RESULTS FROM THE GEMINI ENERGY-ENVIRONMENTAL MODEL

WP 12.18

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January 1993

Energy Modeling Forum
Terman Engineering Center
Stanford University
Stanford, California

ANALYZING STRATEGIES FOR REDUCING GREENHOUSE GAS EMISSIONS: THE GEMINI ENERGY-ENVIRONMENTAL MODEL[1]

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INTRODUCTION

The GEMINI energy-environmental model was developed by Decision Focus Incorporated (DFI) and the U.S. Environmental Protection Agency (EPA) using DFI's Generalized Equilibrium Modeling System (GEMS). The modeling effort was initiated in mid-1990, so that an initial working version of the model for EMF-12 had to be developed from first principles within only a few months. The time commitments associated with EMF-12 were possible to meet because of the model development and analysis capabilities provided by the GEMS system, supported by extensive energy system and technology detail available at DFI from many previous energy modeling and decision analysis efforts.

The GEMINI modeling effort thus has been one of rapid growth and evolution substantially linked to the demands of the EMF-12 process, while simultaneously supporting the fast-response analysis needs of the EPA. Substantial additional work is desirable that was not possible within the context of EMF-12, including enhancements to GEMINI's scope and detail, data updating, and further sensitivity and policy analyses. Many of these efforts are proceeding following the completion of EMF-12. This report summarizes the analyses completed as part of EMF-12, and insights gained by the GEMINI team as an outgrowth of its participation.

OVERVIEW OF GEMINI

Models participating in EMF-12 covered a range of capabilities, and had various specialized applications related to climate change policy analysis. GEMINI can best be described as providing analytical strengths focused on energy production and use in the U.S. and the associated impacts on the global environment. The "twins" that the model name refers to are the energy economy and the environment. Figure 1 provides an overview of the model components of GEMINI, which include a highly detailed U.S. energy-economy sector, a simplified U.S. agricultural sector, a global environment sector, and a representation of emissions from the rest of the world. The energy-economy sector includes four primary resource sectors (oil, gas, coal, and renewable), an electric generation and distribution sector, and four end-use sectors (residential, commercial, industrial, and transportation). Each of these sectors contains considerable technological and market detail, as will be discussed in the next section. Greenhouse gas emissions are calculated from each of the sectors. The agricultural sector was included due to its emissions, and also because of its potential role in producing alternative fuels.

Unlike most economic models, GEMINI is fully integrated with the environment component. Emissions from economic activities affect the environment, and in turn, environmental outcomes can affect economic activities.[2] However, GEMINI is a U.S. policy model only; although non-U.S. emissions are included in the model, there is no explicit representation of economic activity beyond the U.S.

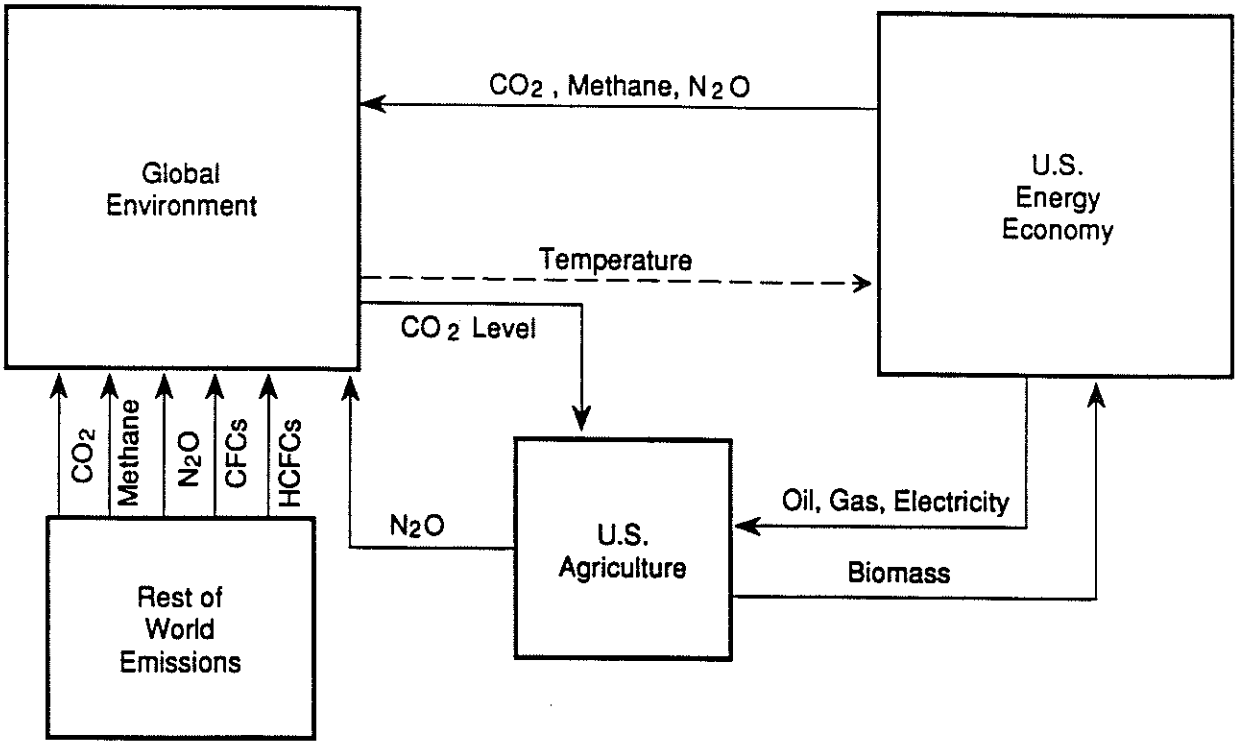

Figure 1. Overview of GEMINI Model Components

Energy use pervades all activities of the U.S. economy, and thus all of the key economic sectors are represented. In comparison to other models used in EMF-12, GEMINI includes considerable detail on end-use technologies and on the use of energy services, as well as on the supply of energy resources, production volumes, and product prices. Thus GEMINI has a strong grounding in the technologies used for providing energy services, both at the end-use level and at intermediate levels such as power generation and oil refining.

This engineering detail is the strength of GEMINI. In turn, GEMINI does not have an explicit macroeconomic capability. The energy flows of the entire U.S. economy are represented, but because non-energy product flows are not represented, it is not straightforward to extrapolate to macroeconomic variables such as GNP, interest rates, or balance of trade. Tax revenues from specific greenhouse control policies can be calculated, but detailed effects of different tax revenue recycling options beyond the energy sector cannot. GEMINI is therefore best categorized as a large-scale technology-based model, one that is founded on microeconomic theory. In contrast to many technology-based models, GEMINI is not solved using optimization techniques, nor is there an overall objective function. Rather, GEMINI reflects the market equilibrium interactions of all of the individually-optimizing agents (producers and consumers) in the energy-economy.

A key characteristic of GEMINI is that its economic behavior is forward-looking. That is, future prices for energy products and services, and future demand levels at those prices, are anticipated by producers. These future outcomes are then incorporated into capital investment decisions, and reflected in technology choice decisions. This can be contrasted with behavioral models where decisions are made based only on current price conditions, or based on current prices as well as previous decisions. Such "myopic" models tend to show more erratic behavior, especially when not tied to previous decisions.

Finally, economic behavior in GEMINI reflects the vintage structure of the capital stock at any point in time. When prices change, a new mix of equipment may become desirable, but early replacement of existing equipment will only occur as rapidly as is warranted given a comparison of the full lifecycle costs of new versus existing equipment. This helps ensure realistic behavior in response to price shifts, in contrast to the unrealistic shifts that are found in models that allow the full capital stock to be adjusted in a single period. Capital-vintaged models are thus well-suited for analyses of how a new equilibrium will be attained over time, in response to some major new policy action.

