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THE COST OF REDUCING CARBON EMISSIONS IN DEVELOPING COUNTRIES: EVIDENCE FROM COLOMBIA

BUREAU FOR LATIN AMERICA AND THE CARIBBEAN
Agency for International Development
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THE COST OF REDUCING CARBON EMISSIONS IN DEVELOPING COUNTRIES: EVIDENCE FROM COLOMBIA

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Since the late 1980s, the issue of global warming and the critical role played by the energy sector has become an increasingly serious one to people throughout much of the industrially developed world. As consensus among scientists has gradually formed in support of the theory that an acceleration of global warming is almost certainly occurring, and as global environmental issues in general receive ever greater attention in the media, a growing number of individuals and institutions have accepted the idea that something needs to be done to slow global warming.

In this context, many suggestions—such as the proposed 20 percent cut in CO_2 emissions made at a conference in Toronto in 1988[1]—have been made for specific country targets for reducing CO_2 emissions.[2] To date, despite the vague and non-binding commitments made by participants at the Rio Conference on the environment in 1992, there has been little demonstrable progress in this area.

There are a number of obstacles to limiting emissions of carbon dioxide. While industrially developed countries are in the strongest position to reduce their collective emissions of such gases—given their relatively high standard of living, stable population size, and relatively high per capita energy usage—they cannot reduce world CO_2 emissions in the long run without cooperation from the developing countries. Unless current trends change, the most significant increases in carbon dioxide emissions in the coming decades will occur in the developing countries.[3] The largest share of these emissions comes from the energy sector.[4]

Any plans by the developing countries to reduce CO_2 emissions face formidable obstacles. First, as the developing countries continue their process of economic development, a by-product is the increased use of energy per capita. Trying to convince poor countries that they should use less energy—that they should not aspire to live as people do in the industrially developed countries—is a dead end.[5] Moreover, while this would be a problem even if the LDCs had stable populations that were gradually increasing in per capita energy consumption, the problem is vastly more serious in

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[1] Dower and Zimmerman (1992).
[2] Duraiappah (1991).
[3] Cline (1992).
[4] Nordhaus (1991).
[5] It should be possible to limit the rate of increase in energy intensity through the adoption of more energy-efficient technologies, however.

the context of rapidly rising populations. As a whole, the developing countries have reduced the rate of increase in the growth of their collective population, but growth rates are still approximately 2 percent annually.

There are solutions to these problems, but they are not easy ones. The developing countries—like the developed countries—could increasingly shift to the use of energy sources that emit less CO_2. If done sufficiently rapidly, this could allow them to continue to increase their per capita energy consumption (even with growing populations) while reducing CO_2 emissions.

The problem is cost. Energy technologies that are more benign in terms of their emittance of CO_2 are generally more costly than those that are less benign. Hence, while it is in the interests of the developing countries to avoid the negative consequences of global warming by investing their own resources to combat the problem, they are likely to find it extremely difficult to justify diverting more of their respective economies' resources to pay for a given level of energy output using energy technologies that emit less CO_2 on a unit basis.

The issue is also one of relative environmental priorities. Developing countries currently face vast environmental problems other than those specifically related to global warming. These include inadequate supplies of clean water and sanitation facilities, water and air pollution (including indoor air pollution from the burning of biomass), as well as numerous environmental problems relating to land and habitat.[6] It is unlikely that developing countries can mobilize sufficient resources among themselves to substantially address all of these environmental concerns simultaneously; hence, only those environmental issues of highest priority to developing countries are likely to be dealt with using their own resources and it seems unlikely that reducing global warming will fall into the highest priority category for many developing countries.

As a consequence, if a significant reduction in world (and therefore developing country) CO_2 emissions is to be effected in the coming decades, a large share of the costs related to such a reduction will necessarily fall on the industrially developed nations. A key question is, thus, how much would various CO_2 reduction options cost?

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[6] World Bank, World Development Report, 1992.

In this paper, I consider the issue of the cost of reducing CO_2 emissions related to the energy sector—and the implications for the structure of the energy sector—in Colombia.[7] While there have been a number of attempts to estimate the costs of CO_2 reduction in various developed countries such as the United States, there appears to be a lack of similar studies for developing countries.[8] Given the major differences in the structure of developing countries and developed ones, it is difficult to assume that results obtained for the latter will necessarily apply to the former. The analysis is based on optimizations using a comprehensive mathematical programming model of Colombia's energy sector in conjunction with an econometric model of the sector. Section one outlines the empirical methods used to analyze the energy/environmental linkages in Colombia. Section two summarizes the simulated results.

Methodology

To analyze Colombia's energy sector and its effect on CO_2 emissions I combine two models—an econometric model of the nation's energy demands and a mixed-integer programming model of the nation's commercial energy supplies —to produce an integrated model that can be used to simulate the operation of the energy sector.[9] The econometric model includes coefficient estimates for all major energy products used commercially in Colombia, permitting the forecasting of energy demands by individual energy product. The mathematical programming model incorporates these coefficient estimates into a highly disaggregated presentation of the supply side of Colombia's energy sector. The supply side of the model comprises all of the major components of the nation's energy production, including all investments, production, and distribution necessary for the delivery of all major energy products to primary and secondary consumers.

