

**THE TRANSITION TO REDUCED LEVELS OF CARBON EMISSIONS**

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## SHORT-TERM DYNAMICS:

### ANALYZING THE TRANSITION OF THE U.S. ENERGY ECONOMY TO REDUCED LEVELS OF CARBON EMISSIONS

An Overview of the Short-Term Dynamics Study Group

## INTRODUCTION

A key focus of the Energy Modeling Forum study on global warming mitigation policies (EMF-12) is the potential costs of stabilizing U.S. carbon emissions at the 1990 level or reducing emissions well below the 1990 level. Considerable effort has been devoted to estimating these costs, measured in a variety of ways including the loss in GDP, the change in net social surplus, or the level of a carbon tax needed to achieve a given carbon emission target. For example, virtually all of the modeling groups participating in EMF-12 estimated the carbon tax required to achieve a 20 percent reduction in carbon emissions from 1990 levels by 2010, and to then maintain this level of emissions beyond 2010. However, most of the initial analyses did not explicitly address the detailed policy implications and trade-offs *during* the transition period, from 1990 through 2010. This chapter presents the results of the "Short-Term Dynamics" Study Group that was formed to examine in detail the questions and issues associated with this potential transition of the U.S. economy to a lower level of carbon emissions.

The motivation for this study group is suggested by the carbon tax results from the FOSSIL2 and GEMINI models depicted in Figure 1. The figure shows the tax rates required to achieve a 20 percent reduction in carbon emissions by 2010, and then to maintain this level of emissions beyond 2010. Although the specific results from the two models are not identical, the overall pattern is strikingly similar: the tax rates and associated costs of *achieving* a 20 percent reduction

by 2010 appears to be much greater than the costs of *maintaining* the reduced emission levels in the long term. Results from at least six of the EMF-12 models share this distinctive, non-monotonic pattern, with considerable higher tax rates during the 1990 to 2010 transition period and lower tax rates beyond 2010. The pattern was particularly strong for the highly detailed models, such as GEMINI and FOSSIL2, that explicitly represent the capital stocks of numerous individual technologies in a large number of energy sector markets, and which determine the mix of technologies and other outcomes based on market factors as well as the cost and performance characteristics of the technologies.

The results of analyses using these models suggest that major changes in energy markets and technologies may be required, at potentially large cost, if the U.S. energy economy is to transition to a much lower level of carbon emissions over the next 20 to 30 years. The EMF-12 Short-Term Dynamics Study Group was formed to examine the issues and trade-offs associated with such a transition in greater detail. The study group included the FOSSIL2 and GEMINI model teams. Building on the insights derived from the basic EMF-12 scenarios, the two teams carried out extensive, complementary analyses designed to address three broad, interrelated sets of questions:

- ♦ What are the implications of alternative paths of carbon emissions from 1990 to 2010? To what extent do the costs of a transition to lower levels of carbon emissions depend on the nature of the transition? What are the key factors that result in the characteristic pattern of higher taxes and costs during the transition?
- ♦ How can costs be reduced by *refining* the goal? In other words, to what extent can the costs of a transition to reduced carbon emissions be reduced by changing the timing of a

carbon emissions reduction policy, the targeted level of reduction, or the sequence of emissions targets during the transition?

- ◆ How can the costs of *meeting* a particular goal be reduced? Given a particular carbon emission reduction target, what policy actions could be taken to lower the costs of meeting the target? Which economic and technology factors are most important in determining the ultimate cost?

The complete analyses carried out by the Short-Term Dynamics Study Group, and the results of these analyses, are presented in the two papers included in this chapter. The remainder of this overview provides a summary of the key insights, results, and conclusions of the analyses.

## SUMMARY OF RESULTS

The principal results of these analyses are clear:

- The nature of the transition to a lower level of carbon emissions *does* matter. The costs can vary dramatically depending on the choice of an emissions target, the date at which the target is achieved, and the ways in which the target is met.
- There are a number of potential policy options that may significantly reduce the costs of a transition to a reduced level of carbon emissions.

What are the factors that cause the costs of a transition to be much greater than the costs of maintaining a lower level of carbon emissions in the long term? The analyses suggest several key factors:

- In the near-term, the costs of carbon-free technologies are higher, for most uses, as compared to more traditional, fossil-fueled alternatives.

- In many markets and applications, carbon-free technologies are simply not yet commercially available.
- Carbon-free technologies are expected to be increasingly available and cost-competitive after the year 2000; by 2020 such technologies may be widely available at *lower* costs than carbon-intensive options.
- The rate of turnover of existing capital stocks, determined in part by the financial, tax, and operating lifetimes of existing equipment, limits the penetration of carbon-free alternatives even when such alternatives are competitive in cost.
- Encouraging (with a carbon tax or other mechanism) or forcing the *early* retirement of existing capital stocks can significantly increase the cost of shifting to carbon-free technologies.
- By 2015 or 2020 much of the existing capital stock has reached the end of its useful life, facilitating a more-rapid and cost-effective transition to carbon-free alternatives.

To what extent does the choice of a carbon emissions reduction target, and the nature of the transition path to the target, influence the cost of meeting the target? The analyses suggest that these choices can have a major influence on the cost:

- Deferring a 20 percent emissions reduction target from, for example, 2010 until 2015, has the potential to reduce the cost by 15 to 25 percent. Moving the target out to 2020 can reduce the cost by 50 percent or more as compared to a 2010 date.
- Greater reductions in carbon emissions have increasing marginal costs. A 20 percent reduction by 2010 may cost 3 times as much as a 10 percent reduction.

- Given a fixed target, such as a 20 percent reduction by 2010, the cost of achieving the target can be minimized by following a smooth path of carbon emission reductions starting in 1995, with gradual reductions at first followed by greater reductions after 2000.

Collectively, these results suggest a number of ways in which the costs to the U.S. of moving towards a lower level of carbon emissions can be reduced. These include, for example, developing policies designed to encourage gradual yet continuous reductions in carbon emissions. Such policies would avoid any requirements that impose large, abrupt reductions in emissions during the next decade, while encouraging and facilitating shifts toward carbon-free technologies. A series of emissions reduction targets that require smooth reductions in carbon emissions starting in the year 2000 and continuing to and beyond 2020 will have a significantly lower cost than would a requirement to meet a single, strong deadline such as a 20 percent reduction by 2010.

Whatever the emissions reduction target, the costs of meeting the goal can be significantly reduced by developing policies that:

- Accelerate the availability of non-carbon (or low-carbon) energy technologies, including (but not limited to) those using renewable resources.
- Reduce the cost of carbon-free technologies suitable for use in electric power generation, transportation, and other key energy producing and consuming sectors.
- Encourage and facilitate the early retirement and more rapid turnover of the capital stocks of energy facilities and equipment, particularly electric generation facilities and end-use energy technologies. Policies designed to facilitate such early retirement must take into account the very real economic costs of doing so.

The most important conclusion of the Short-Term Dynamics Study Group is that it is essential to devote at least as much attention to the question of *how* we achieve a reduction in carbon emissions as is invested in deliberating over the question of *what* level of emissions reduction is necessary or appropriate. If we ignore the nature of the transition, and the potential for policies that can reduce the costs of the transition, we run the risk of achieving less at greater cost than would otherwise be possible.

# A LOW-CARBON ENERGY ECONOMY: THE DYNAMICS OF THE U.S. TRANSITION

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## ABSTRACT

Several models used in EMF 12 project a pattern of high near-term costs and lower long-term costs of meeting a target of 20% reduction in U.S. carbon emissions by 2010. The dynamics of this transition to a low-carbon U.S. energy economy are examined using one of the EMF 12 models - FOSSIL2. Key factors causing the behavior are identified and the sensitivity of the behavior to these factors is examined. Potential means of reducing the costs of the transition are provided with estimates of the cost reductions.

## INTRODUCTION

A central question of the Energy Modeling Forum study on global warming mitigation policies is the likely costs of reducing U.S. carbon emissions below 1990 levels and how these costs change over time. One measure of these costs is the level of carbon tax required to meet a target reduction. One such target is the 20 percent reduction by the year 2010 in EMF Scenario I. Figure 1 depicts the level of carbon tax required to meet the carbon reduction target in Scenario I in the FOSSIL2 model. At least six of the EMF models exhibit this distinct, non-linear pattern over time - higher tax levels in the mid-term (1990-2010) and lower tax levels in the longer term (2020 and after). This result is particularly apparent for the simulation-type models -those that explicitly represent the stocks and flows of U.S. energy markets. This result suggests that fundamental changes in energy markets with relatively high costs may occur in the transition to a low-carbon energy economy over the next 20 to 30 years.

The purpose of this paper is to analyze the dynamics of this transition. The two key questions in this analysis are:

- What are the factors that cause the non-linear pattern of carbon taxes required to meet the 20 percent reduction target?
- What policy actions could be taken to lower the costs of the transition from a high-carbon energy economy to a low-carbon energy economy?

This analysis was conducted with the FOSSIL2 energy model - a dynamic simulation model of the U.S. economy that is maintained by the AES Corporation for the U.S. Department of Energy. This paper contains three major sections. First, the energy characteristics of the transition are described in order to identify the key factors in the transition. Second, the sensitivity of the transition dynamics to the key factors is assessed. Third, conclusions are drawn on policy actions that could reduce the costs of the transition to a low-carbon U.S. energy economy. Potential cost savings are also estimated.

## KEY FACTORS IN THE TRANSITION

In the Reference Case, carbon emissions are projected to rise from about 1300 million metric tonnes (MMT) in 1990 to 2214 MMT by 2030. In EMF Scenario I, carbon emissions fall to slightly over 1000 MMT by 2010 and remain stable thereafter. The principal policy action causing this result is a carbon tax that reaches \$260 per tonne in 2000 and peaks at nearly \$350 in 2015. After 2015, the tax level required for stabilization falls to \$165 in 2020 and \$70 in 2030. In order to identify the key factors producing this behavior, the characteristics of the transition must be examined.

Primary energy consumption declines in absolute terms in Scenario I during the first 5 years, remains level over the next 15 years and rises thereafter. This result is shown in Figure 2. Primary consumption is 14% lower than in the Reference Case in 2000, 23% lower in 2010, and

28% lower in 2030. The effect of the carbon tax in the first 20 years is to substantially reduce total energy consumption, while the effect in the next 20 years is to shift consumption to low-carbon or carbon-free fuels. Figure 3 depicts the primary fuel shares for both the Reference Case and EMF Scenario I. The carbon intensity of primary energy consumption falls slowly in the near term and much faster in the longer term. Carbon intensity of primary energy consumption in Scenario I is 6% lower in 2000, 18% lower in 2010, and 36% lower in 2030.

A similar pattern emerges for electricity consumption and the electricity generation fuel mix. Figure 4 shows electricity consumption in the Reference Case and Scenario I. Scenario I electricity consumption is 19% lower in 2000 than the Reference Case and 30% lower in 2010, but only 37% lower in 2030. As is the case for primary energy, the 2010 to 2030 period is characterized by a much greater shift to low-carbon or carbon-free electricity generation fuels and technologies than the 1990-2010 period. The Scenario I generation share of nuclear, renewables and the non-carbon backstop together is only 1% higher in 2000 and 8% higher in 2010, but 85% higher by 2030. Figure 5 depicts the generation fuel shares for both the Reference Case and EMF Scenario I. The carbon intensity of electricity generation falls slowly in the near term and much faster in the longer term. Carbon intensity of generation in Scenario I is 6% lower in 2000, 18% lower in 2010, and 36% lower in 2030.

This short-term reduction in energy consumption and the long-term shift to low-carbon fuels result from three major factors. First, stock turnover limits the penetration of non-carbon alternatives. The high taxes result in most new energy consuming stock and electricity generating capacity in Scenario I being low-carbon or non-carbon, but the new stock as a fraction of the total stock increases only slowly. Second, the costs of the non-carbon alternatives are high in the near-term. The EMF non-carbon electricity generation alternative has a levelized cost of 75 mills/Kwh, while other alternatives (e.g., photovoltaics) are even more expensive. Third, the non-carbon backstops for electricity generation are not immediately available. In Scenario I, the EMF non-

carbon generation backstop is assumed to not be available until 1996. These factors combine in the FOSSIL2 model to produce the carbon tax pattern shown in Figure 1.

