.5345 billion
8. Fees per ton of coal	\$7.67/Ton

FIGURE 1  
Optimal Pollution Control



allowable pollution, or leases, could split the difference. If the right to a clean environment is retained by the public, the optimal level of pollution abatement then becomes RB, which is higher than RA.

The error of equating MB to MC may be compounded for another reason. Pollution generally increases with economic growth, and the MD curve shifts upward and to the right as the level of pollution increases. For example, as global warming occurs, MD shifts to MD'. Similarly, MB shifts upward and to the right. Additionally, as population increases, more people are affected. This increases damage; thus, the MD function shifts up and to the right as population increases.

In their analyses of the greenhouse effect, Nordhaus (1989) and Crosson (1989) both fail to shift the damage functions. Most of the negative externalities cited here—such as the risks of nuclear meltdown, air pollution, acid rain, and global warming—also pose risks to public goods. For both reasons—increases in pollution and increases in population—the optimal level

of pollution control continues to increase over time—for example, from RB to RC in figure 1. Consequently, the tradable permit policy option does not result in the efficient allocation of resources unless the amount of pollution allowed by the permit depreciates over time.

Another possible source of error in standard economics textbooks arises from the partial equilibrium nature of the analysis in figure 1. Market failure typifies related commodities. For example, Ruderman et al. (1987) and Hirst (1987) have established empirically that energy consumers under-invest in energy efficiency. If the marginal cost of investment in measures to improve energy efficiency is less than the marginal cost of producing additional electricity—as Lovins (1990) and others argue—the MC curve is negative for the initial units of reduced emissions: between points X and Z in figure 1.

If the right to a clean environment belongs to the public, the desired estimate of external cost occurs where MC equals MD and grows over time—from  $T_b$  to  $T_c$  in figure 1. (Similarly, if the right to pollute belongs to the polluter, the desired estimate is where MC equals MB.) These are the ideal numbers to estimate.

The estimates of external costs reported in the tables appearing in section III use MB curves rather than MD curves, so they tend to assume that property rights to pollute have been fully extended to polluters even though that is still subject to political decisions not yet reached. Moreover, for some externalities, the only available estimates are incremental benefits (IB) rather than MB. An incremental benefit shows the amount people would be willing to pay to reduce pollution from the current level to some proposed standard. Theoretically, this is the slope of a line connecting two points on a total benefit curve, rather than the slope of a line tangent to the total benefit curve at the proposed standard.

For other externalities, the only estimates available are average benefits (AB) and average costs (AC). For some externalities, estimates of both MB and MC are not available. In such case, one can infer a shadow benefit or shadow cost from a policy setting the level of pollution. For example, in figure 1, assume that the policy sets the level of reduced emissions equal to P. If the MC curve is known, then one can estimate the externality as equal to the shadow cost SC. If the MB curve instead of the MC curve is known, then one can estimate the externality as equal to the shadow benefit SB. Finally, if both the MB and MC are known at the standard (P) but the rest of the MB and MC curves are unknown, then one can estimate the value  $T_a$  by averaging SB and SC. As one moves from the ideal measures—MB and MC—to relying on averaging SC and SB, the estimates are prone to diverge more from actual values.

If efficient standards are set equal to RB in figure 1 and are adjusted upward over time to RC, then emission control costs are borne by polluters and the externality is internalized. When the externality is fully internalized

through efficient standards, the external cost is zero. According to Kneetsch (1990), the standards more typically are set too low—say, at RA instead of RB—or remain at one level instead of being adjusted upward over time to RC. When the standards are set too low, the pollution control cost incorrectly estimates the cost of the externality. If the standards are set correctly—say, at RB—but are violated so that the level of emission reductions is given by P, then the pollution control cost would equal SC and would incorrectly estimate the pollution control cost. In such case, the marginal cost of pollution would have to equal  $T_b$  for prices to lead to an efficient outcome.

### III. ESTIMATES OF EXTERNALITIES

Table 1 displays a cumulation of estimated external costs for alternative energy sources in units comparable to prices, which have dollars in the numerator and energy quantity in the denominator. The selection of sources for estimates is severely restricted because very few estimates of external costs or benefits can be attributed to specific sources and quantities of energy, a quantity needed for the denominator. Most investigators cited here have stated that their estimates err on the side of under-estimating external costs. For these reasons and for others stated above and below, the cumulations are conservative estimates of external costs.

#### A. Air Pollution and Acid Rain From Fossil Fuels

For both coal and oil, the external costs of water pollution and solid waste are omitted. For both gas and oil, the external costs of acid rain and acid fog are omitted. The contribution to global warming of methane from natural gas is omitted. In the row presenting the cumulative external costs, these omissions are set to zero. In table 1, the cumulative external costs are under-estimated.

The benefits of reducing air pollution from oil and gas are based on estimates of incremental benefits (IB) by Hall et al. (1989). These figures are under-estimates for several reasons. The IB estimates are confined to only two of four pollutants out of compliance with standards for the Los Angeles (L.A.) air basin. The other two pollutants out of compliance are omitted. The following also are omitted: damage from ozone to pulmonary function, damage from pollutants not regulated, and botanical and property damage. The IB are allocated to oil, gas, and other activities based on data from SCAQMD (1988, 1989a,b).

