RESULTS FROM THE U.S. MARKAL MODEL

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U.S. MARKAL RESULTS FOR EMF-12

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INTRODUCTION

MARKAL is a linear programming model that optimizes a network representation of an energy system with respect to specified goals. It was developed in an international effort involving representatives of 15 countries as part of the Energy Technology Systems Analysis Program (ETSAP) of the International Energy Agency. ETSAP remains an active organization of MARKAL users, meeting regularly and publishing a newsletter. Originally written as a mainframe computer model (Fishbone and Abilock, 1981), MARKAL was implemented on a PC in 1990 (Goldstein, 1991). The PC version is being rapidly adopted by existing MARKAL users worldwide. It has also opened use of the model to a wider community.

The energy network constructed by MARKAL extends from energy resources through energy transformation and conversion and end-use demand devices to exogenously specified demands for useful energy. Each step of the network is characterized by a set of technologies from which the model the model may select. US MARKAL is configured into nine 5-year time periods centered on 1985-2025. Many possible energy networks could be drawn for each time period. MARKAL chooses the least cost set of energy system networks, subject to constraints, optimizing over all time periods. The effect is that the model uses existing facilities efficiently and can look ahead when investing in new facilities. MARKAL treats energy supply and demand technologies even-handedly; all technologies, including end-use conservation technologies, compete against each other to meet energy demands. In effect, MARKAL creates a market where energy resources, fuels, and supply and end-use technologies compete to supply specified energy demands. A single interest rate is used throughout the model. Using a common interest rate for both supply and demand technologies emphasizes the even-handed nature of the analysis but may tend to ignore some real costs that drive demand-side interest rates higher in the market place.

U.S. MARKAL is technologically rich, including over 200 individual technologies. Supply technologies include extraction, processing, and conversion. Demand technologies include industrial boilers and machine drive; residential and commercial space and water heating, air conditioning, cooking, and other electrical appliances; and transportation including various automobile engines, trucks, buses, electric and diesel trains, aircraft and vessels. Opportunities for district heating and cogeneration technologies are included. The model allows technological specifications to vary over time; for example, expected improvements in cost and efficiency for new technologies are included in the database.

MARKAL is strictly an energy system model. It is linked to the rest of the nation's economy primarily through exogenous specification of useful-energy demands. These demands are not affected by changes in shadow prices, but the model uses a dummy fuel, "conservation," to allow end-use conservation technologies, e.g., building shell improvements, to contribute to this demand. This allows the model to effectively decrease energy demands by investing in conservation technologies. In addition to end-use conservation, other approaches available to the model to reduce CO_2 emissions included more efficient supply-side technologies, switching to non-carbon energy sources, switching to lower carbon energy sources (e.g., coal to natural gas). The analysis focuses on technological options and does not include behavioral options such as turning down thermostats or car pooling. Human preferences and decisions involve more than the narrow economic decision-making approach taken by MARKAL. In some cases, such as building insulation, the model was allowed to find a cost-effective solution; it brings in conservation faster than experience suggests actually happens. In other case, where there are clearly preference differences unknown to the model, exogenous constraints were used to prevent totally unrealistic solutions, e.g., the model was constrained to maintain the existing percentage of large automobiles and from making drastic shifts from automobiles to mass transit.

MARKAL, with more than a decade of applications in many countries, has proven to be a useful model for energy systems analysis. The model, however, can determine the cost of introducing policy options or of institutional barriers to implementation of cost-effective end-use conservation measures. One of its principal uses has been to assess the potential role of new energy technologies in support of R&D decisions. Before EMF-12, MARKAL was used in a preliminary study to evaluate the cost of CO_2 emissions reductions (Morris et al., 1990). Several improvements were made in the MARKAL database between that analysis and the analysis for EMF-12.

Partly growing out of interactions in EMF-12, MARKAL has been linked with MACRO to form a model that has the technological richness of MARKAL but adding demand elasticity and coupling energy system changes with macroeconomic parameters such as GDP growth (Wene and Manne, 1992). MARKAL-MACRO, however, was not sufficiently developed for inclusion in EMF-12.

EMF-12 APPLICATION

MARKAL runs deviated from the EMF-12 format in that the base year was set at 1985 instead of 1990. Thus, the "reality" fix was at 1985 and the 1990 resource and technology mix was part of the optimization. This created an initial difference between the MARKAL results and those of other models. MARKAL, for example, installed more end-use conservation in 1990 than actually existed.

