REDUCING US CARBON DIOXIDE EMISSIONS: THE COST OF DIFFERENT GOALS

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EXECUTIVE SUMMARY

How much will it cost to reduce the threat of global climate change? As negotiators from around the world struggle to develop an agreement, answering this question becomes critically important. The cautious position taken by the United States derives, in part, from a concern that the costs to its economy from an aggressive program to reduce greenhouse gases would be prohibitively high Is this position well-founded?

In the last two years, there have been several attempts to assess the costs of reducing C02 emissions. Most of these have suggested that they would be as high as $200-$800 per ton of carbon and could reduce annual GNP by as much as 5% by the year 2020. Are these estimates valid?

This paper examines the costs of three separate C02 reduction scenarios: 1) hold emissions at 1990 levels; 2) reduce emissions to 20% below 1990 levels; and 3) allow emissions to rise until the year 2000, after which they are held constant. To arrive at each of these targets it is assumed the U.S. agrees to use a carbon tax with the tax being set at the rate sufficient to meet the target in any given year over a thirty-year period. Thus the level of taxation will change from year to year -- with lower rates of taxation in the early years and higher taxes as the year 2020 approaches.

The report calculates that to stabilize emissions at 1990 levels would require a $17 per ton carbon tax -- or $11.01 per ton of carbon. If the U.S. decided to stabilize at year 2000 levels, carbon taxes would only have to rise to $8.55 or $5.55 per ton of coal. On the other hand, if the U.S. wanted to reduce C02 levels 20 percent below 1990 levels the costs would be significantly higher -- a tax of $60.04 per ton of carbon or $39.01 per ton for coal would be

necessary.

There are three major implications which can be derived from these findings. First, the main impact of a carbon tax will be to contract the coal mining sector substantially. Coal is affected more than other fossil fuels because it produces the most carbon dioxide per unit burned, and because it is the least expensive fossil fuel. Thus, a given carbon tax produces a much larger percentage change in the price of coal than it does in the prices for oil or natural gas. In response, coal users substitute toward other inputs and the demand for coal falls substantially.

Second, a carbon tax will affect aggregate output by changing the rates of capital formation and productivity growth. In the United States, coal is used primarily for firing electric power plants, so one result of a carbon tax is to raise the price of electricity. Higher electricity prices, in turn, raise costs to other industries. As output prices rise, new capital goods become more expensive, reducing the rate of capital formation. This leads to a drop in GNP growth as capital investment slows. Moreover, the slowdown in growth is exacerbated by a reduction in technical changes brought about by higher energy prices. Many industries are characterized by energy-using technical change, so when energy prices rise, productivity growth drops. Together, reduced technical change and slower capital accumulation are responsible for most of the adverse effect of a carbon tax.

Third, the loss of GNP will rise at an increasing rate as the carbon dioxide targets becomes stricter. Put another way, the implicit cost curve slopes upward and its slope increases rapidly as the required reduction grows. Thus, small reductions in carbon emissions can be achieved with small carbon taxes and will have little overall effect on the economy. For larger reductions, however, the cost grows rapidly. This makes it imperative that the costs and benefits of a proposed carbon dioxide control policy be compared before the policy is adopted. The cost of choosing the wrong emissions target could be very high.

REDUCING US CARBON DIOXIDE EMISSIONS:

THE COST OF DIFFERENT GOALS

by

Dale W. Jorgenson and Peter J. Wilcoxen[1]

1. INTRODUCTION

The possibility that carbon dioxide emissions from fossil fuel combustion might lead to global warming through the greenhouse effect has emerged as a leading international environmental concern. Many nations, including the United States, are considering policies to reduce carbon dioxide emissions. Moreover, multilateral action is being discussed under the auspices of the Intergovernmental Panel on Climate Change. For the most part, however, public debate has focused on a few fairly arbitrary targets, such as holding carbon dioxide emissions constant or reducing emissions by 20%. Little attention has been devoted to deciding what the optimal target would be.[2] Finding the optimal target requires an accurate assessment of both the costs and benefits of different policies. In this paper we present a detailed model of the US economy and use it to compute the costs of attaining three different emissions goals by imposing taxes on the carbon content of primary fuels.[3] The goals we consider differ considerably in stringency, so our results give a clear picture of the cost curve lying behind different levels of emissions reductions. We find that costs rise very rapidly, so it is imperative that policy makers carefully assess the benefits of carbon dioxide abatement before adopting a particular target.