Table 1 presents the estimated benefits in these units: per barrel of oil and per million BTU of gas. These units are derived by dividing the benefits by the levels of energy consumption for the entire state of California (CEC, 1989a,b). Because the divisors are the levels of oil and gas consumption for the entire state, the estimates also omit air pollution damage from oil and

gas in non-attainment areas in the rest of the state outside the L.A. basin. These estimated damages are from data specific to California. Because so many known effects are omitted, the estimates are conservative for California but they may be reasonable measures for the nation as a whole.

In table 1, the incremental benefits of reducing precursors to acid deposition are based on a variety of sources. The benefit categories include—in descending order of magnitude—human health, materials, visibility, agriculture, Canadian forests, and U.S. eastern forests (including some recreational fishing).

The 1990 Congress is amending the Clean Air Act to include a provision to reduce sulfur dioxide (SO<sub>2</sub>) emissions—a precursor to acid deposition—nationally by 10 million tons. Some years ago, Lave (1986) concluded that the health benefits alone more than justified this size of reduction. Nonetheless, the NAPAP excluded health benefits of precursor reductions in the economic assessment. Instead, the NAPAP emphasized the small impact on U.S. forests.

The MC reported in table 1, based on a model of electric utilities in the Ohio Valley (Dowlatabadi and Harrington, 1990), are for reductions in the Ohio Valley equivalent to national reductions of 10 million and 12 million tons. As table 1 shows, the MC at 12 million tons reduction (\$7.67/ton coal) is less than the IB (\$18.77). In accordance with the discussion in section II above, the MC and IB are averaged so as to estimate the external cost of reduced emissions of precursors to acid rain. This average is the basis for calculating the cumulative external costs in table 1. If one uses these estimates, then the 10-million-ton reduction specified in the Clean Air Act as amended in 1990 is less than economically efficient.

#### B. *Greenhouse Effect (Global Warming)*

Firor (1990) explains that without the greenhouse effect, the planet would be inhospitably cold. Physical scientists have known since the turn of the century that a greenhouse effect exists. The issue is global warming, which occurs when carbon dioxide (CO<sub>2</sub>) and other gases are released from consumption of fossil fuels and other economic activities. Over the past 160,000 years, the concentration of CO<sub>2</sub> in the atmosphere has been higher than it is today only once—130,000 years ago (Houghton and Woodwell, 1989). At that time, CO<sub>2</sub> concentrations were about 10 percent higher than they are today and the global temperature was about 0.1°C higher. Over the same time period, the level of CO<sub>2</sub> has been as much as one-third lower than it is today and the global temperature has been nearly 1°C lower. These fluctuations in CO<sub>2</sub> and temperature have occurred over as little as 5,000 years. The risk of global warming is that, over as little as the next 50 to 100 years, the level of CO<sub>2</sub> is expected to increase 100 percent and temperatures to increase 3°C plus or minus 1.5°C. Thereafter, these trends are expected to

continue, beyond a doubling of CO<sub>2</sub>, with temperatures increasing so long as we use fossil fuels at present rates of consumption. Even worse news is that the rate of fossil fuel consumption is expected to increase. In this context, physical scientists will not take seriously economists' calculations that the major cost of global warming to the economy is the price of some dikes to save coastal cities (Nordhaus, 1989).

Anthropogenic emissions of CO<sub>2</sub> from the United States in 1987 and from the world in 1986 equalled 4,865 million (table 2) and 20,317 million metric tons, respectively. The percentages of U.S. CO<sub>2</sub> emissions were as follows: 34 percent coal, 48 percent oil, and 18 percent natural gas. To stabilize the atmosphere, a 50-80 percent reduction in CO<sub>2</sub> would be needed (Dudek and LeBlanc, 1990).

Table 2 summarizes calculations designed to illustrate the CO<sub>2</sub> emission levels in the United States achieved by proposed policy alternatives. Table 3 lists measures by increasing cost in columns from left to right, along with the marginal cost of each emission level. Each measure cumulatively incorporates those to the left. For example, the column headed "Solar, Wind, and Geothermal" incorporates CO<sub>2</sub> reductions from energy efficiency.

The Environmental Protection Act of 1990 (EP) is an initiative qualified for the November 1990 California ballot. The EP would require a per capita reduction of greenhouse gases of 20 percent by the year 2000 and of another 20 percent by 2010. If the EP were applicable to the entire United States, then the maximum levels of CO<sub>2</sub> for the United States would be limited to those in table 2 under the column "EP Act of 1990." By 2010, emissions would have to be reduced to 3,506 million metric tons of CO<sub>2</sub>. Presumed in these calculations, subsequent to the EP Act deadline in 2010, emissions would resume growth.

