Planning for Future Uncertainties in Electric Power Generation: An Analysis of Transitional Strategies for Reduction of Carbon and Sulfur Emissions*

by

R.D. Tabors and Burt L. Monroe

MIT-CEPR 91-001WP **January 1991**

* Paper to be presented at the IEEE Power Engineering Society Winter Meeting, New York, NY, February 3-7, 1991.

PLANNING FOR FUTURE UNCERTAINTIES IN ELECTRIC POWER GENERATION: AN ANALYSIS OF TRANSITIONAL STRAGEGIES FOR REDUCTION OF CARBON AND SULFUR EMISSIONS

R D Tabors Member IEEE Burt L Monroe III
Massachusetts Institute of Technology
Program in Technology and Policy
and
Laboratory for Electromagnetic and Electronic Systems

Abstract - The objective of this paper is to identify strategies for the U S electric utility industry for reduction of both acid rain producing and global warming gasses The research used the EPRI Electric Generation Expansion Analysis System (EGEAS) utility optimization / simulation modeling structure and the EPRI developed regional utilities It focuses on the North East and East Central region of the U S Strategies identified were fuel switching -- predominantly between coal and natural gas, mandated emission limits and a carbon tax

The overall conclusions of the study are that using less (conservation) will always benefit Carbon Emissions but may or may not benefit Acid Rain emissions by the off setting forces of improved performance of new plant as opposed to reduced overall consumption of final product Results of the study are highly utility and regional demand specific The study showed, however that significant reductions in both acid rain and global warming gas production could be achieved with relatively small increases in the overall cost of production of electricity and that the current dispatch logics available to the utility control rooms were adequate to reschedule dispatch to meet these objectives

Introduction [1,2]

The electric power sector in the United States accounts for roughly one third of the country s annual emissions of CO_2 Worldwide, the electric power sector accounts for a lesser but rapidly growing percent of total Rain Emissions While the jury is still out on our ability to adapt to global warming, it is clear that utilities need to be cognizant of their alternatives should further emission reductions be mandated, or should they choose voluntarily to reduce emissions below mandated levels. As a long run strategy for CO_2 reduction it is probably the case that electricity generation will need to focus on either non carbon based fuels such as nuclear energy or solar energy, or possibly on recycled carbon such as from biomass.

While the ultimate solution in all likelihood lies in new technologies, there is a need to understand the potential for existing technologies and/or evolved technologies to significantly reduce emissions over the next decade or two[3] It is important to ask:

What are the relative roles of electricity generation technologies and end-use technologies in serving the demand for electricity-related services?

What current generation technologies could be effectively employed to reduce CO_2 emissions if cost per kWh were not the primary objective?

What are the tradeoffs between cost and emission levels possible with existing technologies?

What combinations of technological changes (fuel switching and increased efficiency for instance) could provide the greatest improvements in emission reduction with the lowest total cost?

91 WM 008-3 PWRS A paper recommended and approved by the IEEE Power System Engineering Committee of the IEEE Power Engineering Society for presentation at the IEEE/PES 1991 Winter Meeting, New York, New York, February 3-7, 1991. Manuscript submitted September 4, 1990; made available for printing November 30, 1990.

What technological alternatives could be seen to provide the most robust transitions to what we are now discussing as the long term near zero net emission technologies?

Realities of the Electric Power System

The objective of this paper is to evaluate a range of transitional technologies that could play a major role in the reduction of CO_2 in the near term and also reduction or change in SO_2 The paper focuses on fossil and nuclear based generation technologies and load reduction (conservation) as likely short run alternatives It evaluates a set of strategies available for achieving the change in operating behavior of the electric industry ranging from a carbon tax to environmental dispatch modification The units of comparison presented are cost of generation and absolute volumes of greenhouse gases and acid rain emissions

The study is based on evaluation of the operating characteristics of the electric utility system, not upon simple technology substitution System operation is simulated to capture the dispatch effects of changes in both technology and input prices. While it is often convenient to think of "changing out" an oil or coal steam unit for a natural gas fired unit in reality, the old and new coexist on the system with the new fuel efficient (and less environmentally degrading) facility appearing lower in the loading order The question is how much lower in the order and to what overall effect on the operation of the system?

A significant underlying hypothesis of this effort is that because of the current structure of the utility system in the United States, there are regions in which it may be possible to reduce the emissions with little if any increase in average cost of energy delivered to the end user This occurs because of increased efficiency of power production and an increase in the ratio of hydrogen to carbon in the fuel In a transitional time frame countervailing forces are at work. Demand reduction minimizes consumption but reduces the need to change over to newer, more fuel efficient technologies.

This can be best illustrated through an examination of the "pollution equation" often used in the global warming debate[4] This equation states that carbon emissions from electric power are determined as follows

$$Carbon=\left(\frac{C}{GWH}\right)\times\left(\frac{GWH}{GNP}\right)\times\left(\frac{GNP}{Population}\right)\times(Population)$$

where

C/GWH is "marginal carbon emissions"[5],

GWH/GNP is "energy intensity", and

GNP/Population is a measure of standard of living.

This equation is often used to point out the futility of emissions abatement strategies, given likely increases in population and the desire for increases in standards of living. It is possible, however, that the present value of the energy intensity term is much larger than technologically or economically necessary – implying potential for reductions through end-use efficiency and conservation measures. The marginal carbon emissions term is infinitely larger than technologically necessary. Not only can the marginal carbon emissions term be reduced, but it can be lowered to zero through the use of non-fossil fuel sources such as nuclear or solar[6] A more detailed examination of marginal carbon emissions can provide insights into the effectiveness of various strategies for reducing emissions

