NOTICE

**CERTAIN DATA
CONTAINED IN THIS
DOCUMENT MAY BE
DIFFICULT TO READ
IN MICROFICHE
PRODUCTS.**

BNL--47320

DE92 013609

COMPARISON OF PRE- AND POST-COMBUSTION CARBON REMOVAL

S. C. Morris, J. Lee, G. Goldstein, and M. Steinberg

Brookhaven National Laboratory
Upton, NY 11973 USA

ABSTRACT

Conventional approaches to reduce CO₂ emissions, including fuel switching among fossil fuels, renewables, nuclear, end-use conservation, and increased efficiency, nearly all lead to reduction in coal use. Carbon removal technologies alone have the potential to allow continued use of coal. All approaches must compete economically, technically, and environmentally for market share within the context of the total energy system. MARKAL, a dynamic energy systems model, was used to simulate this competition through 2025 for the U.S. energy system. Three carbon removal technologies were evaluated: CO₂ scrubbing from coal-fired power plant flue gas, CO₂ separation during coal gasification, and carbon separation in the Hydrocarb process. CO₂ was sequestered in depleted gas wells and the deep ocean, and solid carbon in depleted coal mines. All three technologies evaluated offer a more cost-effective path to CO₂ emission reduction than the reference case. Moreover, the ability of pre-combustion methods of carbon removal can be combined with producing motor fuels as well as electric power fuels, a combination that provided greater opportunity for carbon removal.

KEYWORDS

Carbon dioxide; energy systems; coal; global climate.

INTRODUCTION

Because coal has a lower hydrogen-to-carbon ratio than oil or natural gas, strategies to reduce CO₂ emissions almost invariably lead to reductions in coal use. For example, Jorgenson and Wilcoxon (1991), using a general equilibrium model of the U.S. economy, found that a 20% reduction in CO₂ from 1990 levels would lead to a 60% reduction in the use of coal. Our reference scenario virtually eliminates coal use. Clearly CO₂ emissions restrictions, if implemented, will severely affect the coal industry and the ability of the nation to use its coal resources. Technologies for removing and sequestering carbon provide a way to use coal resources while reducing CO₂ emissions. When initially investigated in the 1980s (Steinberg and Albanese, 1983; Steinberg et al., 1984), these technologies appeared impractically expensive. Since most of the energy value in coal is associated with the carbon, precombustion removal of carbon results in a substantial energy - and thus economic - penalty. Scrubbing CO₂ emissions from stacks is also expensive. Increasing concern with the threat of global warming, however, stimulated continuing technological advance and a re-evaluation of the economics. The entire market for coal and the economics of coal-fired electric power plants would be radically altered by carbon taxes of one hundred dollars per ton or more, levels that have been discussed.

MARKAL MODEL

MARKAL is a linear programming model that creates a series of network representations of an energy system over time. The networks extend from energy resources through energy-transformation and end-use devices to exogenously specified demands for useful energy services. The model selects technologies and resources from a database to construct the energy system needed to satisfy specified energy service demands and CO₂ emission constraints at least cost. MARKAL behaves as if it had full knowledge of the past and present; it uses existing facilities most efficiently and can plan ahead for new investments. MARKAL is used internationally to analyze national, state or province, and local

MASTER

energy systems. It was originally written as a main-frame computer model (Fishbone and Abilock, 1981). A standardized PC version is now available (Goldstein, 1991).

The model treats supply and demand technologies even-handedly, making investment decisions without regard to well-known economic and social barriers to energy conservation or more efficient technologies in the residential and commercial sector. The results show the energy system as it would develop under an even-handed, least cost management, not as it would be likely to develop given existing market conditions. In doing this it shows technically feasible paths that can guide planners and policy makers in the direction of a cost-effective energy system.

