Realistic Mitigation Options for Global Warming

Edward S. Rubin, Richard N. Cooper, Robert A. Frosch, Thomas H. Lee, Gregg Marland, Arthur H. Rosenfeld, Deborah D. Stine

Policy responses to global climate change have been hampered by large uncertainties in the magnitude and timing of potential impacts and the economic implications of proposed response measures. Cost-effectiveness is a key measure for comparing a broad range of options to mitigate the effects of greenhouse warming. Although the full cost of many mitigation measures is difficult to assess, analysis suggests that a variety of energy efficiency and other measures that are now available could reduce U.S. emissions of greenhouse gases by roughly 10 to 40% of current levels at relatively low cost, perhaps at a net cost savings. Such measures are proposed as an initial U.S. response to global warming concerns in conjunction with other domestic and international efforts.

Analysis Framework

The potential for man-made emissions of carbon dioxide (CO_2), chlorofluorocarbons (CFCs), methane (CH_4), nitrous oxide (N_2O), and other greenhouse gases to alter the earth's climate has gained widespread attention in recent years. International concern has been spurred by predictions that a doubling of atmospheric CO_2 concentrations could produce a 1° to 5°C increase in average global temperature by the middle of the next century (*1*). The fear of significant climate change impacts, including rising sea levels, altered precipitation patterns, increased storm frequency, and damage to natural ecosystems, has led policy-makers in Europe and elsewhere to call for immediate action to stabilize or reduce the growth in greenhouse gas emissions (*2*). The U.S. government, however, has argued that current scientific understanding of global climate change is still too crude and uncertain to warrant such programs, which it believes could severely damage the economy (*2, 3*). Thus, the scientific uncertainty regarding the timing and severity of future climate impacts, and of its consequences, exacerbates the policy dilemma of what actions, if any, should be taken now to mitigate global warming.

We outline here a framework for evaluating mitigation options in the face of current uncertainties. If any mitigation measures are to be taken, what options and policies make most sense? What are the advantages and disadvantages of different options and how can they be compared? We suggest that cost-effectiveness be an essential guideline in evaluating and comparing alternative mitigation strategies. Because measures to limit greenhouse gas emissions imply investment efforts lasting many years and large enough to affect the macroeconomic profile of a country, the costs of climate policy and the technological means of achieving emission reductions need to be considered prominently, with a focus on obtaining the largest reduction in potential greenhouse warming at the lowest cost to society.

Because of differences in the atmospheric lifetime and heat trapping (radiative forcing) characteristics of different gas molecules, the relative contribution of different species to greenhouse warming is complex (Table 1). Roughly 25% of annual greenhouse gas emissions from human activities comes from the United States (*4, 5*). To date, CO_2 from combustion of fossil fuels has been the primary focus of attention. A comprehensive look at mitigation options, however, must

Table 1. Estimate of current greenhouse gas emissions from human activity (*5*).

Source	Annual emissions (Mt/year)		CO_2-equivalent (Mt/year)*	
	World	U.S.	World	U.S.
CO_2 emissions				
Commercial energy	18,800		18,800	
Tropical deforestation	2,600		2,600	
Other	400		400	
Total CO_2	21,800	4,800	21,800	4,800
CH_4 emissions				
Rice cultivation	110		2,300	
Enteric fermentation	70		1,500	
Fuel production	60		1,300	
Landfills	30		600	
Tropical deforestation	20		400	
Other	30		600	
Total CH_4	320	50	6,700	1,050
CFC emissions				
Total CFCs	0.6	0.3	3,200	1,640
N_2O emissions				
Fertilizer use	1.5		440	
Coal combustion	1.0		290	
Tropical deforestation	0.5		150	
Agricultural wastes	0.4		120	
Land cultivation	0.4		120	
Fuel and industrial biomass	0.2		60	
Total N_2O	4.0	1.4	1,180	410
Overall total			32,880	7,900

*Millions of metric tons based on the estimated global warming potential (GWP) for a 100-year averaging time (*6*): CO_2 = 1, CH_4 = 21, N_2O = 290, CFC-11 = 3500, CFC-12 = 7300 and CFC-113 = 4200. Values give the CO_2-equivalent radiative forcing for an instantaneous injection of 1 kg of gas into the atmosphere. Values for CH_4 include the estimated indirect effects of CO_2 produced. However, the GWP does not incorporate complex couplings with other greenhouse gases such as stratospheric and tropospheric ozone and their precursor emissions. The GWP thus provides only a preliminary basis for comparing diverse mitigation strategies.

E. S. Rubin, Department of Engineering and Public Policy and Department of Mechanical Engineering, Carnegie Mellon University, Pittsburgh, PA 15213.
R. N. Cooper, Department of Economics, Harvard University, Cambridge, MA 02138.
R. A. Frosch, General Motors Research Laboratories, Warren, MI 48090.
T. H. Lee, Department of Electrical Engineering and Computer Science, Massachusetts Institute of Technology, Cambridge, MA 02139.
G. Marland, Environmental Science Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831.
A. H. Rosenfeld, Lawrence Berkeley Laboratory, University of California, Berkeley, CA 94720.
D. D. Stine, National Academies of Science and Engineering, Washington, DC 20418.

consider emissions of all greenhouse gases. To compare the relative importance of different emissions we employ the concept of a global warming potential (GWP) to estimate the CO_2-equivalent emissions of each of the major greenhouse gases (Table 1). This index considers the infrared absorptive capacities, concentrations and concentration changes of individual greenhouse gases, their spectral overlaps, and atmospheric residence times (6). The GWP thus depends on the time interval of integration; short-lived gases become less important as time increases. CO_2 emissions from fossil fuel energy use remain the largest contributor to total worldwide and U.S. emissions, but methane, CFCs, and N_2O also are important. These comparisons have large uncertainties and may change with future revisions.

Table 2. Best-practice technology options available at little or no net cost that are not fully implemented due to institutional and other barriers. Numbers with options refer to steps in Fig. 1. Com., commercial; Res, residential; Ind, industrial.

Option	CO_2-equivalent reduction[a]	Net cost[b]
	Residential and commercial energy use	
Electricity efficiency		
1. White roofs and trees[c]	32	−84
2. Res. lighting[d]	39	−79
3. Res. water heating[e]	27	−74
4. Com. water heating[f]	7	−72
5. Com. lighting[g]	117	−71
6. Com. cooking[h]	4	−70
7. Com. cooling[i]	81	−64
8. Com. refrigeration[j]	15	−60
9. Res. appliances[k]	72	−44
10. Res. space heating[l]	74	−39
11. Com. and Ind. space heating[m]	15	−35
12. Com. ventilation[n]	32	1
Oil and gas efficiency[o]	300	−62
Fuel switching[p]	74	−90
Sector total	890	−62 (−78/−47)
	Industrial energy use	
Electricity efficiency[q]	137	−43
Fuel use efficiency[r]	345	−24
New cogeneration[s]	45	−18
Sector total	527	−28 (−42/−14)
	Transportation energy	
Light-duty vehicles[t]	251	−40
Heavy-duty trucks[u]	39	−59
Sector total	290	−43 (−21/−75)
	Power plants	
Coal plants[v]	45	~0
Hydroelectric plants[w]	12	~0
Nuclear plants[x]	42	2
Sector total	99	1 (0/2)
Landfill gas[y]	230	1 (0.4/2)