Let us disaggregate the marginal carbon emissions term, examining the carbon emitted over any particular time period in a particular electric power system. The system emissions are the sum of emissions from each individual technology type:

$$\frac{C}{GWH_{sys}} = \sum_{i=1}^{N} \left[\left(\frac{C}{GWH}\right) \times \left(\frac{GWH_i}{GWH_{sys}}\right) \right]$$

where

N = Total number of technologies within the system

GWH = Energy generation of technology i and

GWH_{sys} = Total energy generation of the system

The importance of the (GWH_i / GWH_{sys}) term, which represents the percentage of the total system energy which is derived from any particular technology, is evident. If the level of utilization of a technology is low, a low (C / GWH) term will not have much effect on overall system emissions. The level of utilization of a particular technology is a complex function of the system capacity mix, the system reserve margin, the outage rates of all technologies, the character of system demand, and the relative marginal costs of various technologies. In general, the generating units with the lowest marginal cost are dispatched first (if available), followed by more expensive units until system demand is met. In this way, the costs of electricity generation (given any particular capacity mix) are minimized. Since such factors as demand, unit availability, and fuel prices vary continually, calculating such outputs as generation costs and environmental emissions is a nontrivial task, even when the values of the input variables are known. Of particular note is the fact that the relationship between capacity and generation is highly nonlinear (for instance, a system with 40% coal capacity might generate 70% of its energy from coal). More detailed examination of these factors is included within the modeling efforts described below, but is beyond the scope of this discussion.

It can be noted, however, that change of these factors is traditionally driven by shifts in the relative costs of technologies and by load growth or plant retirement, which facilitate the construction of new capacity. Additional changes can be driven by artificially changing the costs of various technologies (taxes, changes in dispatch rules) or by artificially inducing changes in capacity mix (early retirement of existing plants). Load reduction, while reducing the (GWH / GNP) term of the original equation, can suppress changes in the system which might otherwise occur. The balance of these two factors may not be easily predictable.

How low can the (C / GWH) term be? As stated previously, for many non-fossil technologies, such as nuclear, hydroelectric, or solar, the marginal carbon emissions are zero. For those technologies which utilize an input fuel, the (C / GWH_i) term can be expressed:

$$\left(\frac{C}{GWH_i}\right) = \left(\frac{C}{MMBTU_i}\right) \times \left(\frac{MMBTU_i}{GWH_i}\right)$$

where

$MMBTU_i$ = the amount of energy contained in fuel i[8], and

M MBTU / GWH_i = the heat rate of technology i[9].

The C/MMBTU of a fuel is a function of carbon-hydrogen ratios within the fuel, with coal having the highest value (~ 0.03 tons C/MMBTU), followed generally by oil (~ 0.022) and natural gas (~ 0.017)[10]. When contemplating a "fuel switching" strategy, however, one must also account for the efficiency (or heat rate) of the technology which utilizes the fuel. In general this leads to carbon efficiencies in the range of 250-400 tons C per GWH for conventional coal technology, the range resulting from a mix of inefficient older plants and more efficient newer plants. Existing oil capacity has typical values in the range of 200-300 tons C per GWH, with natural gas in the range 175-225 tons C per GWH. Relative to existing coal, new combined-cycle fossil fuel plants can have improvements on the order of 10% (gasified coal), 30% (oil) or 50% (natural gas). Note that sulfur scrubber retrofits raise this value by approximately 10% due to loss of efficiency.

In general, then, it can be stated that the most effective strategies will be those which strike an optimum balance between the displacement of high-emission generation with low-emission generation and load reduction. Closely related to this argument is its corollary that, given the economic/financial structure of the U.S. electric power system and its present operating rules, some policy options will achieve the desired greenhouse gas emission reduction objectives more cost effectively than will others. Given the logic of today's dispatch centers, options which change the relative prices of inputs — fuels, for instance — can easily be incorporated while those that change the basic rules (dispatch according to emissions instead of costs) are far more difficult and costly as, in the short run, they would require the basic reprogramming of the dispatch centers themselves.

The Methodology

Within the U.S. electric utility industry there are models and data bases that have been legitimized by their industry acceptance. By using these accepted tools, discussions can focus on inputs and outputs of the analytic exercise rather than on uncertainties about model structure. This is a non-trivial concern which has limited the usefulness of many previous modeling efforts. These have typically been so large in their scope that actual system structure is buried in many levels of assumed aggregation, causing debate to focus on assumptions rather than on results[11]. Given this concern, this study utilized the Electric Power Research Institute's Electric Generation Expansion Analysis System (EGEAS) modeling system, the EPRI Regional Systems (ERS) Database, and the EPRI Technology Assessment Guide (TAG) in order to conduct a structurally detailed analysis of CO_2 / electric power interactions in a few geographic regions over a limited time frame.

The Model

MIT and Stone and Webster Engineering Corporation developed the Electric Generation Expansion Analysis System (EGEAS) for EPRI in the early 1980s and it is now in use at over 100 utilities in the U.S. and abroad[12]. The EGEAS user provides the model with information about the individual plants within an electric power system and potential alternatives for future capacity expansion. Among these data are size and age of plants, performance data (heat rates, forced outage rates, etc.), capital costs, operating costs, fuel use, environmental characteristics, and financial data. Data about external factors, such as fuel prices and inflation rates, are also provided. EGEAS can then be used to determine cost-optimal plans for future capacity expansion[13] and to simulate the system operation over time. The modeling outputs — production costs, environmental emissions, fuel use, etc. — are reasonably accurate due to a sophisticated production costing algorithm within EGEAS, which accounts for many power system subtleties without the prohibitive computational requirements of chronological models.

The Database

Because the U.S. utility system is effectively fully interconnected, isolating one utility or even one actual region for analysis is a major task. During the period of the so-called energy crises, EPRI began the development of a set of synthetic regional utility data bases which could be used for technology and policy analyses. The current version of the EPRI Regional Systems (ERS) database[14] is being used in this study in order to be able to present results based on system data that are accepted by those in the industry. This analysis covers the North East region of the United States which includes New England, New York, New Jersey, Delaware, eastern Maryland, and eastern Pennsylvania, and the East Central region of the United States which includes the heavy coal burning region of Indiana, Ohio, West Virginia, Kentucky, lower Michigan, western Pennsylvania, western Maryland, and western Virginia.