CO₂ REMOVAL AND SEQUESTERING TECHNOLOGIES EXAMINED

Hydrocarb

Initially developed to produce a clean carbon fuel from coal (Grohse and Steinberg, 1987), Hydrocarb provides an attractive approach for sequestering carbon. Solid carbon is easier to store than CO₂ gas, the security of storage has fewer technological uncertainties, it can be burned if carbon removal is not needed, or can be used as a chemical feedstock. The version of Hydrocarb used in the model uses a combination of coal and wood as a feedstock (75% and 25% of input energy, respectively) and produces carbon and methanol. Reference efficiency was 80%, capital cost \$3.76 million per PJ, annual operating cost \$0.16 million/PJ, availability factor 90%. Overall, 88% of the carbon input is recovered in the products, 78% of which is in the form of solid carbon that could be sequestered. If the carbon in the biomass feedstock is considered in balance with the atmosphere, then all carbon removal can be credited to the coal input. Following this approach, removal efficiency is 95%. Methanol has a lower carbon content than gasoline, so further carbon reduction is achieved by substituting it for gasoline as a motor fuel. The ratio of carbon to methanol produced was fixed, but the model could choose to sequester carbon (for example in depleted coal mines) or burn it in electric power plants and to burn methanol in electric power plants or use it as a motor fuel. Cost of carbon sequestering was assumed to be \$5.3 per ton.

Coal Gasification with CO₂ Removal

Our configuration was a stand-alone gasifier producing hydrogen and CO₂, based on a coal gasification process described by Williams (1990) and Blok et al. (1989). The technology has an energy efficiency of 82% with a capital cost of \$18.1 million/PJ, annual operating cost of \$1.0 million/PJ, availability factor 90%, and CO₂ removal efficiency of 94%. MARKAL was configured with several options available for the use of hydrogen including motor fuel, aircraft fuel, and electric power plant fuel. As much as 10% hydrogen could be added to the natural gas pipeline system.

CO₂ Scrubber

Our CO₂ scrubber configuration was modified by one of us (MS) from Steinberg and Albanese (1983). It has a capital cost of \$200/ton removed, annual operating cost of \$6.9/ton removed, and removes 90% of CO₂ from the stack.

CO₂ Sequestering

Two methods were included for sequestering CO₂ from gasification or scrubbers: deep ocean and depleted natural gas wells. Assumed costs were \$24/ton capacity capital cost and \$2.4/ton operating cost for depleted gas wells and \$200/ton capacity capital cost and \$6.90/ton operating cost for ocean disposal. CO₂ sequestering was mandatory for scrubbers and the gasification technology.

APPROACH

The analysis was structured in nine 5-year periods centered on the years 1985 to 2025. Values for 1985 were constrained to match historical data. The outer time boundary of the analysis was chosen as one

for which technologies now exist or new technologies are sufficiently advanced that costs and efficiencies can be adequately characterized. A 7% discount rate was used throughout the analyses.

Over 200 demand and supply technologies are available in the reference case. MARKAL can respond to CO₂ emissions constraints (or carbon taxes) by selecting more efficient technologies, end-use conservation, switching from high- to low-carbon fossil fuels, or switching to non-carbon fuels, e.g., solar and nuclear. Our analysis is technologically based and does not consider behavioral change options that might reduce the demand for energy services. The world oil price is an exogenously specified parameter in MARKAL. Assumed values are given in Figure 1.

Fig. 1. Assumed world oil price by period.

Carbon separation and sequestering technologies were added to the reference set of technologies in a controlled way to explore their economic viability and their implications for the energy system under different circumstances. Each carbon separation technology was made available to the system alone in separate scenarios and then all three together. All cases were run with CO₂ unbounded, with CO₂ emissions stabilized at 1990 levels by 2010, and with reduction targets for 2010 of 20% and 30% less than 1990 levels. The latter included constraints for 2005 to assure the system was on track toward the target and continuing reductions after 2010, aiming toward a 50% reduction in 2050. These cases are referred to below as unbounded, stable, 20% and 30%.

RESULTS

In the reference case, without carbon sequestering, coal use declines sharply with increasingly stringent CO₂ emission reduction targets, virtually disappearing by 2025. By contrast, all the scenarios examined here with carbon sequestering maintained substantial coal use (Figure 2). Figure 3 shows the amount of carbon sequestered for each scenario with a 20% reduction in CO₂ emissions reduction target. Highlights of each case are reported individually below.

Hydrocarb Alone

Hydrocarb entered the system in the unbounded CO₂ case, although no carbon was sequestered. Carbon was burned in steam-electric plants and methanol used as an automobile fuel. It appears the price advantage of methanol from Hydrocarb over gasoline is behind Hydrocarb's selection in this case. In the stable case, use of Hydrocarb decreased. The system found conservation, increased efficiency, nuclear and renewable energy to be more cost-effective ways to meet this level of CO₂ emissions constraint. At 20% Hydrocarb entered the system rapidly and all carbon produced was sequestered. Methanol was still used as an automotive fuel. The 30% case was technically infeasible in period nine (2025).