Overview of Policy Options

Many models participating in EMF-12 have only carbon dioxide emissions included in their calculations. GEMINI was constructed with a goal of being able to address a comprehensive approach to climate change policy. As such, it includes endogenous calculations of emissions of methane and nitrous oxides as well as carbon dioxide. It also has exogenous projections of CFCs and HCFCs. Also, because GEMINI includes a projection of global environmental responses to U.S. energy policies, emissions of greenhouse gases from the rest of the world are included exogenously.

EMF-12 was designed to address a variety of potential policy options for reducing greenhouse gas emissions, as well as implementation considerations for specific policies, such as timing of taxes or other actions, revenue recycling, and the market level for tax imposition. Central to these options was identifying the tax rate necessary to achieve a range of specific CO_2 reduction goals. EMF-12 scenarios centered around a carbon tax applied only to CO_2 emissions, since this was the capability available in most models.

GEMINI was able to address a large portion of the EMF-12 policy options. The economic and environmental responses to several types of taxes have been addressed. These include carbon taxes, carbon-equivalent taxes (on all types of greenhouse gases), CO_2 taxes (on CO_2 emissions only), Btu-based energy taxes, and ad valorem taxes. Further, because of the sectoral detail, GEMINI has been used to investigate the effect of imposing such taxes as different levels of the economy. It can also be used to address taxes imposed on only specific segments of the U. S. economy.

EMF-12 posed its scenarios in terms of identifying the carbon tax that would achieve specific goals for CO_2 reductions, rather than in terms of the effects of specific tax levels. Some models are designed to answer the former type of question, while others are more suited to analyses posed in the latter form. GEMINI has a unique capability of being able to directly address both policy questions. It can assess the system responses to a specific set of taxes, and it can also directly solve for the time path of taxes necessary to achieve a specific emissions time path goal.

Overview of this Paper

The structure of the GEMINI model, including summaries of technologies and markets induced in each sector, is discussed in the following section. The subsequent section discusses the analyses carried out for EMF-12 using GEMINI, presents key results of these analyses, and summarizes the principal insights obtained. A final section puts the GEMINI analyses in perspective and highlights potentially useful directions for further model development and policy analysis.

STRUCTURE OF THE GEMINI MODEL

With the exception of emissions and environmental processes, GEMINI focuses entirely on the United States. Within the U.S., the emphasis is on energy-economic and agricultural activities, and emissions from these activities. Other U.S. emissions and all emissions from outside the U.S. are treated as exogenous, but are included in calculations of atmospheric concentrations and temperature change.

All currently important energy producing and consuming technologies, and those likely to be important in the 1990-2030 time frame, are explicitly represented. The rationale for including a technology in GEMINI is that it currently accounts for a significant portion of total energy and/or emissions, or might do so in the 1990-2030 time frame. Where it seems likely that significantly more efficient versions of currently-used technologies may gain substantial market share either because they are more economic or because of government intervention, an advanced version of an existing technology is included; examples are advanced/efficient lighting and air conditioners. Aggregation is used where appropriate; for example, while there are 5 or 10 possible ways of gasifying coal, we have included a single coal gasification process in GEMINI. The implicit assumption is that the most economic process will be the one that dominates the market (if coal gasification becomes important); cost and performance parameters represent the most economic process.

Figure 2 shows the energy flows among sectors. Within each sector there is a detailed network of technologies and markets, as described below. The same level of detail is used for supply, conversion, and end-use processes. All energy-economic activities are treated endogenously. The only exception is a time sequence of world oil prices, which is an exogenous input, but the quantity of oil imports to the U.S. is an endogenous model calculation. The level of detail in GEMINI is summarized by Tables 1, 2, and 3 for the energy service demand categories, the electricity generation alternatives, and the renewable energy activities, respectively, in GEMINI.

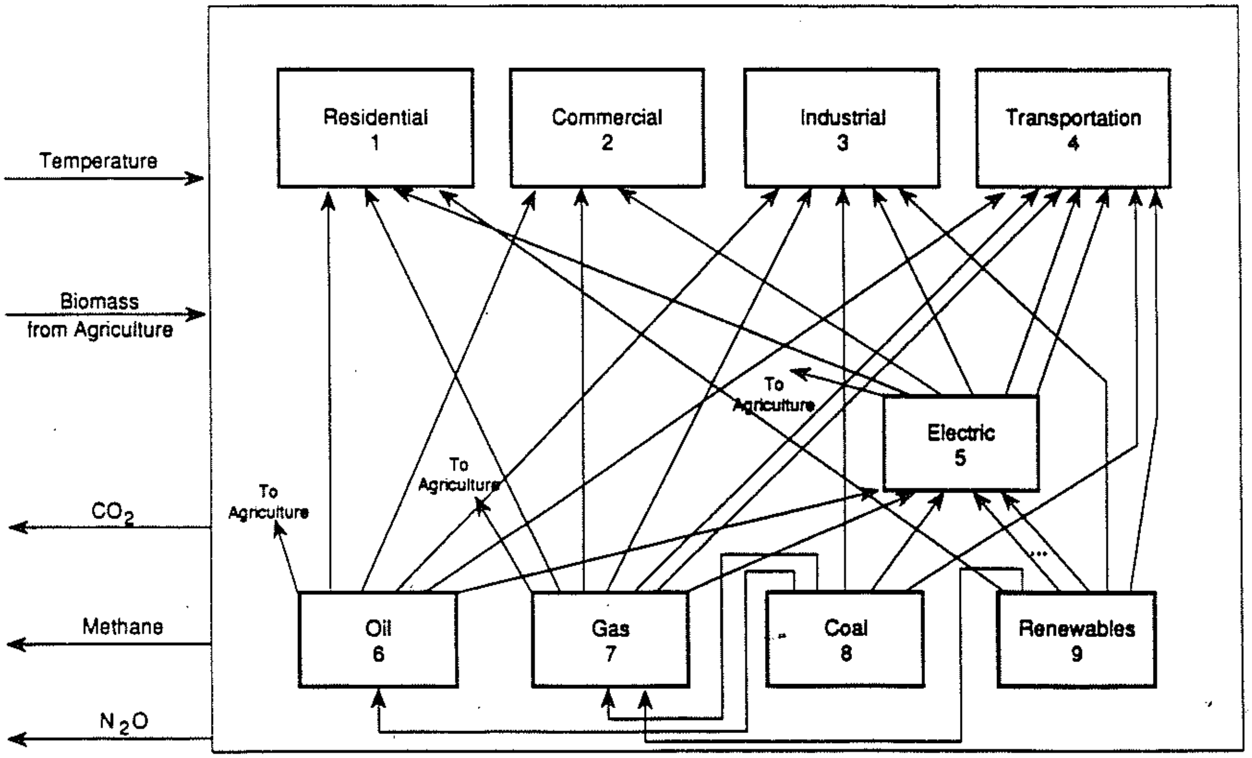

Figure 2. The GEMINI Energy-Economy Submodel Includes Nine Major Sectors

Table 1
FINAL DEMAND CATEGORIES IN GEMINI

<u>Residential</u>
Space Heating and Cooling
Water Heating
Lighting
Appliances
Other Gas (e.g., cooking, clothes drying)

<u>Commercial</u>
Space Heating and Cooling
Lighting
Other Electric (e.g., cooking, office machines)
Other Gas (e.g., cooking)

<u>Industrial</u>
Direct Heat
Indirect Heat
Electromechanical
Feedstocks
Metallurgical Coal