[a]Equivalent CO_2 reduction in millions of metric tons based on 1989 fuel and electricity use. [b]Net implemented cost in dollars per ton of CO_2-equivalent. Costs are mid-range estimates based on a 6% real discount rate, constant 1989 dollars. Parentheses give low/high range for average cost reflecting real discount rates of 3 to 10% plus uncertainty across different studies or estimates. [c]Plant shade trees and paint roofs white at 50% of residences to reduce air conditioning use and the urban heat island effect by 25%. [d]Replace incandescent lighting (2.5 inside and 1 outside light bulb per residence) with compact fluorescents to reduce lighting energy consumption by 50%. [e]Efficient tanks, increased insulation, low-flow devices, and alternative water heating systems to improve efficiency by 40 to 70%. [f]Residential measures above, plus heat pumps and heat recovery systems to improve efficiency by 40 to 60%. [g]Replace 100% of commercial light fixtures with compact fluorescent lighting, reflectors, occupancy sensors, and day lighting to reduce lighting energy consumption by 30 to 60%. [h]Additional insulation, seals, improved heating elements, reflective pans, and other measures to increase efficiency by 20 to 30%. [i]Improved heat pumps, chillers, window treatments, and other measures to reduce commercial cooling energy use by 30 to 70%. [j]Improved compressors, air barriers, food case enclosures, and other measures to improve efficiency 20 to 40%. [k]Implementation of new appliance standards for refrigeration and use of no-heat drying cycles in dishwaters to improve efficiency of refrigeration and dishwashers by 10 to 30%. [l]Improved and increased insulation, window glazing, and weather stripping along with increased use of heat pumps and solar heating to reduce energy consumption by 40 to 60% [m]Use measures similar to residential sector to reduce energy consumption by 20 to 30%. [n]Improved distribution systems, energy-efficient motors, and other measures to improve efficiency 30 to 50%. [o]Efficiency measures similar to those for electricity to reduce fossil fuel energy use by 50%. [p]Switch 10% of building electricity use from electric resistance heat to natural gas heating to improve overall efficiency by 60 to 70%. [q]More efficient motors, electrical drive systems, lighting and industrial process modifications to improve electricity efficiency by 30%. [r]Energy management, waste heat recovery, boiler modifications, and other industrial process enhancements to reduce fuel consumption by 30%. [s]An additional 25,000 MW of co-generation plants to replace existing industrial energy systems. [t]Use existing technology to improve fuel economy to 32.5 mpg (CAFE) with no changes in the existing fleet. [u]Use existing technology to improve fuel economy to 18.2 mpg (CAFE) with no changes in the existing fleet. [v]Improve efficiency of existing plants by 3% through improved plant operation and maintenance. [w]Improve efficiency by 5% through equipment modernization and maintenance. [x]Increase the annual average capacity factor of existing plants from 60 to 65% through improved maintenance and operation. [y]Reduce landfill gas generation by 60 to 65% by collecting and burning in a flare or energy recovery system.

An international perspective, involving both developed and developing countries, also is essential in considering mitigation strategies realistically. Given the limited availability of information on a global basis, however, and because the United States currently is the largest single emitter of greenhouse gases, our analysis focuses on the United States and is based almost entirely on U.S. experience and data. We return later to the international dimensions of the problem. We examined a wide range of mitigation options that are currently available and capable of being widely implemented in the next decade (see Tables 2 and 3). We estimated their emission reduction potential based on current (1989) conditions. To derive first-order estimates of costs across the full set of greenhouse gases, we focused on the direct cost of implementing a given option. Capital investments in mitigation technology were amortized over their useful life and combined with annual operating and maintenance expenses to obtain a total annual cost for each mitigation measure considered. Associated with this cost is a direct or indirect reduction in greenhouse gas emissions. The objective was to build a "supply curve" showing the marginal cost of an incremental reduction in CO_2-equivalent emissions from introducing a new mitigation measure. Given a specified emission reduction target, the least costly combination of methods to reach that target then can be identified.

A basic premise in this approach is that responses to greenhouse warming are regarded as investments in the future of the nation and the planet; nonetheless, such investments should be evaluated in comparison with other claims on a nation's resources. The choice of a discount rate, or interest rate, is a critical parameter in comparing alternative investments (7). To test the sensitivity of results to different assumptions, we used real (inflation-adjusted) discount rates of 3, 6, and 10% to amortize capital investments for greenhouse mitigation. These discount rates are representative of current criteria for public investments in the United States (8). A major limitation of this approach is that it does not reflect other types of indirect costs that may be important in evaluating options. We consider such factors later.

(*Continued on page 261*)

(*Continued from page 149*)

Options for Reducing U.S. Emissions

We grouped the various mitigation measures into two categories. The "best practice" technology options (Table 2) are available at low cost or a net cost savings but are not fully implemented because of various institutional and other barriers. Additional options (Table 3) either are relatively expensive, or have significant other benefits or costs that are not readily quantified, or face implementation obstacles that are not fully represented in our direct-cost estimates. Because of the great uncertainty in projecting economic and emissions trends over many decades, we avoided the use of forecasts or future scenarios in favor of a simpler, more transparent approach based on current emissions and costs. Thus, all of our results apply to a 1989 base year, not future years.

A look at energy efficiency measures for the residential and commercial sector illustrates the approach used in the analysis. In 1989 residential and commercial buildings in the United States used 1630 billion kilowatt-hours (BkWh) of electricity for lighting, air conditioning, space heating, appliances, and other uses. Additional quantities of natural gas and petroleum were used for space heating, water heating, cooking, and other energy needs. Improving the efficiency of such end-use devices can lower greenhouse gas (primarily CO_2) emissions by reducing the demand for fossil fuels used directly for heating or indirectly for electricity generation. Across the United States there are significant regional differences in energy-use patterns that affect the potential for such savings. Buildings in the West and South use greater quantities of electricity for air conditioning whereas those in the North consume more gas and oil for heating. For this first-order analysis we used average data for U.S. buildings.

The potential for saving electricity in residential and commercial buildings has been studied most extensively (9). We considered 12 types of measures (Table 2 and Fig. 1). Aggregate electricity savings for U.S. buildings are displayed in Fig. 1 as a "conservation supply curve" showing the cost and energy savings for each measure based on the mid-range of results from nine studies compiled by Rosenfeld *et al.* (10). For example, for a 6% discount rate, the cost of improved commercial lighting to reduce lighting energy consumption by about 45% is equivalent to 1.5 cents/kWh saved (the fifth step in Fig. 1). If installed in all commercial buildings, the total electricity savings for the United States from this measure would be about 10% or 163 BkWh. On the basis of the current U.S. average electricity price of 6.4 cents/kWh, more efficient commercial lighting would yield a net savings of 4.9 cents/kWh. The implication of the data shown in Fig. 1 is that all investments in energy efficiency measures

Table 3. Additional mitigation options that are costly or that have significant other benefits or costs that are not readily quantified. Some of these options would face serious implementation obstacles because of such factors.