Uncertainties

The primary uncertainties considered within the study were fuel price and load growth An attempt was made to choose a set of possible futures which would provide a reasonable resolution with which to view possible outcomes without prohibitively increasing computational requirements Two fuel price trajectories – base and high – and four load growth trajectories – low base high and very high – were selected Each possible pair of these uncertainties constitutes a future[15] The base fuel price was taken from Data Resources Institute (DRI) forecasts[16] and adjusted regionally according to guidelines in the EPRI Technology Assessment Guide (TAG)[17] The high fuel price uncertainty represented significantly higher prices for both oil and gas The base load growth uncertainties were taken from the ERS[18] Low growth uncertainties were 1% lower than the relevant base growth high growth 1% higher very high growth 3% higher

Technology Options

The generation technology options were taken from the TAG These included

Number of technologies evaluated

• Coal	28
• Liquid and Gas	15
• Nuclear	3

The analysis did not include evaluation of non-dispatchable options such as solar and wind[19] and did not include the addition of storage technologies Those options which appeared in the optimal pathway (a small subset of those considered) for either region or both were

	Size MW	Cost $/KW	Ht Rt BTU/ /kWh	MCE Tons C /GWH
Plv Coal w/scrb	500	1281	9700	300
IGCC	800	467	9000	257
Adv CT, oil-frd	140	385	11100	257
Adv CT, gas-frd	140	373	11500	200
Adv GTCC, oil	210	531	7360	174
Adv GTCC, gas	210	518	7514	130
Adv LWR	1200	1524	10220	0

<u>Strategies</u>

The study defined seven policy strategies for analysis. These are:

Base For each future an optimal (cost-minimizing) 25 year expansion plan was developed based on the regionally and technically available expansion alternatives. In most cases, the optimal plan involved early construction of natural gas-fired combined cycle (GTCC) plants with an eventual switch to integrated gasifier combined cycle (IGCC) plants[20] Oil-fired combined cycle was occasionally superior to natural gas in high fuel price futures. Some high growth futures also led to the construction of combustion turbines fired either by natural gas or oil. Nuclear was not an option in the base strategy. Early plant retirement was also not a possibility

Nuclear (NUC): The nuclear strategy differed from the base in that nuclear options were offered as the only available baseload capacity option (coal options were removed) in the optimization runs. In the North East, the nuclear option was marginally more economical than the IGCC option, while marginally less so in the East Central. Capacity expansion followed similar trajectories with coal options generally substituted by nuclear while the role of the GTCC remained roughly the same

No Nuclear No Coal (NNNC) In this strategy, the system was forced to choose only natural gas and oil based technologies, thus forcing GTCC and CT technologies

Dispatch Modifier (DM) The optimal expansion pathway of the Base strategy was used to define the plant additions. The units were then operated according to carbon emissions instead of marginal cost.

Early Retirement (ER) For all coal plants the existing operating life was reduced by 10 years (generally from 50 to 40) This required a substantial increase in construction, particularly in the early years and specifically in the coal dependent East Central region

Carbon Tax (CT) A substantial tax on the use of fossil fuels was assumed based on carbon content ($5 70/GJ for coal $2 30 GJ for oil and $1 10/ GJ for natural gas)[21] Capacity expansion patterns similar to the base strategy were observed with the exception that fuel switches from natural gas to oil or coal occurred later in the planning horizon

Conservation No attempt was made to explicitly model conservation efforts For each region however four possible load growth paths were defined and simulated separately in order to determine what benefits if any might be obtained through switches from high growth futures to low growth futures

<u>Optimization and Simulation</u>

Within each study region each possible combination of a future and strategy constitutes a "scenario" For each scenario EGEAS defined an optimal expansion path, or timetable of technology choice over a 25 year study period[22] The simulation was then run providing various output attributes which could then be used for strategy evaluation The primary output attributes of interest for this discussion are the costs and environmental emissions in each scenario These included

Cost

- Total discounted cost
- Annual costs in 1988 dollars

Annual Emissions

- Carbon, SO_2, NO_x, TSP, Methane, and N2O

<u>Results</u>

The results are divided into two sections and are based on the included figures. The first is a summary of the environmental performance of each strategy relative to total discounted cost The second is a summary of the general conclusions of the study with regard to the underlying technological characteristics that determine the success of individual strategies.

Strategy Performance:

The first set of figures (Figures 1-1, 1-2, and 1-3) presents trade-off data for the North East region in which each strategy is graphed for two attributes of primary concern for a single future (one combination of demand growth rate and fuel price increase) – the base case. Each figure represents the tradeoff between two attributes, chosen from carbon emissions, sulfur dioxide emissions, and cost Emissions numbers represent total emissions over the twenty-five year study period. Costs are total net present value of system costs as faced by the utility[23] For any particular graph, larger values on either axis are undesirable That is, the most desirable position for any particular strategy is in the lower left corner (approaching zero emissions and zero cost). Strategies which dominate other strategies – strategies which have no other strategies both to the left of and below them – represent the optimum choices for those two attributes. Figure 1-1 illustrates the tradeoff between carbon emissions and costs. The nuclear strategy is dominant over all other strategies for these two attributes, given the assumptions of the study Figure 1-2 illustrates the tradeoff between sulfur dioxide and costs. Of note here is that only the carbon tax and base strategies have clearly dominated positions – that is, for each of these two strategies, there is at least one other strategy which is superior in both attributes. Finally, the tradeoff between the two environmental attributes, and the clear dominance over the base strategy by all other strategies, is shown in Figure 1-3

The second set of figures depicts the trajectories of carbon emissions over time for each strategy, again in the base case. Figure 2-1 shows the North East region and Figure 2-2 shows the East Central region Differences in effectiveness across the two regions are apparent

Base: The base strategy results in rapid increases in the emissions of carbon dioxide and total-suspended particulates (TSP), due to the

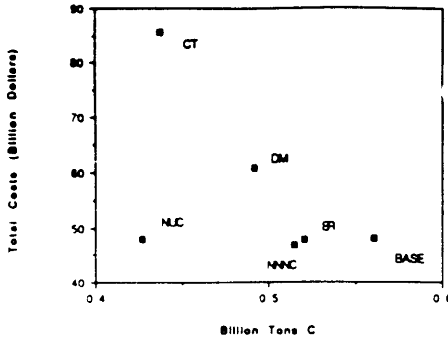

Figure 1-1. Carbon vs cost (NE—base future)