<u>Transportation</u>
Auto
Air
Rail
Truck and Ship

Table 2
ELECTRICITY GENERATING TECHNOLOGIES IN GEMINI

Conventional Nuclear
Advanced Nuclear
Conventional Coal
Advanced Coal
Oil Steam
Conventional Gas Steam
Advanced Gas (ISTIG or combined cycle)
Fuel Cells
Hydroelectric
Crop Biomass
Waste Biomass
Solar Thermal
Photovoltaic
Wind

Table 3
RENEWABLE/NON-FOSSIL ENERGY SOURCES IN GEMINI

Electric	Non-Electric
Hydroelectric	Residential Wood Space Heating
Geothermal	Solar Space Heating
Wind	Industrial Biomass Indirect Heat
Solar Thermal	Ethanol from Biomass
Photovoltaic	Biomass Gasification
Waste Biomass (MSW)	
Crop/Plantation Biomass	

It is important to keep in mind that the final demands ("at the top of the network") are for energy services such as residential space heating or commercial lighting, not for specific forms of energy such as electricity or natural gas. These energy service demands can be satisfied by different technologies and in many cases by different fuels. Changes in demand for individual fuels result from changes in energy service demand, changes in the efficiency of end-use technologies, and changes in market shares of the various technologies. In the case of space heating and cooling, change in energy demand will also result from changes in average building thermal integrity.

End-Use Demand Sectors

For each of the energy services in the residential sector except "other gas," there are multiple end-use technology alternatives that can be used to provide the service. For example, space heating can be provided with conventional or advanced gas furnaces, oil furnaces, electric resistance, solar with electric backup, electric heat pumps, and wood furnaces. Improved efficiency appears to have the greatest potential impact for gas space heating. For this reason, we have chosen to explicitly represent an advanced gas space heating technology with much higher efficiency. The other technologies in the residential sector where technological change is already having, and will likely continue to have, a major impact on energy use via efficiency improvements are lighting and appliances. For both of these, we have explicitly included both conventional and efficient versions. Doing so allows us to better capture the impacts of efficiency improvements, whether mandated or price-driven.

The primary driver of activity in the residential sector is the number of housing units, since all of the energy services included in this sector are building (or household) related. Three levels of building thermal integrity, with price-sensitive choice among them, are represented: the average existing stock, average new construction, and what might be economically possible in the near future. Building thermal integrity is explicitly represented because improving it can substantially reduce the energy used for space heating and cooling. With this representation we can characterize both improvements resulting from higher prices and those resulting from government policies such as mandated building standards.

The commercial sector is very similar to the residential sector, both in end uses and technology alternatives. The primary macro-economic driver is commercial floor space. As in the residential sector, three discrete levels of building thermal integrity are represented. Here they represent systems such as economizers and VAV as well as insulation or tighter construction.

The industrial sector represents all energy use by industry other than that used in the transportation of raw materials or manufactured goods, which is included in the transportation sector. It does not represent factors used in manufacturing goods except energy: it represents the energy-related processes used in producing goods. The five demand categories listed in Table 1 include all industrial energy use. For the first three energy service demands, multiple energy forms (oil, gas, coal, electricity) can be used to provide the service. For electromechanical services, electricity is the only alternative. We have explicitly included a conventional and an efficient electric device technology, because of the significant potential for reducing electricity consumption via such means as adjustable speed drives.

Technologies in the industrial sector include direct and indirect heat via each of the fuels, electric devices, use of metallurgical coal, oil and gas feedstocks, and cogeneration. All of the technologies in the industrial sector provide a single service except cogeneration, which simultaneously produces electricity and steam for indirect heat. This set of technologies and end-uses allows us to test policies such as carbon taxes that favor one fossil fuel over another in addition to reducing total industrial energy consumption via reductions in the price-elastic energy service demands or via more efficient electric devices.

The transportation sector represents all energy used in transporting people and goods, as listed in Table 1. The exception is gas used for pipeline fuel, which is accounted for in the various gas transmission and distribution processes.

For passenger vehicles, the model structure will account not only for the total level of service (vehicle miles), but also the changes in market share among different vehicle fuels as policies affect different fuels by differing amounts. The energy source for almost all transportation is currently oil products, but compressed natural gas, electricity, methanol, and ethanol are possible alternatives.

Electric Sector

The electric sector represents electricity generation from a wide range of existing and future generation alternatives, both fossil and non-fossil (see Tables 2 and 3). It takes as inputs primary resources from the four resource sectors and delivers electricity to the end-use sectors, accounting for the costs and losses associated with transmission and distribution as well as with generation. This is the only portion of the model where regional detail within the United States is incorporated within the model structure. At this point regional detail is used only for solar thermal, photovoltaics, and wind. The reason is that economics and availability of these sources may differ considerably by region, and that these sources may increase dramatically in importance as a result of global climate change concerns. An advanced nuclear technology represents safer, more modular versions of current fission technology. Coal technologies include pressurized fluidized bed combustion (PFBC), more efficient than today's pulverized coal technology. Gas technologies include advanced combined cycle. Fuel cells are included, assumed to be of the molten carbonate type. None of the advanced technologies is assumed to be available at present.

Primary Resource Sectors

Primary resources are supplied from four resource sectors: oil, gas, coal and renewable. Three sources of crude oil are represented: imports, Gulf Coast, and domestic from other locations. The price of oil imports, as delivered to U.S. refineries, is set exogenously. The prices of the other sources, as of all other primary resources in the model, are determined endogenously as functions of the resource base, producer behavior, tax and financial parameters, etc. A refinery process in GEMINI represents the costs and losses associated with converting crude oil into a slate of refined oil products. Synthetic oil, produced by liquefying coal, competes for market share with oil products produced by refining crude.

The gas sector includes gas production, distribution, and the option to convert natural gas to methanol for use as a transportation fuel. Gas sources modeled are conventional and unconventional gas from the lower 48 states, Canadian imports, potential gas from Arctic fields, and LNG imports. The conventional North American gas sources compete for market share with imports of LNG, synthetic gas from coal, and synthetic gas from biomass.

The coal sector includes two domestic sources, East and West, with differing extraction costs and different average costs of transportation. In addition to delivering coal directly to the industrial and electric sectors, three conversion alternatives are represented: methanol production, liquefaction, and gasification. None of these technologies is widely used at present, but each could become important under some scenarios, particularly as conventional oil and gas supplies are exhausted. In the absence of global warming concerns, coal gasification and liquefaction would likely serve as the backstop sources for liquid and gaseous fuels. Gasification and liquefaction, however, would generate much larger quantities of greenhouse gas emissions than would conventional fuels, so that they may not be feasible if major greenhouse gas control literature are implemented.

The renewable supply sector represents the production of fuels from biomass and the potential costs due to siting limits for alternative electricity sources: geothermal, wind, solar thermal, and photovoltaics. Biomass production alternatives include: crops diverted from other uses (e.g., corn for ethanol production) whose production is represented in the agricultural sector; plants grown specifically as biomass energy sources; waste, principally municipal solid waste, used for electricity generation; industrial wastes burned to produce steam, in industries such as paper mills; and wood for residential space heating. The biomass from agricultural crops or plants grown specifically for energy sources can be used either directly for electricity generation, for ethanol production, or gasified to produce synthetic gas that competes with natural gas and synthetic gas from coal.