Mitigation option	CO_2-equivalent reduction[a]	Net cost[b]
Industrial energy use		
Fuel switching[c]	24	60
Transportation energy use		
Demand management[d]	49	−22 (−50/5)
Light-duty vehicle efficiency (change in fleet mix)[e]	53	530 (40/1020)
Aircraft engine efficiency[f]	13	360
Electric supply technology[g]		
Advanced coal[h]	200	280
Natural gas[i]	850	32 (17/46)
Nuclear[j]	1500	49 (28/69)
Hydroelectric	30	38
Biomass	130	36 (29/42)
Wind	30	79 (33/125)
Solar photovoltaic	400	87
Solar thermal	540	160
Sector total[k]	1780	50 (30/70)
Halocarbon use[l]		
Non-halocarbon substitutes[m]	302	0.02
CFC conservation[n]	509	0.04
HCFC HFC/aerosols, etc.[o]	248	0.6
HFC (chillers)[p]	88	3
HFC (auto air conditioning)[q]	170	5
HFC (refrigerators)	11	11
HCFC (other refrigeration)[r]	67	4
HCFC/HFC (refrigerator insulation)	14	28
Sector total	1409	1.4 (0.9/3)
Domestic agriculture		
Nitrogenous fertilizers[s]	126	2.5
Paddy rice[t]	23	0.5
Ruminant animals[u]	84	2.0
Sector total	223	2 (1/5)
Reforestation[v]	242	7 (3/10)
Other options		
New industrial technology[w]	300	?
New transportation fuels[x]	1130	?

[a]Equivalent CO_2 reduction in millions of metric tons per year based on 1989 fuel and electricity use. [b]Net implementation cost in dollars per ton of CO_2-equivalent. Includes direct costs only. Many of these measures have additional indirect costs that could be significant (see text). Values are mid-range cost estimates based on a 6% real discount rate, constant 1989 dollars. Values in parentheses give low/high range for average cost for real discount rates of 3 to 10% plus uncertainty across different studies or estimates. [c]Switch current coal consumption in industrial plants to natural gas or oil where technically feasible (estimated at 0.6 quadrillion Btu). [d]Eliminate 25% of employer-provided parking spaces and tax remaining spaces to reduce solo commuting by 15 to 20%. [e]Improve on-road fuel economy from 32.5 to 46.8 mpg (CAFE) with additional technology measures and downsizing that require changes in the existing fleet mix. [f]Implement improved fan jet and other technologies to improve fuel efficiency by 20%. [g]Potential emission reductions apply only to one technology at a time and are not cumulative. All cost-effectiveness estimates are relative to existing (1989) coal plants. [h]Based on advanced pulverized coal plants. [i]Based on the use of combined cycle systems in place of coal. Co-firing natural gas at existing coal-fired plants has similar costs but lower reduction potential. [j]Based on advanced light-water reactors replacing current fossil-fuel capacity for baseload and intermediate load operation. [k]Based on replacing all fossil fuel plants in the 1989 generating mix. Replacement of coal plants only yields 1470 Mt/year. Remaining potential after maximum demand reductions and plant upgrades is 950 Mt/year. [l]Includes chlorofluorocarbons (CFC), hydrofluorocarbons (HFC), and hydrochlorofluorocarbons (HCFC). [m]Modify or replace existing equipment to use non-CFC materials as cleaning and blowing agents, aerosols, and refrigerants where technically possible. [n]Upgrade equipment and retrain personnel to improve conservation and recycling of CFCs. [o]Substitute cleaning and blowing agents and aerosols with fluorocarbon substitutes. [p]Retrofit or replace all existing chillers to use fluorocarbon substitutes. [q]Replace existing automobile air conditioners with equipment using fluorocarbon substitutes. [r]Replace commercial refrigeration equipment such as used in supermarkets and transportation with equipment using fluorocarbon substitutes. [s]Reduce nitrogenous fertilizer use by 5%. [t]Eliminate all U.S. paddy rice production. [u]Reduce ruminant animal production by 25%. [v]Reforest 28.7 Mha of economically or environmentally marginal crop and pasture lands and nonfederal forest lands. [w]Increase recycling and reduce energy consumption primarily in the primary metals, pulp and paper, chemicals, and petroleum refining industries through new, less energy intensive technology. [x]Based on replacement of highway transport fuels with alternative fuels that emit no greenhouse gases (see text). ?, unknown.

costing less than the price of electricity will produce a net savings at the chosen discount rate. For a 6% real discount rate (comparable to a utility's cost of capital for investments in new electricity generation facilities), implementing all of the measures in Fig. 1 would reduce current electricity use in the U.S. building sector by 45% (745 BkWh), for a net annual cost savings of nearly $30 billion (the area in Fig. 1 between the supply curve and the current average electricity price). The corresponding reduction in CO_2 emissions is estimated at 515 million metric tons (Mt) of CO_2 per year on the basis of a national average emission rate of 0.7 kg of CO_2 per kilowatt-hour for the fuels currently used for power generation (*11*). The average cost per ton of CO_2 reduced thus is −$57.

In addition to electricity savings, we estimate that a combination of fossil fuel efficiency programs aimed at heating systems, water heaters, and other appliances, plus fuel switching from electricity to natural gas or fuel oil in building appliances and heating systems, could produce further emission reductions of up to 374 Mt of CO_2 per year, also at a net savings in cost. Overall, the maximum CO_2 emission reduction potential for the residential-commercial sector thus is estimated at 890 Mt/year, at an average cost of −$62 per ton of CO_2 removed (Table 2).

Analogous to the building sector, a limited number of studies for the U.S. industrial sector suggest the potential for reducing electricity consumption by about 30% with currently available technology (*12*). Most of the savings would come from investments in more efficient motors, electrical drive systems, and lighting. For real discount rates as high as 10%, such savings could lower CO_2 emissions by about 527 Mt/year at a net savings in cost (see Table 2). Case studies of energy-intensive industries such as steel mills and petrochemical plants (*13*) suggest that additional energy savings on the order of 25 to 30% in direct industrial fuel use also may be available at a net cost savings by investing in more efficient furnaces, energy recovery systems, and other process equipment. Increased investments in cogeneration technologies also yield cost-effective CO_2 emission reductions (Table 2). On the other hand, substituting oil or gas for coal in manufacturing processes yielded significantly higher costs with only modest reductions in CO_2 emissions (Table 3). Fundamental improvements in industrial process design, including greater use of recycled materials, offer perhaps the greatest long-term opportunity for reducing industrial energy demand. We estimate the potential for at least a 25% decrease in overall industrial energy demand through process technology improvements over the next 10 to 15 years (Table 3). The cost of such measures, however, cannot readily be estimated or ascribed solely to environmental improvements.