As table 3 shows, this level of reduction requires substituting solar, wind, and geothermal for fossil fuels in the electric utility industry (except some natural gas for peaking power, as the appendix indicates). The marginal cost would be \$49/metric ton (M-Ton) of CO<sub>2</sub>, based on the high range of today's estimated levelized prices of solar power (12 cents/KWh) compared with that of coal without sophisticated air pollution controls (7.5 cents/KWh). This marginal cost is converted to units of natural gas, oil, and coal in table 1. The range of values in table 1 reflects the range of shadow costs from global warming policies varying between doing nothing (Crosson) and implementing a national policy equivalent to the EP Act of 1990. Note that even the EP only buys time: It delays global warming but does not prevent it.

#### C. *National Security*

Broadman and Hogan (1988) estimate the value of a security tariff on crude oil from a macroeconomic model that evaluates the impacts of oil price shocks. The tariff ranges from \$4.20/BBL to \$7.07/BBL, as table 1 shows.

**TABLE 2**  
Policies for Global Warming  
(annual CO<sub>2</sub> emissions in millions of metric tons [M-Tons])

Author:	Crosson	Nordhaus	Dudek and LeBlanc	Dudek and Manne and Riechels	EP Act of 1990	Stable Atmosphere
Policy:	Adapt	Reduce CO <sub>2</sub> 9%	Stable Emissions	Reduce CO <sub>2</sub> 20%	Reduce CO <sub>2</sub> 40%	Reduce CO <sub>2</sub> 50%
Year						
1987	4,865	4,865	4,865	4,865	4,865	4,865
1990	4,932	4,932	4,932	4,932	4,932	4,932
2000	5,166	4,701	4,932	4,686	4,317	3,357
2010	5,417	4,929	4,932	4,439	3,506	2,433
2020	5,686	5,174	4,932	3,945	3,797	2,433
2050	6,619	6,023	4,932	3,945	4,822	2,433

Notes: Column 2 (Crosson, 1989) shows projected CO<sub>2</sub> emissions if no active policies are adopted, and the passive policy is to adapt to global warming. Column 3 (Nordhaus, 1989) shows a 9% reduction from column 2. Column 4 (Dudek and LeBlanc, 1990) shows stable emissions rates, which result in continual global warming. Column 5 (Manne and Riechels, 1989) shows a reduction of 10% by year 2010 and an additional reduction of 10% by year 2020. Column 6 (Environmental Protection Act of 1990) shows limits on emission levels for the United States if the EP Act, a ballot initiative to be on the November 1990 ballot in California, were to apply to the entire United States. The EP Act of 1990 requires reductions from 1987 base year of 20% per person by the year 2000 and another 20% by 2010. Column 7 (stable atmosphere) shows emission rates if reduced by 50% of the 1987 rate, the minimum reduction needed to stop global warming by the year 2010 (Dudek and LeBlanc, 1990).

Sources: Column 2 from appendix (table A.1). Columns 3, 4, 5, and 7 calculated from column 1, as indicated in the notes above. For column 6, calculations assume an annual population growth rate of 0.8% (Chapman, 1990). Population in United States in 1987 = 243,934,000 (CEA, 1989). Emissions/person in 1987 = 4,865/243,934 = 19.94 M-Tons/person. Goals: for year 2000, 15.95 M-Tons/person; year 2010 and thereafter, 11.97 M-Tons/person. Population assumed to grow as follows: 270,557,000 persons in year 2000, 292,998,000 persons in 2010, 317,300,000 persons in 2020, and 402,982,000 persons in 2050. Values in column 6 calculated by multiplying the number of persons times the emissions per person.

The tariff is an average benefit of oil security equivalent to the cost of subsidies for oil security estimated by Hall (1990). Hall calculates the annual cost of the strategic petroleum reserve (SPR) and estimates the increases in defense spending (DS) as a function of imported oil. The sum of the SPR and DS per unit of imported oil equals \$5.79, as table 1 shows.

As Leventhal and Hoening (1990) report, Iran threatened on Tehran radio: "U.S. centers and nuclear reactors can be more vulnerable than the missile bases of the Islamic Republic of Iran." The cost of bunkering against attack, as table 1 reports, is based on two units in Switzerland. Significant omitted

**TABLE 3**  
Measures to Reduce Global Warming: CO<sub>2</sub> Emissions and Marginal Cost of Abatement (annual emissions of CO<sub>2</sub> in millions of metric tons [M-Tons])

Year	Energy Efficiency <sup>a</sup>	Cogeneration and Fuel Switching <sup>b</sup>	Solar, Wind, and Geothermal <sup>c</sup>	Hydrogen Fuel <sup>d</sup>
1990	4,932	4,932	4,932	4,932
2000	4,180	3,998	3,928	3,357
2010	4,309	4,112	3,493	2,433
2020	4,443	4,231	3,603	2,433
2050	4,894	4,631	3,976	2,433
	0.5¢-2¢/kWh <sup>e</sup>	\$4.94/ <sup>f</sup>	\$49/ <sup>g</sup>	\$73/ <sup>h</sup>
	36¢/Gallon Gasoline	M-Ton CO <sub>2</sub> <sup>f</sup>	M-Ton CO <sub>2</sub> <sup>g</sup>	M-Ton CO <sub>2</sub> <sup>h</sup>
		Marginal Cost		

Notes: From left to right, measures to reduce CO<sub>2</sub> emissions are listed in order of increasing marginal cost and are inclusive of measures to the left.