GEMINI RESULTS: EMF-12 AND ASSOCIATED ANALYSES

In this section we summarize the results of analyses performed with GEMINI as part of the EMF-12 activities. The full details of these analyses, including definition of the scenarios and discussion of detailed results can be obtained from a number of project reports prepared by DFI and EPA throughout EMF-12. These reports are:

- Reassessing the Effectiveness and Cost of Taxes to Reduce CO_2 Emissions (EPA "GEMINI Note", March 1991)
- Improving the Efficiency of Environmental Policy: The Implementation of Strategies to Reduce CO_2 Emissions (EPA, August 1991)
- GEMINI: EMF-12 Study Runs (Round 2) (DFI, August 1991).
- Reducing CO_2 Emissions: Implications of Alternative Paths of Emissions (DFI, May 1992).
- Measuring Changes in Energy Efficiency with GEMINI (Initial DFI Draft, May 1992).

The primary focus of the EMF-12 scenarios was to estimate the carbon tax levels necessary to attain different CO_2 control levels. GEMINI also has the ability to specify taxes at any of a variety of market levels. For example, taxes may be levied on the suppliers of fuels, or on the users of fuels. In a simple, purely competitive market, the results would not differ. However, as we demonstrate below, this is not necessarily the case for a complex situation such as the control of greenhouse gases. For the basic EMF scenarios, carbon taxes were imposed at the primary resource extraction level. As part of the EMF-12 activities, GEMINI was used to illustrate how alternatives to this assumption can affect the results.

Taxes as Function of Stringency of CO_2 Emissions Reduction

For EMF-12, three key emissions reduction scenarios were run and compared to a base case:

I. 20% reduction in CO_2 by 2010 from 1990 levels.

II. 50% reduction in CO_2 by 2050, with levels reduced 20% by 2010.

III. Stabilization of CO_2 at 1990 levels, by 2000.

The second scenario is like the first, but with increasing stringency beyond 2010. The third scenario is the least stringent of all. In the case of Scenario II, the goal of a 50% reduction is achieved beyond GEMINI'S time horizon. We approximated this with a requirement of a 35% reduction by 2030, which is the last model year.

Comparison of model results is complicated by the fact that the necessary tax rate varies over time. Figure 3 illustrates the tax path for each of the three scenarios, and the patterns are as one would expect in comparative terms:

- The lowest taxes are associated with the least stringent Scenario (III).
- Scenarios I and II require similar taxes through 2010, but after that Scenario II taxes remain higher, to achieve further reductions.

Compared to results from other models in EMF-12, several points are worthy to note:

- Taxes peak in the time frame of 2005 to 2010, apparently because of the need to force early retirements of high carbon-emitting technologies to meet the emissions constraints. The later the tax is imposed relative to the target date, the higher taxes must be in the interim to meet that goal.
- For the 20% reduction case, peak taxes are about $600/ tonne carbon. These are relatively high peak values among the EMF-12 models, reflecting the greater behavioral and technological detail modelled in GEMINI.

Policy makers often refer to a carbon tax in terms of a single value that does not vary over time. GEMINI found that the time-constant tax rates to meet each of these emissions targets were $120/tonne carbon for Scenario III, $240/ tonne for Scenario I and $400/tonne for Scenario II. These are also in line with expectations of increasing cost for increasing stringency.

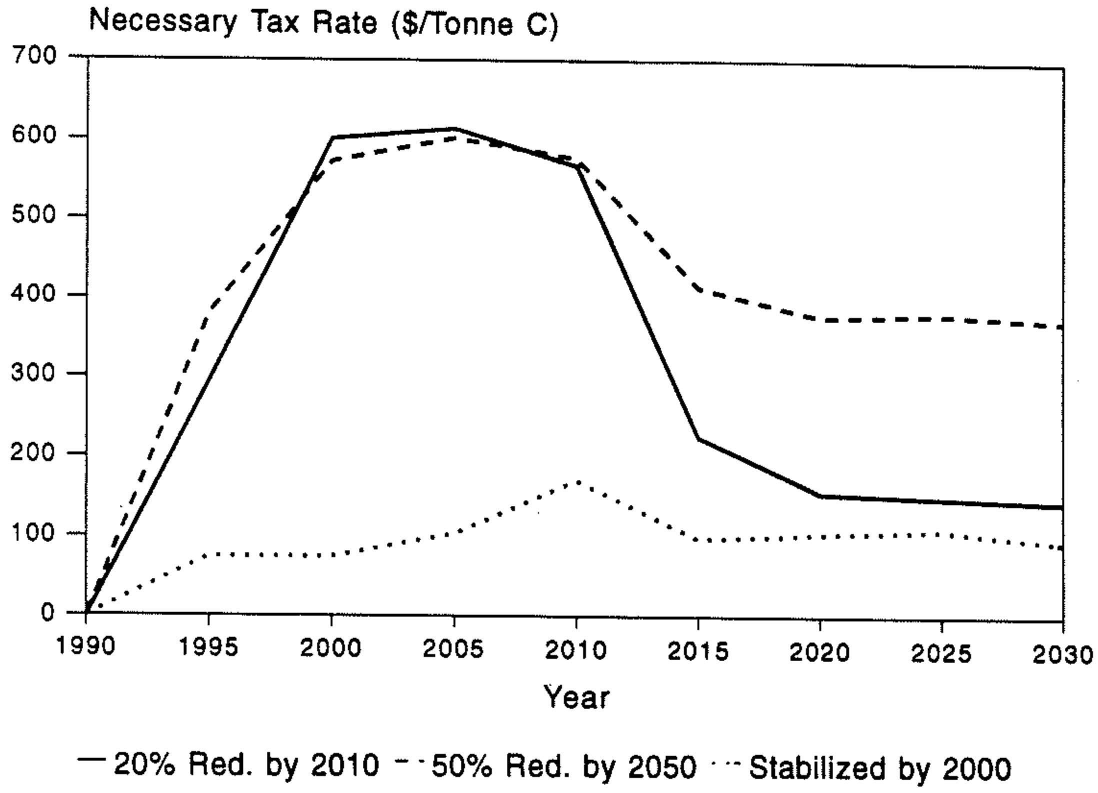

Figure 3. Comparison of Taxes for Three Different CO_2 Emissions Targets

It is difficult to determine from these scenario results whether there is nonlinearity in costs (i.e., cost increasing at an increasing rate with stringency). This is because the three scenarios do not vary along a simple definition of in-creasing stringency; timing of the reductions also varies. An important point is that the correct choice of tax rate will require a very clear definition not only of emissions targets, but also of timing, and of the specific way in which the tax will be imposed.

A set of GEMINI analyses were completed that went beyond the standardized EMF scenarios to address issues of nonlinearity in costs. CO_2 reductions in 2010 (relative to 1990 emissions) of 0% (i.e., stabilization), 5%, 10%, 15%, and 20% were assessed. It was found that costs do increase more rapidly with increasing stringency. Using the change of social surplus as a cost measure (because tax rates are not societal costs *per se*), a greater marginal loss occurred by moving from a 15% to a 20% reduction than in moving in any 5% step from 0% to a 15% reduction. As shown in Figure 4, the tax rates show a similar pattern.

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_2 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 (in terms of emissions) 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.
- In each of the scenarios, the post-2010 carbon taxes are primarily serving to prevent an increase in CO_2 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.

Role of Technology

Another of the standard EMF scenarios (Scenario IV) was to assume accelerated technology conditions, where backstops become available at 50 mills/kwh for electricity and $50/bbl for non-electric energy. Otherwise, the scenario is the same as Scenario I (i.e., 20% reduction by 2010).