## SENSITIVITY OF KEY FACTORS IN THE TRANSITION

The key factors causing the dynamics of the transition to a low-carbon U.S. energy economy were identified in the previous section. This section assesses the sensitivity of the transition dynamics to these key factors. Evaluation of their relative importance provides clues on what policy actions could reduce the cost of the transition.

Sensitivity cases are run that vary assumptions in three areas: the cost and availability of low- or non-carbon technologies; stock turnover (both energy consuming stock and electric generating plants); and consumer discount rates. In each of these cases, the carbon tax levels used in EMF Scenario I are maintained and the sensitivity of each factor is determined on the basis of the impact on carbon emissions, energy consumption and fuel shares.

### Low-Carbon or Non-Carbon Technologies

A major assumption made by the EMF study is the availability of a cost-effective non-carbon electric backstop before the year 2000 (FOSSIL2 assumes this technology is available in 1996). In order to test the importance of this assumption, two new cases were tested: one without a 75 mills/kWh non-carbon option (but with current assumptions about gas and renewable technologies as non-carbon options); and a second which used the optimistic 50 mills/kWh non-carbon option used in EMF Scenario IV, but with a commercial date of 1994. Figure 6 illustrates the carbon emission levels for the two cases (referred to as the "No Backstop" and "Optimistic Backstop" cases) compared to EMF Scenario I. The carbon emissions in 2010 are 4% higher for the No Backstop case (with a 9% difference by 2030), and 12% lower for the Optimistic Backstop case compared to Scenario I. These results are not surprising when one

considers Figure 7, which compares the electric generation fuel use of these cases. Since the No Backstop case has no low-cost alternative to baseload coal, utilities life-extend a large number of coal plants, resulting in more coal and less renewables than the Original 20% case, while the Optimistic Backstop case results in minimal coal life-extensions and significant backstop penetration. The cost assumptions also affect the electricity price, which varies electricity demand modestly. Demand for electricity in 2010 is 4% lower in the No Backstop case and 9% higher in the Optimistic Backstop case.

The "No Backstop" case was also run with enhanced renewable R&D program assumptions (developed by the Sandia National Laboratories for the National Energy Strategy). In this case technology costs are lower and system reliability is higher for several renewable electric options. However, the addition of the enhanced renewable R&D program assumptions to the No Backstop case have a modest effect on emissions in the mid-term (1% less emissions than the No Backstop case in 2010). This is due to the fact that most renewables compete with intermediate load technologies and therefore back out less carbon-intensive gas plants instead of reducing the number of baseload coal plants. Also, since the No Backstop case already has substantial renewable energy market penetration, many renewable options were already constrained by resource availability (eg. cost-effective wind sites). This underscores the importance of developing a non-carbon backstop technology that is not only cost-effective, but also provides a baseload alternative to coal and has high resource availability.

The natural gas combined cycle technology cost and performance assumptions were also tested. In the Original 20% Reduction case, a new gas combined cycle unit was assumed to cost \$650/KW by 2010, with an efficiency of 45%, while the sensitivity case assumed a \$550/KW technology with 50% efficiency. The results were surprising: carbon emissions were virtually the same as the Original 20% case. Upon closer examination, it was discovered that although the low-cost gas option backs out some coal, it also prevents the non-carbon backstop from

penetrating the market in the mid-term. The resulting emissions are similar to Scenario I in 2010, and slightly higher by 2030.

### Stock Turnover

Another set of sensitivity cases looked at stock turnover for both energy consuming stock (such as furnaces or motors) and electric generating plants. The FOSSIL2 model does not allow early retirement of stock based on economics, but retires stock at a fixed rate. To test the importance of the stock lifetime assumptions, we decreased the lifetime of energy consuming stock (excluding transportation stock) by 50% in one case ("Early Retirement-Demand"), and assumed a 20 year lifetime for all coal electric generating plants in a second case ("Early Retirement-Supply"). In the latter case, life-extensions for oil/gas steam plants were also suspended. As shown in Figure 8, both cases result in lower carbon emissions. The Early Retirement-Demand case results in a reduction of emissions by 4% in 2010, while the Early Retirement-Supply case has a greater impact on the system, reducing total emissions by 11% in 2000 and 9% in 2010. The effects of these cases on primary energy consumption and electricity demand are shown in Figures 9 and 10. The principal result of the Early Retirement-Demand case is a reduction in consumption, while the principal result of the Early Retirement-Supply case is a shift to low-carbon fuels. When these two cases are combined, these effect are synergistic - resulting in both a drop in consumption and a shift in fuels. The combination case is projected to reduce emissions by 13% in 2000 and by 14% in 2010.

Since the Early Retirement Combination case has a significant impact on emissions, a logical next step is to combine this case with the Optimistic Backstop case, which ensures that most of the retired coal plants were replaced by a non-carbon option. This combination case proves to be highly effective. As shown in Figure 11, total emissions are projected to be reduced by 16%

in 2000 compared to Scenario I, and by 19% in 2010. As illustrated by Figure 12, this reduction is due largely to fuel switching in the electricity generation sector.

### Consumer Discount Rates

In order to test the FOSSIL2 consumer discount rate, or "hurdle rate" assumptions, all consumer discount rates (residential, commercial and industrial) are set to 7% real. This reduction (from 20% to 40%) results in consumers having the same discount rate as an electric utility. This results in a modest emissions reduction in 2000 compared to Scenario I, but most of the difference disappears by the year 2010. There are two reasons for this result. First, Scenario I already includes the conservation savings that would occur under a high carbon tax future, including an aggressive nation-wide electric utility conservation program. Many conservation measures would look appealing to consumers facing a \$300/ton carbon tax, regardless of their discount rate. Fully 50% of the carbon emission reduction in 2010 between the EMF Reference Case and Scenario I can be attributed to end-use conservation and fuel switching. Second, the FOSSIL2 conservation supply curves contain only measures which are currently on the market, which is a very conservative assumption. Although an increase in efficiency of these measures (and a decrease in cost) due to R&D is assumed under the carbon reduction scenarios, the extra savings do not occur until after 2010.

### Reducing the Cost of the Transition

The final step in this analysis is the determination of the carbon taxes necessary to meet the 20% reduction by 2010 target for selected sensitivity cases. This calculation was performed for the following cases: accelerated low-cost non-carbon backstop technology (optimal backstop), early retirement of electricity generation stocks, early retirement of demand stocks, early retirement of both demand and electricity generation stocks, and combined early stock retirement and a combination of accelerated low-cost non-carbon backstop technology. The tax levels for

these cases are shown in Figure 13. Table 1 presents the total 1990-2030 carbon tax bill - both undiscounted and discounted - under each case. (Results are rounded to the nearest \$100 billion). These results suggest that a large potential exists for reducing the costs of the transition of the U.S. energy economy. Under the combined assumptions of accelerated stocks retirement and low-cost/early availability of a non-carbon backstop, this analysis indicates that costs could be reduced by 75%.

Table 1: Carbon Tax Bills under Sensitivity Cases

Case	Total Carbon Tax Bill 1990-2030 (Billion \$1990)		
	Undiscounted	Discounted at 5%	Discounted at 10%
Scenario I	\$9,200	\$3,800	\$1,800
Optimal Backstop	\$3,500	\$1,800	\$1,100
Early Retirement - supply	\$6,700	\$2,400	\$1,000
Early Retirement - demand	\$8,300	\$3,300	\$1,600
Early Retirement - supply/demand	\$5,100	\$1,900	\$800
Early Retirement/Optimal Backstop	\$2,600	\$1,000	\$400

## CONCLUSIONS

The costs of the transition to a low-carbon U.S. energy economy under the base EMF 12 assumptions are likely to be substantial. However, these costs could be reduced substantially through the implementation of policy actions with the following goals:

- reducing the costs of low-carbon or non-carbon backstop technologies;
- accelerating the introduction and reducing the financial risk of low-carbon or non-carbon backstop technologies;
- accelerating the turnover of both energy consuming stocks and electricity generating capacity.

The assumption most important to the total transition cost is the availability and cost of non-carbon backstop technologies. Although the non-carbon technologies assumed in the EMF exercises are hypothetical, this conclusion is nonetheless valid for policy makers. Some low-carbon and non-carbon technologies for both transportation and electricity generation are available or under development. Policy actions focusing on lowering the costs of these technologies and removing barriers to their widespread use in the marketplace could significantly lower the costs of reducing U.S. carbon emissions.

# REDUCING CO<sub>2</sub> EMISSIONS: IMPLICATIONS OF ALTERNATIVE PATHS OF EMISSIONS CONSTRAINTS

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## INTRODUCTION

Considerable attention has been paid to the costs of stabilizing CO<sub>2</sub> emissions in the United States at 1990 levels, and to the costs of achieving a 20% reduction in emissions by 2010. In either case it is typically assumed that CO<sub>2</sub> emissions will remain constant in the long-term after 2010. However, most analyses have not explicitly addressed how the implications of such policies depend on the nature of the transition between 1990 and the longer-term after 2010. In other words, to what extent does the path of the CO<sub>2</sub> emissions constraint between 1990 and 2010 matter? To what extent does varying the 20% target reduction or the 2010 target date change the costs and other implications? These questions are associated with what has been termed the "short-term dynamics" of the transition between today's economy and one in 2010 or beyond in which significant constraints on CO<sub>2</sub> emissions (or incentives to reduce CO<sub>2</sub> emissions) are in place.<sup>1</sup>

This paper reports the results of a set of analyses designed to address these questions. The analyses were carried out using the GEMINI energy-environmental market model developed by the EPA and DFI. In order to address the range of questions and scenarios, five coordinated sets of analyses were carried out:

- Alternative CO<sub>2</sub> emissions reduction paths between 1990 levels and a 20% reduction by 2010, including a linear path, alternatives that imply either faster or slower than linear reductions, and a "defer as long as possible" path.

- Alternative CO<sub>2</sub> emissions reduction targets for 2010, including stabilization (at 1990 levels) and 5%, 10%, 15%, and 20% reductions.
- Alternative dates at which a 20% emissions reduction would be achieved, comparing a target of 2010 with a five-year delay to 2015.
- Alternative CO<sub>2</sub> emissions reduction paths in which the start of 20% emission reductions is delayed until 2000. Until 2000, emissions are stabilized at 1990 levels. These paths are similar in shape to those in the first set of analyses, shifted 10 years later.
- Alternative CO<sub>2</sub> emissions reduction paths which have different shapes (e.g., different time-patterns of emissions reductions), but which have the same cumulative emissions over the years 1990 to 2030.

In all cases a carbon tax, applied at the primary resource production level, was the mechanism used to induce the required CO<sub>2</sub> emission reductions. Thus, for each scenario, the appropriate CO<sub>2</sub> emissions constraint from 1990 through 2030 was specified, and then GEMINI solved for the time-sequence of carbon tax rates necessary to meet the constraint. Although we recognize that numerous policy options beyond carbon taxes may be considered, particularly with the more aggressive reduction targets, we judged that relying on the carbon tax mechanism throughout these analyses would provide the clearest indication of the differences between the alternative paths. Thus, all other parameters and assumptions remained constant across all scenarios that were evaluated. All analyses were carried out for the period from 1990 through 2030.

In comparing the implications of these scenarios, we focused on two key results:

- The change in net social surplus as compared to an unconstrained base case (over the full 1990 to 2030 period). The change in social surplus is measured as the sum of the change

in consumer surplus plus the change in producer surplus as a result of a policy change (in this case the carbon tax).

- The nature of the carbon tax that is required to achieve the desired constraint.

While the first measure provides a better approximation of the economic impacts of the CO<sub>2</sub> emission reductions, it is clear that both measures are of significant interest to policy makers. In addition, we examined the differences among the scenarios in terms of primary fuel mix, the penetration of renewables technologies, and other outcomes of interest.

## SUMMARY OF RESULTS

This section provides a brief summary of key results and insights. A more detailed discussion of the scenarios and results follows, organized around the five sets of analyses outlined above.

