REVIEW OF COST ESTIMATES FOR REDUCING CO2 EMISSIONS

FINAL REPORT

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OVERVIEW

THERE IS CONSIDERABLE UNCERTAINTY ASSOCIATED WITH THE COSTS OF REDUCING CO2 EMISSIONS.

- *Since the ground breaking work of William Nordhaus in 1977, cost estimates for reducing CO2 emissions have been developed by numerous groups.*
- *The various studies have reported sometimes widely divergent cost estimates for reducing CO2 emissions.*
 - *Some recent analyses have indicated that large reductions in CO2 emissions could be achieved at zero or negative costs (e.g. Rocky Mountain Institute 1989).*
 - *In contrast, a recent study by Alan Manne of Stanford and Richard Richels of the Electric Power Research Institute (Manne-Richels 1989) concluded that in the U.S. the total discounted costs of reducing CO2 emissions by 20 percent below the 1990 level could be as much as 3.6 trillion dollars over the period from 1990 to 2100. Costs of this order of magnitude would represent about 5 percent of U.S. GNP.*
- *The purpose of this briefing paper is to summarize the different cost estimates for CO2 emission reduction and to identify the key issues and assumptions that underlie these cost estimates.*

"APPLES-TO-APPLES" COMPARISONS OF THESE DIFFERENT COST ESTIMATES ARE SOMETIMES DIFFICULT TO MAKE.

- *Some cost estimates are given in total cumulative dollars.*
- *Some costs are specified in terms of the marginal cost of reducing CO2 emissions expressed as dollars per ton for the last ton of carbon removed. Other analyses report only the average cost of CO2 emission reductions on a dollars per ton basis.*
- *Some cost estimates cover only the direct capital and operating costs required while others cover direct costs plus the indirect costs of GNP losses.*
- *Some cost estimates cover only a relatively short time period of 20 years while other analyses report costs for a much longer period of 110 years.*

ALTERNATIVE ESTIMATES OF THE MARGINAL COST OF CO₂ REDUCTION

Source: Nordhaus 1990, EPA/Brookhaven-MARKAL Model, 1990.

EVEN COMPARABLE METHODS OF ESTIMATING CO2 EMISSION REDUCTION COSTS CAN DIFFER WIDELY.

- *A compilation of alternative cost estimates by William Nordhaus indicates that there is general agreement that marginal costs rise sharply as the percent reduction of CO2 increases.*
- *However, for a given percentage removal target, marginal cost estimates can differ significantly. For example:*
 - *Edmunds and Reilly (1983) estimated that a 40 percent reduction in CO2 below baseline levels would cost \$30 per ton of carbon removed. Although they have not been published, Edmunds more recent estimates are reportedly significantly higher (Nordhaus 1990).*
 - *Nordhaus and Yohe (Nordhaus 1990) have estimated that the cost of a 43 percent reduction in CO2 emissions would cost \$200 per ton of carbon removed.*
- *The variation in comparable cost estimates in part is due to differing assumptions about the supply and demand for energy.*

**THE BROAD RANGE OF CO2 REDUCTION COST ESTIMATES REFLECTS
ALTERNATIVE ASSUMPTIONS ABOUT KEY SUPPLY AND DEMAND
PARAMETERS.**

■ **Key demand-side factors include:**

- *The economic growth rate*
- *The impact of technological change and other non-price related factors on the energy intensity of the economy*
- *The cost of conservation*

■ **Key supply-side factors include:**

- *The size and rate of development of the fossil fuel resource base*
- *The cost and availability of synthetic and renewable resources.*
- *The cost and availability of low or no CO2 emitting electric generation technologies*

PART OF THE VARIATION IN COST ESTIMATES IS ALSO DUE TO THE DIFFERENT TIME PERIODS EXAMINED.

- *In a global climate change context, short-term means 10 to 20 years.*
- *Long-term studies can cover a period of 110 years or more.*
- *Long-run cost estimates are generally higher due to:*
 - *Cumulative growth in energy use and energy-related CO2 emissions*
 - *Depletion of low CO2 emitting natural gas resources*
 - *Depletion of low cost conservation opportunities*

SUMMARY OF COST ANALYSES

U.S. CO2 COST STUDIES PERFORMED TO DATE

BOTTOM-UP STUDIES

Rocky Mountain Institute (1989)

EPA/Brookhaven-MARKAL Model (1990)

ICF Resources (not yet released)

TOP-DOWN STUDIES

Nordhaus-Yohe (1983)

Edmunds-Reilly (1983)

Nordhaus (1977,1979)

Manne-Richels (1989, 1990)

Congressional Budget Office (not yet released)

Others in Progress

THE COST ESTIMATES TEND TO FALL INTO TWO CATEGORIES.