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[7] The approach taken here does not evaluate the reduction of all CO_2 emissions in Colombia. It includes only emissions related to the commercial energy sector, which is by far the largest emitter of CO_2.

[8] A number of studies that attempt to quantify the costs of CO_2 reduction in developed countries are summarized in Wuebbles (1991) and Reilly (1991).

[9] For the complete specification of the integrated model, and its two major components, see Linden (1992).

Moreover, the supply side is treated in a highly disaggregated fashion; for example, coal mines, oil and gas fields, refineries, pipelines, and electric power infrastructure, are all treated at the individual project level or at a slightly more aggregated level.

To solve the model with constraints on CO_2 emissions required a two-stage process.[10] The first stage was:

Minimize f(**x**) [MIN1]

subject to **x** is in A

where:

f(**x**) is the total emissions of CO_2 during all of the time periods included in the model (twenty-one years);

x is a vector of activity levels that comprises all energy investments, production, and distribution ; it includes elements for each of the twenty-one years of the model; and

A is a set of constraints on **x** (they total approximately 10,500 in the basic formulation of the model, including the demand constraints that are generated by the coefficients of the econometric model).

In the second stage the CO_2 emission results that stem from the optimal solution to MIN1 were used to derive an additional set of constraints on the emission of CO_2 in the second minimization problem (MIN2):

Minimize g(**x**) [MIN2]

subject to **x** is in B

where:

[10] The model was run on a Sun Sparcstation II workstation. Solution times ranged from approximately 5 hours CPU time to approximately 18 hours.

g(**x**) is the total discounted cost of meeting the nation's energy demands during all of the time periods included in the model (twenty-one years);

x is a vector of activity levels that comprises all energy investments, production, and distribution ; it includes elements for each of the twenty-one years of the model; and

B is a superset of A that add restrictions on CO_2 emissions.

The integrated model provides a number of alternative ways of reducing CO_2 emissions. The use of fossil fuels to generate electric power can be replaced entirely with hydroelectric power. Natural gas can partially substitute for refined products and coal (natural gas emits substantially less CO_2 per BTU than do these alternatives). Electric automobiles and electric buses (like those already in use in Colombia's capital, Bogotá) can partially substitute for gasoline consumption and wood methanol can partially substitute for gasoline and diesel fuel. If managed properly, wood methanol, unlike methanol derived from natural gas or coal, does not lead to a net increase in CO_2 emissions when burned.[11] Finally, electric power can be partially substituted for refined products used by the industrial, commercial, and residential sectors.

To estimate the cost of various degrees of reduction in CO_2 emissions I ran twelve optimizations for the period 1990-2010 (with ceilings for CO_2 emissions imposed after 1995) using the integrated model (see figure 1).[12] The optimizations included six levels of reduction in CO_2 emissions: a 20 percent cut in emissions during the course of the fifteen-year period from 1996-2010; a 10 percent cut; a 0 percent cut (i.e. emissions allowed to remain at their 1995 levels throughout the period 1996-2010); a 5 percent increase; a 10 percent increase; and no reduction during the course of the fifteen years (i.e. no limits on CO_2 emissions imposed). These six

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[11] DeLuchi (1990) and Sperling and DeLuchi (1989).

[12] The complete optimization period was from 1990-2010, but CO_2 constraints were imposed beginning in 1996. I only began CO_2 emissions constraints in this year to allow greater flexibility in the assumed degree of substitutability among different fuel types as a consequence of projected trends in emerging technologies and to allow some lead time for construction of electric power plants.

constraints for CO_2 emissions were each paired with [a] a low-case and [b] a high-case scenario for domestic output of oil and gas and for world energy prices.[13]

Figure 1

Scenarios for Model Optimization

Scenario	Oil & Gas Production	World Energy Prices	Cut in CO_2 Emissions
1	Low	Low	- 20%
2	Low	Low	- 10%
3	Low	Low	- 0%
4	Low	Low	+ 5%
5	Low	Low	+ 10%
6	Low	Low	No limit
7	High	High	- 20%
8	High	High	- 10%
9	High	High	- 0%
10	High	High	+ 5%
11	High	High	+ 10%
12	High	High	No limit

Results

Direct Costs of CO_2 Emissions Reduction

As discussed earlier, a key element in the issue of reducing world emissions of carbon dioxide gas is cost. While there are a number of estimates of the cost of CO_2 reduction for the