Energy efficiency includes electricity efficiency from urban shade trees, white surfaces, appliance efficiency, and other efficiency measures (Akbari et al., 1989). Energy efficiency also includes a 35-mpg CAFE standard (Akbari and Rosenfeld, 1990).

Cogeneration and fuel switching in the electric sector are detailed in Dudek and LeBlanc (1990). The emissions in this column account for emission reductions from energy efficiency. Solar, wind, and geothermal are assumed to eliminate all but 12% (for peaking power) of CO<sub>2</sub> emissions from the electric sector. The emissions in this column account for emission reductions from cogeneration and fuel switching and reductions from energy efficiency.

Hydrogen fuel is assumed available in year 2010 at a price of \$20/MMBTU in 1987 \$ (Manne and Riechel, 1989). At that time, emissions are reduced to the level that stabilizes the atmosphere, given in table 2.

<sup>a</sup>From table A.2.

<sup>b</sup>From table A.3.

<sup>c</sup>From table A.4.

<sup>d</sup>By the year 2010, a quantity of hydrogen fuel sufficient to stabilize the atmosphere is substituted for other fuel (Manne and Riechels, 1989), and the levels of emissions are 50% less than those of 1987 (see table 2).

<sup>e</sup>Electricity efficiency investments (Akbari et al., 1989; Akbari and Rosenfeld, 1990):

1. Shade trees/light surfaces save yearly 0.51 QUADS at 0.5¢/kWh.
2. Appliance efficiency annual savings: 50 billion kWh at 2¢/kWh.
3. Additional efficiency annual savings: 800 billion kWh at 2¢/kWh.

<sup>f</sup>Cogeneration and fuel switching in 31 eastern states, \$4.94/M-Ton CO<sub>2</sub> (Dudek and LeBlanc, 1990).

<sup>g</sup>Assuming the levelized MC of electricity from coal is about 7.5¢/kWh and solar is about 12¢/kWh (Walton and Hall, 1990), the MC of reduced CO<sub>2</sub> equals 4.5¢/kWh. A kilowatt hour of electricity from coal requires about 10,000 BTU, or 2.02 pounds of CO<sub>2</sub>, or \$49/M-Ton of CO<sub>2</sub>.

<sup>h</sup>Calculated from Manne and Riechels (1989): \$20/MMBTU for hydrogen fuel, \$10/MMBTU for synthetic fuel, and \$300 pounds of CO<sub>2</sub>/MMBTU from synthetic fuel.

<sup>i</sup>Increased gas mileage for cars, from 27 mpg to 35 mpg, cost \$370/vehicle (Akbari and Rosenfeld, 1990). Assuming 18,000 miles/year, calculate 153 gallons (23¢) saved per year. At \$1.00/gallon, \$153/year saved. Assuming 5-year life and 10% interest, the present value equals \$580. Net savings: 580 - 370 = 210, for an annual savings of \$53.39 (at 10% interest, 5 years), or \$0.36/gallon.

costs of national security include materials diversion and the transfer of technology used to make nuclear weapons.

#### D. *Nuclear Safety and Waste Disposal*

The nuclear industry argues for liability limits in the event of a serious accident since private insurers are not willing to provide coverage. The Price-Anderson Act established limits that subsidize the nuclear industry. Dubin and Rothwell (1990) estimate the value of the subsidy, converted here into kilowatt hours (see appendix), given in table 1. Because owners, operators, and vendors do not pay for insurance covering the most serious types of accidents, they are not subject to market incentives requiring the optimal amount of safety. Even if insurers were willing to offer policies, moral hazard is a well-known market failure.

The Nuclear Regulatory Commission (NRC) has the responsibility to require safety measures. Harding (1990) points out that the risk-benefit studies used by the NRC to decide on safety measures exclude the value of the reactor and the cost of replacement power. Consequently, the Dubin and Rothwell (1990) estimates are conservative—as they acknowledge—since the estimates rely on the NRC's assumption of a maximum damage equal to \$10 billion. This compares with a total cost of the Chernobyl accident varying between \$41 billion (Ansbaugh et al., 1988; Parks, 1990) and \$673 billion, depending on whether one uses the official exchange rate or the black market exchange rate (Keller, 1989). Table 1 displays the cost of additional safety measures based on estimates by Harding (1990).

The expected cost of reactor loss in table 1 is estimated as the probability of a permanent shut-down times the value of a reactor. The estimate of the probability would, ideally, equal the frequency of shut-down of existing and future reactors, whether from an accident or from a political-economic calculus concerning the risk of a reactor design and competency of the operator. Dremmen and Chapman (1990) list those reactors that have been shut down, and the reasons for the shut-downs. Of those listed as shut down specifically for safety reasons, most were smaller than today's reactors and built during the early stages of the industry. Two relatively modern reactors of one reactor design have been shut down, Three Mile Island because of an accident and Rancho Seco because of the perceived risk of the reactor design and operation. Estimating a frequency of future failure from the past may be unsatisfactory—especially since that reactor design will not be replicated—but the alternative is to set to zero the probability of future shut-downs.