EMF-12 scenarios were largely based on economic parameters, e.g., GNP growth rates. Since MARKAL does not include a macroeconomic component, indicators of useful energy demand over time must be obtained exogenously. These were based on early outputs of FOSSIL2, kindly provided by Sharon Belanger. Where possible, these exogenous parameters were specified in non-energy terms, e.g., vehicle miles traveled, square feet of residential and commercial buildings to be heated, and converted internally by the MARKAL Users Support System (MUSS) into energy units. This application was run with a 7% discount rate for all cost decisions. All costs were in 1980 dollars; results were converted to 1990 dollars for EMF-12 summary data using an inflation factor of 1.53.

Cases run are given in Table 1. CO_2 emissions limit scenarios were solved by specifying absolute constraints on total CO_2 emissions in each time period. The model found the new least-cost resource and technology mix that would meet specified energy demands while keeping within the CO_2 constraint. In the carbon tax cases, the model added an addition cost to each fuel in proportion to its carbon content.

Table 1. MARKAL cases run for EMF-12.

Case ID	Case Description
BEMF1	Reference, CO2 Unbounded
BEMF10	CO_2 Emissions stable at 1990 level
BEMF125 (20%/50%)	CO_2 emissions in 2010 20% less than 1990, thence decreasing toward 50% less than 1990 in 2050.
CTAX1	Carbon tax of $15/ton in 1990 escalating at 5% real per year.
CTAX5	Carbon tax of $15/ton in 1990 escalating at 10% real per year.

SUMMARY OF RESULTS AND INTERPRETATION[1]

CO_2 Reductions. Figure 1 shows CO_2 emissions over time for different cases. The 20%/50% CO_2 reduction case was constrained to achieve the results shown beyond 2000. The EMF-12 carbon tax case ($15 carbon tax increasing at 5%/year) resulted in close to stability, while the same tax increasing at 10% year was close to the 20%/50% case. Looking at the last time period, about 90% of the CO_2 reduction from the reference case to the 20%/50% case was achieved through reductions in coal use, 6% from reductions in natural gas and 4% from reductions in oil. Although for some cases there were increases in gas use in intermediate years, switching from coal or oil to gas was not chosen by the model as a cost-effective approach to reducing CO_2.

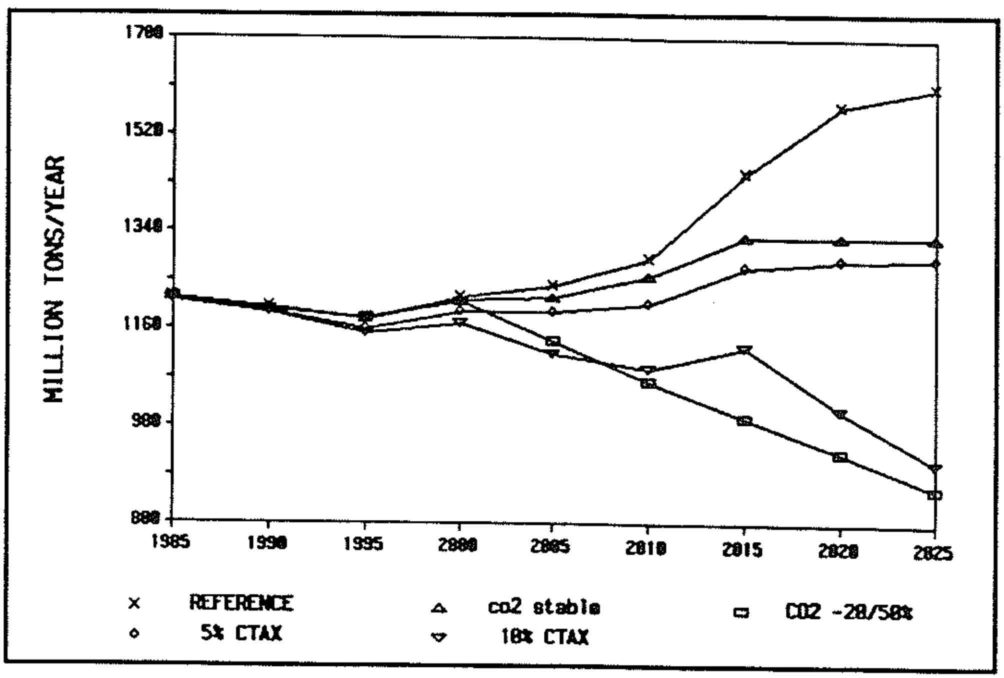

Figure 1. CO_2 emissions over time for 5 cases.