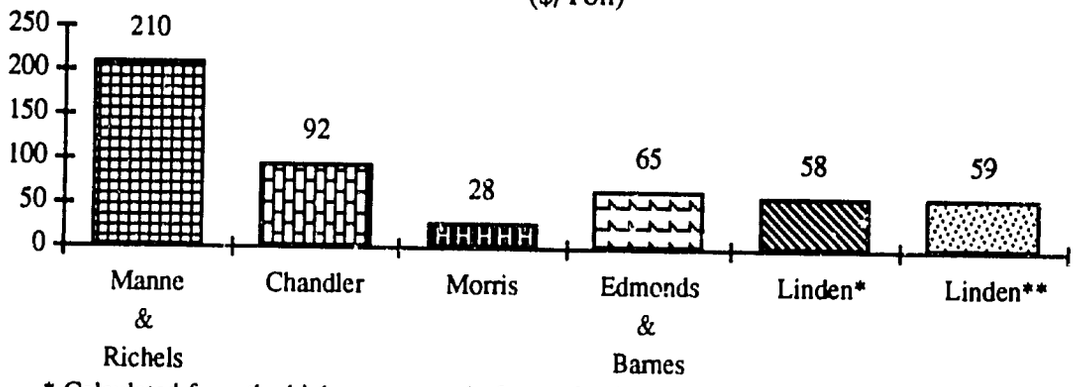
[13] The two sets of projections for oil and natural gas production came from the state oil company, Ecopetrol. For world energy prices, the low-case scenario assumes that world prices fall to their 1988 level in real terms—their lowest real level in the past two decades—while the high-case scenario assumes that energy prices rise gradually throughout the simulation period.

industrially developed countries, there is a notable gap in comparable studies for developing countries.[14] The optimization exercise undertaken offers a comprehensive estimate of the cost of adopting a CO_2 emissions-reduction program that can be compared with existing studies. The results could be used as an aid in the negotiation of an agreement between the industrially developed countries and the less-developed countries, that could cover both emissions-reduction targets and financial compensation to the LDCs. Given the enormous potential costs of reducing CO_2 emissions, it is important to set CO_2 targets that are economically realistic, and the results should offer some progress in this area.

The results suggest that the cost of CO_2 emissions reduction in Colombia should closely approximate the cost estimates for the United States and other industrially developed countries. Figures 2, 3, and 4 show the unit cost per ton of carbon removed for three levels of CO_2 reduction:

Figure 2

Unit Cost of CO_2 Emissions Reduction
Based on a 20% Reduction
($/Ton)[15]



* Calculated from the high-case scenario for production of domestic crude oil and natural gas and for world energy prices.

** Calculated from the low-case scenario for production of domestic crude oil and natural gas and for world energy prices.

Note: All estimates are in 1989 U.S. dollars. The Manne and Richels, Chandler, and Morris estimates are for the United States. The Edmonds and Barnes estimate is for the world.

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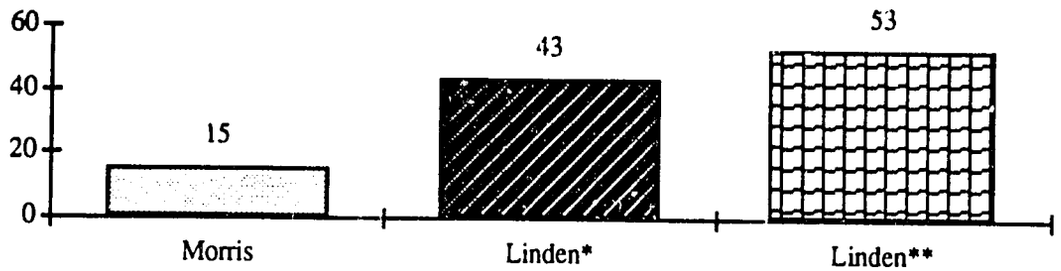
[14] Reilly (1991).

[15] All estimates other than Linden come from Wuebbles (1991).

20 percent, 10 percent, and 0 percent. In each case, I provide my results—under the two sets of assumptions for domestic energy prices and production levels—and compare them with previous studies of industrially developed countries.

Figure 3

Unit Cost of CO_2 Emissions Reduction
Based on a 10% Reduction
($/Ton)[16]



* Calculated from scenario that assumes high case for production of domestic crude oil and natural gas and high case for world energy prices.

** Calculated from scenario that assumes low case for production of domestic crude oil and natural gas and low case for world energy prices.

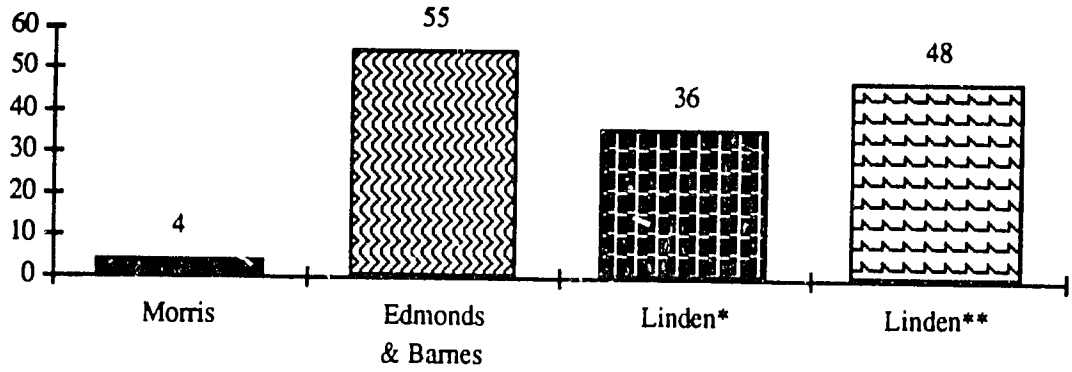
Note: All estimates are in US$ of 1989. The Morris estimate is for the United States.