For the transportation sector currently available technology can improve the efficiency of light-duty vehicles, heavy-duty trucks, and commercial aircraft that account for the bulk of transportation energy demands. Conservation supply curves (analogous to those in Fig. 1) derived for light- and heavy-duty vehicles [from (*14*)] suggest that for discount rates of 3 to 10% the corporate average fuel economy (CAFE) of U.S. automobiles could be increased to 32.5 miles per gallon (mpg) and of trucks to 18.2 mpg (CAFE) at a net cost savings. These efficiency gains would be obtained wholly from a set of existing technological measures, such as improved engine designs, drive trains, transmissions, and aerodynamics improvements requiring no change in the overall fleet mix (Table 2).

Fuel economy improvements beyond these levels also are achievable (Table 3). However, it is achieved largely through weight reduction and vehicle downsizing, which results in a change in amenities and incurs much higher cost per unit of CO_2 reduced (*5*). There is significant disagreement, however, between results of government- and industry-sponsored studies in the assumptions that underlie these cost and effectiveness estimates, including the interactions among combinations of technologies and the effects of consumer preferences and market behavior. Changes in car size and amenities also may result in significant indirect costs that are not considered in this analysis (for example, costs related to consumer comfort, life-style changes, and auto safety).

Similarly, transportation management methods that reduce fuel use and CO_2 emissions by reducing traffic congestion and vehicle miles of travel also involve indirect costs that are pervasive and difficult to quantify. One strategy would be to decrease CO_2 emissions 50 Mt/year by taxing or eliminating free parking spaces to force a shift toward vanpooling and greater use of existing mass transit (*5*). The net negative cost (Table 3) is attributed to savings in parking space construction costs and out-of-pocket travel expenses that exceed the estimated value of time lost from longer commuting trips. Such estimates remain highly controversial because of the difficulty in estimating indirect costs and subsidies for alternate transportation modes (*15*).

Greenhouse gas emission reductions from the energy sector also may be had by changing fuel and energy supplies, particularly for electric power generation. Such measures are substantially more costly than the demand-side options in Table 2. In the near term, the most cost-effective reductions in CO_2 emissions are likely to come from modest efficiency gains and improved utilization of existing power plants (potentially about 100 Mt/year; see Table 2). Replacement of some gas- and oil-fired capacity with more efficient gas-based systems may provide some additional gains at relatively low cost (*16*).

We also considered the longer term prospect of reducing power plant CO_2 emissions by up to 83% (1473 Mt/year) by replacing all existing U.S. coal-fired power plants with lower emitting technologies once existing plants are fully depreciated or by eliminating all power plant emissions by use of nuclear and renewable energy sources (Table 3). Although emissions can be greatly reduced, none of the available alternative systems are as cheap as existing coal plants (*17–19*). Average mitigation costs range from roughly

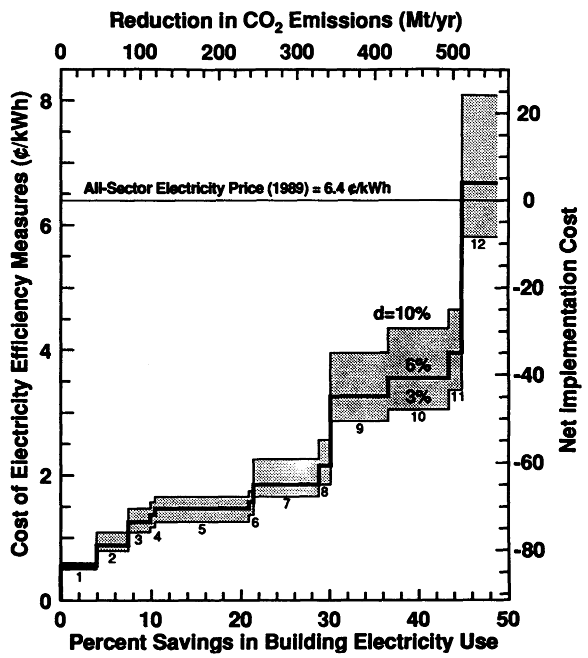

Fig. 1. Representative marginal cost curve for building sector electricity use. Each step corresponds to the annualized investment cost of a given technological option (see Table 2), expressed in cents per kilowatt-hour for real discount rates of 3, 6, and 10%. Electricity savings for each option are given as a percent of total 1989 building sector electricity use. Eleven measures costing less than the average 1989 price of electricity (6.4 cents/kWh) would reduce building energy use by 734 BkWh (45%) at a net cost savings. The corresponding reduction in CO_2 emissions is based on the national average emission rate for 1989.

$30 to $70 per ton of CO_2 removed, depending on the combination of technologies selected. New gas-fired combined cycle systems appear to be the least costly option; however, the long-term availability and price of natural gas remain uncertain. Significant increases in the use of natural gas also could exacerbate the leakage of methane from pipelines and distribution systems, offsetting some of the benefits of CO_2 reductions (*20*). Our estimates do not reflect such interactions. Nuclear plants and renewables are the most expensive at today's costs. Although these systems emit no CO_2, other technical, economic, and political factors militate against their widespread use (*21*). Nuclear energy remains the most widely deployed nonfossil technology now available for power generation. Many of the renewable options either have limited generation potential or significant technological or cost barriers to overcome (*18, 22*). Thus, all of the major electricity supply options face significant implementation barriers as greenhouse gas mitigation measures. In the longer term, a variety of advanced power generating technologies and CO_2 removal methods now under development could become important (*23*).

Reducing transportation sector emissions through the use of alternative fuels also is technologically feasible, but a careful accounting is needed to assess the overall effectiveness. When considered on a systems basis, most alternative fuels that are now emerging in the United States or used commercially elsewhere (*24*), such as reformulated gasoline, natural gas, methanol produced from natural gas, or electricity produced from fossil fuels, reduce greenhouse gas emissions by less than 25% relative to gasoline; some result in a net increase in greenhouse gas emissions (*25*). Alternative fuels that can eliminate or nearly eliminate greenhouse gas emissions include methanol and ethanol produced from newly grown biomass (using biomass fuels to also produce and transport the fuel), plus electricity or hydrogen produced from nonfossil fuels. However, the technology and infrastructure to produce and use such fuels on a widespread basis remain to be developed. Because U.S. experience with alternative transportation fuels is still limited, and because of the complexity of the overall system, we did not estimate cost-effectiveness for this option. The emission reduction potential, however, is large (see Table 3).

Potential mitigation measures outside the energy sector involve landfills, CFC use, agricultural activity, and forests. Landfill gases are the major source of anthropogenic methane emissions in the United States (*26*). The collection and combustion of landfill gas also would reduce methane emissions by about 65% [based on analyses in (*27*)]. The costs shown in Table 2 reflect the full cost of abatement, about $1 per ton of CO_2 equivalent. Should such measures be implemented to control air toxics, the marginal cost of greenhouse gas mitigation would be small or negligible.

In a similar vein, significant reductions in CFCs and other halocarbons responsible for stratospheric ozone depletion are expected under the Montreal Protocol and the 1990 U.S. Clean Air Act Amendments (Table 3). Our estimates are based on replacing CFCs by fluorocarbon or nonhalocarbon substitutes plus increased conservation of current CFC supplies (*28*) but do not include indirect effects such as the increased CO_2 emissions that may result from any decrease in the energy efficiency of appliances now using CFCs (*5*). Because the costs of CFC reductions will be incurred regardless of global warming concerns, the marginal cost of greenhouse gas mitigation may be a small or negligible portion of the costs shown here. However, because many CFC substitutes still have relatively high levels of radiative forcing (*29*), future mitigation strategies may have to consider the cost of replacing these chemicals.