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1. Department of Economics, Harvard University. This research was sponsored by the Environmental Protection Agency under contract 68-W8-0113. We are grateful for the help and advice of our colleagues Mun Sing Ho, Richard Goettle, Edward Hudson, Barbara Fraumeni, Daekeun Park, Daniel Slesnick, Joel Scheraga and Michael Shelby. Needless to say, we alone are responsible for any remaining deficiencies.

2. The most notable exception is the work of Nordhaus (1989, 1990) who has devoted a great deal of effort to measuring the benefits of reducing global warming in order to be able to calculate the optimal reduction. Preliminary work on benefits has also been done by Peck and Teisberg (1990).

3. In Jorgenson and Wilcoxen (1990b) we also examined the effect of reducing carbon dioxide emissions by imposing taxes on the energy content of primary fuels or by imposing ad valorem fuel taxes.

The greenhouse effect comes about because several trace gases in the atmosphere, often called greenhouse gases, are transparent to visible light but reflect infrared. Sunlight passes through such gases unimpeded and is absorbed by objects on the ground. Later, much of that energy is re-emitted as infrared radiation. Since greenhouse gases reflect infrared, they tend to trap energy in the atmosphere, which results in heating. The concentration of greenhouse gases in the atmosphere determines how much energy is trapped and thus how much heating occurs.[4]

Carbon dioxide (CO_2) is the most important contributor to the greenhouse effect, although other gases are also important. These other gases include methane *(CH_4),* chlorofluorocarbons (CFC's), ozone (03), Nitrous Oxide *(N_20)*, and other oxides of nitrogen *(NO_X).* Much of the carbon dioxide in the atmosphere originates as a natural consequence of respiration, but combustion, particularly of fossil fuels, has increased the atmospheric concentration by 25% since the industrial revolution (Schneider, 1989). At present rates of emission, carbon dioxide accounts for about half the increase in the concentration of greenhouse gases, while other gases account for the remainder (Houghton and Woodwell, 1989).

That greenhouse gases trap energy and lead to heating of the atmosphere is not controversial; however, a great deal of uncertainty exists about how much heating will be produced by a given increase in greenhouse gases, and when the heating will occur. Current research indicates that the concentration of greenhouse gases is likely to double sometime in the next century, with mean surface temperatures rising by 1.5 to 5.5 degrees centigrade.[5] Historical data indicate that global temperatures have risen by 0.5 degrees centigrade during the past 100 years, and that the rate of increase has been accelerating.[6]

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4. A very thorough discussion of the greenhouse effect and numerous references to the literature are given by EPA (1989).
5. Schneider (1989), p. 774. However, there is a wide spectrum of scientific opinion, as described by Stevens (1989).
6. Schneider (1989), p. 772. This is also subject to dispute, as pointed out by Stevens (1989). For example, Solow (1990) presents a strong case against the position that a rapid acceleration global warming has already been observed.