- ***"Bottom-up" studies identify individual technologies for incremental CO2 reduction.***
 - ***Some bottom-up studies, such as the EPA/Brookhaven study, use a mathematical optimization framework to determine the least cost solution to reducing CO2 emissions.***
 - ***Other bottom-up studies, such as the Rocky Mountain Institute study, cost out each technology, and sum to get a total cost estimate. These studies readily generate a CO2 reduction cost "curve."***
- ***"Top-down" studies estimate total U.S. macroeconomic costs over some period of time.***
 - ***Some top-down studies, such as Edmunds-Reilly, are econometric studies, that use statistical equations to represent energy supply and demand market interactions.***
 - ***Other top-down studies, such as Manne-Richels, impose a mathematical optimization framework on an econometric representation of supply and demand***

BOTTOM-UP STUDIES TEND TO BE SHORT-TERM ANALYSES.

- *The Bottom-up studies tend to be short-term because detailed costs can only be quantified using existing technologies.*
- *Typically, all existing technologies are assumed to reach full market penetration by 2010, so the analysis tends to end by then or sooner.*
- *The major issues that are addressed in the Bottom-up studies are:*
 - *Cost and performance estimates of existing and near commercial energy technologies*
 - *Cost of implementation*
 - *Baseline energy use assumptions*

ROCKY MOUNTAIN INSTITUTE ELECTRICAL EFFICIENCY SUPPLY CURVE

Source: Rocky Mountain Institute, 1989.

THE ROCKY MOUNTAIN INSTITUTE IS ONE EXAMPLE OF A BOTTOM-UP APPROACH TO ESTIMATING THE COST OF CO2 EMISSION REDUCTIONS.

- *RMI has constructed an electrical efficiency supply curve. Each step of the supply curve denotes the quantity of electricity that can be conserved or otherwise displaced for the cost level designated on the Y axis.*
- *Although RMI did not do so, this cost curve, along with assumptions about electric generation fuel mix, could be used to estimate the cost of reducing CO2 emissions from electric utilities.*
- *Based on existing technologies, their analysis indicates that conservation efforts could lead to a substantial reduction in electricity use in the United States at zero cost or at a cost savings.*
- *RMI's supply curves do not address issues associated with timing and the demand for these electricity-saving technologies. The fact that these existing technologies are currently not more widely used may indicate that:*
 - *Consumers may not have adequate information, i.e. they are not aware of the cost savings potential of the technology; or*
 - *RMI may not have accounted for some additional costs for these electricity savings technologies, e.g. loss of convenience, safety, comfort.*

TOP-DOWN STUDIES TEND TO COVER LONGER PERIODS OF UP TO 110 YEARS.

- *Because top-down studies can use econometric equations to represent long-term supply and demand trends, CO2 cost issues can be examined for longer periods of time than is possible with bottom-up approaches.*
- *Top-down studies require many assumptions about long-term economic development and energy use. The key assumptions that must be made include:*
 - *Availability and cost of conventional and synthetic fuels*
 - *Technology development over time*
 - *Conservation*
 - *Economic growth*

MANNE-RICHELS GLOBAL 2100 MODEL

Source: Manne-Richels, 1989.

THE MANNE-RICHELS MODEL IS ONE EXAMPLE OF A TOP-DOWN APPROACH TO ESTIMATING THE COST OF CO2 EMISSION REDUCTIONS.