The agricultural sector is a source of methane from paddy rice production, ruminant animals, and N_2O from fertilizers and land clearing. For the United States, these sources of methane and N_2O are small, though on a worldwide basis they are significant (*30*). Improved agricultural practices and technology can play a role in reducing these emissions, although the cost-effectiveness for such measures is not easily derived (*5*). The values shown in Table 3 are based on rough estimates of the cost of reducing the supply of U.S. ruminant products and rice through taxes, subsidies, and buy-outs but do not reflect any indirect costs associated with lost production (*31*).

Sequestering CO_2 in new forest growth can offset anthropogenic emissions by fixing carbon in plant tissue. Long-term sequestration requires that forests are periodically harvested for lumber and wood products that remain in service and do not return CO_2 to the atmosphere by combustion. Based on work by Moulton and Richards (*32*), we estimate that a reforestation program for the U.S. involving approximately 30 million hectares of economically marginal crop lands, pasture lands, and non-federal forests (about 3% of U.S. land area) could sequester roughly 5% of current U.S. CO_2 emissions at an average cost of $7 per ton of CO_2. Higher rates of sequestration probably could be achieved, but costs and land availability are much more uncertain (*5*).

Comparing Options

Because there is no single magic bullet, any approach to greenhouse gas mitigation must involve a mixed strategy employing a variety of measures (Fig. 2). Energy efficiency improvements in the buildings, transportation, and industrial sectors emerge as the most cost-effective measures for reducing greenhouse gas emissions. The results in Fig. 2 suggest that such measures, combined with the phaseout of CFCs already in progress, can reduce greenhouse gas emissions by 800 to 3100 Mt/year, equivalent to 10 to 40% of current U.S. emissions. Energy cost savings would exceed annual investment expenditures by about $10 to $110 billion per year (the area between the supply curve and the *x*-axis). Additional measures aimed at methane, CO_2, and N_2O emissions could reduce CO_2-equivalent emissions by another 200 to 800 Mt/year at a direct cost of less than $1 billion per year. In contrast, new electricity supply options that emit no CO_2 could achieve further reductions of 400 to 1000 Mt/year, but would involve high implementation costs (for example, $30 billion per year for the most optimistic case in Fig. 2).

For comparison with our results, a range of results from other studies (*33*) also is presented in Fig. 2. Energy models, which employ inferences from historical economic data and assumptions about economic structure, have been used to analyze the effects of carbon and energy taxes for abating CO_2 emissions (*34*). These models typically project emissions well into the next century. Although many features of such models are important to framing a conceptually sound approach to mitigation policy, current models remain limited by structural assumptions and a general lack of detail (*5*). Thus, neither technological costing nor energy modeling offers a fully satisfactory means of evaluating costs. Both approaches, however, indicate that mitigation costs increase rapidly with increasing emission reductions. Overall abatement requirements, driven by policy decisions and the growth in future emissions, thus are critical to total mitigation costs.

Policy Measures and Indirect Costs

Is there really a "free lunch" from investing in energy efficiency measures to reduce greenhouse gas emissions? Past experience in attempting to implement energy efficiency programs in buildings has revealed a number of obstacles to achieving the maximum technical efficiency. Perhaps most important is the empirical evidence that most businesses and homeowners will not invest in large-scale energy-savings improvements unless the investment can be recovered almost immediately—typically in no more than 2 to 3 years (*35*). Such payback periods imply discount rates on the order of 30 to 50% or more, in contrast to the 3 to 10% range typical of supply-side investments. At these high effective rates of return, the maximum potential

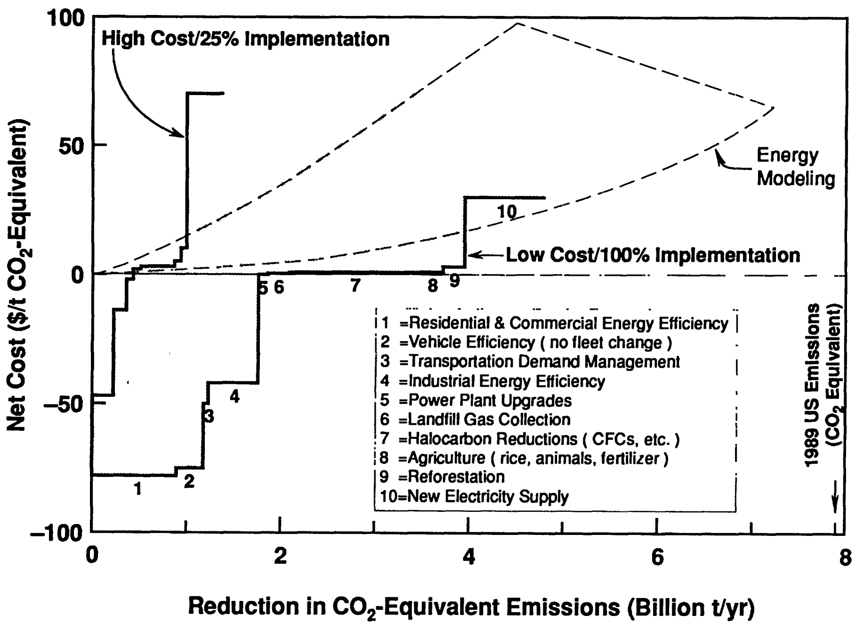

Fig. 2. Cost-effectiveness versus emission reduction potential for various mitigation options. The results derived in this study are shown as steps for ten major categories of mitigation options ordered by cost-effectiveness. For each sector, the "high" and "low" direct-cost estimates from Tables 2 and 3 are combined with implementation rates of 25 and 100% of the maximum potential reduction for each measure to characterize the range of uncertainty (*48*). The energy modeling results that employ other methods of analysis are shown by the dashed lines encompassing a range of studies summarized by Nordhaus (*33*). All costs are in constant 1989 dollars. Emissions are in metric tons.

energy savings is greatly diminished (*36*), producing a large gap between best practice and average practice. Similar empirical evidence for the industrial sector indicates that expected rates of return much greater than 10% are required to stimulate most private investments in industrial energy efficiency improvements. Criteria for energy conservation investments may require rates of return of at least 30%, even for corporations that aggressively pursue such opportunities (*37*).

There are many explanations for this behavior. Information about the cost, reliability, and performance of efficient technologies, which are continually changing, is not widely diffused among consumers, purchasing agents, and contractors. Hence, less efficient technologies continue to be used. Other consumers simply do not have the capital required for the initial investments or can obtain it only at high interest rates (for example, credit card customers). In other cases institutional arrangements such as landlord-tenant and builder-buyer relationships provide little or no incentive to invest in energy efficiency measures. Why should a landlord pay more for an efficient furnace when it is the tenant who pays the heating bill?