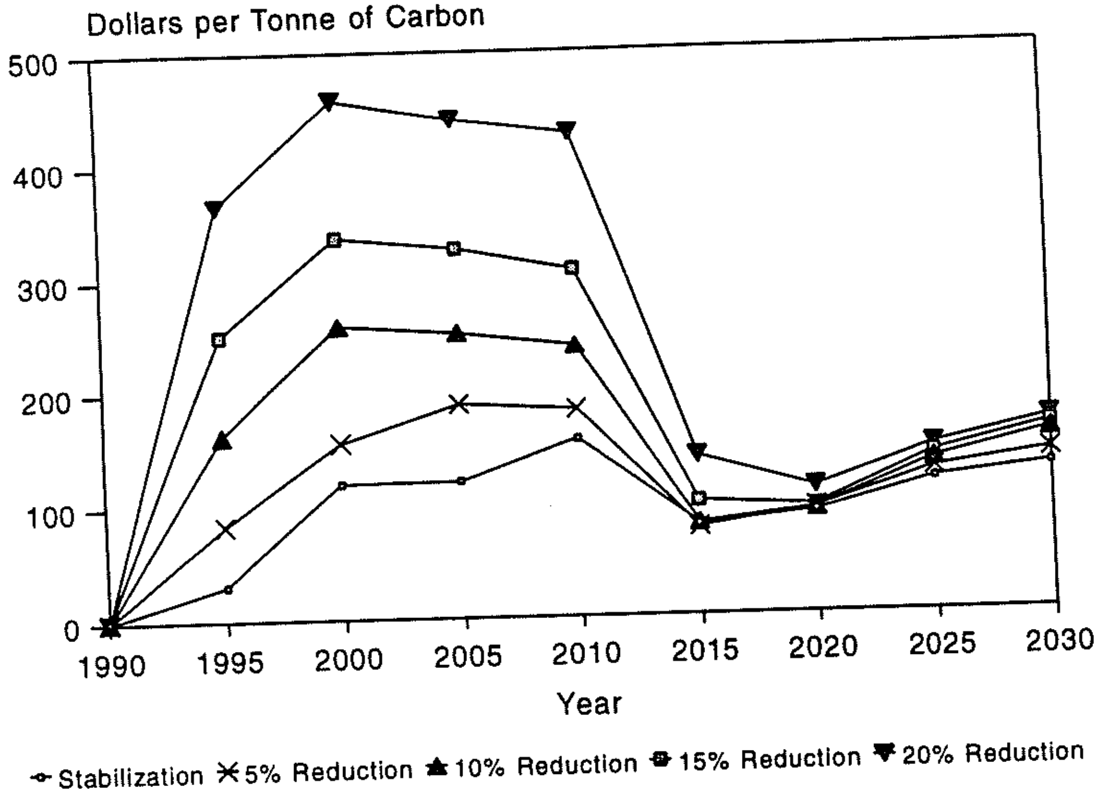

Figure 4. Tax Rates for a Range of Reduction Targets by 2010

Figure 5 compares the necessary tax rates in both cases. It is apparent from the drastic reduction in the necessary tax rate, once the backstops become competitive, that availability of improved technologies is a key to easing the attainment of emissions targets. Without such advancements in technology, much more disruptive taxes must be imposed.

Role of Other Greenhouse Gases

Two of the standard EMF scenarios examined the effect of achieving the 20% reduction goal in terms of the carbon equivalents of any greenhouse gas. (Scenarios I, II and III were defined in terms of CO_2 only.) For comparison again to Scenario I (20% reduction by 2010), two integrated greenhouse gas scenarios were applied:

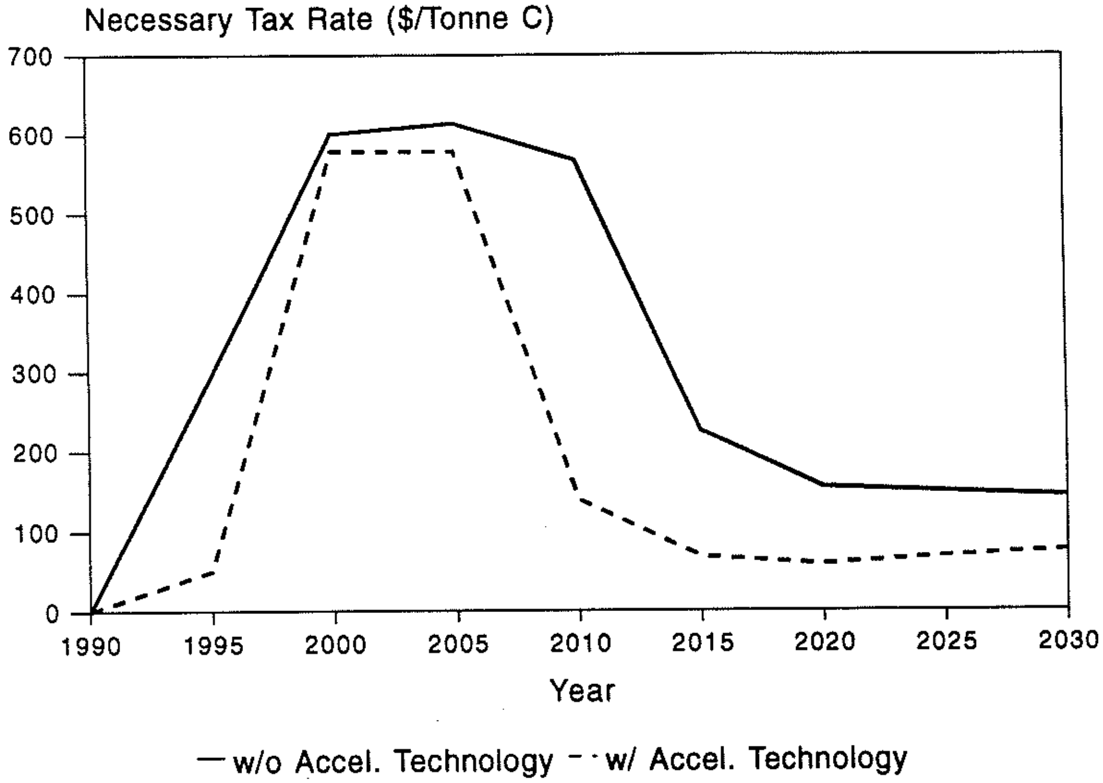

Figure 5. Comparison of Taxes to Attain 20% Reduction by 2010,

VII. Achieve a 20% reduction over 1990 levels by 2010 in terms of carbon equivalents.

VIII. Impose the carbon tax rates necessary for a 20% reduction of CO_2 (i.e., the Scenario I tax results) on all greenhouse gases, adjusted to reflect their carbon-equivalent values.

Because GEMINI models most of the greenhouse gases, and because it can be run to both solve for necessary taxes, as well as to determine the outcome of specific taxes, both of these scenarios were possible to assess using GEMINI. Figure 6 compares the necessary tax rates of Scenarios I and VII. The tax rates to achieve a 20% reduction in carbon equivalents of any greenhouse gas emissions is much lower than if the reduction must come only from CO_2. (It should be noted, however, that in this case, the taxes are low in part because of the assumption that CFCs and HCFCs will be reduced about 70% for regulatory reasons, regardless of the tax rate.)

To simulate Scenario VIII, the tax rates of Scenario I (see Figure 3) were imposed on methane and N_2O sources (after adjustment for their radiative forcing relative to CO_2) as well as on CO_2. In this scenario, a 35% reduction is achieved, instead of the 20% reduction when the tax is applied to CO_2 only.

Thus, a given goal can be achieved with much lower taxes, and conversely, much greater reductions can be achieved at a given tax rate, if all greenhouse gases play a role in the control policy. Since it should not matter how the environmental goal is achieved, the less disruptive approach should be preferable. These results present a forceful case for a policy not focused solely on CO_2 emissions.