- *Their model consists of an energy technology assessment model and a macroeconomic model.*
- *The Energy Technology Assessment (ETA) component of the model has explicit representation of electric and non-electric supply technologies.*
- *The macro component of the model determines output of the economy based on inputs of capital, labor, electricity, and non-electric energy.*
- *The model is solved to determine the maximum GNP level subject to constraints on the energy resources available.*
- *The model has been used to examine the costs of reducing CO2 emissions for the U.S., Other OECD countries, the Soviet Union and Eastern Europe, China, and a catchall Rest of the World region.*

MANNE-RICHELS ESTIMATES OF ECONOMIC COSTS OF CO2 EMISSION REDUCTIONS

Source: *Manne-Richels, 1989.*

Note: *Manne-Richels defined the carbon limit as holding carbon emissions at their 1990 level through 2000, reducing emissions by 20 percent by 2020, and then holding them at this level thereafter.*

CO2 REDUCTION COST ESTIMATES DIFFER IN PART DUE TO THE TIME FRAME CONSIDERED.

- *Bottom-up approaches typically show lower costs for CO2 emission reductions. In contrast, some top-down approaches have estimated higher costs.*
- *Some of the apparent discrepancy in cost estimates is simply a function of the time period covered.*
- *For example, CO2 emission reduction cost estimates developed by Manne-Richels do not become significant until after 2010, which is where most bottom-up approaches typically stop.*
- *Long-run cost estimates are generally higher due to:*
 - *Cumulative growth in energy use and energy-related CO2 emissions*
 - *Depletion of low CO2 emitting natural gas resources*
 - *Depletion of low cost conservation opportunities*

REVIEW OF COST ESTIMATING ISSUES

THE MANNE-RICHELS ANALYSIS WILL BE USED AS THE FOCUS FOR THIS REVIEW.

- *Their study (Manne-Richels 1989) has received much attention as one of the most recent and comprehensive studies of the cost of reducing CO2 emissions.*
 - *Their CO2 cost estimates were cited in the most recent draft of the White House Council of Economic Advisors Report.*
 - *Their study has received a certain amount of peer review. Some reviewers have concluded that their cost estimates are too high (Williams 1989, 1990), while others have maintained that some of the Manne-Richels assumptions are too optimistic leading to cost estimates that are too low (Hogan, Jorgenson 1990).*
- *Their Global 2100 model provides a convenient framework for examining the key supply and demand factors that will determine the ultimate costs of reducing CO2 emissions.*
- *Other analyses will also be reviewed where appropriate to provide alternative estimates of the main assumptions used in the Manne-Richels analysis.*

DEMAND-SIDE ISSUES

- ***Economic Growth Rate***
- ***Changes in the Energy Used Per Dollar of GNP Produced***
- ***Cost of Conservation***

THE RATE OF ECONOMIC GROWTH WILL BE A KEY DETERMINANT OF THE COSTS OF REDUCING CO2 EMISSIONS.

- *Manne-Richels assume that the potential rate of economic growth will slow in the 21st century due to declining population growth. The annual rate of potential growth in U.S. GNP is assumed to decline from 3.0 percent in the 1990-2000 time frame to only 1.0 percent by 2060.*
- *The rate of growth in GNP projected by the Global 2100 Model will differ from these potential rates due to changes in energy costs and other assumptions.*
- *All other things being equal, higher rates of GNP growth will lead to higher energy use, CO2 emissions, and higher costs of limiting CO2 emissions at a specified level.*

THE EFFECT OF ENERGY USE PER DOLLAR OF GNP ON THE COST OF REDUCING CO2 EMISSIONS (1990-2100)

Source: Manne-Richels, 1989.

A SECOND KEY DEMAND-SIDE DETERMINANT OF THE COST OF REDUCING CO2 EMISSIONS WILL BE THE RATE OF CHANGE IN THE AMOUNT OF ENERGY USED PER DOLLAR OF GNP.

- *Approximately 98 percent of all U.S. CO2 emissions are energy-related. Consequently, if the U.S. economy uses less energy per dollar of GNP over time, the cost of limiting CO2 emission rates would be substantially reduced.*
- *The results of Manne-Richels analysis indicate that if, excluding the effect of changes in energy prices, energy use per dollar of GNP were to decrease at a rate of 1 percent per year, the total costs of reducing CO2 emissions over the period from 1990 to 2100 would be cut in half, falling from 3.6 to 1.8 trillion dollars, relative to a scenario in which there is assumed to be no change in energy use per dollar of GNP.*
- *The Manne-Richels paper notes that the rate of change in energy use per dollar of GNP in the U.S. economy is highly controversial.*

THE IMPACT OF OIL PRICE INCREASES ON ENERGY USE PER UNIT OF GNP

ENERGY-GNP RATIO

MBtu/ 1989 \$

U.S. OIL PRICE

1989 \$/BBL

Source: U.S. EIA, "Annual Energy Review 1988," May 1989.