Such obstacles make it unlikely that the cost and emissions reduction potential suggested in Table 2 will be approached in the absence of effective policy tools and incentives to develop and implement energy efficiency programs [see (*5*) for discussion]. Several measures at the state and federal levels appear to be especially attractive as reasonable first steps. Revision of state public utility regulations to make it profitable for electric and gas utilities to promote energy efficiency measures in buildings and industrial facilities is one such measure. Among the efforts to move in this direction are state and regional programs in the Pacific Northwest, New England, and California (*38*). This approach brings the technical expertise and long-term investment perspective of the utility into the demand sector. Because investments in energy efficiency are less costly than new generating capacity, ratepayers ultimately benefit. Adoption of nationwide building codes and efficiency standards that lower the energy demands of new buildings, appliances, and industrial equipment also merit consideration. Efficiency standards already exist for common appliances such as refrigerators. Extension of such standards to buildings and other energy-intensive products could afford a workable approach to improving energy efficiency over time.

For the transportation sector, improvements in auto efficiency could be achieved through modest increases in the corporate CAFE standards now in place, coupled perhaps with incentives for manufacturers to install more energy-efficient technology. However, CAFE currently is beset by political controversy surrounding the effects of vehicle downsizing on safety, competitiveness, and other issues. Similarly, policies that seek to reduce greenhouse gas emissions by way of taxes on fuel carbon or energy content likely would face stiff political opposition. For example, a tax of \$25 per ton of CO_2 (roughly \$100 per ton of carbon) would be equivalent to an additional 28 cents per gallon of gasoline. Historically, such energy tax proposals have not fared well in the United States. On the other hand, information and public education programs to promote energy efficiency, conservation, and recycling, plus new research and development (R&D) programs on end-use energy efficiency, could enjoy more immediate success.

The costs of implementing policy measures to overcome institutional barriers and market imperfections that hamper energy efficiency gains are not reflected in our analysis. Nor are a number of other indirect costs such as the effects on the economy of any major actions that are undertaken or the reduction in other externality costs that would accompany greenhouse gas abatement (for example, a reduction in emissions that contribute to acid rain and urban air pollution). Thus, pending additional data, the true magnitude of potential cost savings, if any, from investments in energy efficiency cannot be firmly established.

International Considerations

Although we have not explicitly treated scenarios of future emissions growth in our analysis, it is clear that the pressures of economic development and population growth worldwide will exacerbate the likelihood of greenhouse warming and the potential for adverse impacts globally. Though the United States is currently the largest single emitter of greenhouse gases, emissions growth in developing countries, particularly from increased energy use, is likely to shift this balance in the future. Developing countries now account for about 23% of world commercial energy use, up from 17% two decades ago. Projections suggest this share will grow to about 40% by 2030 (*1*). Nations such as China, India, and Russia, which rely on vast coal resources for much of their energy, pose a special concern. China, for example, currently foresees a fourfold increase in coal consumption by the middle of the next century. The resulting increase in global CO_2 emissions would doom any international effort to stabilize or reduce worldwide greenhouse gases. Thus, efforts by the United States to reduce its greenhouse gas emissions, while important and necessary, will do little to ameliorate global warming unless accompanied by sustained actions in the international arena.

International efforts to address global climate change was a central issue of the June 1992 United Nations Conference on Environment and Development. Although the conference failed to produce a global commitment to stabilize greenhouse gas emissions by the turn of the century, it did succeed in obtaining broad international agreement to pursue greenhouse gas reductions. Historically, such agreements have been the first step toward major international action (39). Nonetheless, the difficulties in achieving significant worldwide reductions in greenhouse emissions cannot be underestimated. Despite its emphasis on sustainable development, the United Nations conference revealed deep concerns that environmental control could impede economic development and that international withdrawal from fossil fuel use would harm nations whose economies depend heavily on the production, processing, and exportation of fossil fuels such as petroleum.

To begin addressing environmental concerns, programs to assist developing nations adopt the appropriate technology and infrastructure are especially critical (40). Japan, for example, has announced a long-term plan to develop and market "clean" technologies to developing countries. Other industrial nations need to follow suit. Mitigation options internationally also will involve measures beyond those considered for the United States. Tropical deforestation is one such example. Significant increases in the rate of deforestation appear to be occurring in many developing countries in response to pressures for economic development and other social needs (26). Efforts to limit the rate of deforestation to mitigate greenhouse warming must take account of a host of indirect costs or benefits that cannot readily be valued, including improvements in human welfare and losses in biodiversity. The feasibility and cost of programs to slow the rate of deforestation thus are difficult to evaluate. Based on the direct cost of providing economic incentives to practice sustainable forestry in developing countries (41), we estimate a mitigation cost of roughly \$0.4 per ton of CO_2. This is about 5% of the estimated direct cost of reforestation in the United States (Table 3). Such relative costs suggest opportunities for international cooperation in seeking cost-effective measures internationally for greenhouse gas mitigation.

Measures to reduce the rate of population growth worldwide also must be recognized as a key mitigation strategy. At any given rate of greenhouse gas emissions per capita, a smaller population will produce lower total emissions and less stress on the environment in general (42). Although some researchers suggest that reducing population growth rates will lead to increased growth in per capita income that could increase total greenhouse gas emissions, a recent analysis of countries with widely different income and population growth characteristics suggests a net decline in future CO_2 emissions, even after allowing for higher per capita income (5). Given the complexity of the links between population growth and emissions, we did not estimate cost-effectiveness. The direct costs of family planning measures are relatively small (43), but this option remains beset by social, political, and ideological barriers in many countries.

Should significant global warming actually become observable in the next century, international deliberations also might consider the use of geoengineering measures that directly or indirectly affect the earth's radiative balance (for example, stratospheric particles that screen out sunlight). Our analysis of nine such measures suggests that some of these may be very inexpensive and capable of reducing greenhouse warming on a substantial scale (5). Similar proposals have been put forth in the context of stratosphere ozone depletion (44). Because the feasibility and side effects of geoengineering options are poorly understood, and because their social acceptability is arguable, significant additional research is needed to assess further their merits as realistic options in the event that future climate change warrants their consideration.

Conclusions and Recommendations

Our analysis for the United States suggests that a variety of measures are available to slow or reduce the growth in greenhouse gas emissions at low cost, perhaps even at a net cost savings. In most cases such measures will bring ancillary benefits, such as a reduction in urban air pollution. If other implementation costs are not excessive, many of these measures may be viewed as "no regrets" options that are worth pursuing independently of greenhouse concerns.

In consideration of the existing U.S. commitment to the phaseout of CFCs and other halocarbon emissions, our results indicate that any new initiatives to reduce U.S. emissions should focus first on energy conservation and efficiency measures that reduce emissions of CO_2 and methane. The choice of policy instruments will affect overall costs and feasibility and must be considered carefully. In all cases, experience with initial undertakings should be used to resolve some of the current uncertainties regarding actual implementation costs. This approach will allow future plans and policies to be developed more effectively. In addition, greenhouse warming should become a factor in planning for the future energy supply mix of the United States and other nations. Recommended measures include an expanded R&D program to develop safe, lower cost nonfossil energy sources, improve the efficiency of existing fossil fuel technology (particularly combined cycle systems using natural gas or coal), and assess the feasibility of CO_2 sequestration and disposal from fossil fuel facilities. A systems approach that considers interactions and externality costs across the entire fuel cycle from supply to conversion and end use should be used to guide energy supply choices and to guard against unanticipated side effects.