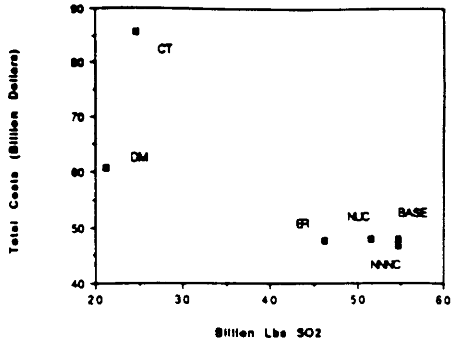

Figure 1-2. SO_2 vs cost (NE—base future)

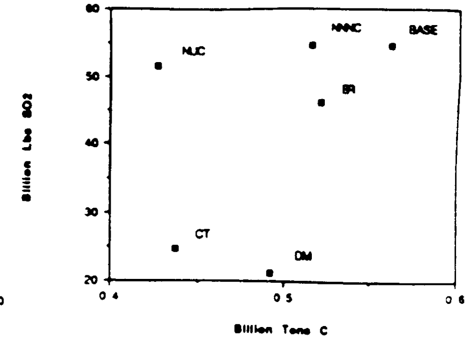

Figure 1-3. Carbon vs SO_2 (NE—base future)

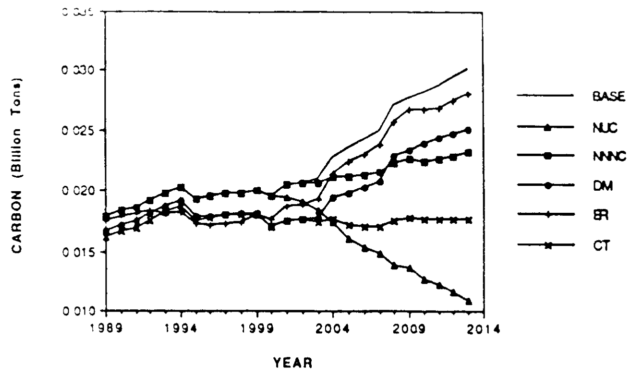

Figure 2-1. Northeast base case carbon emissions by strategy

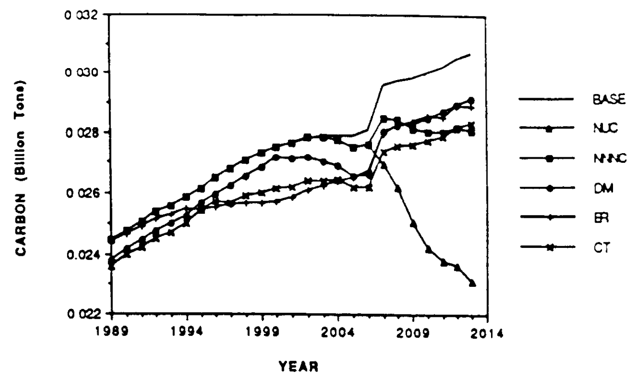

Figure 2-2. East central base case carbon emissions by strategy

continued use of coal-fired units. Since new baseload units are IGCCs, however, some reduction in the levels of acid rain emissions, sulfur dioxide and nitrogen oxides, is realized. This is illustrated in Figures 3-1 (North East) and 3-2 (East Central), with each environmental emission shown relative to its 1989 level.

Nuclear. Based on the EPRI capital cost numbers used in this study, nuclear has a set of obvious advantages. While maintaining costs at or below the level of the base strategy, nuclear results in significant decreases in all atmospheric emissions. Carbon emissions decrease both relative to the base strategy and in absolute terms, while acid rain emissions (SO_2 and NO_x) are similar to those in the base strategy[24]. It is the only strategy which reduces all emissions in both regions regardless of the rate of growth in demand. This reduction is shown in Figure 4 and is particularly dramatic in comparison to the base strategy shown above in Figure 3-1. The issues of nuclear waste and nuclear safety were not, however, taken into account. Similarly the capital costs appear to be optimistic given recent experience, and social acceptability is still the major issue.

No Nuclear No Coal: This options results in modest environmental gains at approximately the same cost as the base strategy. This is best illustrated in Figure 1-1, where the NNNC option is seen to improve the level of carbon emissions at essentially no cost. The natural gas dependent expansion path, however, creates reliability problems in later years of the study, particularly at higher growth rates[25]. This is more pronounced in the East Central region than in the North East due to the current mix of technology. It is unclear that the level of gas implied in this strategy can be made available to the electric utility industry. It is also critical to note th :he costs presented do not assume any increase associated with increased demand for natural gas. The basic structure of the strategy would not change but the total cost would increase as a function of increasing gas prices.

Dispatch Modifier. The dispatch modifier approach, as modelled, is very attractive for all emissions. As would be expected, carbon reductions are significant in all futures, relative to the base strategy. In several futures, the dispatch modifier approach is among the most effective in reduction of SO_2. This is seen below in Figure 5, which depicts North East SO_2 emissions over time for each strategy in the base case. These gains come at significant cost in the North East region, which can be seen in the tradeoff curves of Figure 1. Because of the capacity mix in the North East, there are many relatively expensive units which are run for increased periods under this strategy, while the more economically efficient coal units are bumped in the loading order. In the East Central region, however, the cost impacts and environmental impacts are minimal. The tradeoffs for the East Central region base case, and the minimal cost impact of the dispatch modifier strategy, are shown below in Figures 6-1, 6-2, and 6-3. Because the system is dominated by coal, the dispatch modifier does not cause significant change in the loading order, but does allow for some improvements in emissions through the use of limited natural gas capacity. It must be remembered that this option is not optimized with respect to the