The key results of these analyses are clear: The nature of the emissions constraint path *does* matter. The change in social surplus can vary by 50% or more among several different paths to the same emissions reduction target. In particular:

- As measured by the change in social surplus, the lowest cost transition path from 1990 to a 20% reduction in 2010 involves a gradual constraint at first, with the rate of decrease in total CO<sub>2</sub> emissions increasing as 2010 approaches. This result holds even though the gradual constraint implies a much more rapid reduction from 2005 to 2010 than is required for any period under the linear constraint.
- The final set of analyses showed that this result holds even when the time patterns of emissions reductions are calibrated to have the same cumulation reductions over the 1990-2030 time period.

- As would be expected, a larger emissions reduction by 2010 implies a greater cost impact on society. However, this appears to be nonlinear, with a greater *marginal* loss of social surplus when the target is changed from 15% to 20% than was observed for the increments between zero and 15% (all for reductions achieved by 2010). A similar effect is noted with respect to the typical carbon tax rate needed to achieve each level of emissions reduction.
- Deferring a 20% emissions reduction target from 2010 to 2015 can reduce the loss in social surplus by roughly 15 to 25% (over the period 1990 through 2030). This savings could be compared to the estimated benefits of achieving an earlier emissions reduction.

The analyses suggested that the timing of an emissions reduction target (e.g., the date at which a given level of reduction is achieved) can be important, as can the date at which an emissions reduction effort begins:

- Delaying the *start* of emission reductions by 10 years, with stabilized emissions from 1990 to 2000, can reduce the tax rates required to achieve a 20% reduction by 10 to 25%. The loss in social surplus can be reduced by roughly half, in 1990 dollars.

Carbon tax rates required to achieve given emissions reductions are also sensitive to the timing and pattern of such reductions:

- The carbon tax rate required at each point in time to achieve a given reduction in emissions is closely correlated with the *rate* of emissions reduction (e.g., the slope of the constraint curve) over the period in which the tax is applied. In other words, among a set of different constraint paths, the path with the smallest slope in the constraint curve during a given period requires the lowest tax rate during that period. The tax rate in a given period is also influenced by the timing of emission reduction; in general, the greater the delay in emissions reductions, the lower the required tax rate.

- For the scenarios in which emissions reductions begin in the 1990-1995 period, the lowest *maximum* tax rate over the 1990 to 2010 period is achieved with a *linear* emissions constraint path. For the scenarios in which the reductions begin in 2000, the delay factor begins to dominate. Since the slower than linear constraint path has a smaller slope in the earlier years, this path has the lowest maximum tax rate.

The key differences among the scenarios—in particular, the reduced loss of social surplus and the typically lower tax rates associated with deferred and/or more gradual reductions in CO<sub>2</sub> emissions—appear to result from three key factors:

- Deferring reductions (or increasing the rate of reductions over time) allows greater time for capital stock turnover from more to less carbon-intensive technologies; accelerating the rate of capital stock turnover increases the marginal costs.
- A number of non-carbon renewable energy sources become increasingly competitive over time. In particular, many such technologies become cost-competitive *without* a carbon tax early in the 21st century. Thus, emissions reductions can be achieved after 2005 or 2010 at lower cost than is feasible prior to the year 2000.
- Given present value discounting of the change in social surplus, any deferral of such losses (without changing the absolute magnitude) will reduce the net present value.

#### ALTERNATIVE PATHS TO A 20% REDUCTION BY 2010

We selected four CO<sub>2</sub> reduction paths to study the impacts of different paths between current (1990) CO<sub>2</sub> emissions and a 20% reduction by 2010:

- Scenario 1 is a linear reduction of CO<sub>2</sub> emissions between 1990 and 2010. After 2010, emissions are stabilized at 2010 level.

- Scenario 2 is a defer-as-long-as-possible path to the 20% reduction; that is CO<sub>2</sub> emissions are stabilized between 1990 and 2005 and a 20% reduction is imposed starting in 2010. Thus, the entire 20% reduction is required over a 5-year period. After 2010, emissions are stabilized at 2010 levels.
- Scenario 3 imposes a gradual reduction in CO<sub>2</sub> emissions between 1990 and 2010, with reductions in each period greater than or equal to the reduction in the previous period. Thus, the initial reduction is slower than in the linear case, with more rapid reduction after 2005. After 2010, emissions are stabilized at 2010 level.
- Scenario 4 imposes a gradual reduction in CO<sub>2</sub> emissions between 1990 and 2010, with reductions in each period less than or equal to the reduction in the previous period (with initial reductions faster than in the linear case). After 2010, emissions are stabilized at 2010 level. Table 1 and Figure 1 display the CO<sub>2</sub> constraints used.

Table 1. CO<sub>2</sub> Constraints for 20% Reduction by 2010  
(Million Tonnes of Carbon)

Year	Scenario 1 Linear	Scenario 2 (Deferred)	Scenario 3 (Slower than Linear)	Scenario 4 (Faster than Linear)
1990	1450	1450	1450	1450
1995	1380	1450	1410	1335
2000	1310	1450	1350	1265
2005	1240	1450	1270	1200
2010	1170	1170	1170	1170
2015	1170	1170	1170	1170
2020	1170	1170	1170	1170
2025	1170	1170	1170	1170
2030	1170	1170	1170	1170

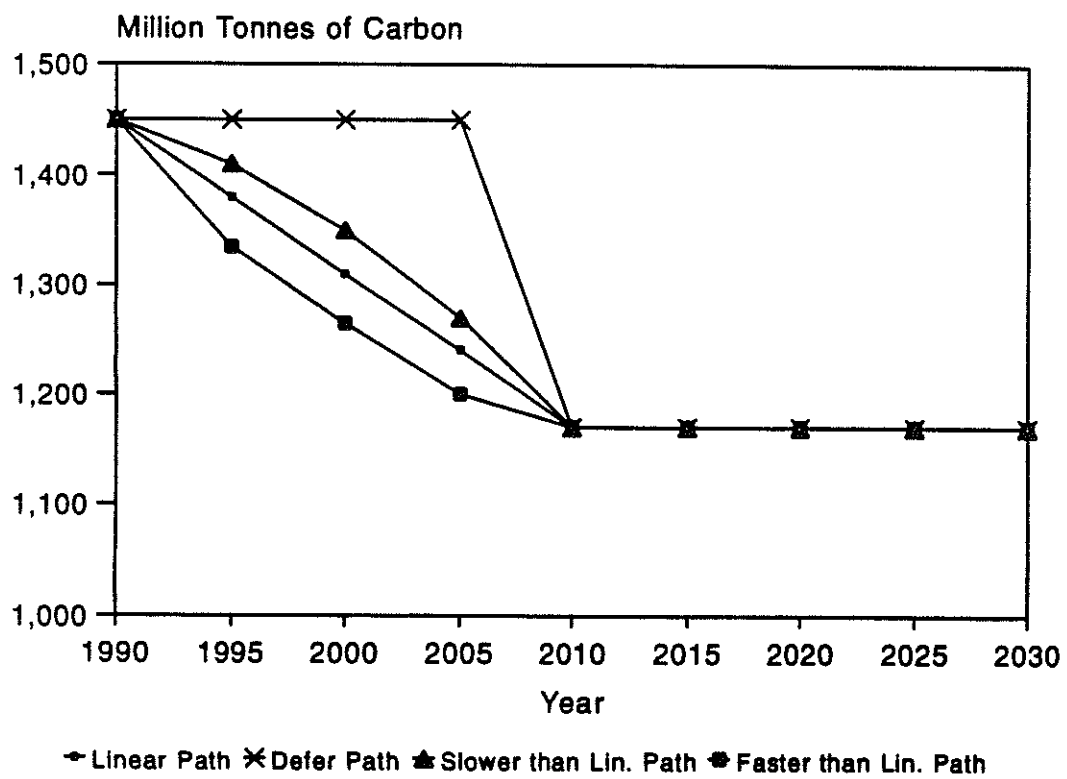


Figure 1. CO<sub>2</sub> Constraints for 20% Reduction by 2010

The carbon tax rates required to meet each of the CO<sub>2</sub> emissions reduction paths are shown in Figures 2 and 3. Figure 2 shows all 4 scenarios; Figure 3 shows scenarios 1, 3, and 4 in more detail. The nature of the emissions constraint path has a significant impact on the carbon tax rates required to meet the constraints, and on the change in social surplus resulting from such options. In general, tax rates are closely connected to the timing and magnitude of emission reduction targets. In all cases, the carbon tax rate required in each period to achieve a given reduction in emissions is correlated with the slope of the constraint curve over the 5-year period; the steeper the slope, the larger the tax rate required.

Thus, it is not surprising that the highest tax rate is registered when the largest change in the carbon constraint is imposed. That is, the highest tax rate is registered in 2010 when the largest reduction in CO<sub>2</sub> is imposed in the defer-as-long-as possible scenario. The tax rate, \$2345 per tonne of carbon, suggests that such a steep reduction is a rather unrealistic scheme.

Since the goal is to achieve a 20% reduction by 2010 in all cases, it is clear that the path that minimizes the maximum change in the rate of emissions must be linear. As a result, among these four scenarios, the lowest maximum tax rate required to achieve a 20% CO<sub>2</sub> reduction by 2010 is achieved with a linear emissions constraint path between 1990 and 2010.

The lowest cost transition path for a 20% reduction in 2010, as measured by the change in social surplus, is scenario 3—a gradual constraint at first, with the rate of decrease in CO<sub>2</sub> emissions increasing as 2010 approaches. There are three major reasons for this result:

- Deferring reductions allows greater time for capital stock turnover; accelerating the rate of capital stock turnover increases the marginal costs.
- Since we are discounting the value of future dollars, the present value of the change in social surplus due to a high carbon tax imposed in the future will be smaller the later the tax is imposed.

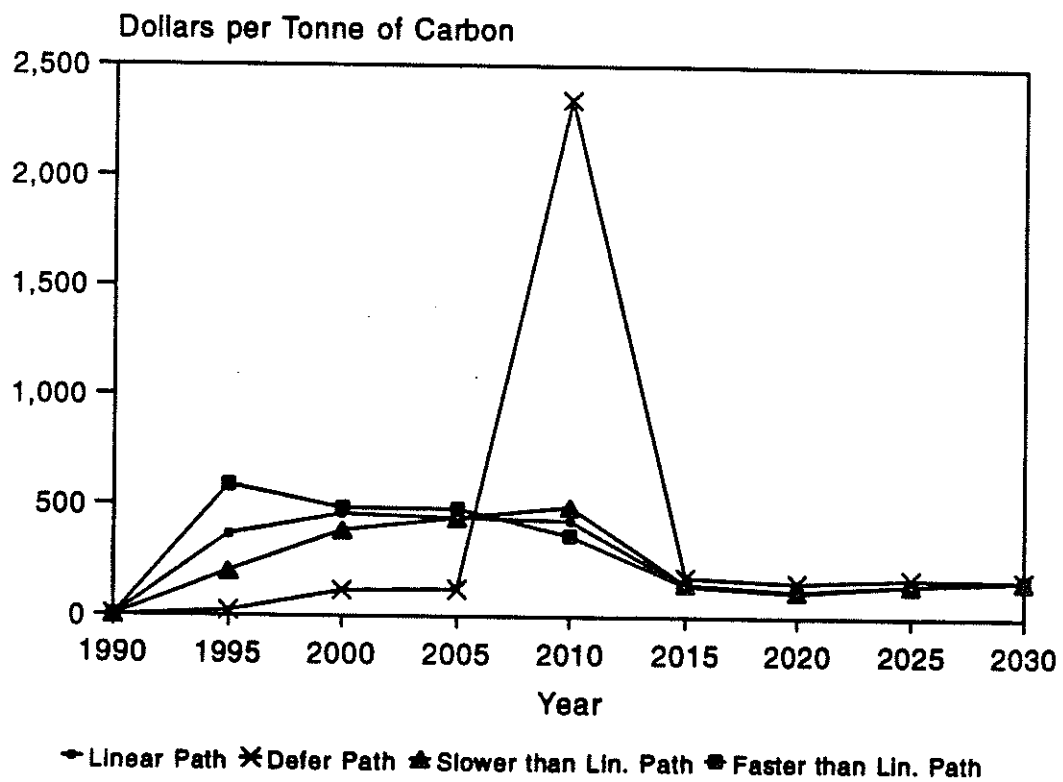


Figure 2. Tax Rates for 20% Reduction by 2010 (All Scenarios)