This framework also affords a method that other countries can adopt to identify cost-effective measures to undertake initially. We urge that the United States exert strong international leadership in seeking cost-effective measures globally. Indeed, many of the most cost-effective mitigation options may be found at first in some of the poorest developing countries. Because such countries may be unwilling or unable to afford such measures, developed countries may choose to underwrite such efforts. This targeted redistribution of mitigation efforts could prove less costly to the industrialized nations than strategies directed solely toward their domestic economies. Bilateral agreements to promote technology and information transfer, an expanded program of international R&D, plus full U.S. participation in international efforts to curtail deforestation and to slow the growth in world population, are other essential elements of a realistic approach to mitigating greenhouse warming.

Finally, the United States and other nations should give much higher priority to the study of mitigation and adaptation strategies, commensurate in breadth and depth with current research efforts in the earth and environmental sciences (45). To develop sensible and politically acceptable policies for dealing with global climate change, we need to know a lot more about the full social and economic consequences of alternative mitigation measures, the potential human and ecological impacts of global warming, and the costs of adapting to climate change (46). International cooperation will be needed on many of these research efforts. Comprehensive integrated assessments (47) can help keep research efforts focused on delivering the type of information most needed for mitigation policy decisions.

REFERENCES AND NOTES

1. *Policy Implications of Greenhouse Warming—Synthesis Panel* (National Academy Press, Washington, DC, 1991).
2. G. Porter, *Global Environmental Politics* (Westview Press, Boulder, 1991).