ENERGY USE PER DOLLAR OF GNP HAS DECLINED DRAMATICALLY IN THE U.S. DUE IN PART TO A SHARP INCREASE IN ENERGY PRICES.

- *The historical data suggest a strong relationship between changes in energy prices and changes in energy use per dollar of GNP:*
 - *Oil prices more than tripled over the period from 1972 to 1985 while the Energy-to-GNP ratio declined sharply over this time period*
 - *Since 1986, oil prices have fallen dramatically and the Energy-to-GNP ratio has remained relatively unchanged*
- *The issue for estimating the cost of CO2 emission reductions is whether, excluding the impact of changes in energy prices, the U.S. will use less or more energy per dollar of GNP produced in the future.*
- *Based on this historical data, analysts have drawn different conclusions about future changes in energy use per dollar of GNP and the related cost of limiting future CO2 emissions.*

**ROBERT WILLIAMS OF PRINCETON UNIVERSITY BELIEVES THAT
REDUCTIONS IN ENERGY USE PER DOLLAR OF GNP OF LARGER THAN 1.0
% PER YEAR ARE POSSIBLE IN THE U.S.**

- *Williams (Williams 1989) believes that there are two underlying trends that will tend to make the U.S. economy less energy intensive:*
- *Increasing competitive pressures will lead to continuing declines in energy use per dollar of production in the basic materials industries such as petrochemicals and cement, where energy is a large cost component.*
 - *Rising affluence will continue the structural shift that is occurring in the U.S. away from goods to less energy intensive services, and away from the energy intensive basic industries toward the less energy intensive fabrication and finishing sectors.*

ECONOMETRIC ANALYSIS INDICATES THAT THE U.S. ECONOMY WILL BECOME MORE RATHER THAN LESS ENERGY INTENSIVE OVER TIME.

- *Manne-Richels Global 2100 model assumes that the rate of change in the energy use per dollar of GNP will remain constant over the next century.*
- *Hogan and Jorgenson's analysis (Hogan, Jorgenson 1990) indicates that because of technological advances the rate of change in energy use per dollar of GNP is not constant over time.*
- *Based on data covering the period from 1958 to 1979, Hogan and Jorgenson's analysis indicates that in 1972, the U.S. economy was following a declining trend in energy use per dollar of GNP. The estimates of the energy intensity trends in 1972 are roughly midway between the Manne-Richels two scenarios.*
- *But, technological change in the U.S. economy is increasing the role of energy, capital and labor, while reducing material inputs. Consequently, by 1989, the Hogan and Jorgenson analysis indicates that the energy intensity of the U.S. economy was increasing rather than decreasing.*
- *They conclude that because the U.S. economy will continue to become more energy intensive, existing models are substantially underestimating the costs of reducing greenhouse gas emissions.*

THE COST OF FUTURE ENERGY CONSERVATION IS ANOTHER KEY DETERMINANT OF THE COSTS OF REDUCING CO2 EMISSIONS.

- *In the Manne-Richels model, demand-side conservation opportunities are represented by an elasticity of substitution parameter (ESUB). This parameter denotes the amount of capital and labor required to replace one unit of energy. For example, energy conservation through the use of more insulation in residential walls is a substitution of capital and labor for energy.*
- *Manne-Richels note that in cases where energy costs are a small proportion of total output, ESUB is roughly equal to the absolute value of the price elasticity of demand.*
- *Manne-Richels assume a value of 0.4 for the elasticity of substitution. Higher values for ESUB would indicate lower costs of reducing CO2 emissions.*

ROCKY MOUNTAIN INSTITUTE ELECTRICAL EFFICIENCY SUPPLY CURVE

Source: Rocky Mountain Institute, 1989.

PROCESS-SPECIFIC ANALYSES INDICATE THAT THERE ARE MANY LOW COST CONSERVATION OPPORTUNITIES.