With the decrease in fossil fuel use under CO_2 constraint, energy demands were met by increased end-use conservation, renewables, and nuclear. The relative contribution of these three, in terms of primary energy supply, can be considered in two different ways. The most straight-forward is the difference between the reference case and a CO_2 emissions reduction case for a year after emissions were reduced. Looking at the 20%/50% reduction case in 2025 yields 57% increase in renewables, 39% increase in nuclear, and 3.5% increase in conservation compared to the reference case. The low contribution of conservation was because most available conservation technologies were already included in the reference case, as discussed below. Another way to look at this result is that a substantial amount of CO_2 reduction is included in the reference case "automatically." The effect of this can be seen by comparing the relative contribution of the three "fuels" between the base year (1985) and 2025 for the 20%/50% reduction case: 65% increase in renewables, 18% increase in nuclear and 18% increase in conservation. Of the absolute increase in these "fuels" in the CO_2 emissions reduction case, 88% of the conservation and 48% of the renewables were included in the reference case on the basis of cost-effectiveness alone. Nuclear, on the other hand, decreased over time in the reference case and grew only as a consequence of CO_2 constraints. By either measure, the model finds increasing use of renewable energy sources the most cost-effective method of reducing CO_2 emissions, although it is insufficient to do the job alone.

Average incremental costs from unbounded to stable CO_2 emissions was $4/ton and from stability to 20%/50% was $33/ton, 1990 dollars, discounted to present value in the base year, 1985. This is the reduction in CO_2 emissions between cases over the study period divided by the difference in total system cost between cases. Marginal costs of CO_2 reduction are time dependent. These are shown in Figure 2 as undiscounted costs per ton.

Primary Energy Use. Overall primary energy use for the cases run is shown in Figure 3. The reduction in coal, the increase in nuclear and renewables, and the relative stability of natural gas use with CO_2 constraints is apparent in the figure. Key areas are discussed individually below.

End-Use Conservation. US MARKAL has available to it a wide range of end-use conservation technologies. These include building shell conservation, higher efficiency household appliances, furnaces, industrial motors, and automobiles. Behavioral changes that reduce energy services provided, such as turning down the thermostat or car pooling, were not included. MARKAL finds most of the available energy conservation technologies cost-effective and brings them into the base case. Thus, while CO_2 emissions restrictions increase the use of conservation, the difference among scenarios was not great. Market penetration of conservation increases through 2010, then levels off. This was because most conservation technologies in the model are available now or in the near future. In contrast, the technology database includes new supply technologies that become available throughout the study period. Conservation enters the system gradually due to turnover of existing capital stock and exogenously set market penetration rates. It is reasonable to expect that new and better conservation technologies will continue to become available in future years, but we have not been able to characterize them adequately to include in the model.

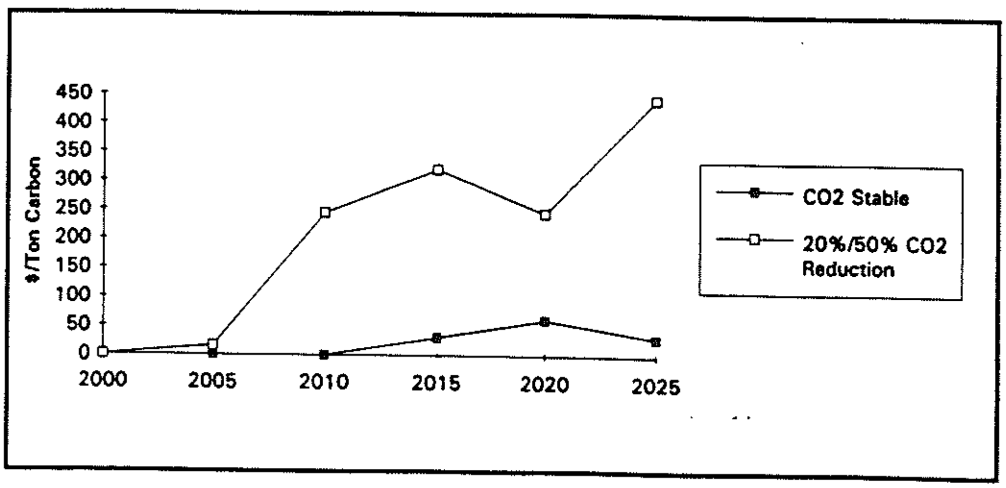

Figure 2. Marginal cost of CO_2 reduction (1990 dollars).