#### E. *Private Costs*

Akbari and Rosenfeld (1990) estimate the private cost of conservation measures. They estimate savings of up to 900 billion kWh from white sur-

faces, urban shade trees, efficient appliances, and additional efficiency measures identified by the U.S. Department of Energy. These investments cost 0.5 to 2 cents/kWh, as table 1 reports. Akbari and Rosenfeld also present an estimate that equals \$370 per vehicle for the cost of increasing the corporate average fuel economy (CAFE) standards from 27 to 35 mpg, which would save 11.5 percent of the energy used for transportation. This computes to 36 cents per gallon of gasoline saved. These estimates of the cost and amount of available energy efficiency are quite conservative compared with those of Lovins (1990).

Table 1 summarizes the private cost of electricity from solar, wind, and nuclear facilities estimated by Walton and Hall (1990).

The private cost of nuclear power is lower in other countries, such as Japan (Navarro, 1988), but this lower private cost is achieved at an increased external cost due to fewer safety requirements and more risky practices. For example, Navarro reports that the Japanese use dense-pack sites so that in the event of a meltdown or attack by terrorists, several units could be lost. Navarro explains part of the cost differences between the United States and Japan by the difference in response to new information about safety: When additional safety features are identified or safety violations are discovered by the NRC, remedies are required immediately in the United States but not in Japan. The resultant lower capacity factor in the United States could alternatively be attributable to excess caution by regulators, or to misfeasance by nuclear plant owners and operators.

#### F. *Cumulative External and Total Social Cost*

For each fossil fuel (gas, coal, and oil), table 1 presents a row titled "cumulative external cost" with a range of values. The range of values presents the cumulative externalities with and without the marginal cost of slowing global warming. The marginal cost estimate equals \$49/metric ton, consistent with the measures to reduce carbon emissions given in column 4 of table 3.

The range of cumulative external costs for nuclear power reflects the range of Harding's (1990) estimated maximum damage from the worst credible accident.

The total social costs in table 1 are the sums of the cumulative external costs and private costs. Compare these estimates for the United States with external costs for the Federal Republic of Germany as estimated by Hohmeyer (1990).

#### IV. POLICY

Technological change has altered private costs of technologies for energy demand and supply. New investment opportunities permit substantial energy

conservation at present prices. The price of solar power now is less than the price of nuclear power in the Sunbelt. The economy continues to make massive and economically inefficient investments in nuclear power, coal, oil, and gas. The economy, in an equally inefficient manner, continues to underinvest in conservation, in renewable energy sources (e.g., solar, wind, and biomass), and in relatively clean geothermal energy.

Economists typically favor little to no market intervention, based on a *priori* assumptions that the degree of market failure is small and the likelihood of mal-intervention by government is large. Most economists traditionally have advocated government intervention to alleviate market failure in some aspects of energy production and consumption—e.g., electric utilities. However, evidence indicates that economists tend to underestimate market failure involving energy for two reasons. First, analyses of market failure typically focus on a narrow aspect and ignore the cumulative effect. Second, quantifying externalities is difficult and in some cases is impossible.

Rather than face criticism for the difficulties inherent in estimation and for the absence of measurements, economists habitually assume that external costs are zero. The estimates presented here are subject to the criticisms that befall every application of economic analysis with actual data. The estimates here omit important externalities and so tend to be biased below the true external costs. Even so, the cumulative estimates of external costs are of a magnitude that indicates significant economic inefficiency.

Air quality has not attained minimum standards set to protect health. The 10-million-ton reduction of sulfur proposed in the 1990 amendment to the Clean Air Act leaves incremental benefits of reductions equal to two times the estimated marginal cost of reductions. The estimates indicate that a larger reduction of sulfur is required for economic efficiency. Analysis have estimated that global warming will continue beyond the effect of a doubling of CO<sub>2</sub> unless fossil fuel consumption is reduced. Meanwhile, consumption increases. The estimated national security costs and benefits of oil from the Middle East equal one-third to one-half the market price today. The nuclear option spreads nuclear weapons around the globe, provides targets for terrorists, and makes nuclear material more easily accessible to terrorists. Economists face the challenge of entering the policy debate on how best to internalize the external costs. Mal-intervention by government is more likely if economists continue to present studies that underestimate cumulative external costs and provide the bases for inaction.

#### A. Conservation

Estimates presented here indicate two sources of market failure that result in under-investment in energy efficiency. First, the price of most conventional energy reflects only private costs and omits external costs. Second,

consumers under-invest relative to the price based on private costs. The first source of market failure is obvious. The second requires some explanation.