CO₂ scrubbers and coal gasification with CO₂ separation were constrained to zero in this scenario, but their potential value to the system can be seen in their reduced costs. Reduced cost is the net change in total system cost were one unit of the technology allowed to enter. CO₂ scrubbers had positive reduced costs except for the last period of the 20% case where the reduced cost was \$80,000/PJ. That is, except for the most restrictive period, adding scrubbers would increase total costs to meet designated

constraints. Reduced costs of coal gasification with CO₂ separation were consistently zero or negative, indicating their introduction would have reduced total costs. They ranged \$0-7 million/PJ.

Fig. 2. Coal use in 2025 by scenario.

Fig. 3. Carbon sequestered by scenario and year for the 20% case.

Coal Gasification with CO₂ Separation Alone

The coal gasifier with CO₂ separation entered the unconstrained case to a small degree in the last period of the unbounded case. Hydrogen produced was mixed with natural gas in the existing distribution system. With CO₂ emissions stability, the technology entered one period earlier. CO₂ produced was sequestered in depleted gas wells. Hydrogen production was again mixed with natural gas. In the 20% case, the technology entered the system in 2010 and reached a production level of 4.7 EJ hydrogen by 2025. Hydrogen initially was mixed in natural gas pipelines, but in the last period, 41% was liquefied and used in the transportation sector (aircraft fuel). CO₂ produced was sequestered in depleted gas wells. The 30% case was technically infeasible in the ninth period.

Hydrocarb had negative reduced costs in the range \$0-4 million per PJ, although there was no clear trend in its value to the system with increasing CO₂ constraint. Scrubbers had positive reduced costs ranging \$0.01-0.2 million/PJ, independent of CO₂ constraint.

CO₂ Scrubbers

CO₂ scrubbers did not enter the unconstrained case. They entered all cases with CO₂ emissions constraint, entering earlier and with increasing activity as the constraint became more stringent.

Both Hydrocarb and gasification with CO₂ separation had negative reduced costs in this scenario. Hydrocarb ranged \$0.4-6 million/PJ, with the higher reduced costs in the early (2000-2010) periods, while gasification ranged \$0-5 million/PJ.

Hydrocarb, Gasification with CO₂ Separation and CO₂ Scrubbers Combined (All)

In this scenario, all three carbon separation technologies were included and could compete directly. Carbon removal from technology each is shown in Table 1.

While this scenario was designed to allow competition among carbon removal technologies, a synergistic effect resulted. Carbon separated from coal by Hydrocarb was burned in steam-electric power plants, then scrubbed to remove CO₂ that was then sequestered. Twenty-one to 37% of total coal followed this course in 2025. Fourteen to 30% of coal underwent CO₂ separation in gasification. Hydrogen produced was partially mixed with natural gas and partially used in the transportation sector (trucks and airplanes). The remainder of the coal used in 2025 was burned directly in steam electric plants with CO₂ scrubbers. Availability of all three technologies allowed increasing coal use even under 30% CO₂ reduction. High efficiency, advanced coal technologies had the primary role in the unbounded and stability case, but increased efficiency alone was inadequate to meet 20% and 30% reduction targets where almost all coal underwent carbon separation.

Table 1. Carbon separation by technology for the 20% case of the Scenario with all three carbon removal technologies included.					
Technology	Million Tons per Year Removed				
	2005	2010	2015	2020	2025
Hydrocarb	0.	0.	82.	216	229.
Scrubbers	85.	160.	240.	340.	360.
Gasifiers	0.	0.	0.	116.	300.
Tot Sequestered	85.	160.	240.	396.	513.

Note: Carbon separated by Hydrocarb is not sequestered.

CONCLUSIONS

Figure 4 plots the marginal cost of CO₂ removal by period for the 20% removal case for each scenario. Marginal cost of removal was initially highest for the gasification alone scenario, but marginal costs for this scenario soon became the lowest. The scrubbers alone scenario had lower marginal costs than the Hydrocarb alone scenario in the intermediate term (2010-2015), but in 2020-2025 the situation reversed and the Hydrocarb scenario had lower marginal costs of removal. Since the CO₂ constraint increases with time, this suggests that the pre-combustion technologies are more cost effective for meeting more stringent CO₂ emissions targets.