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- *Analysis done by the Rocky Mountain Institute (RMI 1989) indicates that conservation efforts could lead to a 40 percent reduction in electricity use in the United States at zero cost or at a cost savings.*
 - *Robert Williams (Williams 1989) cites a number of studies done in the U.S and Europe that indicate that large reductions in energy use can be achieved that would cost little or actually save money on a life cycle cost basis.*
 - *A recent Swedish study (Bodlund 1989) indicated that it would be feasible to reduce CO2 emissions from the heat and power sector in Sweden by one-third from 1987-2010 without increasing the cost of energy services.*
 - *A study by Marc Ross (Ross 1989) from the University of Michigan indicated that energy use could be reduced substantially in the U.S. manufacturing sector through "good housekeeping," conservation, and process changes, at a cost savings.*
 - *These process-specific analyses suggest that the cost of energy conservation may be lower than assumed by Manne-Richels and consequently CO2 emission reductions could be achieved at a lower cost.*

EFFECT OF DISCOUNT RATES ON CONSUMER INVESTMENT DECISIONS

BUY NOW, PAY LATER?

Given a choice between these refrigerators, which differ only in price and energy efficiency, the rational consumer would buy Brand A. It costs more to buy but less to operate. Graph at top shows the true cumulative costs over time. After 10 years, the more expensive refrigerator has saved its owner about \$200.

According to a Department of Energy study, the average consumer implicitly undervalues by 65 percent the worth of energy savings offered by more efficient refrigerators. (DOE calculations were based on efficiency ratings of all refrigerators sold in a given year.) Why else, researchers say, would anybody buy Brand B.

TRUE COSTS

IMAGINED COSTS

BY MICHAEL REGAN—THE WASHINGTON POST

Source: *Washington Post*, February 12, 1990, p. A3.

OBSERVED HIGH CONSUMER DISCOUNT RATES WILL REDUCE THE AMOUNT OF CONSERVATION RELATED CO2 EMISSION REDUCTIONS.

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- *Process-specific analyses typically use real discount rates in the 5 to 10 percent range to calculate life cycle costs.*
 - *Studies of consumer behavior indicate that consumers typically have much higher discount rates, as high as 100 percent, which would tend to raise the cost of energy conservation measures.*
 - *High consumer discount rates may reflect:*
 - *Lack of information, consumers may not be aware of the tradeoff of capital versus operating costs for a given energy investment decision*
 - *Other costs, consumers may face other costs, such as a loss of comfort, convenience, or safety, that are not factored into life cycle cost estimates.*
 - *Irrational behavior*
 - *Whatever the reason, observed high consumer discount rates indicate that the process-specific analyses yield unrealistically estimates of the amount of low-cost energy conservation opportunities available and therefore underestimate the cost of reducing CO2 emissions.*

SUPPLY-SIDE ISSUES

- ***The Size and Rate of Development of the Fossil Fuel Resource Base***
- ***The Cost and Availability of Synthetic and Renewable Resources***
- ***The Cost and Availability of Low or No CO2 Emitting Electric Generation Technologies***

THE AVAILABILITY OF OIL AND NATURAL GAS WILL AFFECT FUTURE CO2 EMISSION RATES.

- *On a Btu basis, CO2 emissions from natural gas are only 54 percent of emissions from coal.*
- *While the CO2 emission rate for oil is higher than natural gas, it is still 20 percent less than coal.*
- *Consequently, displacing coal use with increased oil and natural gas production is one way to reduce CO2 emissions.*

CO2 EMISSION RATES FOR FOSSIL FUELS (LB/MMBTU)

<i>OIL</i>	<i>173</i>
<i>GAS</i>	<i>117</i>
<i>COAL</i>	<i>216</i>

Source: Rotty, Ralph, "Carbon Dioxide from Fossil Fuel Combustion Trends, Resources, and Technical Implications, in Trablanka, J. R. ed., Atmospheric Carbon Dioxide and Global Carbon Cycle, U.S. DOE, Washington D.C., 1985.

MANNE-RICHELS ESTIMATES OF MAXIMUM U.S. NATURAL GAS PRODUCTION

Source: Manne-Richels, 1989.

MANNE-RICHELS ASSUMPTIONS PLACE RESTRICTIONS ON THE FUTURE AVAILABILITY OF OIL AND NATURAL GAS IN THE U.S.