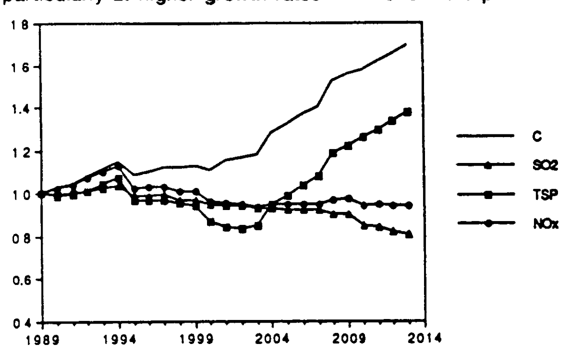

Figure 3-1. Northeast base strategy normalized emissions

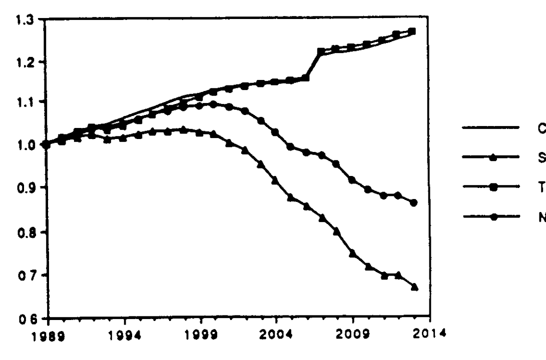

Figure 3-2. East central base strategy normalized emissions

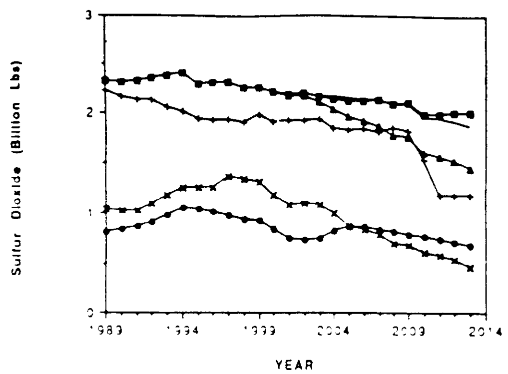

Figure 4 Northeast nuclear strategy normalized emissions

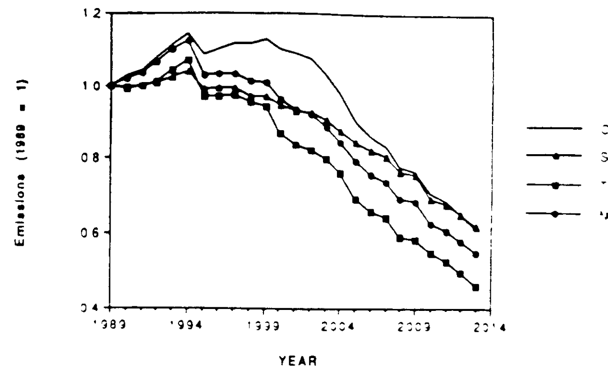

Figure 5 Northeast base case sulfur dioxide emissions by strategy

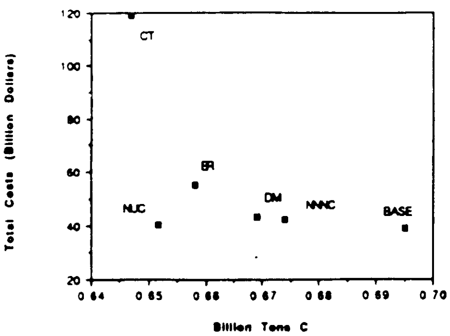

Figure 6-1 Carbon vs cost (EC—base future)

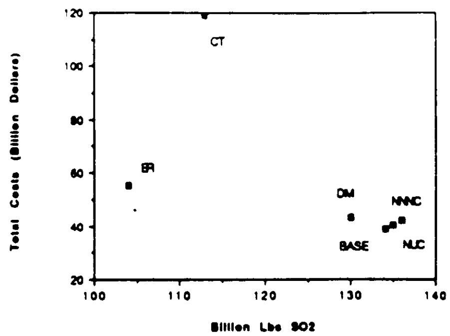

Figure 6-2. SO_2 vs cost (EC—base future)

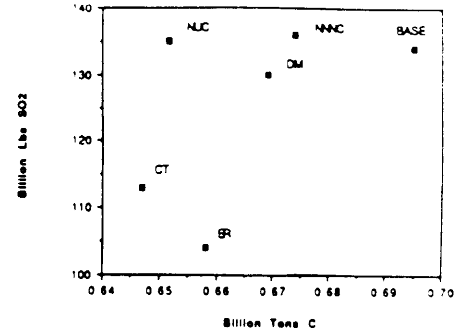

Figure 6-3. Carbon vs SO_2 (EC—base future)

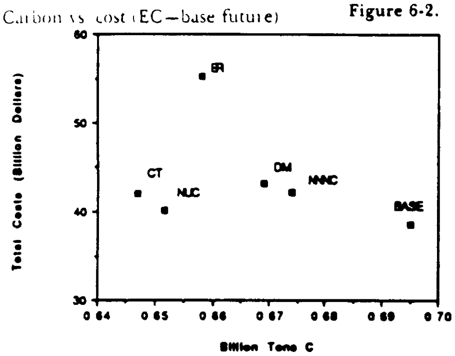

Figure 6-4. Carbon vs net societal cost (EC—base future)

carbon emissions but is, rather, the optimized base strategy generation mix dispatched under a least emissions criteria. For this strategy to be evaluated thoroughly, an emission minimization algorithm must be substituted for the cost minimization algorithm. This would then create an environmentally optimal plan as opposed to an economically optimal plan as the starting point of the analysis of any given future. Such a strategy may provide a useful operating rule for the short run in the transition but not for the long run (due to economic disincentives against investment in the construction of high marginal cost, low-emission capacity).