As these figures show, my cost estimates are well within the range of previous estimates. In the case of a 20 percent cut in CO_2 emissions, my estimates ($58 and $59) are well above the figure obtained by Morris ($28), yet still far below the $210 figure found by Manne and Richels. In the case of a 10 percent reduction, the Morris study is the only one of the group that is directly comparable. The $15 figure Morris obtains is well below the $43 and $53 figures I obtain, but this is to be expected, given that the Morris estimate is the lowest one in the case of a 20 percent cut. In the case of a 0 percent cut in emissions, my results are again between the extremes found by existing studies.

[16] All estimates other than Linden come from Wuebbles (1991).

Figure 4

Unit Cost of CO_2 Emissions Reduction
Based on a 0% Reduction
($/Ton)[17]



* Calculated from scenario that assumes high case for production of domestic crude oil and natural gas and high case for world energy prices.

** Calculated from scenario that assumes low case for production of domestic crude oil and natural gas and low case for world energy prices.

Note: All estimates are in US$ of 1989. The Morris estimate is for the United States. The Edmonds and Barnes estimate is for the world.

While it is important to compare the unit costs of carbon removal in a developing country such as Colombia with those in the industrially developed countries, an even more relevant consideration is the total direct net cost of implementing various CO_2 reduction programs.[18] As mentioned previously, it is essential for countries such as Colombia to estimate—before beginning any CO_2 reduction program—the additional costs that such a program will entail. Figures 5 and 6 indicate the net costs to Colombia of various alternative CO_2 reduction programs under the production and price assumptions used previously.

[17] All estimates other than Linden come from Wuebbles (1991).

[18] Net direct costs in this study do not include any cost savings that may result from reduced climate change stemming from lower CO_2 emissions by Colombia.

Figure 5

Cost of Reducing CO_2 in Colombia
High Prices and Production Scenarios
($ 1989 Billions)

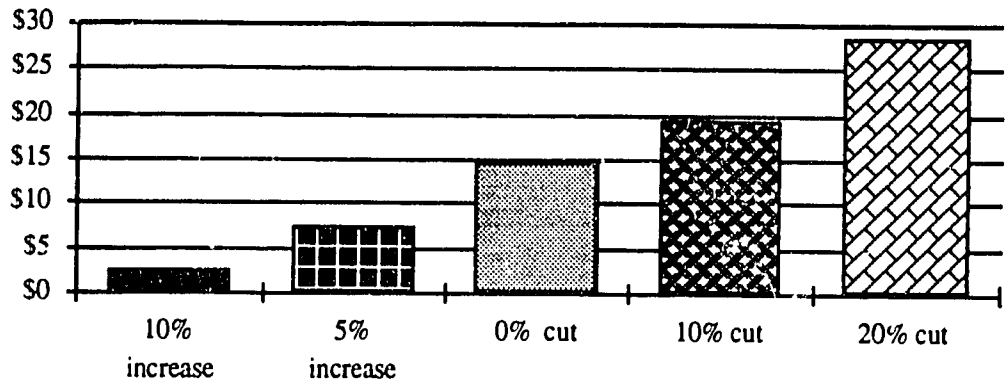
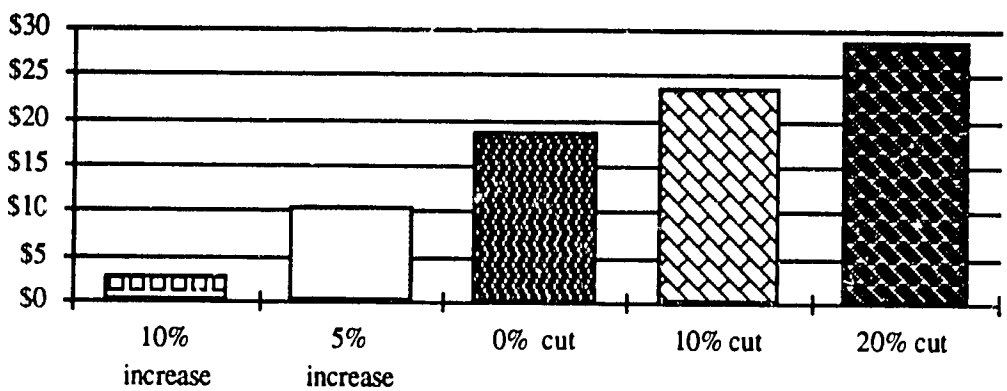


Figure 6

Cost of Reducing CO_2 in Colombia
Low Prices and Production Scenarios
($ 1989 Billions)