- *They use upper bound estimates for U.S. oil and natural gas resources from the U.S. Geologic Survey. Nonetheless, both oil and gas production are projected to steadily decline.*
- *Oil imports are limited to 20 Quads (9.4 MMBD) due to national security concerns. In contrast, the U.S. Energy Information Administration (EIA 1990) projects oil imports to increase from 15.2 Quads (7.2 MMBD) in 1989 to 22 Quads (10.4 MMBD) by 2010.*
- *Manne-Richels do not specify their assumptions about natural gas imports. The U.S. EIA projects that U.S. imports of natural gas will increase from 1.3 Quads in 1989 to 2.9 Quads in 2010.*
- *Without these constraints on the availability of oil and natural gas, the Global 2100 model would choose to increase oil imports in order to meet CO₂ emission restrictions rather than use more costly demand-side and supply-side alternatives.*
- *Thus, relaxation of these oil and gas supply constraints would lower the estimated cost of reducing CO₂ emissions.*

CARBON TAX REQUIRED TO REDUCE CO2 EMISSIONS TO 80 PERCENT OF THE 1990 LEVEL

Source: Manne-Richels, 1989.

IN THE MANNE-RICHELS ANALYSIS, THE COST AND AVAILABILITY OF SYNTHETIC FUELS DETERMINE THE LONG-RUN MARGINAL COST OF CO2 EMISSION REDUCTIONS.

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- *Manne-Richels estimated that the carbon tax required to reduce CO2 emissions to 80 percent of their 1990 level would first increase to about \$600 (in the highest cost case) by 2020 and then settle at about \$250 per ton carbon by 2040.*
 - *This \$250 carbon tax is equivalent to the long run marginal cost of CO2 emission reductions.*
 - *Manne-Richels note that this long-run cost is determined by the cost differential between coal-based and biomass-based synthetic fuels. Specifically, the long-run cost is equal to:*

*Cost Differential between coal-based Synfuels and biomass based fuels
Carbon Differential between coal-based Synfuels and biomass based fuels*

- *Consequently, a smaller differential between the cost of coal-based and biomass-based synfuels would lead to a lower carbon tax and lower estimates of CO2 emission reduction costs.*
- *This method of estimating the long-run marginal cost of CO2 reduction implicitly assumes that biomass based synfuels will be the lowest cost alternative source of low CO2 emitting energy supply.*

ALTERNATIVE ESTIMATES OF THE LONG-RUN MARGINAL COST OF CO2 EMISSION REDUCTIONS

Dollars per Ton
Carbon Removed

Sources: Manne-Richels 1989, Williams, 1989.

DOE ESTIMATES OF SYNTHETIC FUELS PRODUCTION COSTS IMPLY SIGNIFICANTLY SMALLER LONG-RUN MARGINAL COSTS FOR CO2 EMISSION REDUCTIONS.

- *In calculating the cost of synthetic fuels, Manne-Richels cost estimates are based on current technology.*

- *Robert Williams used DOE cost estimates (DOE 1989) to show that the long-run marginal cost of CO2 emission reductions could be as low as \$106 per tonne using existing technology for producing methanol and biomass.*

- *Near commercial technologies for producing methanol from biomass using the Texaco coal gasifier and the Institute of Gas Technology's biomass gasifier would reduce the marginal cost to \$59 per tonne.*

U.S. SOURCES OF 1988 ENERGY-RELATED CO₂ EMISSIONS

SOURCES BY FUEL TYPE

SOURCES BY SECTOR

Source: ICF Resources, Inc.

ANY ATTEMPT TO REDUCE CO2 EMISSIONS SIGNIFICANTLY WILL REQUIRE FINDING ALTERNATIVES TO CONVENTIONAL COAL-FIRED ELECTRIC GENERATION.

- *Coal used for electric generation accounts for 28 percent of current U.S. CO2 emissions.*
- *Because coal is relatively inexpensive, it will continue to be an attractive source for new electric generation, especially after natural gas resources are depleted.*