Regulators set electricity and natural gas prices at the historical average cost, which is much lower than private long-run marginal cost. However, even if regulators set prices equal to the long-run marginal cost, consumers would under-invest in energy efficiency. Electric and gas utilities build new power plants and pipelines at an interest rate equal to about 10 percent for investor-owned-utilities (IOUs) and 7 percent for government-owned utilities. Some consumers face interest rates for investment in measures to improve energy efficiency equal to 15–20 percent. Other consumers are unable to qualify for loans.

Even if consumers faced interest rates equal to those for IOUs and if prices were set at the long-run marginal cost, consumers still would under-invest in energy efficiency. Ruderman et al. (1987) estimate discount rates for appliance efficiency investments from 18–825 percent, depending on the appliance. They conclude that consumers are not able to evaluate the payoff of such investments. Huang (1990) and Kawajia et al. (1990) empirically establish opportunities for efficiency investments that cost less than new power plants.

Lovins (1990), Koomey and Rosenfeld (1990), and Messenger (1990) discuss various policy options to rectify the market failures causing underprovision of energy efficiency. But both Lovins and Messenger bias their policy recommendations toward continuing under-investment in energy efficiency by omitting the external cost of conventional energy sources.

#### B. Alternatives for Energy Supply

In the Sunbelt, solar power generally has a lower private cost than does nuclear power (Walton and Hall, 1990). Moreover, solar power is available during peak and mid-peak periods when power is more valuable, while half of the power from nuclear facilities is available during the off-peak period when power is less valuable. Summing external plus private costs results in a total social cost estimate for nuclear power that is twice that for solar power, and nuclear power is less valuable on a kilowatt-hour basis.

Even when one ignores the cost of delaying global warming, the estimates of external costs of conventional energy sources are, at a minimum, substantial percentages of private costs as follows: 12 percent for natural gas, 112 percent for oil, 39 percent for coal, and 14–17 percent for nuclear power. When one includes the cost of delaying global warming, the estimated premiums for cumulative external costs for fossil fuels are higher: 95 percent for natural gas, 123 percent for oil, and 277 percent for coal. The estimates suggest that adding these premiums—in the form of taxes—to the private costs of nuclear power, coal, oil, and natural gas would improve economic efficiency. Energy taxes of this magnitude would generate revenue in the

tens of billions of dollars—perhaps enough to eliminate the social security tax or reduce the income tax rate and thereby increase economic efficiency a second way by eliminating taxes that induce inefficiency. However, utilities, the automobile industry, and other special interests no doubt would lobby against such a change in the tax system.

Revenue-neutral schemes such as those suggested by Koomey and Rosenfeld (1990) might have more political promise. For example, one could design electricity rates so that the tail-block rate is set equal to a weighted average of the social costs of conventional energy sources, with the weights equal to the proportion of power generated from each source. One could set the initial block rates low enough so as to avoid monopoly profit. The high tail block rate would encourage customers to invest in technologies that are energy efficient.

### C. Global Warming

The California ballot initiative, EP, scheduled for the November 1990 ballot, would require a reduction in per capita greenhouse gases of 20 percent by the year 2000 and another 20 percent by 2010. As reported by Dudek and LeBlanc (1990), world-wide reductions in greenhouse gases by that amount are not sufficient to stabilize the atmosphere. However, the targets in the EP Act of 1990 could be met by investing in energy efficiency and eliminating most fossil fuels from the electricity industry. If the northern U.S. states connected transmission grids with the Sunbelt, then these emission reductions of CO<sub>2</sub> could be achieved with solar power at today's cost equating \$49/metric ton (M-Ton) of CO<sub>2</sub> (see table 3 and appendix), or 12 cents/kWh. This cost is not much higher than retail electricity rates in the Northeast.

According to estimates here, stabilizing the atmosphere and allowing for continuing population, energy, and economic growth requires an alternative liquid fuel—from biomass or hydrogen. This is the most expensive measure to reduce CO<sub>2</sub>. Calculated from Manne and Richels' (1989) estimated cost of hydrogen or a fuel from biomass at \$20/MMBTU, a carbon dioxide tax of \$73/M-Ton of CO<sub>2</sub> would be necessary (table 3). Clearly, the relationship between transportation and energy externalities needs an immediate and a substantial research effort. If the cost of alternative liquid fuel is unacceptably high, stabilizing the atmosphere may require controlling population as Chapman and Drennen's (1990) analysis suggests.

Howe (1990) reports that economists now question whether our economies can afford to slow global warming and reduce external costs. Sweden has established a policy to eliminate nuclear power without increasing emissions of CO<sub>2</sub> (Mills, 1990). The implications are that pursuing economic efficiency not only is affordable but may be necessary for survival.