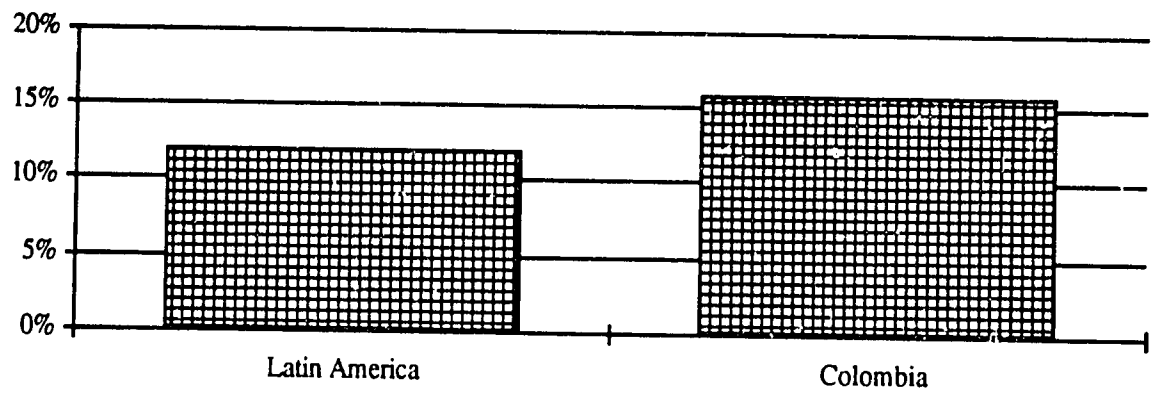


These figures indicate that any serious attempt to reduce CO_2 emissions in Colombia during the period 1996-2010 would be very costly. Merely maintaining CO_2 emissions at their 1995 levels until the year 2010 would cost approximately $15 to $19 billion during the course of the full optimization period. In an economy such as Colombia's, with a gross domestic product of under $50 billion, such an expenditure is probably not practical with the nation's own resources. To reduce emissions by 20 percent from their 1995 levels would cost substantially more, approximately $29 billion.

Since Colombia accounts for slightly over 6 percent of energy consumed in the Latin America and Caribbean region. this would imply that the cost to the entire region of a 20 percent CO_2 emissions reduction could easily approach $473 billion over the course of the twenty-one-year period.[19] This would imply an average of nearly $1.4 billion a year in spending for Colombia during the course of the twenty-one-year period and nearly $23 billion a year for the Latin America and Caribbean region as a whole. In the case of Colombia this annual expenditure would amount to the equivalent of 16 percent of its 1991 level of gross domestic investment or 15 percent of its 1991 export level each year for twenty-one years. For Latin America as a whole the cost would be 12 percent and 15 percent, respectively (see tables 7 and 8).

Figure 7

Annual Cost of Reducing CO_2 Emissions
by 20% over a 21-Year Period
(% of 1991's Gross Domestic Investment)

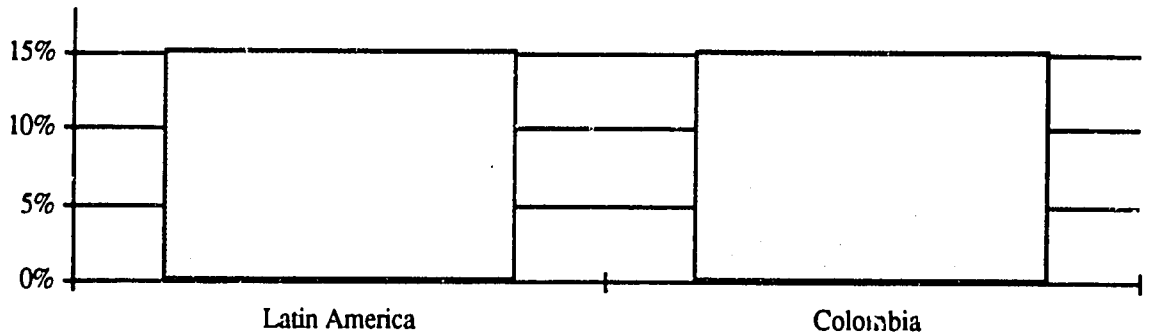


Given that the average change in gross domestic investment for the Latin American region was approximately -3.1 percent during the decade of the 1980s, there is little likelihood that countries in the region will be able to afford the expenditures needed to reduce CO_2 emissions by 20 percent.

[19] These costs are discounted costs expressed in 1989 dollars.

Figure 8

Annual Cost of Reducing CO_2 Emissions
by 20% over a 21-Year Period
(% of 1991's Exports of Goods and Services)



Moreover, the cost estimate probably significantly underestimates the true cost of a CO_2 reduction program for Latin America as a whole. Except for Brazil, Colombia has the largest potential for hydroelectric power generation in Latin America. Hence, other countries in the region that rely more heavily on fossil fuels to generate electric power and that have less potential to increase hydroelectric capacity may find it significantly more costly to achieve any given level of reduction in CO_2 emissions. They would need to convert either to nuclear power plants, which are far more costly than hydroelectric sources, or to the use of natural gas, which still emits nearly 50 percent as much CO_2 as coal per BTU used, or to convert to other costly alternative sources of producing electricity. This would probably also be the case for many developing countries in Africa and Asia.