The environmental consequences of global warming could be severe. It might change patterns of precipitation, cause land to be inundated by increases in the sea level, or increase the frequency of violent storms such as hurricanes. As a consequence, a sizable constituency has developed for policy measures to reduce greenhouse gas emissions. For example, the Toronto Conference on the Changing Atmosphere, held in June 1988 and attended by representatives from 48 nations, recommended that world carbon dioxide emissions be reduced to 20% below 1988 levels by the year 2005, and eventually to 50% of 1988 levels (National Resources Defense Council, 1989). In the United States, Senator Timothy Wirth has introduced legislation that would sharply reduce carbon dioxide emissions.[7] In addition, environmental groups such as the Natural Resources Defense Council have called for strong, immediate action to reduce the emission of greenhouse gases.[8]

One of the policies proposed for fighting the greenhouse effect is a tax on the carbon content of fossil fuels.[9] This is known as a "carbon" tax, and it could be an effective way to reduce CO_2 emissions. For example, a carbon tax would lead to substitution of other inputs for fossil fuels, and to an increase in the use of fuels such as natural gas that have lower carbon content and hence contribute less to the greenhouse effect. In this paper we examine the costs of a carbon tax in detail, focusing in particular on how those costs change as CO_2 emissions goals become more stringent.

Ours is by no means the first study of greenhouse abatement policies. An important series of studies of the effect of CO_2 restrictions on the US energy sector was initiated by Edmonds and Reilly (1983, 1985).[10] The Edmonds-Reilly approach uses a very detailed model of the

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7. Schneider (1989), p. 771. A detailed analysis of the potential economic impact of the legislation introduced by Senator Wirth is presented by the Congressional Budget Office (1990).

8. See, for example, National Resources Defense Council (1989).

9. Many other policies have been suggested, see EPA (1989). These options are discussed from an economic point of view by Lave (1990), Goulder (1990), North (1990) and Wood (1990).

10. The Edmonds-Reilly model has subsequently been used by Reilly, Edmonds, Garner and Brenbert (1987), Cline (1989), the Environmental Protection Agency (1989), the Congressional Budget Office (1990), and others

energy sector, but it excludes the rest of the economy. Thus, it cannot be used for computing the economy-wide costs of CO_2 abatement, nor can it be used to analyze the impact of restrictions on US economic growth.

Manne and Richels (1990) examined several CO_2 reduction policies using GLOBAL 2100, a five region model of the world economy. GLOBAL 2100 combines a process analysis model of the energy sector with a macroeconomic growth model.[11] The growth model is based on an aggregate production function with inputs of capital, labor, electricity, and nonelectric energy. The production function allows for the possibility that there are "autonomous energy efficiency improvements" which reduce the share of energy in GNP over time. The energy submodel is fairly detailed, including ten electric generation technologies and six sources of nonelectric energy. After examining a number of scenarios combining different assumptions about when various technologies become available, *Manne* and Richels conclude that a US policy of reducing carbon emissions to the 1985 rate by the year 2000 and subsequently to 80% of that rate by 2020 would lower annual GNP by 5% by the year 2030. The carbon tax needed to achieve this drop in emissions is enormous, varying over time between $350 and $800 per ton of carbon.[12]

Nordhaus (1989) has recently assessed several policies for controlling greenhouse emissions using rough estimates of the costs and benefits of each.[13] Estimates of benefits are taken from EPA (1988), which quantifies the cost of global warming. A number of alternative abatement strategies are considered-controlling CFC's, reducing $C02$ emissions, reforestation, and imposing a tax on gasoline. Comparing estimates of the marginal cost of reducing greenhouse

11. It is a descendant of Manne's earlier work on ETA-MACRO. See Manne (1981).

12. A non-technical description of the results of Manne and Richels is presented by Passell (1989).

13. Nordhaus (1989) is one of a series of studies beginning with Nordhaus (1977). Additional references are given by Nordhaus (1979, 1982), Nordhaus and Ausubel (1983), and Nordhaus and Yohe (1983).

emissions by the equivalent of one ton of $C0_2$, Nordhaus argues that the optimal reduction in emissions of greenhouse gases could be achieved with a large reduction in CFC's and a comparatively small reduction in carbon dioxide emissions. Reforestation and gasoline taxes are found to be excessively costly in relation to the amount of carbon removed from the atmosphere.