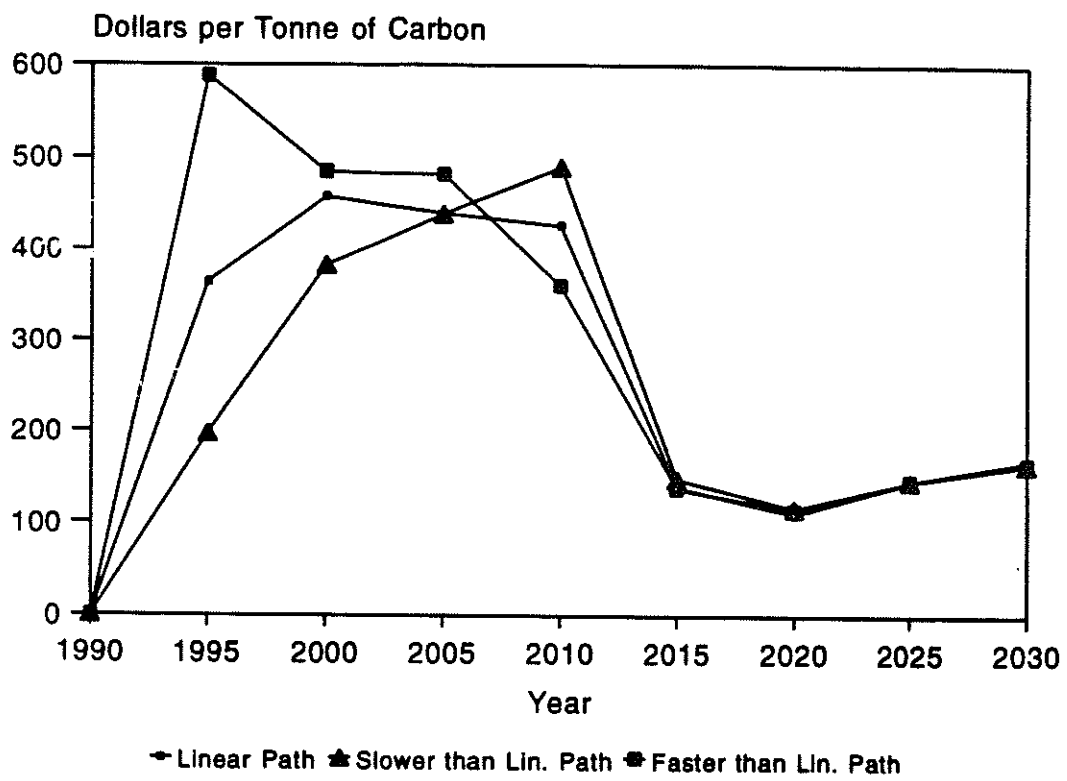


Figure 3. Tax Rates for 20% Reduction by 2010 (Scenarios 1, 3, and 4)

- Several renewable energy sources become available after the year 2000. In fact some of these technologies become cost-competitive after 2000 without a carbon tax. Thus, achieving a greater share of the overall 20% reduction in the later half of the 20-year transition period is less costly.

With a relatively low discount rate (3%), the defer-as-long-as-possible scenario has the highest cost, a not surprising result given the very large cost imposed from 2005 to 2010 under this scenario. With higher discount rates, however, the highest cost transition path to a 20% reduction by 2010 is scenario 4, involving a steep constraint at first with the rate of change in reductions decreasing over time. Table 2 shows the change (from the base case, without any constraint on CO<sub>2</sub>) in the present values of the social surplus and the levelized costs (over the period 1990-2030), calculated for three different discount rates.

Table 2. Present Value of Change in Social Surplus And Levelized Costs for 20% Reduction by 2010 (Billion Dollars)

Discount Rate	Scenario 1 Linear		Scenario 2 (Deferred)		Scenario 3 (Slower than Linear)		Scenario 4 (Faster than Linear)	
	Total	Level	Total	Level	Total	Level	Total	Level
3%	-8185	-324	-10312	-408	-7039	-287	-9590	-380
5%	-6135	-329	-6601	-354	-5082	-286	-7405	-397
10%	-3262	-301	-2228	-205	-2460	-249	-4218	-389

Table 3 shows the primary energy consumption for selected years for each of the paths considered for the 20% reduction by 2010. The rate at which renewable energy sources are introduced is correlated with the total CO<sub>2</sub> emissions allowed in the 1990-2010 period. The amount of renewable energy consumption is higher the faster the reductions are imposed

(equivalently, the lower the carbon constraint). CO<sub>2</sub> emissions reductions are largely obtained by shifts from fossil to non-carbon resources, rather than by reductions in end-use demand.

Table 3. Primary Energy Consumption For a 20% Reduction by 2010

	Scenario 1 (Linear)		Scenario 2 (Deferred)		Scenario 3 (Slower than Linear)		Scenario 4 (Faster than Linear)	
	1995	2005	1995	2005	1995	2005	1995	2005
Oil	31.8	28.9	33.1	32.3	32.3	29.5	31.2	28.2
Gas	19.6	18.4	20.4	24.2	19.9	19.2	17.6	17.3
Coal	13.9	11.7	14.8	13.4	14.2	11.8	13.6	11.4
Nuclear	5.6	4.5	5.7	4.6	5.6	4.6	5.6	4.5
Renewables	6.5	20.6	5.5	11.3	6.3	19.8	10.2	22.3
Total	77.4	84.1	19.5	85.7	78.4	84.9	78.2	83.7

#### ALTERNATIVE CO<sub>2</sub> REDUCTION TARGETS IN YEAR 2010

In addition to the 20% reduction scenario, we analyzed four other scenarios to study the impact of alternative reduction targets by the year 2010:

- Scenario 5 stabilizes CO<sub>2</sub> emissions at 1990 levels through 2030.
- Scenario 6 reduces CO<sub>2</sub> emissions by 5% by 2010, with a linear path between 1990 and 2010. After 2010, emissions are stabilized at the 2010 level.
- Scenario 7 reduces CO<sub>2</sub> emissions by 10% by 2010, with a linear path between 1990 and 2010. After 2010, emissions are stabilized at the 2010 level.
- Scenario 8 reduces CO<sub>2</sub> emissions by 15% by 2010, with a linear path between 1990 and 2010. After 2010, emissions are stabilized at the 2010 level.

Table 4 and Figure 4 display the CO<sub>2</sub> constraints used.

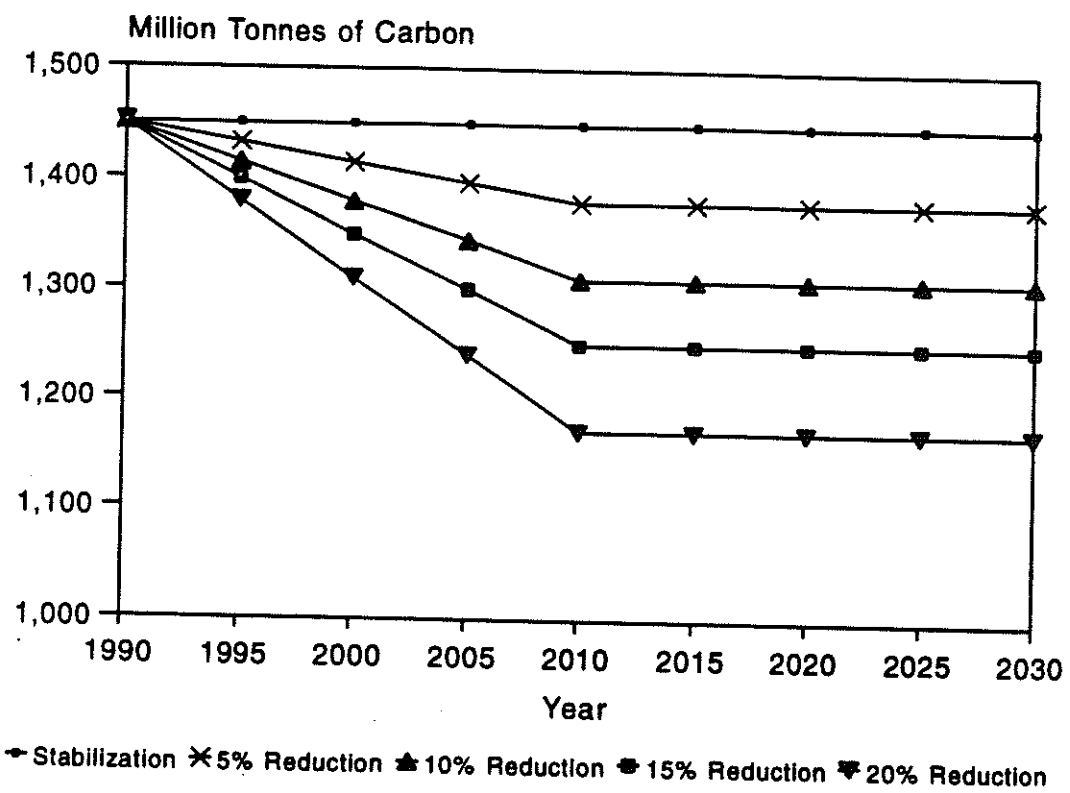


Figure 4. CO<sub>2</sub> Constraints for Stabilization and 5 to 20% Reduction by 2010

Table 4. CO<sub>2</sub> Constraints For 5 TO 15% Reduction by 2010  
(Million Tonnes of Carbon)

Year	Scenario 6 (5% Reduction Linear)	Scenario 7 (10% Reduction Linear)	Scenario 8 (15% Reduction Linear)
1990	1450	1450	1450
1995	1433	1415	1400
2000	1415	1380	1350
2005	1397	1345	1300
2010	1380	1310	1250
2015	1380	1310	1250
2020	1380	1310	1250
2025	1380	1310	1250

As would be expected, a larger emissions reduction by 2010 implies a greater cost impact on society, and higher carbon taxes are required to achieve such reductions. Figure 5 shows the tax rates required to achieve each of these scenarios. What is perhaps less intuitive is that the tax rates needed to keep emissions stabilized after 2010 (at each of the five alternative levels) are relatively low with a slow rate of increase, and do not seem to have significant differences even though the CO<sub>2</sub> constraints are different. That is, the tax rates needed to maintain the status quo after 2010 is independent of what the status quo is as of 2010. The main reasons for this result are:

- The major changes in capital stock and fuel use required to meet each of the 2010 targets have been implemented by 2010; beyond 2010 the carbon tax is serving primarily to maintain the status quo as of 2010.
- A non-zero tax is still needed to provide incentives for the use of non-carbon technologies for both new (given slow growth in end-use demand) and replacement capacity.