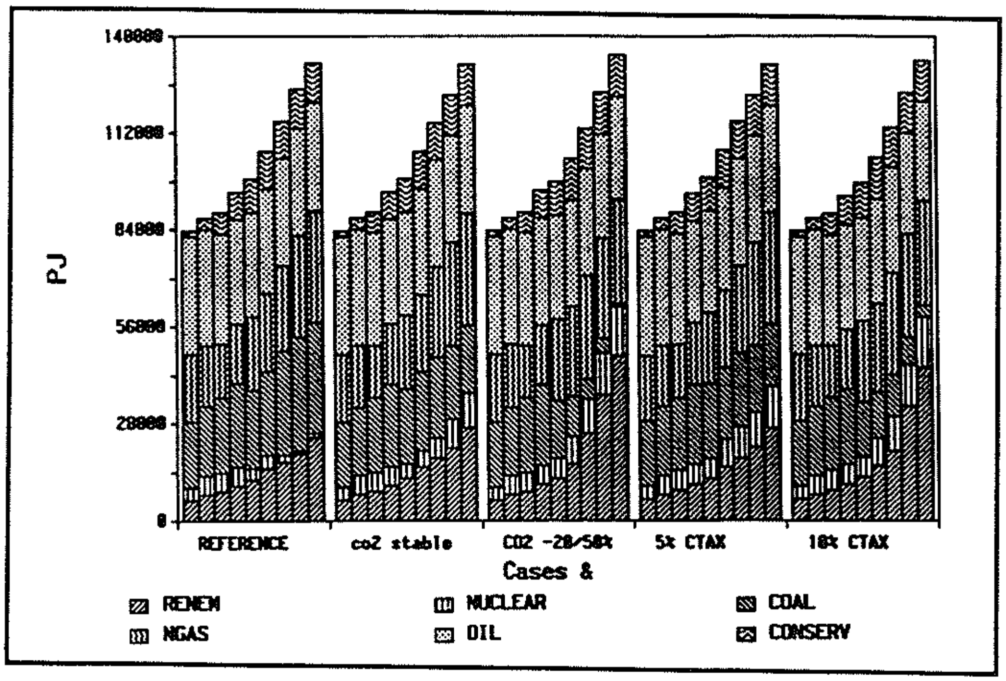

Figure 3. Primary energy use for 5 cases.

Table 2. Comparison of renewable electricity production by type between the reference case and the 20%/50% CO_2 reduction case in 2025.

Type	Reference Case (PJ)	20%/50% Case (PJ)
Hydro	1695	1640
Geothermal	1943	2049
Wind	1103	4415
Wave and OTEC	0	214
Biomass and MSW	0	32
PV	1	380
Solar Thermal	552	552

Renewables. Of the large increase in renewable energy use contributing to CO_2 emissions reduction (comparing the reference case to the 20%/50% reduction case), only a small portion was applied by end-users. That was solar thermal space and hot water heating in the residential and commercial sector. There was no increase in industrial use of renewables. All the rest of the renewables increase was in electric power generation and central heating plants. There was an increase in district heating use by the residential and commercial and industrial sectors and of the heat from cogeneration plants in the industrial sector. Much of this heat was generated by solar or geothermal. Output of renewable electric technologies in 2025 was 75% higher in the 20%/50%

reduction case than in the reference case. Differences in individual classes of technology are shown in Table 2. The largest absolute difference is in the use of wind.

Nuclear. The model allows continued construction of light water reactors and introduction of several advanced reactor types. Electricity used in producing nuclear fuel was included, so CO_2 emissions associated with that electricity production were captured in the results. Fuel use in uranium mining and milling operations was not included, although in other analyses this was shown to make little difference. In the reference case, use of nuclear power declines. In the CO_2 emission constrained cases, nuclear was an important contributor to achieving CO_2 reduction (Figure 4).