Fig. 4. Marginal cost of CO₂ reduction by year and scenario for the 20% removal case.

Figure 5 shows the cumulative cost and carbon emissions over the 45-year study period for each case run. The slope of the line connecting each case of a scenario is the average discounted cost per ton of carbon removed. As the target level became more stringent, the incremental cost increased. Rates are tabulated in Table 2. These costs represent the average cost to decrease CO₂ by the given increment, including all available technology options used, e.g., conservation, increased efficiency, fuel switching, renewables and nuclear. The role of the three carbon removal technologies investigated is seen by the differences between each case and the reference case. All three technologies evaluated offered a more cost-effective path to CO₂ emission reduction than the reference case. The gasifier with CO₂ removal had a lower average cost per ton removed than Hydrocarb, although Hydrocarb offered a cost-effective

Table 2. Average discounted cost of CO₂ removal by increment over entire study period (1990\$/ton).

Case	1st	2d	3d
Reference	5.7	26.	nf
Scrubbers	5.9	19.	nf
Gasifiers	5.3	22.	nf
Hydrocarb	5.5	24.	nf
All	4.4	13.	36.

Increments:

1st = unbounded to stable;
 2d = stable to 20% reduction;
 3d = 20% to 30% reduction.

nf = not technically feasible.

option for locations where sequestering CO₂ gas would be impossible or prohibitively expensive. The combination of all technologies had the lowest average incremental costs and achieved 30% reduction. Moreover, the combination case achieves substantially greater coal use under all emissions targets. While the combination scenario was designed to determine the effect when the three carbon removal technologies were in competition among themselves as well as with the reference technologies, it demonstrated a surprising synergistic effect. Considerably more coal was used and more carbon sequestered than in any case restricted to a single removal technology. This was achieved largely through an interaction between Hydrocarb and CO₂ scrubbers. Hydrocarb and the gasifier technology are attractive for their ability to supply motor fuels as well as electric power fuels. It is important not to restrict consideration of carbon removal to the electric utility industry alone.

Fig. 5. Carbon emissions reduction cost curve (average incremental cost for stability to 20% case indicated).

ACKNOWLEDGMENTS

Research supported by the U.S. Department of Energy under contract no. DE-AC02-76CH00016. Helpful suggestions were provided by referees.

REFERENCES

- Blok, K., C. Hendriks, and W. Turkenburg (1989). The role of carbon dioxide removal in the reduction of the greenhouse effect. In: *Energy Technologies for Reducing Emissions of Greenhouse Gases*, Vol 1, pp. 135-155. International Energy Agency/Organization for Economic Cooperation and Development, Paris.
- Fishbone, L.G. and H. Abilock (1981). MARKAL, a linear-programming model for energy systems analysis: technical description of the BNL version. *Energy Research* 5: 353-375.
- Goldstein, G.A. (1990). PC-MARKAL and the MARKAL Users Support System (MUSS) User's Guide (BNL 46319), Brookhaven National Laboratory, Upton, NY 11973.
- Grohse, E.W. and Steinberg, M. (1987). Economical clean carbon and gaseous fuels from coal and other carbonaceous raw materials (BNL 40485). Brookhaven National Laboratory, Upton, N.Y.
- Jorgenson, D.W. and P.J. Wilcoxon (1991). The cost of controlling U.S. carbon dioxide emissions. In: *Proceedings of the Workshop on Economic/Energy/Environmental Modeling for Climate Policy Analysis* (D.O. Wood and Y. Kaya, eds.), pp. 266-376. University of Tokyo Global Environmental Study Laboratory and Massachusetts Institute of Technology Center for Energy Policy Research.
- Steinberg, M. and Albanese, A. (1983). Advanced technologies for the recovery, disposal and reuse of carbon dioxide for atmospheric control (BNL 33960). Brookhaven National Laboratory, Upton, N.Y.

- Steinberg, M., Cheng, H.C. and Horn, F. (1984). A systems study for removal recovery and disposal of carbon dioxide from fossil fuel power plants in the U.S. (BNL 35666). Brookhaven National Laboratory, Upton, N.Y.
- Williams, R. (1990). Hydrogen from coal with sequestering of the recovered CO₂: a competitive way to use coal in a greenhouse-constrained world. Center for Energy and Environmental Studies, Princeton University, Princeton, NJ.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

**DATE
FILMED**
7 / 9 / 92