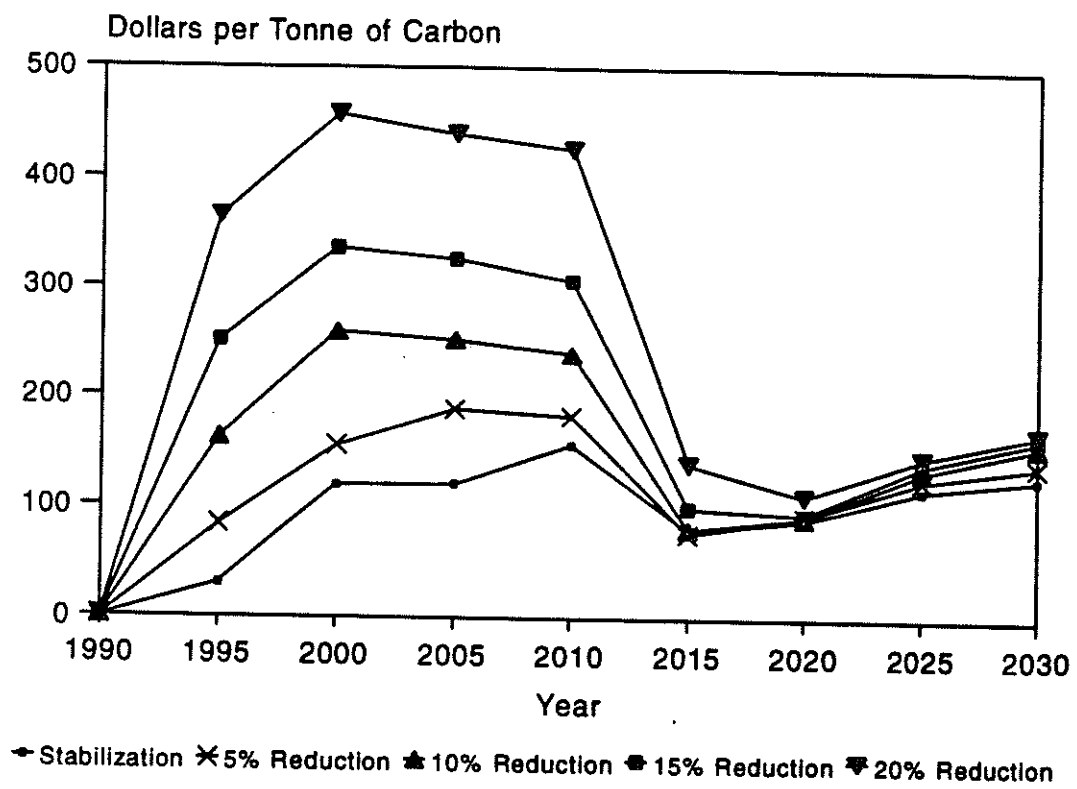


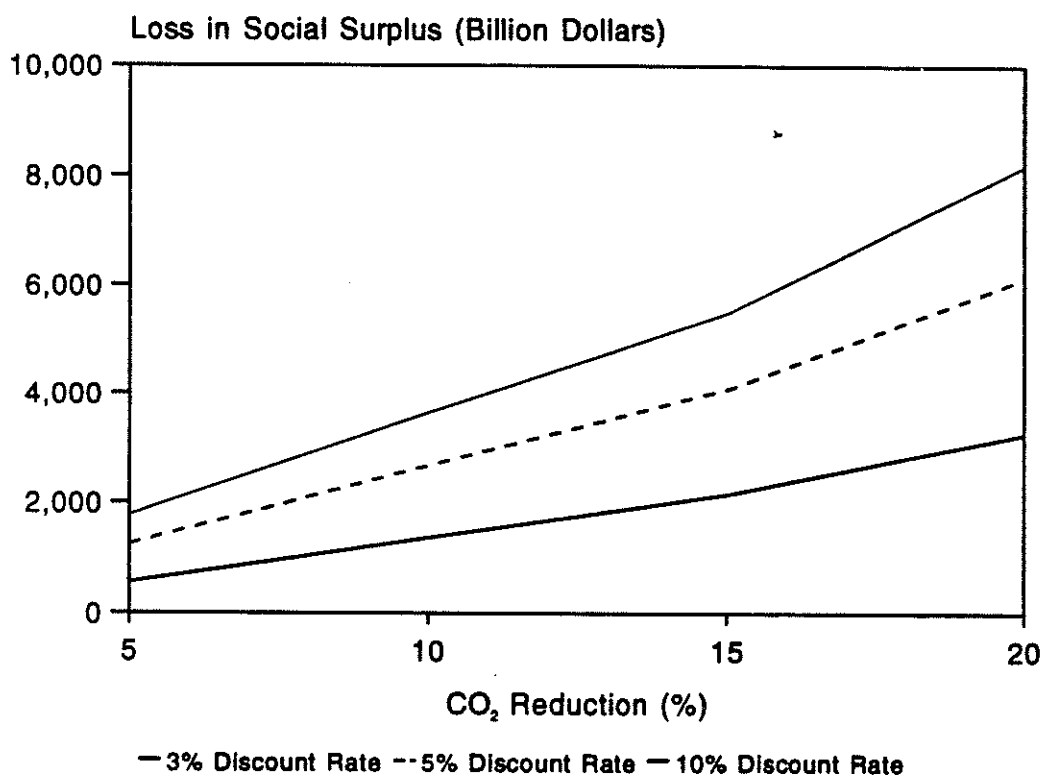
Figure 5. Tax Rates for Stabilization and 5 to 20% Reduction by 2010

- In each of the scenarios, the post-2010 carbon taxes are primarily serving to prevent an increase in CO<sub>2</sub> emissions above the level reached by 2010. At the margin, this is the same goal for all levels of reduction; thus the carbon tax required after 2010 is essentially the same for all five scenarios.

An interesting result is that the cost of achieving an emissions target by 2010, as measured by the change in social surplus, is nonlinear with respect to the targeted reduction. As shown in Table 5 and Figure 6, the marginal loss of social surplus is greater when the target is changed from 15% to 20% than was observed for the zero to 15% increments. This is explained by the fact that to meet a given CO<sub>2</sub> constraint, renewable energy sources must be made more cost-competitive via, in part, the carbon taxes. But if the CO<sub>2</sub> constraint is tighter, then more renewable sources have to become cost-competitive. The cheaper renewable technologies are introduced first, while the more expensive renewable technologies are introduced when taxes and prices are higher. Thus, accelerating the use of renewables results in higher marginal costs for greater CO<sub>2</sub> reductions. A similar effect was found for the maximum carbon tax rate needed to achieve each level of emissions reduction. Table 5 and Figure 6 show the change (from the base case) in the present values of the social surplus and the levelized costs.

Table 5. Present Value of change in Social Surplus and Levelized Costs for Stabilization and 5 to 20% Reduction by 2010 (Billion Dollars)

Discount Rate	Stabilization		5% Reduction, Linear		10% Reduction, Linear		15% Reduction, Linear		20% Reduction, Linear	
	Total	Level	Total	Level	Total	Level	Total	Level	Total	Level
3%	-566	-22	-1768	-70	-3634	-144	-5482	-217	-8185	-324
5%	-344	-18	-1248	-67	-2677	-143	-4091	-219	-6135	-329
10%	-61	-6	-556	-51	-1357	-125	-2149	-198	-3262	-301



**Figure 6. Loss In Social Surplus for Different Reduction Targets and for Different Discount Rates**

In addition to evaluating the linear paths to achieve different reduction targets by 2010, we analyzed other scenarios with gradual reductions (with initially slower-than-linear reductions) to achieve the same reduction targets by 2010. We found similar results as before: a slower-than-linear reduction has a lower social cost impact but requires a higher maximum tax rate than a linear reduction for the same target by 2010. Figure 7 shows the maximum tax rate for the different CO<sub>2</sub> emissions reduction target by 2010 with both linear and slower-than-linear paths of reduction.

In terms of primary energy consumption, as would be expected, renewables consumption is correlated with the level of CO<sub>2</sub> reduction targeted by 2010. Imposing linear reductions to achieve the desired targets translates into lower CO<sub>2</sub> emissions in each period, with greater rates of reduction for larger reduction targets by 2010. Lower emissions are achieved in part through accelerated introduction of renewables. Figure 8 shows the consumption of renewables in 2010 for each level of reduction target. Comparing the stabilization scenario (labeled 0% reduction) to the full 20% reduction, the greatest percentage increase is by solar thermal, while the largest absolute increase is for the biomass technologies.

#### ALTERNATIVE DATES AT WHICH A 20% REDUCTION IS ACHIEVED:

##### 20% REDUCTION BY THE YEAR 2015

In order to evaluate the implications of delaying a 20% reduction from 2010 until 2015, we analyzed three scenarios leading to a 20% reduction by 2015:

- Scenario 10 is a linear reduction of CO<sub>2</sub> emissions between 1990 and 2015. After 2015, emissions are stabilized at 2015 level.

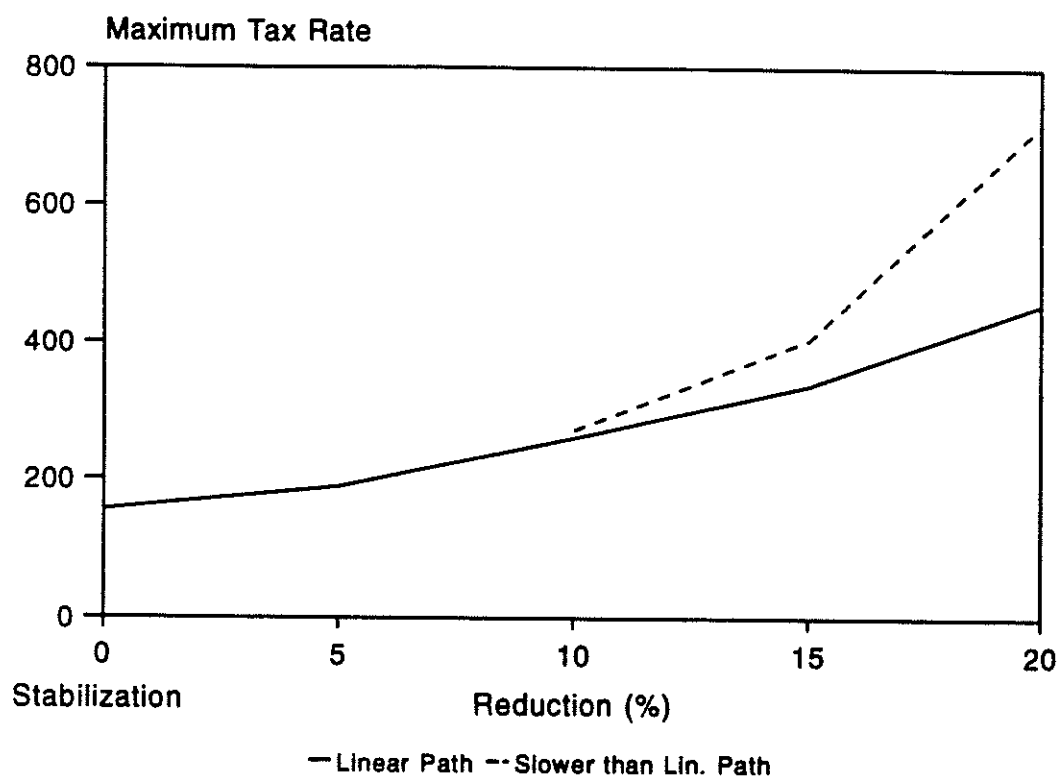
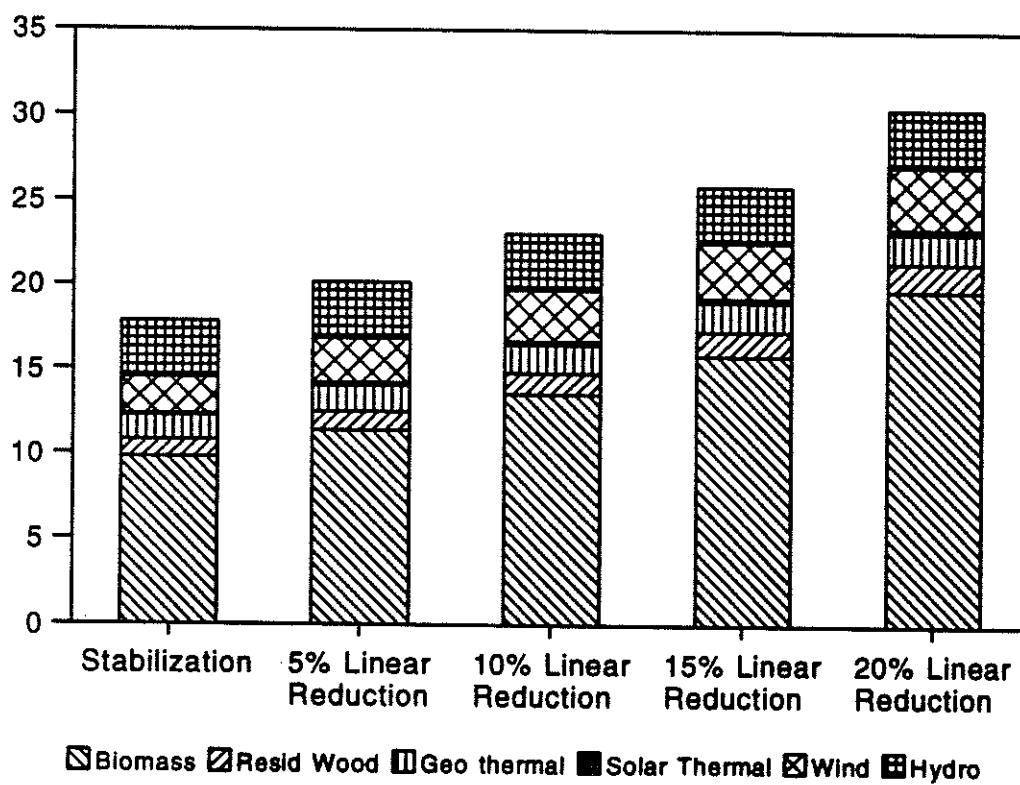