## APPENDIX

### TABLE A.1

Annual Emissions of CO<sub>2</sub> With No Active Policy to Abate Emissions  
(in millions of metric tons [M-Tons] of CO<sub>2</sub>)

	Electricity	Transportation	Residential and Industrial	Total
1987	1,638 <sup>a</sup>	1,498 <sup>b</sup>	1,729 <sup>c</sup>	4,865 <sup>d</sup>
1990	1,675 <sup>e</sup>	1,528 <sup>f</sup>	1,729 <sup>c</sup>	4,932 <sup>h</sup>
2000	1,805 <sup>e</sup>	1,632 <sup>f</sup>	1,729 <sup>c</sup>	5,166 <sup>h</sup>
2010	1,945 <sup>e</sup>	1,743 <sup>f</sup>	1,729 <sup>c</sup>	5,417 <sup>h</sup>
2020	2,096 <sup>e</sup>	1,861 <sup>f</sup>	1,729 <sup>c</sup>	5,686 <sup>h</sup>
2050	2,623 <sup>e</sup>	2,267 <sup>f</sup>	1,729 <sup>c</sup>	6,619 <sup>h</sup>

Notes: QUAD = quadrillion BTUs, MMBTU = millions of BTUs, BTU = British Thermal Unit.

<sup>a</sup>In 1987, electric sector used 15.19 QUADs coal, 2.94 QUADs gas, and 1.26 QUADs petroleum (DOE, 1988). Emission rates of CO<sub>2</sub>: 202 pounds/MMBTU coal; 156 pounds/MMBTU oil; 115 pounds/MMBTU natural gas (Dudek and LeBlanc, 1990). In million metric tons (M-Tons) of CO<sub>2</sub>, in 1987 electricity generation emitted 1,395 from coal, 89 from oil, and 154 from gas, for a total of 1,638 million M-Tons CO<sub>2</sub>.

<sup>b</sup>In 1987, transportation sector used 21.12 QUADs (DOE, 1988). [(21.12 QUADs x 156 pounds CO<sub>2</sub>/MMBTU) / 2,200 pounds/M-Ton] x 1,000 = 1,498 million M-Tons CO<sub>2</sub>.

<sup>c</sup>1,729 = 4,865 - 1,638 - 1,498.

<sup>d</sup>In 1987, U.S. total energy consumption from fossil fuels (DOE, 1988) equaled 18 QUADs, coal: 32.63 QUADs, oil: and 17.18 QUADs, natural gas: [(18 x 202 + 32.63 x 156 + 17.18 x 115) / 2,200] x 1,000 = 4,865.

<sup>e</sup>Calculated assuming an annual growth rate of 0.75%. Dudek and LeBlanc (1990) calculate, based on the National Electricity Council plans for increases in oil and coal, additional emissions of 126 million M-Tons from 1987 to 1997, which is equivalent to an annual rate of 0.75%.

<sup>f</sup>Calculated assuming an annual growth rate of 0.66%. From DOE (1988), energy consumption in transportation grew during 1977 to 1987 from 19.77 QUADs to 21.12 QUADs, an annual increase of 0.66%.

<sup>g</sup>Assume direct use of residential and industrial energy does not grow, a continuation of the past decade (DOE, 1988).

<sup>h</sup>Sum across the row.

**TABLE A2**  
Annual Emissions of CO<sub>2</sub> With Energy Efficiency to Abate Emissions  
(in millions of metric tons [M-Tons] of CO<sub>2</sub>)

	Electricity	Transportation	Residential and Industrial	Total
1990	1,675 <sup>a</sup>	1,528 <sup>a</sup>	1,729 <sup>a</sup>	4,932 <sup>a</sup>
2000	1,007 <sup>b</sup>	1,444 <sup>c</sup>	1,729 <sup>d</sup>	4,180 <sup>e</sup>
2010	1,049 <sup>f</sup>	1,531 <sup>g</sup>	1,729 <sup>d</sup>	4,309 <sup>e</sup>
2020	1,092 <sup>f</sup>	1,622 <sup>g</sup>	1,729 <sup>d</sup>	4,443 <sup>e</sup>
2050	1,233 <sup>f</sup>	1,932 <sup>g</sup>	1,729 <sup>d</sup>	4,894 <sup>e</sup>

Notes: QUAD = quadrillion BTUs, MMBTU = millions of BTUs, BTU = British Thermal Unit.

<sup>a</sup>From table A.1.

<sup>b</sup>Shade trees and light surfaces save 0.51 QUADs of peak power (Akbari et al., 1989). Assume 8,000 BTU/kWh new gas turbine and 115 pounds/MMBTU, and calculate 18.4 million M-Tons CO<sub>2</sub> saved from gas-fired electricity generation. Assume this occurs during the period from 1990 to 2000.

<sup>c</sup>Appliance efficiency annual savings: 50 billion kWh/Year in 1987. Additional electricity efficiency annual savings: 800 billion kWh/Year in 1987 (Akbari et al., 1989). Electricity efficiency total savings equals 850 billion kWh. Assume coal is displaced, with a heat rate of 10,000 BTU/kWh. [850,000,000,000 kWh x 0.01 MMBTU/kWh x 202 pounds/MMBTU] / (2,200 pounds/M-Ton x 1,000,000) = 780 million M-Tons CO<sub>2</sub> reduced. For year 2000, 1,007 = 1,805 (from table A.1) - 18 - 780.