Whalley and Wigle (1990) have used a global static general equilibrium model to determine the effects of various carbon taxes. Their model divides the world into three regions: high income countries, low income countries, and oil exporters. They conducted several experiments, each designed to achieve a 50% decrease in the production of energy from sources that contribute to the greenhouse effect. (Underlying this is an implicit assumption that greenhouse gases and certain forms of energy are produced in fixed proportions.) Their results show that world welfare would fall by more than $250 billion annually (US dollars). Depending on how the carbon tax was implemented, the revenue raised could be substantial-from $100 billion to $300 billion dollars a year in the high income countries alone. An interesting feature of the study is the possible distributions of these revenues among the three regions.

From these studies a great deal of valuable information has been accumulated about the economic impact of policies to limit the emissions of greenhouse gases. However, the analysis of the impact on US economic growth of restrictions on these emissions is seriously incomplete. In order to measure this cost it is essential to model the responses of businesses and households at a highly disaggregated level. Policies such as carbon tax are intended to reduce fossil fuel use by inducing producers and households to substitute toward other inputs, and a detailed model is needed to capture these effects. Moreover, carbon taxes are likely to affect the price of new capital goods, and thus will affect the rate of capital accumulation. To capture this effect requires a model with endogenous capital formation. In addition, carbon taxes will increase the price of energy to purchasers, which may reduce or accelerate technical

change. To address these concerns requires a disaggregated, dynamic general equilibrium of the US economy in which technical change is endogenous. In the remainder of this paper we present such a model and use it to examine the effects of several carbon taxes.

2. AN OVERVIEW OF THE MODEL

The results presented in Section 3 are based on simulations we conducted using a disaggregated, econometrically estimated intertemporal general equilibrium model of the United States. The model itself is an extension of our earlier work on environmental regulation, and is documented in detail in Wilcoxen (1988), Jorgenson and Wilcoxen (1990a), and Jorgenson and Wilcoxen (1990c). Rather than presenting the entire model again, in this section we will confine ourselves to outlining a few of its key features and discussing how we extended it to calculate carbon emissions.

2.1. Producer Behavior

Several of the model's most important features are closely connected to our submodel of producer behavior. For example, production is moderately disaggregated: total output is divided into 35 separate commodities, each of which is produced by one or more of 35 industries. The industries correspond roughly to two-digit SIC classifications, and are shown in Table 2.1. This level of detail allows us to measure the effect of shocks on fairly narrow segments of the economy. Since carbon dioxide emissions are concentrated in energy production--a small part of the overall economy-a disaggregated model is essential for examining the sectoral effects of global warming policies.

Each of the 35 industries is represented by an econometrically estimated nested translog unit cost function. At the function's top level, output is produced using capital, labor, energy and materials (KLEM). Capital and labor are both primary factors purchased directly from households. Energy and materials, on the other hand, are translog aggregates of intermediate goods. The energy aggregate is composed of inputs of coal, crude petroleum, refined petroleum, electricity and natural gas,[14] while the materials aggregate is composed of inputs of

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14. Sectors 3, 4, 16, 30 and 31 in Table 2.1.

Table 2.1: Definitions of the Industries

Number	Description
1	Agriculture, forestry and fisheries
2	Metal mining
3	Coal mining
4	Crude petroleum and natural gas extraction
5	Nonmetallic mineral mining
6	Construction
7	Food and kindred products
8	Tobacco manufactures
9	Textile mill products
10	Apparel and other textile products
11	Lumber and wood products
12	Furniture and fixtures
13	Paper and allied products
14	Printing and publishing
15	Chemicals and allied products
16	Petroleum refining
17	Rubber and plastic products
18	Leather and leather products
19	Stone, clay and glass products
20	Primary metals
21	Fabricated metal products
22	Machinery, except electrical
23	Electrical machinery
24	Motor vehicles
25	Other transportation equipment
26	Instruments
27	Miscellaneous manufacturing
28	Transportation and warehousing
29	Communication
30	Electric utilities
31	Gas utilities
32	Trade
33	Finance, insurance and real estate
34	Other services
35	Government enterprises

all other intermediate goods. Minimizing costs subject to this specification allows us to derive

factor demands for capital, labor and intermediate inputs of the 35 commodities. When fully parameterized, these demands completely describe producer behavior.