Implications for the Structure of the Energy Sector

Electric Power Sector

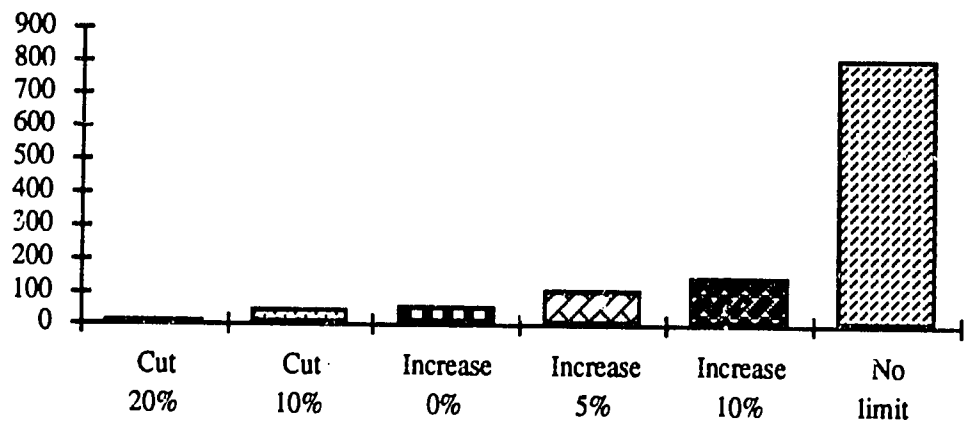
In addition to providing estimates of the cost of various scenarios for reducing CO_2 emissions, the results also depict the operation of the energy sector when CO_2 constraints are

imposed. One major effect of imposing constraints on CO_2 emissions occurs in the electric power sector. Given Colombia's abundance of hydroelectric generating potential, the country could eliminate the use of fossil fuels in generating electric power. Although this does not in fact occur under any of the scenarios, the amount of coal and gas used in power generation is far lower when CO_2 emissions are constrained than in the cases with no CO_2 constraints (see figures 9 and 10).

The dramatic differences between those scenarios that include CO_2 limits and those that do not are especially apparent when one considers the two scenarios with the most moderate CO_2 constraint (allowing CO_2 emissions to rise 10 percent in each three-year time period after 1995) with the two cases with no CO_2 limits (which represent an approximate 20 percent rise in CO_2 emission in each three-year time period after 1995). Total coal and gas used by the electric power sector in the latter cases is between five and seven times greater than it is in the former.

Figure 9

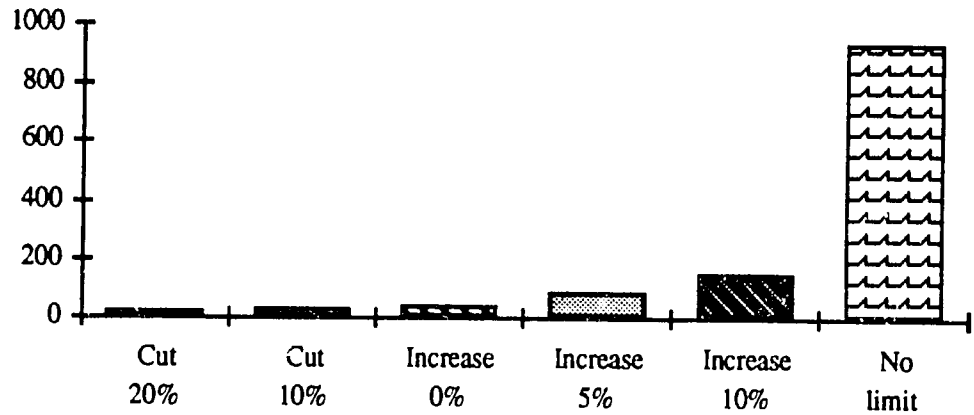
Coal and Gas Used in Power Generation
High Prices and Production Scenarios[20]
(Million MBTU)



[20] Calculation made for fuel used after 1995.

Figure 10

Coal and Gas Used in Power Generation
Low Prices and Production Scenarios[21]
(Million MBTU)



The dramatic drop in the levels of coal and gas used when any limits on the CO_2 emissions are imposed, shown in figures 9 and 10, suggests that substituting away from the use of these thermal sources in power generation is among the most cost-effective ways of reducing CO_2 emissions in Colombia. Consequently, it suggests that if Colombia decides to limit CO_2 emissions even in a very modest way it would be economically desirable to sharply reduce the aggregate use of coal and natural gas in generating electric power.

Of these two fuels, however, coal is the more cost-effective fuel to substitute away from in a CO_2 emissions reduction program. The distribution of the use of these fuels in power generation clearly emerges from the model solution and is presented in figures 11 and 12.

[21] Calculation made for fuel used after 1995.