Figure 7. Maximum Tax Rates for Stabilization of CO<sub>2</sub> to 20% Reduction by 2010  
(dollar per tonne of carbon)



**Figure 8. Renewables Consumption in 2010 for Alternative CO<sub>2</sub> Reduction Targets by 2010 (quads)**

- Scenario 11 is a gradual reduction of CO<sub>2</sub> emissions between 1990 and 2015, with reductions in each period greater than or equal to the reduction in the previous period (slower than linear reduction). After 2015, emissions are stabilized at 2015 level.
- Scenario 12 is a gradual reduction of CO<sub>2</sub> emissions between 1990 and 2015, with reductions in each period less than or equal to the reduction in the previous period (faster than linear reductions). After 2015, emissions are stabilized at 2015 level.

Figure 9 displays the CO<sub>2</sub> constraints used. To evaluate the delay from 2010 to 2015, scenario 1 can be compared with scenario 10, scenario 3 with scenario 11, and scenario 4 with scenario 12.

The principal result is that deferring a 20% reduction in CO<sub>2</sub> emissions from 2010 to 2015 can reduce the loss in social surplus by roughly 15% to 25% over the period 1990-2030. However, deferring the 20% reduction from 2010 to 2015 does not necessarily guarantee that the loss in social surplus will be smaller, unless comparable paths are taken to the respective targets. As Table 6 shows, the loss in social surplus is smaller for the slower-than-linear scenario 11 than for the two scenarios with more accelerated reductions. This is analogous to the findings for scenarios 1, 3, and 4 with the 20% reduction by 2010. Comparing the carbon constraints with similar path patterns (e.g., linear to linear, slower-than-linear to slower-than-linear) but different dates to achieve a 20% reduction in CO<sub>2</sub> (2010 versus 2015), we observe that the loss in social surplus is smaller when the 20% reduction is deferred. But, as shown in Figure 10, if a 20% reduction is deferred to 2015, but the path to constrain emissions is, for example linear, then the loss in social surplus will be larger than if the 20% reduction is achieved by 2010, and the emissions constraint is slower than linear. Thus, this reinforces the key conclusion that the path taken to a reduction target can be as important as the level and the timing of the target.

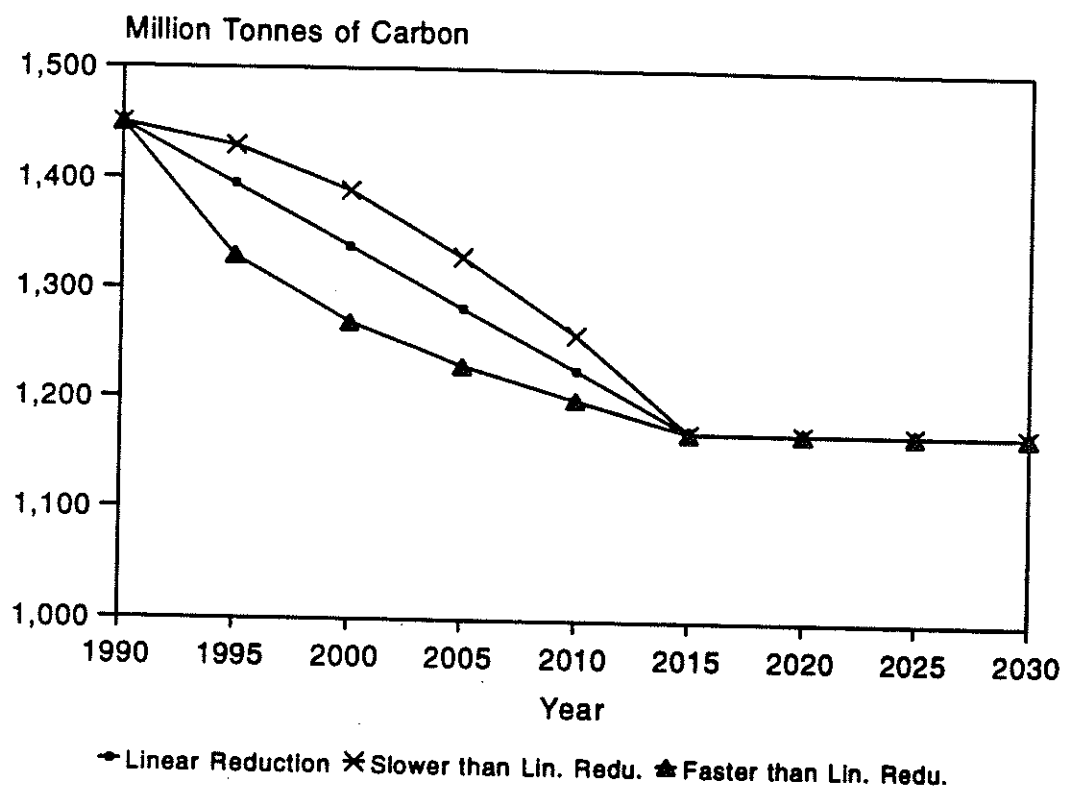


Figure 9. CO<sub>2</sub> Constraints for 20% Reduction by 2015

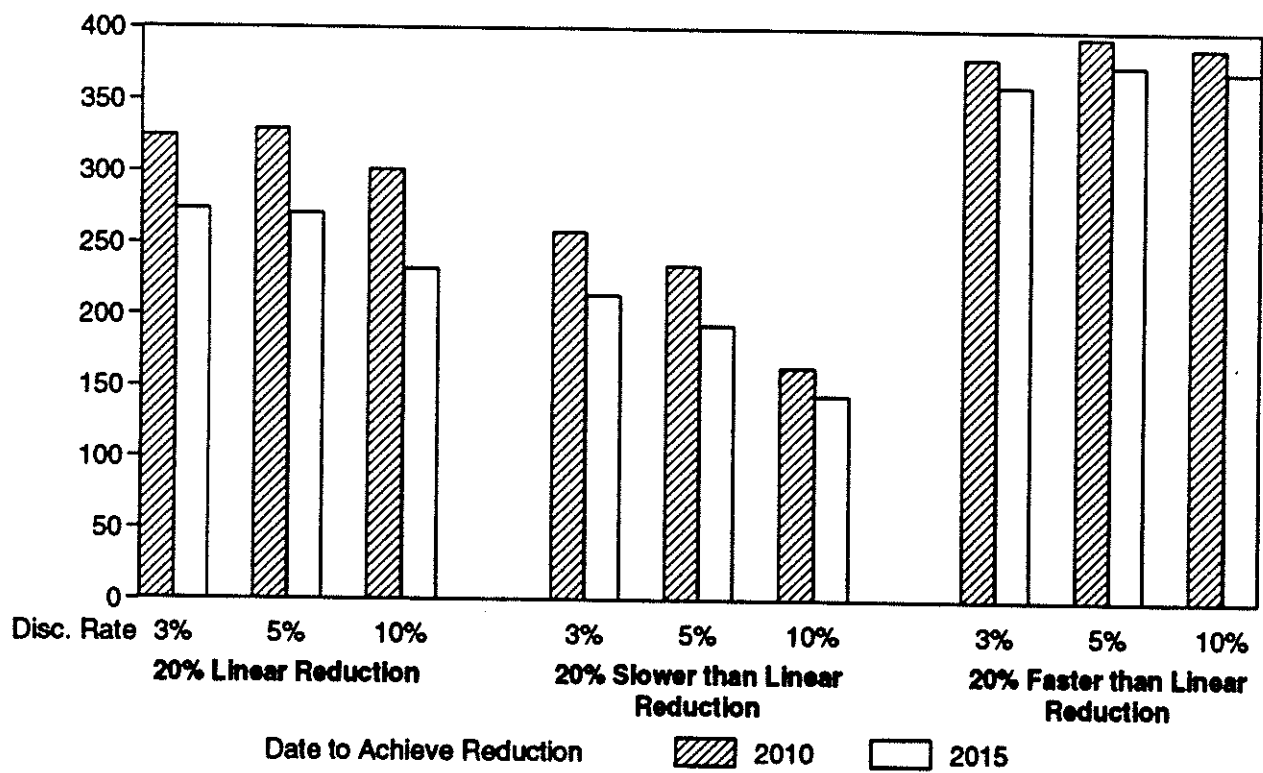


Figure 10. Comparison of Levelized Change in Social Surplus for 20% Reduction by Date (Billion Dollars)

Table 6. Present Value of change in Social Surplus and Levelized Costs for 20% Reduction by 2015 (Billion Dollars)

Discount Rate	Scenario 10 (Linear)		Scenario 11 (Slower than Linear)		Scenario 12 (Faster than Linear)	
	Total	Level	Total	Level	Total	Level
3%	-6861	-272	-5311	-210	-9116	-361
5%	-5044	-270	-3647	-195	-7050	-378
10%	-2559	-236	-1559	-144	-4041	-372

#### DELAYING THE START OF EMISSIONS REDUCTIONS BY 10 YEARS

In order to evaluate the implications of delaying the beginning of emissions reductions by 10 years, we analyzed 3 scenarios that ultimately achieve 20% reductions by 2020. Thus, these paths are identical to those in Scenarios 1, 3, and 4 except that reductions in emissions begin in 2000 instead of 1990. During the years 1990 to 2000, we have constrained the emissions to remain stabilized at 1990 levels.

- Scenario 13 - This path keeps the current level constant for 10 years, then follows a linear path to reducing CO<sub>2</sub> emissions 20% by the year 2020. This corresponds to Scenario 1 with a 10-year delay.
- Scenario 14 - This path keeps the current level constant for 10 years, then follows a slower than linear path to reducing CO<sub>2</sub> emissions 20% by the year 2020. This corresponds to Scenario 3 with a 10-year delay.
- Scenario 15 - This path keeps the current level constant for 10 years, then follows a faster than linear path to reducing emissions 20% by the year 2020. This corresponds to Scenario 4 with a 10-year delay.

Figure 11 displays the CO<sub>2</sub> constraints used. Figure 12 shows a graph of the carbon tax required for each of these scenarios.

In each case, the required tax rates are typically 10-25% lower than the scenarios in which there was no delay in emissions reductions. If we shifted each of the new scenario graphs back 10 years, we find that the tax rates are generally below the corresponding prior scenario value. This is because many of the renewable technologies have become more cost competitive so less incentive (i.e., tax) is necessary to induce their use. Figure 13 shows a comparison of the carbon tax rate for the linear and delayed linear scenarios. Note that at the point after the 20% target is reached, the carbon tax reaches an equilibrium level. This level is very close to the prior scenarios at \$150/tonne of carbon.

For the delayed scenarios, the smallest maximum tax rate occurs for the slower than linear path (Scenario 15). In the scenarios without a delay, the smallest maximum tax rate was for the linear path (Scenario 1). There are two main reasons for this:

- Renewables have become significantly more cost competitive in the years 2010 and 2015 when the largest reduction is required in the slower than linear path. Thus, less incentive (less tax) is necessary to induce substitution to renewables. As a result, the carbon tax increase in the slower than linear delayed scenario is not as pronounced as the peak carbon tax in the original slower than linear scenario.
- Stabilizing emissions in the delayed scenarios for the years 1990 to 2000 induces more capital turnover than would have occurred if the level of emissions was not constrained. As a result, less capital changes are necessary during the years of large reductions for the slower than linear path. Thus, less tax incentive is necessary.