Early Retirement: The value of the early retirement option varies regionally and with the load growth of the system. Under all but the highest of the modelled growth scenarios in the North East, early retirement is the only option which dominates the base strategy in all measures. That is, early retirement of coal capacity leads to a reduction in emissions with a cost savings. These gains are due to the displacement of inefficient, more polluting capacity with efficient, cleaner technologies. They are felt more in the beginning of the study period than in the end. As load growth increases the need for new coal capacity in early years becomes greater, until the point at which the potential for carbon gains is no longer present. The migration of the early retirement option can be noted in the carbon-cost tradeoffs of Figures 7-1, 7-2 and 7-3, which show the desirability of the option in the low growth case (7-1) and its ineffectiveness in the very high growth scenario (7-3), where even the base strategy has better attributes. Early retirement is environmentally attractive in the East Central region but carries a greater cost penalty due to the magnitude of the retired capacity in the early years of the study While in the North East base case, early retirement has similar costs to the base strategy, early retirement in the East Central results in an increase in total costs over the base strategy of approximately 20% (See Figure 5 1) These results imply that early retirement may be a very attractive option if applied in conjunction with aggressive load management, allowing for an acceleration of the environmental gains offered by the transition

Carbon Tax. The carbon tax is consistently the highest cost alternative, as would be expected. It should be noted, however, that this is in reality a distributional effect, since this alternative provides significant revenues which are available for other purposes or which might in some way be returned to electricity consumers. For instance in the base case of the East Central region, the total net present value of the costs of electricity generation under the carbon tax strategy is $119 billion Over this time period, however, a total tax revenue of $77 billion was created. The costs of the strategy to society as a whole are actually $42 billion less than 10% more than the base strategy Figure 6-4 illustrates the change in the original tradeoff curve (Figure 6-1) which results if net costs to society are plotted instead of utility costs. When viewed from this perspective, the carbon tax is much more attractive

The environmental effects of the tax are substantial This strategy allows for very high levels of sulfur dioxide reduction (see Figure 5) and for a stabilization of carbon emissions[26] in many futures (for an example, see Figure 2-1). It is the only non-nuclear case which is fairly robust in this regard. The strategy, as with several others, creates a strong incentive for the use of natural gas, while also creating strong incentives for quicker introduction of post-transition non-fossil alternatives. The disadvantages of the strategy clearly lie in the unknown social impacts of such drastic economic measures. It should be noted that this strategy also creates an incentive for demand reduction[27], an effect unaccounted for within this formulation. The price elasticity of demand is negative, meaning that demand will decrease with the increase in energy cost, but the current formulation is equivalent to an assumption that this elasticity is zero This demand reduction would certainly cause the costs faced by the utility to be lower than stated and would probably lower emissions as well.

Conservation: This strategy was not modelled explicitly as a policy option as were the previous six. By examining the effects of variations in load growth on various strategies, however, we can identify those strategies in which load reduction is desirable. It is assumed that some load reduction can be obtained at some cost, but attempts to explicitly determine such costs have not been made. The environmental effects of conservation depend strongly on both the characteristics of the existing generation system and the characteristics of expansion alternatives Clearly, with any given supply system, conservation reduces the emissions

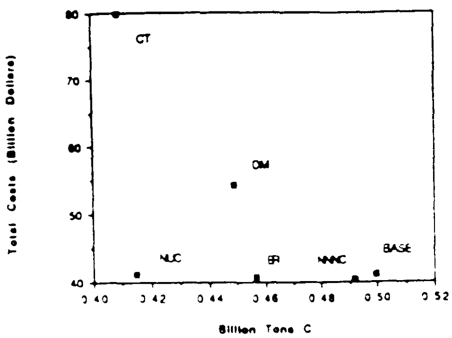

Figure 7-1 Carbon vs cost NE—low growth

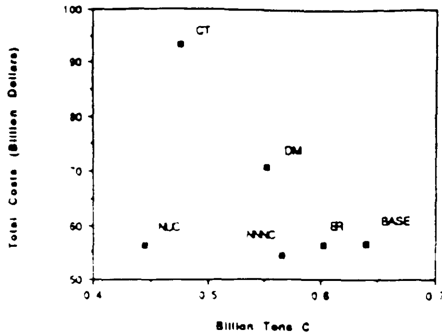

Figure 7-2 [illegible] cost NE—high growth

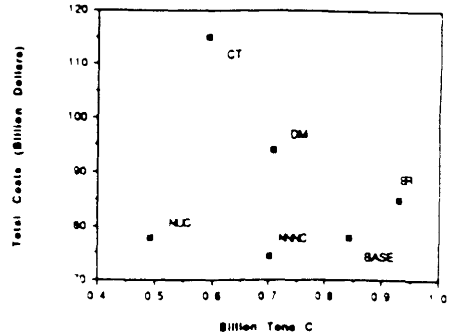

Figure 7-3 Carbon [illegible] NE—[illegible]

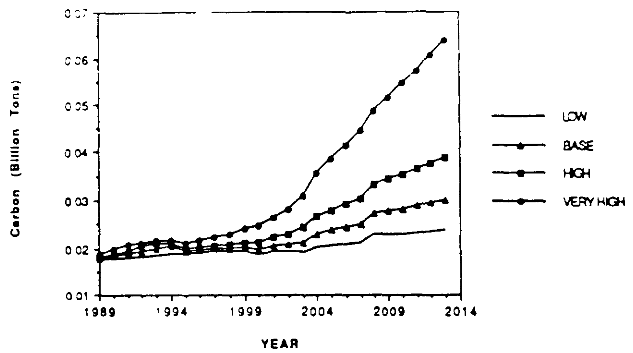

Figure 8-1 Northeast base strategy carbon emissions by growth rate

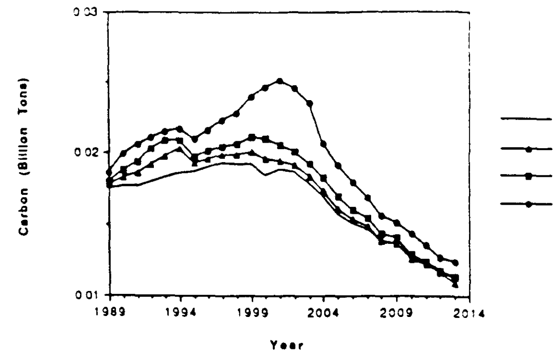

Figure 8-2. Northeast nuclear strategy carbon emissions by growth rate

of all types from that system What conservation also does, however, is reduce the need to change the system through the addition of new capacity If this new capacity would have lower emissions than the existing capacity it would displace (as is almost always the case), an increase in emissions due to the continued or expanded use of existing capacity can be the result of conservation It is the relative weighting of these two factors which determines the overall effect of conservation Therefore, the effects of a shift from a high growth future to a low growth future may or may not be desirable For example, with the implementation of the base strategy in the North East, increases in load growth clearly increase carbon emissions, as shown in Figure 8-1 Figure 8-2 illustrates that the positive effects of conservation are not so clear in the nuclear case, particularly in the later years of the study period