3. R. A. Kerr, *Science* **251**, 868 (1991).
4. G. Marland, in "Trends '90: *A Compendium of Data on Global Change*, T. A. Borden, P. Kanciruk, M. P. Farrell, Eds. (*Rep. ORNL/CDIAC-36*, Oak Ridge National Laboratory, Oak Ridge, TN, 1990).
5. *Policy Implications of Greenhouse Warming—Report of the Mitigation Panel* (National Academy Press, Washington, DC, 1991). Some cost and emission reduction estimates in this report have been refined in the present paper.
6. J. T. Houghton, G. J. Jenkins, J. J. Ephrams, Eds. *Climate Change, The IPCC Scientific Assessment* (Cambridge Univ. Press, Cambridge, 1990). See also *Scientific Assessment of Stratospheric Ozone* (World Meteorological Organization, Geneva, 22 October 1991), which cautions that ongoing evaluations of indirect effects may result in net effects which differ significantly from those published in 1990.
7. High discount rates place a low value on future outcomes while low discount rates make investing now to avoid greenhouse warming more attractive. However, a low discount rate likely means that other attractive investment opportunities are being ignored. Because the time scales of greenhouse warming are long in comparison with traditional investment decisions, some argue that the traditional concept of a discount rate is inappropriate or that a zero discount rate should be employed. Additional discussions relative to greenhouse warming may be found in (*15*).
8. *Discount rates to be used in evaluating time-discounted costs and benefits* (OMB Circ. A-94, Office of Management and Budget, Washington, DC, 1974); R. D. Reischauer, Statement of the Director, Congressional Budget Office, before the Committee on Energy and Natural Resources, U.S. Senate, March 1990.
9. A. Lovins, *Advanced Electricity-Saving Technology and the South Texas Project* (Rocky Mountain Institute, Snowmass, CO, 1986); P. Miller, J. Eto, H. Geller, *The Potential for Electricity Conservation in New York State* (American Council for an Energy-Efficient Economy, Washington, DC, 1989); *Efficient Electricity Use: Estimates of Maximum Energy Savings* (*Rep. CU-6746*, Electric Power Research Institute, Palo Alto, CA, 1990); *Confronting Climate Change: Strategies for Energy Research and Development* (National Academy Press, Washington, DC, 1990).
10. A. Rosenfeld *et al.*, *A Compilation of Supply Curves of Conserved Energy for U.S. Buildings.* (*LBL-31700*, Lawrence Berkeley Laboratory, Berkeley, CA, 1991).
11. J. Edmonds, W. Ashton, H. Cheng, M. Steinberg (*U.S. Department of Energy, Rep. DOE/NBB-0085*, 1989).
12. Electric Power Research Institute, *EPRI J.* **15**(3), 4 (1990); *Improving the Efficiency of Electricity End-Use.* (International Energy Agency, Paris, 1989); M. Ross, *Science* **244**, 311 (1989).
13. W. G. Larsen, thesis, University of Michigan, Ann Arbor (1990); M. Ross, *Energy* **12**, 1135 (1987).
14. R. H. Shackson and H. J. Leach, *Using Fuel Economy and Synthetic Fuels to Compete with OPEC Oil* (Carnegie Mellon Univ. Press, Pittsburgh, 1980); M. Ledbetter and M. Ross, in *Proceedings of 25th Intersociety Energy Conversion Engineering Conference*, Reno, NV, 12 to 17 August 1990 (American Institute of Chemical Engineers, New York, 1990); C. Difiglio, K. G. Duleep, D. L. Greene, *Energy J.* **11** (January 1990).
15. For example, see the discussions by R. Crandall and D. Foy in (*5*), chap. 5.
16. M. Gluckman *CO_2 Emission Reduction Cost Analysis* (Electric Power Research Institute, Palo Alto, CA, 1990). Because much of the data on plant heat rate improvements was obtained in the early 1980s, the current potential may be lower than cited here; *Rep. OTA-O-482* (U.S. Congress, Office of Technology Assessment, Washington, DC, February 1991).
17. *Rep. EPRI P-6587-L* (Electric Power Research Institute, Palo Alto, CA, 1989).
18. *Rep. SERI/TP-260-3674* (Solar Energy Research Institute, Golden, CO, 1990).
19. L. L. Wright and A. R. Ehrenshaft, *Oak Ridge Natl. Lab. Rep. ORNL-6625*, 1990; *1990 Production Costs: Operating Steam-Electric Plants* (Utility Data Institute, Washington, DC, 1991); The average 1990 cost of producing electricity from U.S. coal-fired plants was 2.0 cents/kWh. Estimated costs for new generation systems were 3.0 to 4.5 cents/kWh for gas-combined cycles, 4.7 to 8.6 cents/kWh for nuclear, 4.9 to 14 cents/kWh for renewables, and 10 to 14 cents/kWh for solar systems. Existing fossil fuel plants are assumed to operate well beyond the book life used for depreciation. More rapid replacements must consider the cost of unrecovered capital. Long-term estimates must consider the full replacement cost of all new plant options.
20. Pipeline leakage accounts for an estimated 36% of current U.S. methane emissions (*5*). CO_2-equivalent emissions must account for differences in radiative forcing (see Table 1).
21. *Rep. OTA-E-216*, (U.S. Congress, Office of Technology Assessment, Washington, DC, February 1984); J. G. Morone and E. J. Woodhouse, *The Demise of Nuclear Energy*? (Yale Univ. Press, New Haven, CT, 1989).
22. *Energy Technology Status Report* (California Energy Commission, Sacramento, CA, June 1991).
23. W. Fulkerson, *Oak Ridge Natl. Lab. Rep. ORNL-6541* (1989).
24. J. Sathaye, B. Atkinson, S. Meyers, *Rep. LBL-24736* (Lawrence Berkeley Laboratory, Berkeley, CA, 1988).
25. M. A. DeLuchi, R. A. Johnston, D. Sperling, *Transp. Res. Rec.* **1175**, 33 (1988); *Comparing the Impacts of Different Transportation Fuels on the Greenhouse Effect* (California Energy Commission, Sacramento, 1989); S. P. Ho and T. A. Renner, paper presented at the Air and Waste Management Association Conference on Tropospheric Ozone, Los Angeles, CA, 19 to 22 March 1990 (Air and Waste Management Association, Pittsburgh, 1990).
26. World Resources Institute, *World Resources 1990–91* (Oxford Univ. Press, New York, 1990).
27. "Air Emissions from Municipal Solid Waste Landfills—Background Information for Proposed Standards and Guidelines" (U.S. Environmental Protection Agency, Research Triangle Park, NC, March 1990); Standards of Performance for New Stationary Sources and Guidelines for Control of Existing Sources: *Municipal Solid Waste and Landfills* (U.S. Environmental Protection Agency, Research Triangle Park, NC, March 1990).
28. "An Industry Perspective on Technology Transfer and Assistance to Help Less Developed Countries (LDCs) *Phaseout of Chlorofluorocarbons (CFCs)*" (Du Pont, Wilmington, DE, 1989); *Economic Implications of Potential Chlorofluorocarbon Restrictions: Final Report* (Putnam, Hayes, and Bartlett, Washington, DC, 1987); "Regulatory Impact Analysis: Protection of Stratospheric Ozone, vol. III, Part 7, *Solvents*." (U.S. Environmental Protection Agency, Washington, DC, 1987); "Regulatory impact analysis: Protection of stratospheric ozone, vol. III, Part 3, *Mobile Air Conditioning* (U.S. Environmental Protection Agency, Research Triangle Park, NC, 1987).
29. K. Shine, *Nature* **344**, 492 (1990).
30. P. J. Crutzen *et al.*, *Tellus* **38B**, 184 (1986); D. J. Wuebbles and J. Edmonds, *A Primer on Greenhouse Gases* (U.S. Department of Energy, Washington, DC, 1986).
31. B. Gardner, *The Economics of Agricultural Policies* (Macmillan, New York, 1987).
32. R. J. Moulton and K. R. Richards, *Costs of Sequestering Carbon Through Tree Planting and Forest Management in the United States* (U.S. Forest Service Rep., U.S. Department of Agriculture, Washington, DC, 1990).
33. W. D. Nordhaus, *Am. Econ. Rev.* **81**, 146 (1991).
34. J. A. Edmonds and J. M. Reilly, *Energy Econ.* **5**, 74 (1983); D. W. Jorgenson and P. J. Wilcoxen, *Environmental Regulation and U.S. Economic Growth* (Harvard Institute of Economic Research, Cambridge, 1989); A. S. Manne, R. G. Richels, W. W. Hogan, *Energy J.* **11**, 51 (1990); W. D. Nordhaus, paper presented at the 1990 Annual Meeting of the American Association for the Advancement of Science, New Orleans, LA, 15 to 20 February 1990.
35. E. Hirst and M. Brown, *Closing the Efficiency Gap: Barriers to the Efficient Use of Energy* (Contr. DE-AC05-84OR21400, Oak Ridge National Laboratory, Oak Ridge, TN, 1990); S. Wiel, *Public Util. Fortn.* (6 July 1989).
36. This point is illustrated quantitatively in (*5*) where we have extended our sensitivity analysis to include a 30% discount rate for all energy demand sectors.
37. K. C. Nelson, *Chem. Process.* (January 1989).
38. E. Hirst, Electric-Utility Energy-Efficiency and Load-Management Programs: Resources for the 1990s (Cont. DE-AC05-84OR21400. Oak Ridge National Laboratory, Oak Ridge, TN, 1989); D. Moskovitz, "Profits and progress through least-cost planning" (National Association of Regulatory Utility Commissioners, Washington, DC, 1989); National Association of Regulatory Utility Commissioners (NARUC), resolution adopted by the annual meeting, Boston, 15 November 1988.
39. D. D. Stine, thesis, American University, Washington, DC (1992).
40. *Climate Change: The IPCC Response Strategies* (Island Press, Covello, CA, 1991); D. A. Tirpak and D. A. Lashof, Eds., *Policy Options for Stabilizing Global Climate, Report to Congress* (Environmental Protection Agency, Washington, DC, 1989); B. Gardner, *The Economics of Agricultural Policies* (Macmillan, New York, 1987).
41. *The Forestry Fund: An Endowment for Forest Protection, Management, and Reforestation in Costa Rica* (World Wildlife Fund, Washington, DC, 1988).
42. *Population Growth and Economic Development: Policy Questions.* (National Academy Press, Washington, DC, 1986).
43. D. G. Gillespie, H. E. Cross, J. G. Crowley, S. R. Radloff, in *The Demographic and Programmatic Consequences of Contraceptive Innovation*, S. Segal, A. Tsui, S. Rogers, Eds. (Plenum, New York, 1989); "Report on progress towards population stabilization" (Population Crisis Committee, Washington, DC, 1990).
44. R. J. Cicerone, S. Elliott, R. P. Turco, *Science* **254**, 1191 (1991).
45. *Our Changing Planet: The FY 1992 U.S. Global Change Research Program* (U.S. Geological Survey, Reston, VA, 1991).
46. *Policy Implications of Greenhouse Warming* (Report of the Adaptation Panel—National Academy Press, Washington, DC, 1991).
47. E. S. Rubin, L. B. Lave, M. G. Morgan, *Iss. Sci. Techn.* **8**, 47 (Winter 1991–92).
48. In the case of CFCs the 25% case corresponds not to a lower rate of implementation (which is expected to be 100% under present U.S. laws) but to a lower global warming potential. As noted in (*6*), the indirect effect of CFCs on stratospheric ozone is suspected to offset some or even all of the direct warming of CFC emissions. The magnitude of this effect is highly uncertain. Here, we use the 25% case to reflect some degree of uncertainty, in the GWP values for CFCs (Table 1).
49. Other contributors to the Mitigation Panel report (*5*) on which this paper is based were P. Brewer, R. Crandall, R. Evenson, D. Foy, R. Garwin, J. Glas, K. Lee, J. Mathews, M. Russell, S. Schneider, E. Skolnikoff, and E. Weiss. The work of the Synthesis Panel (*1*) chaired by Daniel J. Evans also contributed to our recommendations. This study was sponsored by the Committee on Science, Engineering, and Public Policy of the National Academies of Science and Engineering and the Institute of Medicine. R. Coppock and the academy staff provided invaluable assistance.