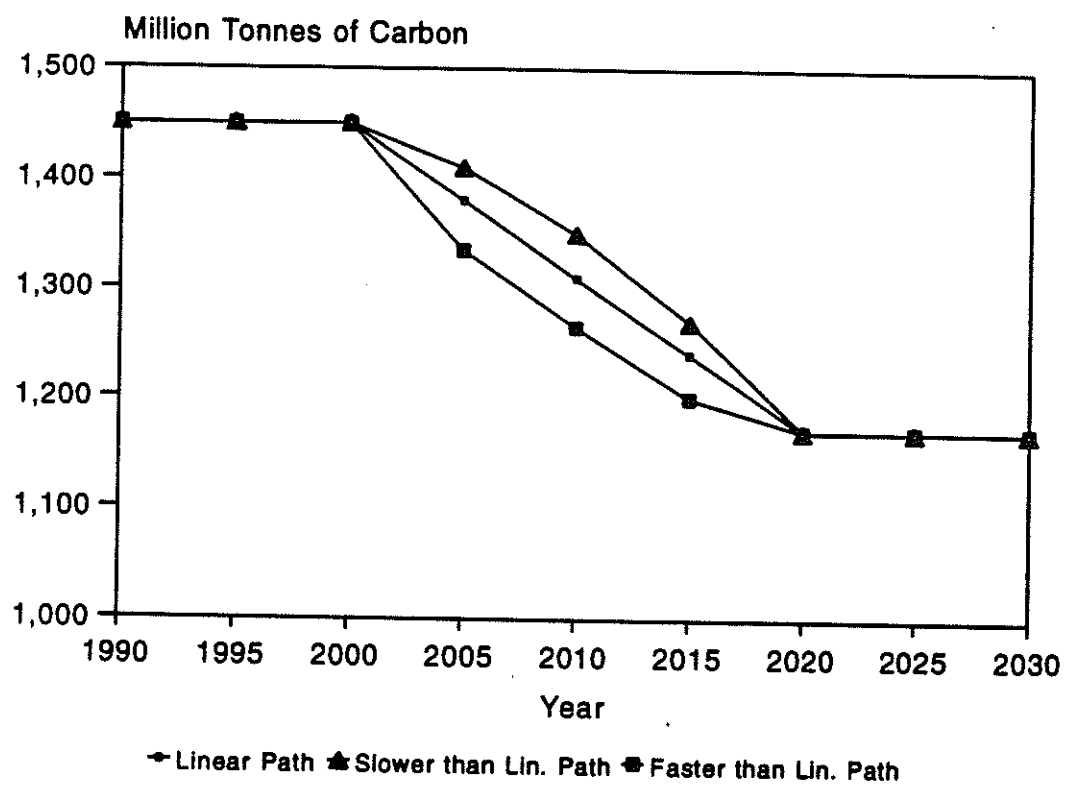


Figure 11. CO<sub>2</sub> Constraints for 20% Reduction from 2000 to 2020

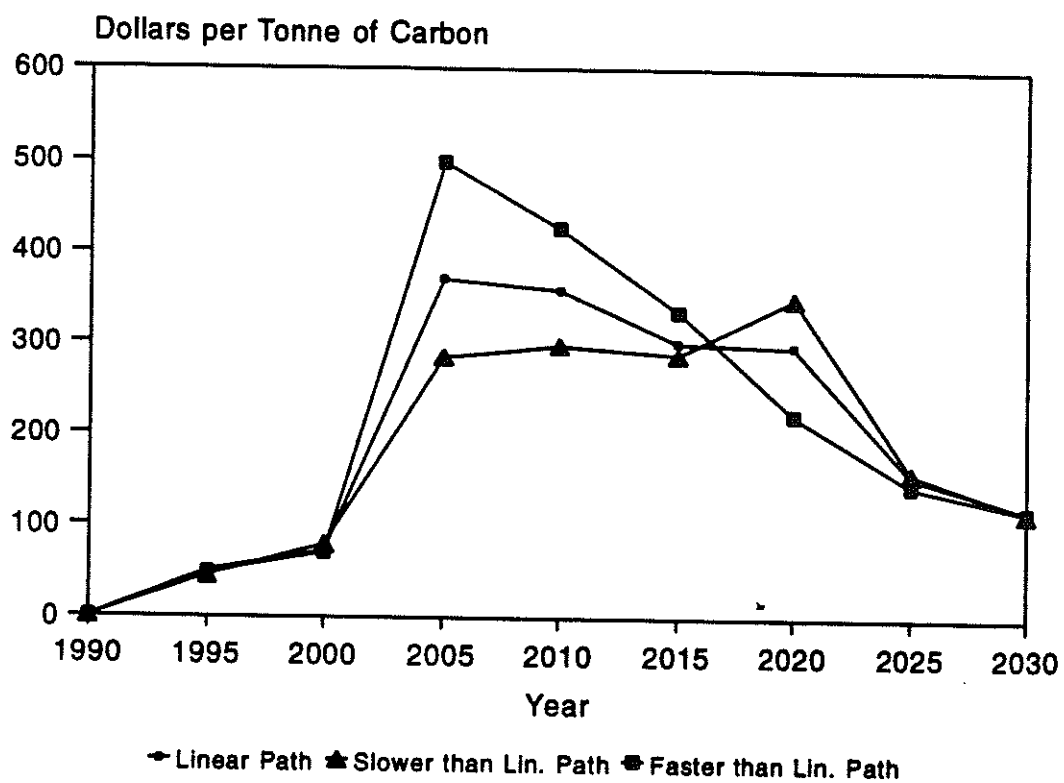
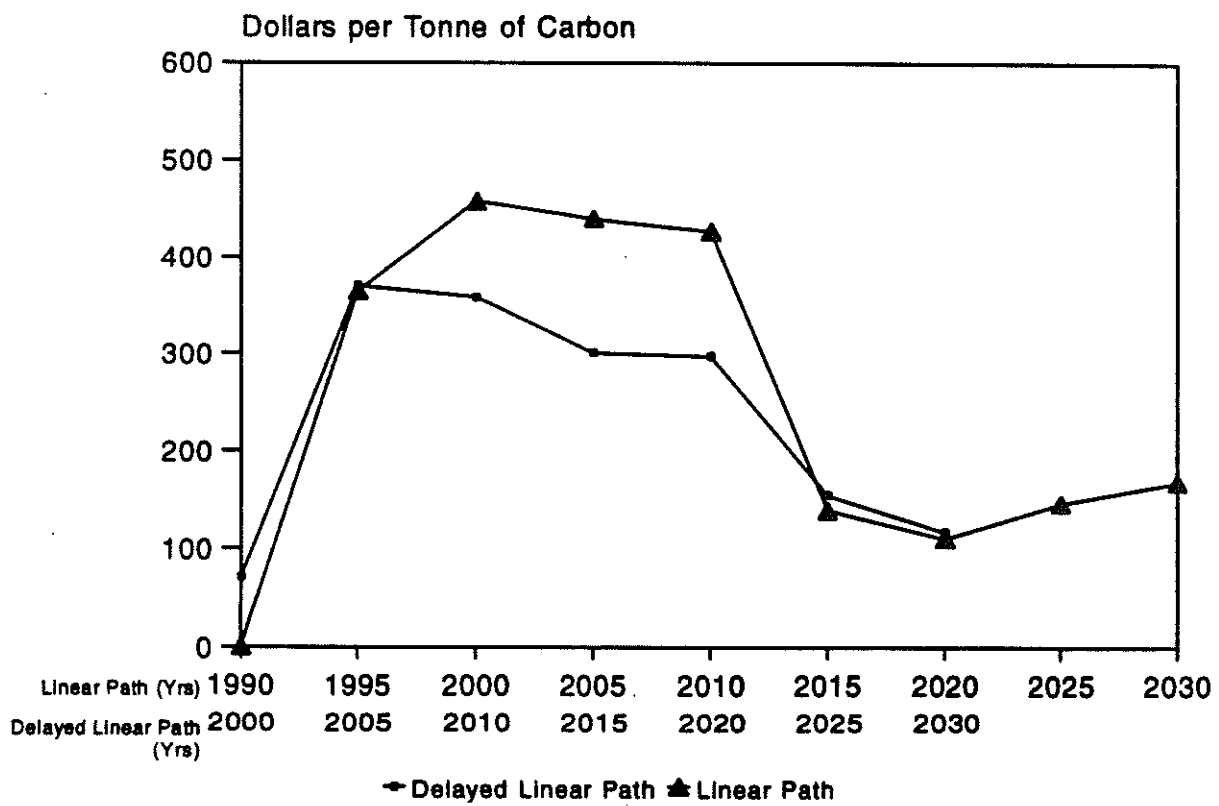


Figure 12. Tax Rates for 20% Reduction from 2000 to 2020



**Figure 13. Linear Path and Delayed Linear Path Scenarios**

Table 7 shows the present values of the change in social surplus (as compared to the base case) for these delayed scenarios. Also shown is the extent to which the loss in surplus is reduced by the 10-year delay, for each pair of corresponding paths.

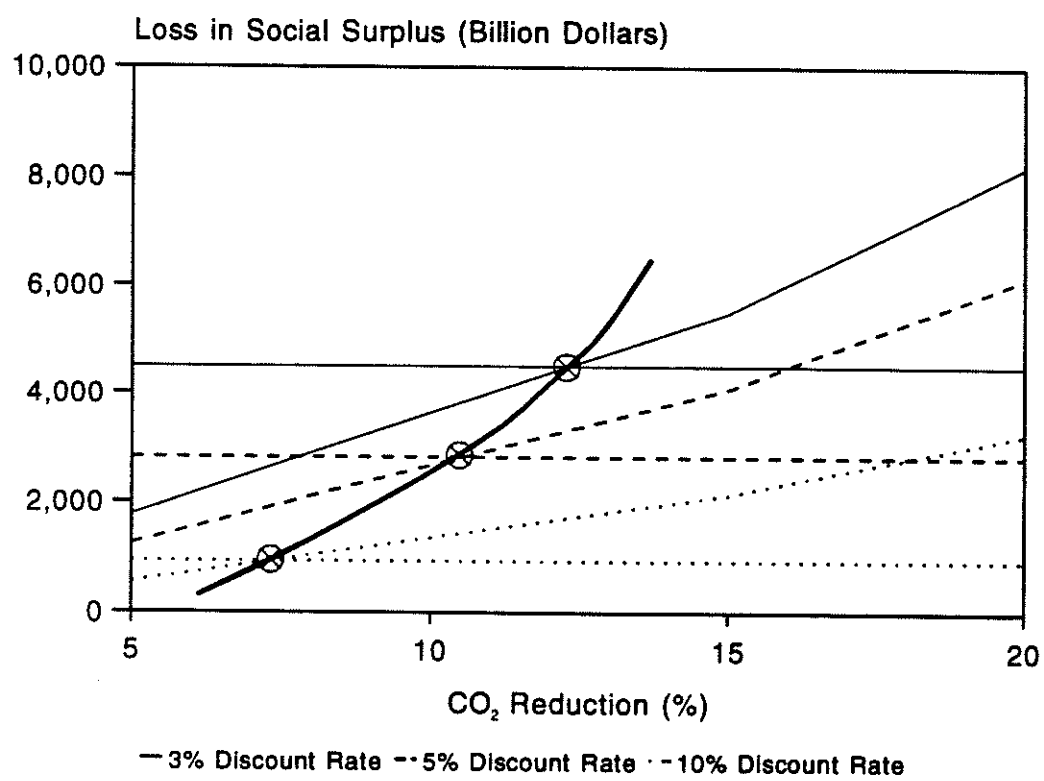
Table 7. Present Value of change in Social Surplus for 20% Reduction

Discount Rate	Scenario 13 (Linear)	Percent of Scenario 1	Scenario 14 (Slower Than Linear)	Percent of Scenario 3	Scenario 15 (Faster than Linear)	Percent of Scenario 4
3%	-4481	54.6%	-3910	59.9%	-5237	54.6%
5%	-2823	46.1%	-2397	54.1%	-3386	45.7%
10%	-933	28.6%	-732	41.3%	-1191	28.2%

As expected, the losses in social surplus for the delayed scenarios are smaller than the scenarios without a delay for all three discount rates. This is due to two main factors:

- The tax is implemented further in the future, thus making the present value of the losses smaller.
- Newer technologies have had longer to evolve and have become more cost competitive on their own thus decreasing the social cost of making these technologies viable in the market place.