Figure 11

Gas Percentage of Total Fuel Used in Power Generation
Low Prices and Production Scenarios[22]

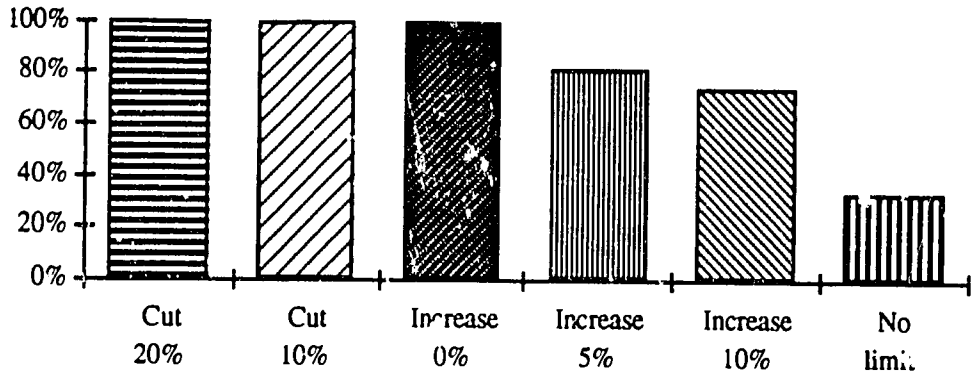
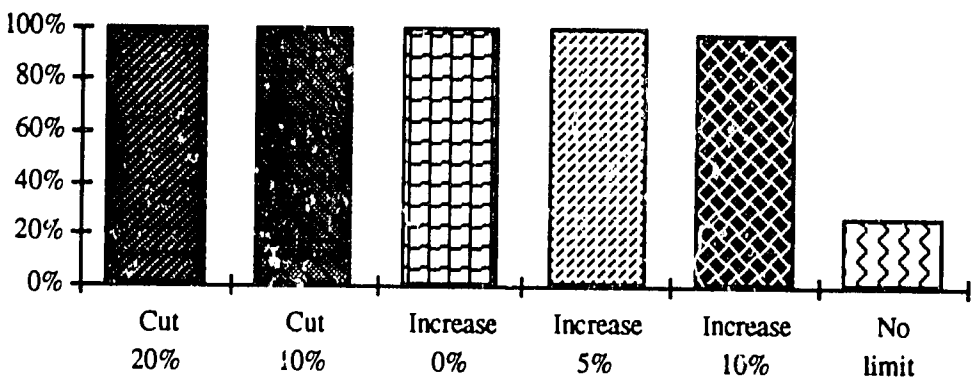


Figure 12

Gas Percentage of Total Fuel Used in Power Generation
High Prices and Production Scenarios[23]



As these figures indicate, there is a strong direct relationship between the severity of the CO_2 constraint imposed and the share of natural gas in total fuel used. The reason is straightforward: coal emits more than twice as much CO_2 per BTU as natural gas. Thus, even though both fuels are used far less when CO_2 constraints are imposed than when they are not, the use of coal is more severely affected than is natural gas. In fact, for the three most severe limits on CO_2 emissions, no coal is used at all by the electric power sector in either of the price/production scenarios.

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[22] Calculation made for fuel used after 1995.
[23] Calculation made for fuel used after 1995.

It is not surprising that a sharp increase in construction of hydroelectric plants occurs under all of the scenarios that cut CO_2 emissions. A somewhat surprising result, however, is that thermal electric plants continue to be constructed under all scenarios (combined-cycle natural gas plants on the Atlantic Coast and coal plants in the interior regions). Their comparatively low investment costs provide the most cost-effective way of meeting maximum quarterly power demand as well as the desired reserve capacity for the nation.[24]

Finally, the optimization results suggest that electric vehicles are an unattractive way to limit CO_2 emissions compared with the use of wood methanol. The capital cost of electric vehicles appears to be the critical factor. They cost substantially more than their gasoline counterparts, which would imply a costly subsidy by the government for the private sector. In addition, electricity is an expensive source of energy to run the vehicles (this is true even when electric automobiles are recharged during off-peak hours). In contrast, methanol vehicles are projected to cost little more than gasoline vehicles by the middle-1990s.[25] Consequently, even with the high cost of wood methanol (assumed to cost $80 per barrel),[26] it is a clearly superior choice from a least-cost perspective. This would change, however, if sales of electric automobiles were to rise sharply in the middle-1990s, forcing purchase prices to levels approximating those of gasoline-powered vehicles.[27] Nevertheless, the cost of electric buses is unlikely to fall significantly, and buses are a far larger consumer of gasoline in Colombia than are automobiles. Hence, the use of wood methanol rather than electric vehicles is likely to prove to be a more economically attractive way to reduce consumption of gasoline.

Refined Products and Natural Gas

The introduction of CO_2 constraints also would affect Colombia's refineries. The imposition of such constraints tends to promote imports of refined products rather than domestic

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[24] Practically no coal is burned when CO_2 emissions are constrained, however.
[25] Ivey, Buderi, and Therrien (1991).
[26] Sweeny (1990).
[27] I have seen no study that projects that this will happen, though.

production, as CO_2 is emitted in both the refining and consumption stages for domestically produced refined products while it is produced only in the latter stage when imports are used. The effect of this difference is not substantial in the case of existing refineries; the only significant difference is the increased use of natural gas as a refinery fuel instead of fuel oil.