<sup>d</sup>Increased gas mileage for cars, from 27 mpg to 35 mpg (Akbari and Rosenfeld, 1990). Assuming 18,000 miles/year, 153 gallons (23%) saved. Personal cars and light trucks consume 50% of the energy used in transportation (Pirog and Stamos, 1987). CAFE standard of 35 mpg saves 23 x 50 = 11.5%. Calculate this entry equal to 0.885 times entry in table A.1.

<sup>e</sup>Assume direct use of residential and industrial energy does not grow, a continuation of the past decade (DOE, 1988).

<sup>f</sup>Sum across the row.

<sup>g</sup>Assumes a 0.4065% annual growth rate after year 2000. From table A.1, without active CO<sub>2</sub> abatement policy, the growth rate is assumed equal to 0.75% (table A.1, note e). With electricity efficiency, the growth rate is assumed to drop by 45.8%, a drop proportional to the energy savings from efficiency. That is, (1.00 - 0.458) x 0.75 = 0.4065.

In 1987, 2,571 billion kWh/Year consumed: 917 billion kWh nuclear, hydro, and geothermal; 1,464 billion kWh coal; 118 billion kWh oil; 273 billion kWh gas. This includes 15.19 QUADs coal, 2.94 QUADs gas, and 1.26 QUADs petroleum (DOE, 1988). Total fossil fuel electricity generation: 1,464 + 118 + 273 = 1,855 billion kWh. Savings of 850/1,855 = 45.8% of carbon emissions.

<sup>h</sup>Assumes a 0.5841% annual growth rate after year 2000. From table A.1, without active CO<sub>2</sub> abatement policy, the growth rate is assumed equal to 0.66% (table A.1, note f). With active transportation efficiency, the growth rate is assumed to drop by 11.5%, proportional to the energy savings from 35 mph CAFE standards (see note c, above): (1.00 - 0.115) x 0.66 = 0.5841.

**TABLE A3**  
Annual Emissions of CO<sub>2</sub> With Energy Efficiency, Fuel Switching, and Cogeneration (in millions of metric tons [M-Tons] of CO<sub>2</sub>)

	Electricity	Transportation <sup>a</sup>	Residential and Industrial <sup>b</sup>	Total <sup>c</sup>
1990	1,675 <sup>d</sup>	1,528	1,729	4,932
2000	825 <sup>e</sup>	1,444	1,729	3,998
2010	852 <sup>f</sup>	1,531	1,729	4,112
2020	880 <sup>f</sup>	1,622	1,729	4,231
2050	970 <sup>f</sup>	1,932	1,729	4,631

Notes: QUAD = quadrillion BTUs, MMBTU = millions of BTUs, BTU = British Thermal Unit.

<sup>a</sup>Same as table A.2.

<sup>b</sup>Same as tables A.1 and A.2.

<sup>c</sup>Sum across the row.

<sup>d</sup>From table A.1.

<sup>e</sup>Calculated from estimates in Dudek and LeBlanc (1990). Cogeneration efficiency reduces CO<sub>2</sub> annually by 140 million M-Tons, or a reduction of 140/1,638 = 8.5%. Fuel switching from residual oil to natural gas in 31 eastern states reduces CO<sub>2</sub> annually by 42 million M-Tons (42/1,638 = 2.5%) at \$4.94/M-Ton. Calculate 182 million M-Tons reduction by year 2000. Subtract 182 from 1,007 (table A.2) to get 825.

<sup>f</sup>Assumes a 0.324% growth rate after year 2000. From table A.1, the growth rate without active CO<sub>2</sub> abatement is assumed equal to 0.75%. Assume that electricity efficiency reduces the growth rate by 45.8% (table A.2, note f), cogeneration efficiency reduces the growth rate by 8.5% (note e above), and fuel switching reduces the growth rate by 2.5% (note e above). The growth rate is reduced by 45.8 + 8.5 + 2.5 = 56.8%. (1.00 - 0.568) x 0.75 = 0.324.

**TABLE A4**  
Annual Emissions of CO<sub>2</sub> With Energy Efficiency, Solar, Wind, and Geothermal  
(in millions of metric tons [M-Tons] of CO<sub>2</sub>)

	Electricity	Transportation <sup>a</sup>	Residential and Industrial <sup>b</sup>	Total <sup>c</sup>
1990	1,675 <sup>d</sup>	1,528	1,729	4,932
2000	755 <sup>e</sup>	1,444	1,729	3,928
2010	233 <sup>e</sup>	1,531	1,729	3,493
2020	252 <sup>e</sup>	1,622	1,729	3,603
2050	315 <sup>e</sup>	1,932	1,729	3,976

Notes: QUAD = quadrillion BTUs, MMBTU = millions of BTUs, BTU = British Thermal Unit.

<sup>a</sup>Same as table A.2.

<sup>b</sup>Same as tables A.1 and A.2.

<sup>c</sup>Sum across the row.

<sup>d</sup>From table A.1.

<sup>e</sup>Assumes that by year 2010 and thereafter solar, wind, and geothermal replace all but some natural gas for peaking capacity, equal to 12% of that in table A.1. Assumes that by year 2000, 25% of the fossil fuel emissions in table A.2 are eliminated.

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