Coal. In the reference case, coal use grows steadily, but drops rapidly with CO_2 constraints (Figure 5). Conventional coal-fired electric plants disappeared soon after CO_2 emissions controls were imposed in all but the CO_2 stability case. There and in the reference case there was still a substantial reduction after 2000 and almost all remaining plants were retrofit or repowered. In the reference case, conventional coal-electric plants were replaced by fluidized bed or integrated coal-gasification combined-cycle. Introduction of these new technologies decreased rapidly as CO_2 emissions constraints increase (Figure 6). New, high efficiency coal technologies can contribute to moderate CO_2 emissions reduction goals, but substantial reductions in CO_2 emissions seem incompatible with continued use of significant quantities of coal. An exception is the availability of carbon sequestering technologies, which MARKAL analyses indicate may be a cost-effective approach to meeting more stringent CO_2 emission constraints while maintaining the ability to make use of coal (Morris et al., 1992; Oakken et al., 1992).

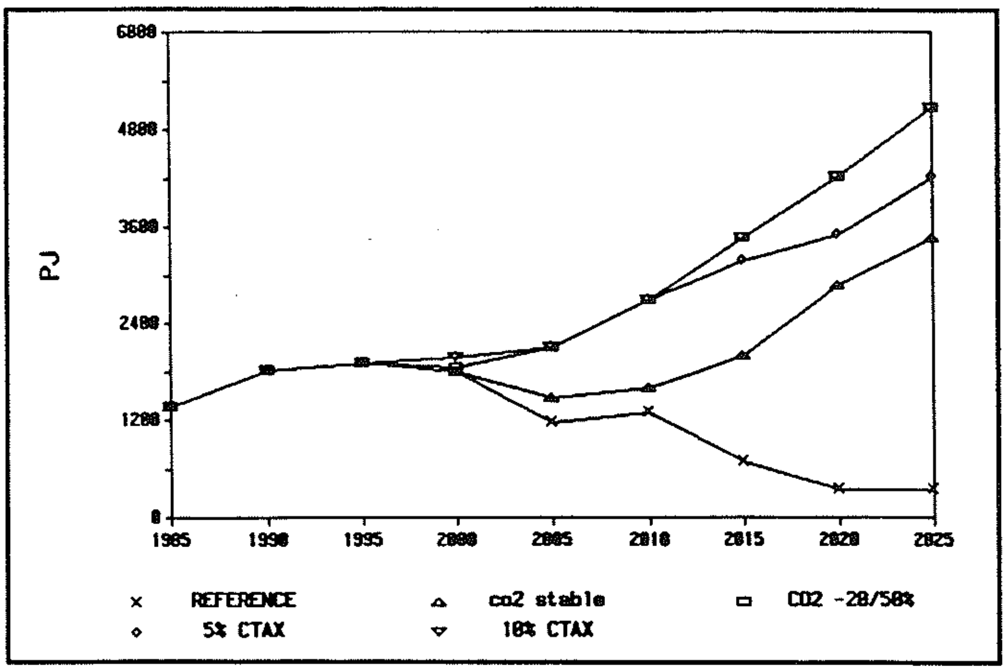

Figure 4. Nuclear electricity produced for 5 cases.