Alternative Emissions Reduction Time Paths

Considerable attention has been paid to the costs of stabilizing CO_2 emissions in the United States at 1990 levels, and to the costs of achieving a 20% reduction in emissions by 2010. Few analyses have explicitly addressed how the implications of such policies depend on the nature of the transition between 1990 and the longer-term after 2010. This issue was beyond the scope of the basic EMF-12 scenarios, but its importance became clear when understanding model differences. We gave this issue special attention using GEMINI, which is well suited to evaluate transitional impacts, by performing the following sets of analyses:

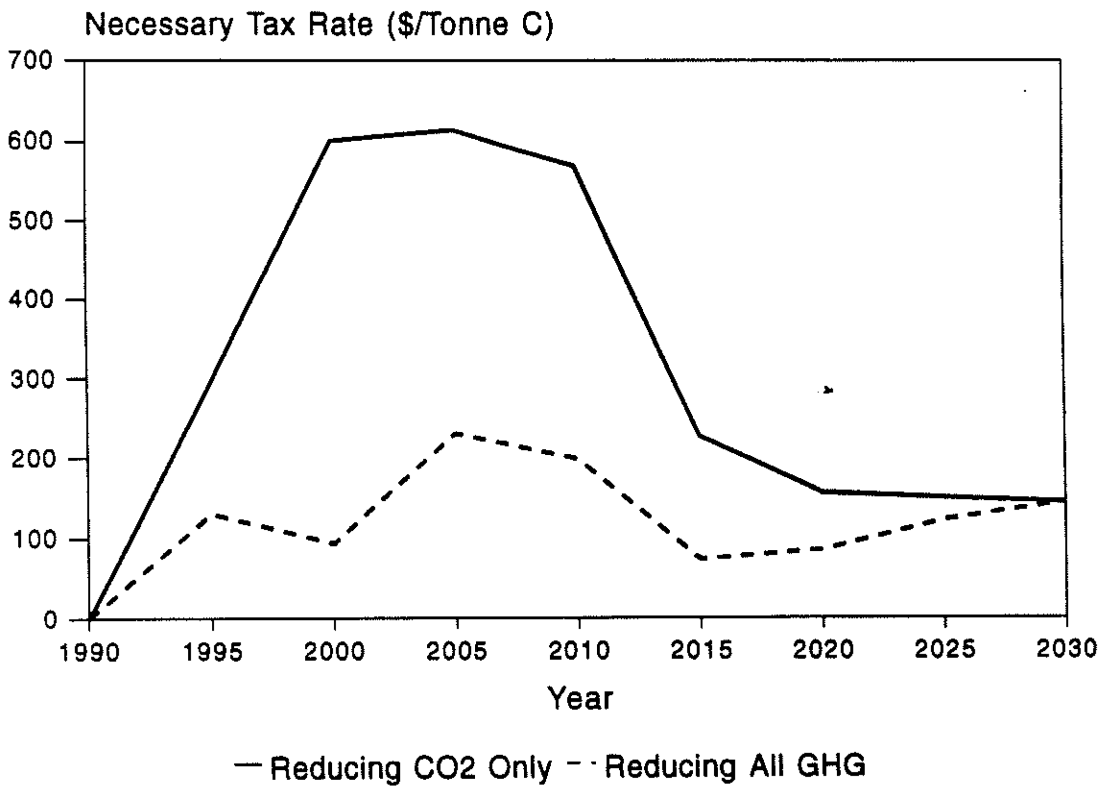

Figure 6. Emission Taxes Necessary to Achieve a 20% Reduction in Carbon Equivalents by 2010, Reducing CO_2 Only and Reducing Any Source of Carbon Equivalents

- Alternative CO_2 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 (see Figure 7).
- Alternative dates at which a 20% emissions reduction would be achieved, comparing a target of 2010 with a five-year delay to 2015.
- CO_2 emissions reduction paths in which the start of 20% emission reductions is delayed until 2000. Until 2000, emissions are stabilized at 1990 levels. These path are similar in shape to those in Figure 7, shifted 10 years later.

- CO_2 emissions reduction paths which have different shapes (e.g., different time-patterns of emission reductions), but which have the same cumulative emissions over the years 1990-2030.

The key insight is that the nature of the emissions constraint path over time can be very important. The change in social surplus (i.e., producer plus consumer surplus) can vary by 50% or more among several different paths to the same emissions reduction target. Tax rates required to meet alternative paths of CO_2 constraints can vary by similar amounts. In particular:

- 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_2 emissions in- creasing 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.
- This result holds even when the emissions reduction paths are calibrated to have the same cumulative reductions over the 1990-2030 time period.
- Deferring a 20% emissions reduction target by five years, from 2010 to 2015, can reduce the loss in social surplus by as much as 15 to 25%. This savings could be compared to the estimated benefits of achieving an earlier emissions reduction. (This result would not necessarily hold for further deferrals, as lower cost low-carbon technologies increasingly become available.)

The carbon tax rates required to meet three of the CO_2 emissions reduction paths in Figure 7 are shown in Figure 8. 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

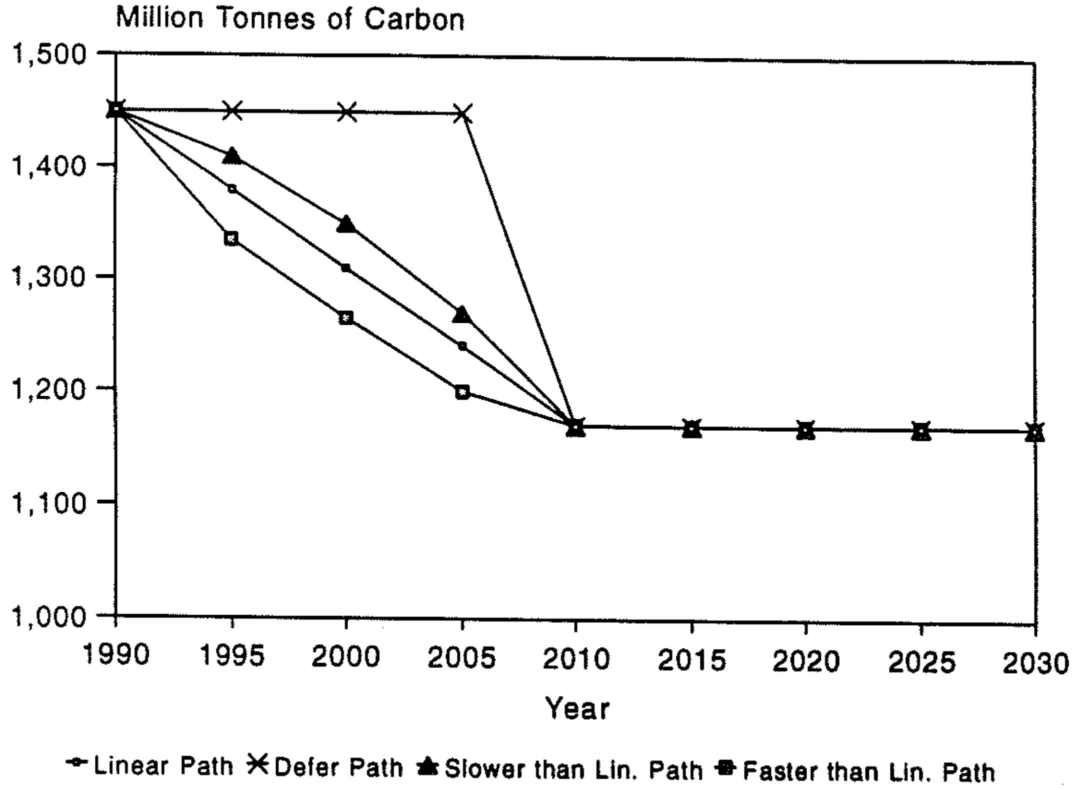

Figure 7. Alternative CO_2 Emissions Reduction Paths Evaluated with GEMINI

resulting from such options. In general, tax rates are closely connected to the timing and magnitude of emission reduction targets. (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 necessary in 2010 when the largest reduction in CO_2 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 an unrealistic scheme; thus, this scenario was not included in Figure 8.)