CO_2 limits can have a major impact on construction of a new refinery, however. When the most severe CO_2 limits are imposed (a 20 percent reduction after 1995), a refinery is not constructed at all in the low-case scenario for production and prices, and a minirefinery is built under the high-case scenario (see figures 13 and 14).

More relaxed emission constraints also have a substantial impact, however, as even the most limited constraints lead to a sharp reduction in the size or even elimination of a new refinery.

Figure 13

Refinery Size
High Case for Production and Prices
(Thousands of Barrels per Day Capacity)

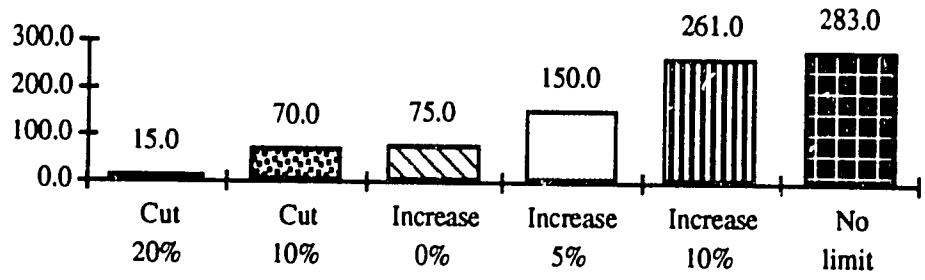
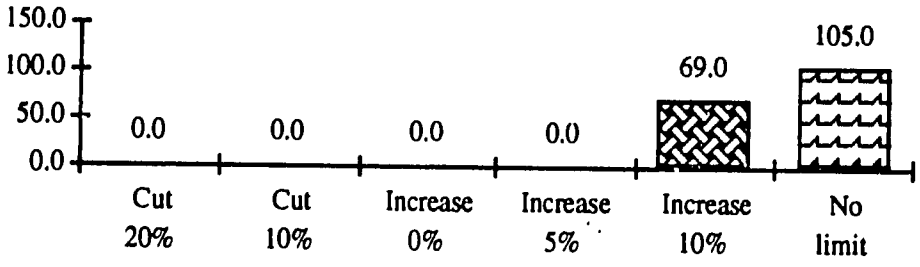


Figure 14

Refinery Size
Low Case for Production and Prices
(Thousands of Barrels per Day Refining Capacity)



Finally, domestic consumption of natural gas is also directly affected by the imposition of CO_2 constraints, both as a refinery fuel and to meet the greater demand in the interior of the country for natural gas to substitute for refined products that occurs as stricter CO_2 constraints are imposed.

Conclusion

The integrated optimization model I have developed is an ideal tool for use in analyzing the impact of programs that would reduce Colombia's emissions of CO_2 gases, and it could easily be modified to include emissions of other greenhouse gases such as nitrous oxide. The integrated structure of the model permits the use of CO_2 emissions constraints that apply simultaneously to the entire energy sector. This permits the model to choose an optimal least-cost approach to any program to reduce CO_2 emissions.

The model could also serve as a useful tool for a developing country such as Colombia in negotiating a program for reducing CO_2 emissions with the industrially developed countries in which, for example, the latter could contribute some share of the additional costs incurred by Colombia in adopting more benign CO_2-emitting energy technologies.

The most important conclusions that can be derived from the results of the optimization model are (1) the high costs associated with reducing CO_2 emissions and (2) the fact that Colombia's unit costs of emissions reduction appear to conform to the patterns established for the industrially developed countries.

These cost estimates beg the question, given the grave problems that the developing countries face today, would investment of billions of dollars by the industrially developed countries and the developing countries in the latter be the best use of those resources? In particular, it is important to consider the merit of investing billions of dollars in developing countries to combat global warming—and thus the economic and other problems that would likely result from such

warming—versus using these resources to meet the increasingly serious economic, social, and other environmental problems now facing those countries.

Finally, in addition to the economic cost implications of a CO_2 emissions reduction program, such a program would also imply substantial changes for the structure of Colombia's energy sector. The biggest losers under such a program would be domestic coal producers that produce for the internal market (such as coal-fired power plants). This industry, which provides employment to thousands of workers in labor-intensive operations in the interior of Colombia, would have to shrink dramatically in size. The biggest winners would be the natural gas industry and the hydroelectric component of the electric power industry. Of the two, the latter would be a potentially disturbing change. A substantial increase in the nation's dependence on hydroelectric power generation, while desirable from the standpoint of CO_2 emissions reduction, would further increase the country's vulnerability to conditions of drought that devastated the nation in 1992.

In sum, despite the attention global climate change has received as a result of such things as the 1992 Rio conference on the environment, careful analysis should be taken before a developing country such as Colombia begins a program to reduce CO_2 emissions. Nevertheless, as new energy technologies develop during the second half of the 1990s, such as more cost-effective solar power, wind power, and technologies that permit ever greater energy efficiency on the consumption side, the trade-offs suggested here related to a CO_2 reduction effort may be greatly reduced.

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