MANNE-RICHELS

ALTERNATIVE ELECTRIC GENERATION TECHNOLOGIES

Technology Name	Heat Rate Btu/kWh	Capital Cost, \$/kW	Carbon Emission Coefficient ²	Fuel Cost \$/M Btu	Cost Components, mills/kWh December 1988 Dollars			
					Fuel	O&M	Capital	Total
GAS-N	7,500	580	0.109	2.34 ³	17.5	3.3	10.4	31.2 ⁴
COAL-N	9,800	1,445	0.246	1.50	14.7	10.2	26.7	51.6 ⁵
COAL-R								
Coal gasif. (20% CO ₂ removal)	9,300	1,695	0.187	1.50	14.0	10.4	31.3	55.7
CO ₂ disposal - 100 mi pipeline		70				1.0	1.2	2.2 ⁶
Total		1,765						57.9
Coal gasif. (93% CO ₂ removal)	12,300	1,905	0.022	1.50	18.5	14.7	35.2	68.4
CO ₂ disposal - 100 mi pipeline		200				3.0	3.6	6.6 ⁷
Total		2,105						75.0
ADV-HC	10,000	2,600	0.000			10.0	100.9	110.9 ⁸
ADV-LC	10,200	1,750	0.000	0.80	8.2	11.5	31.3	51.0 ⁹

1 Cost and performance data are from Vejtasa and Shulman (1989).

2 Carbon Emission Coefficient (CEC) is defined as billions of metric tons of carbon emitted to the atmosphere per trillion kWh (Billion tons/TkWh) of electricity generated.

3,4 Based on price of gas in 1988. Gas prices are linked to that of oil, and they rise over time.

5 Costs similar to AFBC & IGCC without CO₂ control.

6,7 Pipeline at 25% capacity.

8 Advanced solar and biomass-based.

9 Advanced nuclear technology with passive safety features.

THE MANNE-RICHELS ANALYSIS INCLUDES THE ANALYSIS OF 5 ALTERNATIVES TO CONVENTIONAL COAL-FIRED ELECTRIC GENERATION.

- **GAS-N: Natural gas combined cycle plants**
- **COAL-R (20%): Coal integrated gasification-combined cycle (IGCC) plants with 20 percent CO2 removal. CO2 is assumed to be transported 100 miles via pipeline and injected into depleted natural gas fields.**
- **COAL-R (93%): Coal integrated gasification-combined cycle (IGCC) plants with 93 percent CO2 removal. CO2 is assumed to be transported 100 miles via pipeline and injected into ocean deep water.**
- **ADV-HC: High cost non-carbon based electric generation. Costs and performance data in this category are for advanced solar technology similar to concentrator photovoltaic cells.**
- **ADV-LC: Low cost non-carbon based electric generation. Costs and performance data in this category are for advanced nuclear design with passive safety features.**

THE COST OF CO₂ EMISSION REDUCTIONS FOR ALTERNATIVE ELECTRIC GENERATION TECHNOLOGIES

(Compared to a New Pulverized Coal Plant)

Source: Manne-Richels, 1989. Williams 1989.

ROBERT WILLIAMS BELIEVES THAT THERE ARE A NUMBER OF LOWER COST NON-CARBON BASED ELECTRIC GENERATION TECHNOLOGIES.

- *The alternative electric generation technologies included in the Manne-Richels analysis have CO2 emission reduction costs (relative to conventional pulverized coal-fired generation) that range from a minus \$3.00 per ton removed for combined-cycle gas plants (with gas at \$5.00 per MMBTU) to \$240 per ton removed for solar generation.*
- *Robert Williams (Williams 1989) believes that there are a number of electric generation technologies that will have lower costs for CO2 removal.*
 - *Hybrid solar/natural gas generation technology would have a CO2 removal cost of \$73 per ton (with gas at \$5.00 per MMBTU).*
 - *Wind electric generation could have CO2 removal costs of \$150 per ton, still well below the upper bound Manne-Richels cost estimate.*
 - *Photovoltaic electric generation could actually save money with CO2 removal costs of minus \$71 per ton.*
- *Using Williams alternative generation technologies would lead to significant reductions in the total costs of CO2 emission reductions estimated by Manne-Richels.*

THIS SUMMARY HAS IDENTIFIED SUPPLY AND DEMAND AREAS WHERE FURTHER ANALYSIS COULD LEAD TO BETTER COST ESTIMATES FOR CO2 EMISSION REDUCTION.

■ ***Demand issues that may warrant further analysis include:***

- ***The impact of technological change on the energy intensity of the U.S. economy***
- ***Consumer behavior in energy related purchasing decisions***
- ***Cost and quantity of conservation***

■ ***Supply issues that may warrant further analysis include:***

- ***The cost of low CO2 electric generation technologies***
- ***The cost of low CO2 synthetic fuel production***

■ ***Research in these areas could improve cost estimates for CO2 emission reductions.***

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