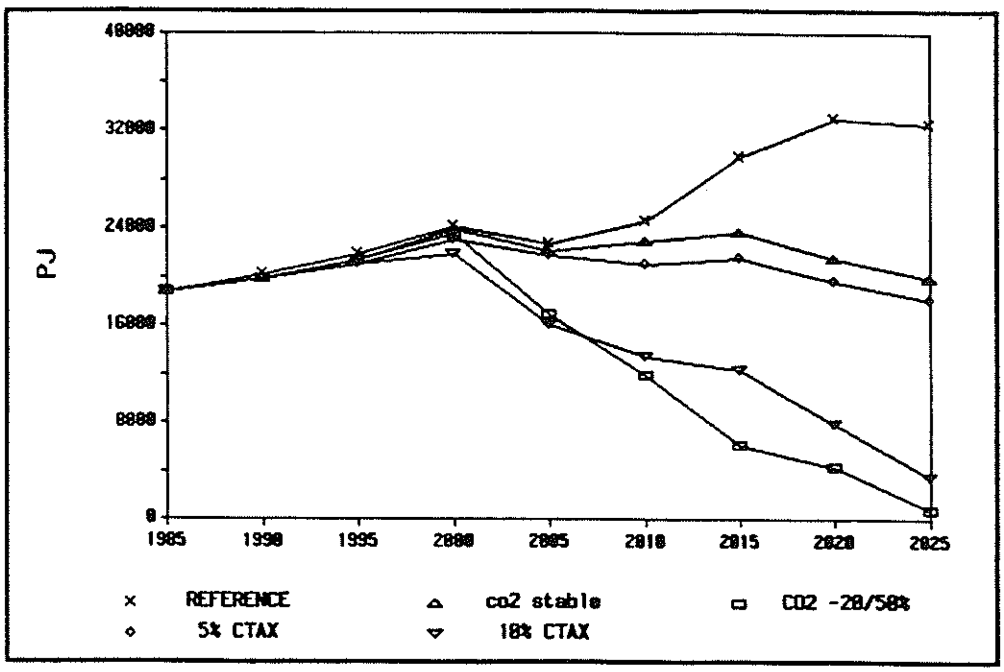

Figure 5. Use of coal in 5 cases.

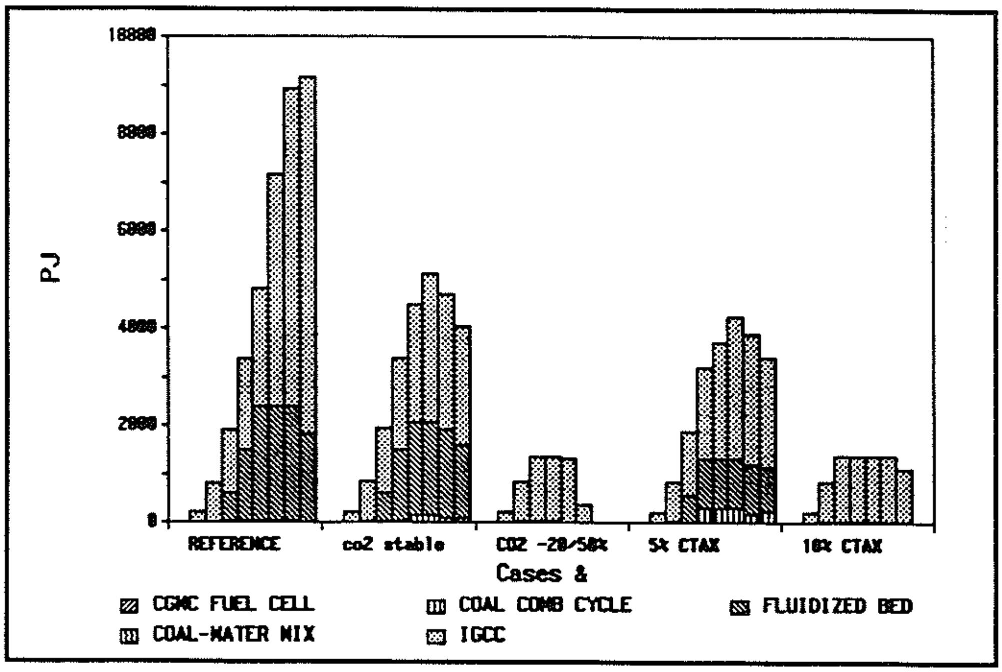

Figure 6. Activity of advanced coal technologies in 5 cases.

REFERENCES

Goldstein, G. 1991. PC-MARKAL and the MARKAL users support system (MUSS) (BNL46319), Brookhaven National Laboratory, Upton, NY 11973.

Fishbone, L.G. and Abilock, H. 1981. "MARKAL, a linear-programming model for energy systems analysis: technical description of the BNL version." *Energy Research*, 5, 353-375.

Manne, A.S. and C-O. Wene. 1992. MARKAL-MACRO: a linked model for energy-economic analysis (BNL 47161), Brookhaven National Laboratory, Upton, NY 11973.

Morris, S.C., B.D. Solomon, D. Hill, J. Lee, and G. Goldstein. 1990. A least cost energy analysis of U.S. CO2 reduction options, in J.D. Tester, D. Wood, and N. Ferrari (eds), *Energy and the Environment in the 21st Century*, MIT Press, Cambridge, MA, pp. 865-876.

Morris, S.C., J. Lee, G. Goldstein and M. Steinberg. 1992. Comparison of pre- and post-combustion carbon removal. *Energy Conversion and Management 33*: 747-754.

Okken, P.A., P. Lako, D. Gerbers, T. Kram, and J.R. Ybema. 1992. CO_2 removal in competition with other options for reducing CO_2 emissions. *Energy Conversion and Management 33*: 737-745.

ENDNOTES

1. A data entry mistake was found during work of the Technology Study Group that had little overall effect but a significant effect for a few technologies. The results in this section reflect a correction of the mistake.