Underlying Technological Characteristics of Successful Strategies:

The somewhat counterintuitive effects of conservation deserve further examination Due to the differing environmental characteristics of various expansion alternatives, the effects of conservation are different depending on which emissions are of concern. In order for the effect of an expansion alternative to be great enough to offset conservation savings, it must have significantly lower emissions and displace a significant portion of the original high-emission capacity. In the case of carbon emissions, only two existing alternatives accomplish this goal: nuclear and gas-fired combined cycle. The nuclear alternative not only has zero emissions, but its ability to operate economically at baseload allows it to displace large amounts of generation from original capacity. (Problems with this option, however, are substantial, as previously discussed.) The gas-fired GTCC option has lower emissions than typical coal capacity (by about 50%), but significant operation at baseload is costly and possibly infeasible due to natural gas resource limitations

In the case of acid rain emissions, SO_2 and NO_x, an additional alternative is available: IGCCs. The ease with which this option displaces original coal capacity and its favorable environmental characteristics make this a highly economical option for reduction of these emissions Conservation can delay the construction of new IGCC and GTCC capacity, actually causing SO_2 and NO_x emissions to increase over what might otherwise be possible

What then, are the implications for technology choice? If your concern is carbon emissions, then the use of coal burning base load and residual oil burning intermediate load must be avoided. The most effective measures, without regard for resource or cost constraints, would then be the following measures, in rough order of importance

- Increased use of zero-carbon baseload
  Nuclear, hydroelectric, and non-fossil renewables

- Increased use of low-carbon baseload
  Gas-fired GTCC (forced baseload)

- Reduced demand
  Assumes demand reductions are on the same order as load growth
  More substantial reductions could move this higher in list

- Increased use of decreased-carbon intermediate / peaking load or higher efficiency baseload
  Unforced GTCCs or IGCCs. The effects of these are different but both small compared to above actions

If your concern is acid rain emissions, the following measures are most effective (again in the absence of resource or cost constraints) for avoiding the use of high-emission capacity – uncontrolled coal baseload and uncontrolled residual oil intermediate load:

- Increased use of zero- or low-sulfur baseload
  Nuclear, hydroelectric, non-fossil renewables, forced GTCCs, pulverized coal with scrubbers, IGCCs. The natural baseload operation of the "clean coal" technologies makes SO_2 emissions a much more tractable problem than CO_2.

- Reduced demand

- Increased use of low-sulfur intermediate and peaking load
  Gas- and oil-fired GTCCs.

Note that the cost-effectiveness issue is very important. The technologies best suited for emissions reduction by their technological characteristics may not necessarily provide the most cost-effective means of reduction. The uncertainties about nuclear power and the constraints on widespread natural gas use are clear examples of this. It should also be noted that while conservation may indeed be the most cost effective method of emissions reduction at the margin, there is a finite limit to the amount of conservation which can be accomplished in the long term.

The various policy strategies which have been modelled accomplish these tasks with varying effectiveness The nuclear option is particularly effective because it accomplishes the most significant tasks (zero-emissions baseload) at little or no change in total cost Again, the feasibility of this option is questionable for many reasons The no-nuclear / no-coal strategy provides some emissions reductions because new demand caused by load growth and by plant retirement allows natural gas combustion to replace some amount of coal combustion The effects on baseload however are slow and minimal with sacrifices of reliability as the baseload demand increases The dispatch modifier is very effective because low-emissions capacity (gas-fired GTCC) is forced into baseload Again the high usage of natural gas is definitely costly and may be infeasible The early retirement option is highly effective because the most inefficient and highly-polluting plants are explicitly removed from the system When done at a reasonable level the emissions benefits are substantial with little or no cost increases due to the usage of high-efficiency new capacity Clearly there is an optimal level however as costs are seen to increase rapidly with the high demand for new capacity seen in the East Central region or in the high growth cases of the North East Finally the carbon tax is highly effective, because the carbon emissions are (crudely) internalized within the system, allowing the appropriate levels of each reduction action to be chosen according to an optimization criterion The feasibility or advisability of such drastic economic measures is not clear however

As a final note, it should be stated that the range of policy strategies examined is not intended to be either comprehensive or exhaustive Obviously there are many other possible policy strategies with varying possibilities for success Even with the strategies considered, there are many possible combinations (i e . early retirement / conservation or carbon tax / nuclear) or modifications (i e phased carbon tax or SO_2-dispatch) which might be considered It is hoped that the limited window provided by this analysis helps to highlight those strategies which are likely to be successful and thus worthy of further investigation

1 The authors wish to acknowledge the support of the MIT Center for Energy Policy Research in carrying out this effort An earlier version of this paper was presented at the conference Energy and the Environment in the 21st Century, March 1990 and will appear in the published proceedings of that conference

2 This paper focuses on the transitional strategies available to electric utilities for reducing CO_2 emissions given a set of governmental policy decisions There is a debate currently underway concerning the ability of the bioshpere to absorb additional CO_2 and also man's ability to adapt to changing environment Given these caveats, this paper focuses on the possible alternatives in the short and medium term which are available to the electric power sector in the United States.

3 Given the long time lags between increased CO_2 emissions and the possible effects of increased CO_2 concentrations, even small reductions in CO_2 emissions in the near term may have significant long-term impact.

4 The general formulation of this equation — Impact = Population * Impact per capita — is attributed to Erlich and Holdren, 1971.