Because the path with the smallest change in the rate of emissions is the linear one, the linear path results is the lowest maximum tax rate. However, a perhaps better measure of economic disruption, or social cost, is the change in social surplus. We found that the lowest cost transition path for a 20% reduction in 2010, as measured by the change in social surplus, is a

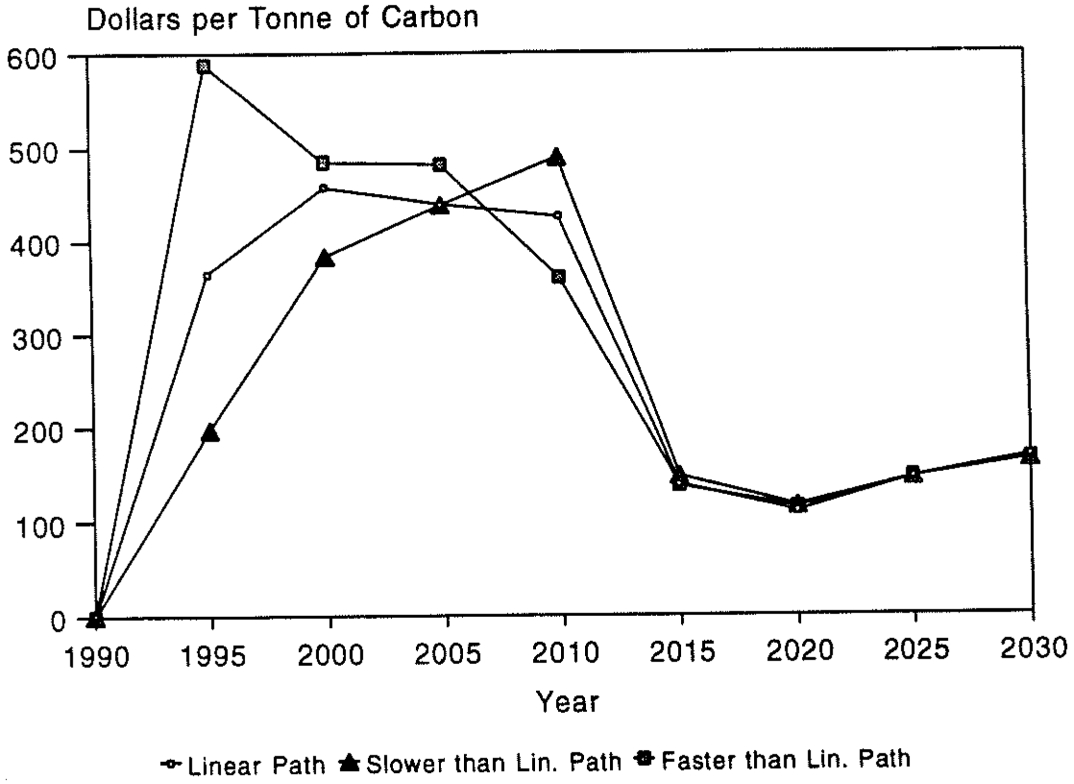

Figure 8. Carbon Taxes Required to Meet Alternative Emissions Paths

gradual constraint at first, with the rate of decrease in CO_2 emissions increasing as 2010 approaches.

The key differences among the scenarios appear to result from three key factors:

- Deferring reductions allows greater time for capital stock turnover from more to less carbon-intensive technologies; accelerating the rate of capital stock turnover increases the 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.

The principal result of this set of analyses is that the nature of a CO_2 emissions constraint path (e.g., the rate of reduction over time) can have a significant impact on the costs of meeting such a constraint. 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.

Implementation of Taxes at Different Market Levels

One of the more unique applications of GEMINI during the EMF-12 program was to look at the effects of taxes when applied at different levels of the fuels markets. This application was initiated because we felt that much of the discussion concerning the necessary tax levels for specific emissions goals has not been clear about the exact nature or implementation features of such taxes. Taxes can be applied in a number of forms and at a number of different points in the economy. Models have been used to compare the relative virtues of different types of taxes, such as carbon, energy, and ad valorem, and this implementation issue is fairly well understood. Going beyond this distinction, we used GEMINI to illustrate the different results that would come from applying taxes at any one of three points in the market: the primary production level, the fuels distribution level, and the end-use level.

The purpose of the analysis was not to determine the best market level, but to advance recognition of the importance of clearly defining the implementation assumptions behind statements about the effectiveness of different tax rates. GEMINI is well suited to such analysis because it explicitly models all stages of the markets for energy services from primary production to end use.

The extent to which a tax is effective at changing attributes that contribute to emissions depends on the level of the market at which it is assessed, as well as the type of tax. Taxes imposed at the primary production level may not capture the costs of transportation and distribution and conversion to more useful energy forms. Imposing the same tax at the end use level does capture such attributes. For example, when one form of fossil fuel is converted to another, such as when coal is converted to a synthetic oil or gas, an ad valorem tax at the primary production level would only capture the value of the coal in the synthetic fuel. When applied further along the market chain, then the tax would capture the full value of the synthetic fuel, including the value added in the conversion from coal. Clearly the two implementations of an ad valorem tax will create different incentives for production of synthetic fuels.

A range of ad valorem taxes was modeled at the primary production level, from 26% to 200%. (We started with 26% since this was found by Jorgenson and Wilcoxen to achieve stabilization of CO_2 emissions at 1990 levels.) None of these tax levels achieved stabilization using GEMINI, although reductions do occur relative to the GEMINI base line. The results in terms of energy use by fuel type, and resulting total CO_2 emissions are presented in Table 4 for the lowest and highest rates investigated.

Table 4

AD VALOREM TAXES AT PRIMARY PRODUCTION LEVEL

		Tax Rate = 25%		Tax Rate = 200%	
	1990	2000	2030	2000	2030
Oil (quads)	35	35	30	31	7
Gas (quads)	19	22	9	18	6
Coal (quads)	16	18	55	15	51
Other (quads)	10	13	23	19	57
TOTAL (quads)	81	88	117	84	121
CO_2 (TgC)	1364	1413	2279	1216	1849

Note in Table 4 that as the ad valorem tax rate is increased, synthetic oil from coal rapidly becomes a substitute for imported (and some domestic) oil due to the much lower relative price of coal. Given the higher carbon content of coal relative to oil and natural gas, this leads to higher CO_2 emissions. In addition, the process of converting coal to synthetic oil involves energy losses, increasing the amount of CO_2 still further. Thus primary energy use actually increases by 2030 under the 200% ad valorem tax.

For comparison, ad valorem taxes were then modeled at the distribution to end users point in the market. Results are presented in Table 5. Such an implementation proves more effective in controlling CO_2 emissions. A 200 to 150% tax achieves stabilization at 1990 levels. A 50% tax rate achieves CO_2 emissions similar to those of the 200% rate imposed at the primary production level. The synthetic fuels effect causes the greatest impact in the differences between the two implementation schemes. The difference is enough to prevent any reduction in carbon emissions when applied at the primary production level.