One additional observation can be made by comparing the delayed with the original scenarios. Suppose one chooses to maintain a certain level of loss in social surplus. What degree of linear emissions reduction starting in 1990 will result in the same loss in social surplus as will a 20% linear reduction in emission that is delayed by 10 years? At a discount rate of 3%, delaying a 20% reduction by 10 years is equivalent to a 12.5% linear reduction from 1990 to 2010. At a discount rate of 5%, delaying 10 years is equivalent to a 11% linear reduction from 1990 to 2010. At a discount rate of 10%, delaying 10 years is equivalent to a 7.5% linear reduction from 1990 to 2010. Figure 14 captures this observation.



**Figure 14. Comparison of Loss in Social Surplus for Different Reduction Targets and Delayed 20% Reduction for Different Discount Rates**

In Figure 14, the line drawn through the point of intersections captures the effect of the discount rate on the change in social surplus between delaying 10 years and not delaying. The fact that this line is upward sloping implies that decreasing the discount rate makes the scenarios without a delay relatively more attractive than the delayed scenarios.

## DIFFERENT PATHS WITH EQUIVALENT CUMULATIVE EMISSIONS

It may be noted that Scenarios 1, 3 and 4 each have different *cumulative* emissions reductions over the period from 1990 to 2030. The faster than linear path has the greatest reduction in cumulative emissions, while the slower than linear path has the least reduction. In other words, the area under each CO<sub>2</sub> constraint path is different. To compensate for this difference, two new CO<sub>2</sub> emissions constraint paths were evaluated. The first further constrains CO<sub>2</sub> emissions of the slower than linear path during the years 2010 to 2030 such that the cumulative emissions of this new path equals the cumulative emissions of the linear path (Scenario 1). The second reduces the constraint on CO<sub>2</sub> emissions for the faster than linear path during the years 2010 to 2030 such that the cumulative emissions for this new path also equals the cumulative emissions for the linear path. As a result, the area under each of the new constraint paths equals the area under the linear constraint path; all three have the same cumulative emissions over the 1990 to 2030 periods. The new scenarios are defined as follows:

- Scenario 16 - This path follows the slower than linear path (Scenario 3) for the years 1990 to 2010, but during the years 2010 to 2030 falls below the constant value of Scenario 3 such that the cumulative emissions reduction from 1990 to 2030 equals the cumulative emissions reduction of the linear path.
- Scenario 17 - This path follows the faster than linear path (Scenario 4) for the years 1990 to 2010, but during the years 2010 to 2030 falls above the constant value of Scenario 4 such

that the cumulative emissions reduction from 1990 to 2030 equals the cumulative emissions reduction of the linear path. Figure 15 displays the CO<sub>2</sub> constraints used.

Of primary concern in the new scenarios is the present value of social surplus relative to the linear path. The question becomes, "Does the slower than linear path with cumulative emissions equal to the linear path still have the least present value of social cost?" The answer is "Yes." As seen in Table 7, the present value of social costs is still lowest for the slower than linear path and highest for the faster than linear path. However, as would be expected, the cost savings for the slower than linear path (as compared to the linear path) is reduced (by 10 to 30 percent depending on the discount rate).

Table 7. Present Value of Social Surplus and Levelized Cost  
For Scenario 16, Scenario 17, And the Linear Path

Discount Rate	Scenario 1 (Linear)		Scenario 16 (New Slower than Linear)		Scenario 17 (New Faster than Linear)	
	Total	Level	Total	Level	Total	Level
3%	-8185	-324	-7395	-302	-9424	-384
5%	-6135	-329	-5299	-298	-7319	-412
10%	-3262	-301	-2531	-257	-4211	-427

Figure 16 displays a comparison of the carbon tax rates required for Scenario 16 relative to those needed for Scenario 3. For the years 1990 to 2010, the required carbon tax for Scenario 16 is essentially equivalent to that of Scenario 3. For the years 2010 to 2030, the carbon tax required for the new slower than linear path, Scenario 16, is somewhat higher than Scenario 3 to induce a greater reduction in emissions during these years. It is interesting to note that in Scenario 16, the carbon tax rate converges to the level of Scenario 3 at ~\$150/ton carbon. This result parallels the discussion above regarding alternative CO<sub>2</sub> emissions reduction targets in the

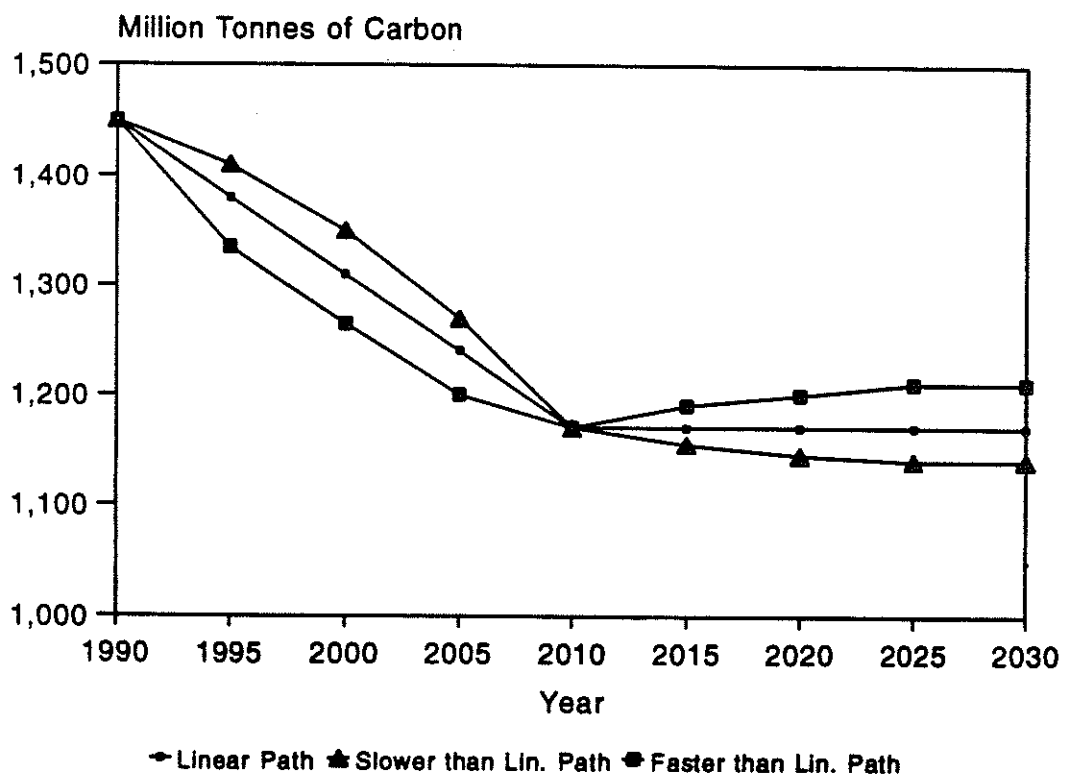


Figure 15. Alternative Constraint Paths with Equivalent Cumulative Emissions

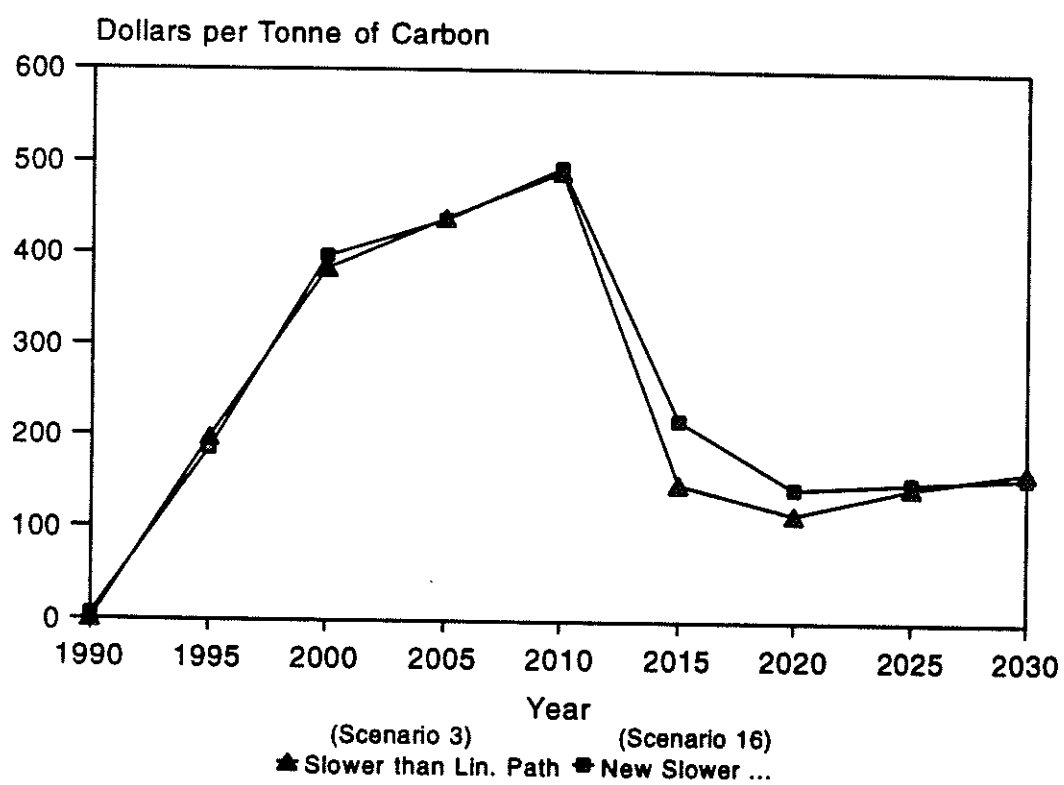


Figure 16. Carbon Tax Rates of Scenario 3 Versus Scenario 16

year 2010; when emissions were stabilized at a certain target level, the carbon tax rates necessary to maintain this level converge to a single value independent of the target level.

## CONCLUSION

The principal result of this set of analyses is that the nature of a CO<sub>2</sub> emissions constraint path (e.g., the rate of reduction over time) can have a significant impact on the costs of meeting such a constraint. Starting with gradual emissions reductions, delaying the date of an emissions reduction target, and/or delaying the start of emissions reductions can all reduce the social costs of such emissions reductions considerably. In some cases, the cost savings achieved by modifying the path of emissions reductions over time can exceed the savings achieved by setting a less ambitious target for the ultimate level of emissions reduction.<sup>2</sup>

These results reflect, in part, the challenges of inducing significant structural changes and capital stock adjustments in the U.S. economy over a relatively short period (relative to the average useful life of much of society's capital stock). The results also reflect the fact that most low-or zero-carbon emission energy technologies are not yet cost-competitive with conventional options, but several are expected to reach a competitive price/performance level early in the next century.

We believe these results should be of interest to policymakers and policy analysts alike. For policymakers, the key point is that debate over mitigation policy options should fully reflect the time-pattern of costs and benefits, not just a simple emissions reduction target percentage. Policy analysts should endeavor to explicitly address technological change and capital stock turnover phenomena in analyses of CO<sub>2</sub> emissions reduction alternatives.

## ENDNOTES

1. Only in the world of global climate change discussions and debate is a 20 to 30 year time horizon referred to as the "short-term!"
2. Of course, *any* choice of CO<sub>2</sub> emissions reduction policy should not be made on the basis of the cost of such a policy alone; rather, the costs must be balanced against the benefits which are likely to be gained.