5 As with "marginal costs" (i.e., $/GWH) in an electric power system, this value is marginal to the system and not necessarily to the technology with which the cost is associated. The marginal costs or emissions are the average cost or emissions per GWH of the technology which is loaded at the margin of the system

6 Carbon dioxide emissions are no more technologically fundamental to electric power than tetraethyl lead was to gasoline use in automobiles. It is economic and political infeasibility which limits non-fossil fuel use

7 Units are classed within a single technology types if all characteristics of the units are identical, including fuel type used At the finest grain level, this summation could be across single generating units in order to fully account for differences

8 This is an industry standard unit which can be confusing. An MMBTU is 10^6 BTUs, not 109

9 Equivalent to BTU/kWh a more typical unit

10 Typical values for fuels used in the United States

11 Most previous efforts have modeled the entire global energy / CO2 system over time scales on the order of 100 years Perhaps foremost among these are Edmonds and Reilly 1986 (used as the basis of many energy / climate studies) Nordhaus and Yohe 1983 and Manne and Richels 1990 Detailed evaluations of these and other modelling efforts can be found in Keepin 1986 and Ausubel and Nordhaus 1983 among others

12 EPRI 1982

13 Using one of three methods linear programming Bender s decomposition or dynamic programming Bender s decomposition was the primary method used in this study

14 EPRI 1989a

15 The "base future" or "base case" for any region refers to the combination of the base fuel price and base load growth for that region

16 DRI, 1989

17 EPRI 1989b

18 Growth rates vary annually, but are approximately 1 5% per year in the North East and 1 0% per year in the East Central

19 The Technology Assessment Guide deems these technologies to be feasible only in the West region While clearly the feasibility og these technologies is more limited and longer term in the North East and East Central regions, their complete exclusion may not be inherently necessary

20 The use of IGCC plants in the base strategy implies that the cost estimates for the technology are accurate and that the cost effectiveness of the option will be recognized by utility planners If this is not the case a more accurate base case might involve new coal capacity with sulfur scrubbers, an option with higher costs and significantly higher environmental emissions

21. These taxes, in 1985$, are the same as those used in several EPA studies. In the EPA studies, the taxes were phased in over a period from 1985 to 2050. In the present study, the taxes were implemented immediately (1989) and are, thus, even more extreme

22 With a 25 year extension period to account for end effects

23. This is as opposed to social costs, a distinction which is significant in evaluating the carbon tax strategy This is discussed in greater detail below.

24 The dominant effect in the acid rain emissions from a power system is the percentage of system energy generated by uncontrolled coal and oil capacity While the SO2 and NOx emissions from nuclear power per KWH are well below those of the IGCC capacity constructed in the base case, both are orders of magnitude below the emissions per KWH from existing uncontrolled capacity Since each displaces a similar amount of generation from this older capacity the overall acid rain emissions are similar between the two scenarios

25 In later study years where the cost of gas is high, the system may actually choose to let energy go unserved instead of operating a large amount of high cost generation sacrificing system reliability in order to keep costs down As a result, the costs of the NNNC strategy, while similar to those of the base strategy, do not represent costs for similar qualities of service

26 This should not be confused with a stabilization of atmospheric CO2 concentrations, which would require significant worldwide cuts (on the order of 50%)

27 "Demand reduction" is defined here as a decrease in load in response to price increases "Conservation" is defined as programmatic efforts to reduce load growth through physical change

References

Ausubel J H and Nordhaus W D, "A Review of Estimates of Future Carbon Dioxide Emissions" in National Research Council (NRC), Changing Climate National Academy Press, Washington, DC, 1983, pp 153-185

Data Resources Institute (DRI), Forecast of Fuel Prices, DRI, October, 1989

Edmonds, J, and Reilly, J, "The IES/ORAU Long-Term Global Energy-CO_2 Model Personal Computer Version A84PC" Publication No 2797, Institute for Energy Analysis, Oak Ridge Associated Universities, Washington, DC, 1986

Electric Power Research Institute (EPRI), Electric Generation Expansion Analysis System (EGEAS), EPRI EL-2561 EPRI, Palo Alto, CA, 1982

EPRI, The EPRI Regional Systems Database Version 3 0, EPRI P-6211, EPRI, Palo Alto, CA, 1989a

EPRI, TAGt — Technical Assessment Guide, Volume 1: Electric Supply — 1986 (Revision 6), EPRI P-6587s-L, EPRI, Palo Alto, CA, 1989b.

Erlich, P R, and Holdren, J P, "Impact of Population Growth", Science, Vol. 171, 1971, pp 1212-17

Keepin, B, "Review of Global Energy and Carbon Dioxide Projections", Annual Review of Energy, Vol 11, 1986, pp 357-92.

Manne, A S, and Richels, R G, "Global CO_2 Emission Reductions — The Impacts of Rising Energy Costs", this volume, 1990

Nordhaus, W D, and Yohe, G W, "Future Paths of Energy and Carbon Dioxide Emissions", in NRC, Changing Climate, National Academy Press, Washington, DC, 1983, pp 87-153

Richard D. Tabors was born in Cleveland, Ohio on October 16, 1943 He received his BA from Dartmouth College in Biology and his MA and PhD from the Maxwell School of Syracuse University in Geography and Economics in 1965, 1970 and 1971 respectively

From 1970 to 1976 he was on the faculty of Harvard University where he worked on Environmental and Resource Planning From 1976 to the present he has been at Massachusetts Institute of Technology where he is Assistant Director of the Laboratory for Electromagnetic and Electronic Systems He teaches in the Technology and Policy Program Dr Tabors is author of a number of papers on electric power pricing and is co-author with Fred C Schweppe, Michael Caramanis and Roger Bohn of Spot Pricing of Electricity, (Kluwer Academic Press, 1988) He has also written about natural gas fired combined cycles (IEEE/PAS 1985) and extensively on environmental planning (IEEE/PAS, 1989) He is the co-author with Thomas H Lee and Ben C Ball, jr of Energy Aftermath (Harvard Business School Press, 1989), an analysis of U S private and governmental energy policy from the early 1970's to the present

Dr Tabors is a founder and principal of Tabors Caramanis & Assoc Inc of Cambridge MA He is a member of IEEE

Burt L. Monroe was born in Louisville, Kentucky in 1968 He received his BSEE from the University of Louisville in 1988 and his MS in Technology and Policy from Massachusetts Institute of Technology in 1990

From 1988 to 1990, Mr Monroe worked as a Research Assistant at MIT on modeling of energy systems and their impact on environmental emissions

In 1990 Mr Monroe was awarded a Rhodes Scholarship He is now working toward his doctorate at Oxford University.