This illustrates the importance of focusing carefully on the level of the market at which a tax is imposed. To the extent that policy analysts have failed to identify the proper point in the market at which to impose a tax, the ability to reduce emissions may be biased and the cost of achieving any emission reduction target will be correspondingly biased. Although the point was illustrated here with an ad valorem tax, the presence of differences due to implementation decisions is true to any type of tax. Interestingly, the direction of the bias changes when carbon taxes are considered.

Table 5
TAXES AT END-USE LEVEL

		Tax Rate = 26%		Tax Rate = 50%		Tax Rate = 200%	
	1990	2000	2030	2000	2030	2000	2030
Oil (quads)	35	34	29	33	27	29	18
Gas (quads)	19	22	13	21	13	17	12
Coal (quads)	16	17	47	17	41	14	17
Other (quads)	10	14	24	15	30	22	59
TOTAL (quads)	81	87	113	86	111	82	106
CO_2 (TgC)	1364	1384	2094	1332	1885	1131	1023

Evaluating Energy Efficiency Improvements

Several of the models participating in the EMF-12 study rely on assumptions regarding the rate of "Autonomous Energy Efficiency Improvement" (AEEI). The AEEI is meant to reflect all changes in the consumption of energy per unit of economic output except those induced by changes in energy prices. There is considerable disagreement about the correct value of the AEEI, and some model results tend to be sensitive to the assumption. Many of the components of the AEEI are determined endogenously in GEMINI, rather than being specified as direct assumptions. We used GEMINI to examine how energy efficiency evolves over time, how the rate of change differs among sectors, and to what extent the rate of change is sensitive to policy actions, energy price scenarios, and other factors.

Several components of efficiency improvements are represented in GEMINI:

- Gradual improvements in existing electric generation and end-use technologies.
- New technologies, or improvements so large they are modelled as separate technologies.
- Improvements in residential and commercial building thermal integrity.
- Improvements in electricity generation efficiency.

All of these categories have both autonomous and market-driven components; the actual change in efficiency in a given market, end-use, or sector depends on the market interactions of competing technologies and fuels, on capital stock changes, and on other factors. A number of GEMINI runs were performed to determine the overall impact of these components on the GEMINI results, and to determine the relative contribution of each. Observations from these analyses include:

- The annual change in energy efficiency ranges between 0% and 2.2% for the Base Case scenario and between -.4% and 1.6% for a No Technological Change Scenario (in which technology efficiencies were frozen, but market shares of technologies and fuels were allowed to shift over time).
- In all scenarios the rate of change in energy efficiency is consistently higher for the residential and commercial sectors than the industrial and transportation sectors. This is explained, in part, by the fact that the residential and commercial sectors have been modeled to have a greater availability of new, more efficient processes.

- In typical scenarios, the rate of improvement in energy efficiency increases for 10 to 20 years, and then decreases gradually. Efficiencies increase rapidly in early years due to the introduction of more efficient processes. For example, standard lighting is replaced by efficient lighting, mostly in the short term, and hence efficiency improvements are realized.
- Under a carbon tax scenario, the residential sector has the largest range of change in energy efficiencies, rising to 2.2% by 2000 and then plummeting to almost 0% by 2030. On the other hand, transportation has a lower initial rate of improvement, but a large rate in the long run. One possible explanation for this phenomenon is that in the near term, the residential sector has more efficient processes available and can substitute towards more economical processes when prices rise. However, the residential sector improvements cannot be sustained. Transportation cannot transfer to cleaner and more efficient fuels in the near term, but can do so in the longer term.

LESSONS FROM THE EMF-12 EXERCISE

There are a number of contributions that GEMINI has made to the EMF-12 process, as well as a number of insights that the GEMINI team gained from the exercise.

- GEMINI provides insights about the adjustment phase of attaining a policy goal, and makes an interesting comparison with longer-term projections that focus on the ultimate steady-state outcomes. Models like GEMINI indicate a much higher tax rate required to attain specific goals than do long-run models. GEMINI also indicates that the higher taxes are needed in the early years, which would then settle to lower values similar to those of the long-run models after a 20-30 year adjustment period.

- As a related result, GEMINI was used to consider the advantages of different time paths for achieving specific CO_2 emissions goals. That is, whether a given percent reduction goal is better met over a period of 10, 20, or 30 years, and whether the phase-in should be rapid or gradual. It was found that costs can be considerably reduced if the adjustment period is extended.

- GEMINI has the capability of computing the changes in consumer and producer surplus due to the outcomes of different scenarios. The GEMINI contribution included a demonstration of cases where it can be important for policy makers to consider social surplus in addition to control costs or GNP effects.

- GEMINI was used to demonstrate how the specific assumptions about a tax or trading implementation can matter, for example, showing how a tax rate applied at different levels of the market can produce different environmental outcomes. Thus it is not sufficient to identify the desired tax rate to attain a carbon goal, but the implementation of that tax must also be specified.

- GEMINI was one of the few models in EMF-12 that is able to address all greenhouse gases in the form of a carbon tax. It has been used to demonstrate the substantially higher tax rates needed to achieve specific emissions goals if only CO_2 is addressed. Emissions of methane are an important additional gas to try to control, and those emissions are strongly correlated with increases in use of natural gas to reduce total carbon dioxide emissions.

- Many of the EMF-12 models address technological change parametrically, usually as an exogenous assumption. GEMINI models the decisions that result in technological change, such as when to replace capital equipment and with what form of new technologies. Thus the rate of technological change is an implicit output of GEMINI. The GEMINI team investigated that implicit rate and its components to determine how the endogenous results compare to the assumptions of others. It was found that the rates of improvement in energy-efficiency can vary considerably across sectors of the economy and over time.

The EMF-12 experience has led us to a strong belief in the importance and value of a technology-based modeling approach. It is one that is able to address concerns related to economic transitions in a major policy initiative, and is also well-suited to addressing specific details of implementation plans. Without a solid understanding and management of these aspects of a policy decision, longer term goals may not be achieved.

There is also great value in a model that has a fundamentally simple structure, as does GEMINI. This leaves substantial flexibility to address the full range of questions that are relevant to policy making. Nevertheless, EMF-12 has highlighted a number of areas where a future version of GEMINI could be improved:

- The transportation sector merits greater detail to better analyze attributes affecting choice of transportation mode.
- The electricity sector would benefit from a simple representation of load shapes, so that the dispatchability of different energy sources is realistically accounted for.
- While GEMINI is not a macroeconomic tool and should not strive to be, it would be valuable to develop an explicit model of the linkages between macroeconomic drivers and GEMINI end-use demand assumptions.

There are a number of future applications possible for GEMINI, with or without the enhancements described above.

- GEMINI'S emissions trading capability can be enhanced to work in emissions offsets modeling, where the supply curves for emissions allowances become endogenous to the model.
- The flexibility of GEMINI to address most of the important greenhouse gas policy questions makes it a natural step to link its use with a decision framework for greenhouse policies. EPA is currently developing a Policy Evaluation Framework to integrate models and analyses of both costs and benefits of climate change policy options.
- GEMINI embodies an excellent approach for addressing transitions among different technologies. As such, it is one of the key models suited to the planned EMF-13 on conservation and energy efficiency polices.

ENDNOTES

1. This work was supported in part by the U.S. Environmental Protection Agency under EPA contract #68-CO-0012. Valuable assistance was provided by Joel Scheraga, Neil Leary, and Bruce Schillo, all of the USA EPA.

2. Although GEMINI was designed to have this full integration via environmental feedbacks to the economy, these linkages were not used during the EMF-12 effort. They have, however, been used in subsequent analyses.