To parameterize the producer submodel (and, indeed, the rest of the model) we constructed a special data set of consistent input-output tables running from 1947 through 1985.[15] This data set allowed us to estimate all parameters in all of the model's behavioral equations, a feature which most clearly distinguishes our model from others. This method of parameterization, known as the econometric approach, stands in marked contrast to the calibration method used for most general equilibrium models. Calibration involves choosing the model's parameters so that the model will replicate a particular year. [16] Because it requires fairly little data, calibration has been widely applied in general equilibrium modeling.

By taking the econometric approach, however, we gained several advantages over calibration. First, by using a long time series of data (rather than a single point) we are able to estimate more flexible functional forms. Thus, our approach imposes less structure on the data than the simple functional forms used for calibration. We do not, for example, need to assume that production is Cobb-Douglas or CES. A second advantage is that estimated parameters based on a long time series are less likely to be corrupted by noise. Calibrated parameters, on the other hand, are forced by construction to absorb all noise present in the data. This poses a severe problem when the benchmark year is unusual in some respect because calibrated parameters will be build that distortion into the model. Estimation avoids this problem by reducing the influence of any particular year's data on the parameters. Most importantly, however, by estimating each industry's cost function on a consistent set of time series data, our model

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15. The data set is discussed in detail by Wilcoxen (1988), Ho (1989) and Jorgenson and Wilcoxen (1990c).
16. See Mansur and Whalley (1984) for more detail. A example of the calibration approach is Borges and Goulder (1984).

implicitly incorporates elasticities of substitution consistent with historical observations.[17]

The third important feature of the producer submodel is our treatment of technical change. As part of each industry's cost function, we include several terms to allow for technical change.[18] Most other models used to study global warming, such as Manne and Richels (1990), assume a constant exogenous rate of technical change. In our model, however, technical change is endogenous. Moreover, it is determined at the industry level, which allows different sectors to grow at different rates. In addition, each industry's technical change may be biased toward some inputs and away from others. Differing rates of biased technical change are a common feature of historical data, but are necessarily absent from aggregated models. By including endogenous industry-level technical change, our model is able to capture the medium run evolution of individual sectors much more accurately.

In sum, the salient features of the production submodel are that it is disaggregated and econometrically estimated, and that it allows for industry-level biased technical change. In addition, it fully captures substitution among intermediate inputs. We now turn briefly to a discussion of the model's final demands: consumption, investment, government spending and foreign trade.

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17. For a more complete discussion of the econometric approach see Jorgenson (1982) and Jorgenson (1986).

18. Our approach to endogenous productivity growth was originated by Jorgenson and Fraumeni (1981). The implementation of a general equilibrium model of production that incorporates both substitution among inputs and endogenous productivity growth was proposed by Jorgenson (1984). The first model to use such a specification was Wilcoxen (1988).

2.2. Consumption

Our final demand vector giving household consumption by commodity is the end result of

a three-stage intertemporal optimization problem. At the first stage, each household allocates full wealth (the sum of financial wealth, discounted future labor earnings and an imputed value of leisure time) across different time periods according to its rate of time preference and its intertemporal elasticity of substitution. We formalize this decision using a representative agent who maximizes an intertemporal utility function subject to an intertemporal budget constraint. The agent's optimal allocation must satisfy a set of necessary conditions which can be summarized in the form of an Euler equation.[19] The Euler equation is forward-looking, so current consumption, and hence the rate of saving, will depend on expectations about future prices and interest rates. Because capital formation is an important contributor to economic growth, this formulation of the savings decision plays a significant role in the model. We will return to this point in the section on investment.

Once households have allocated full wealth across periods, they begin the second stage of their optimization: deciding on the mix of leisure and goods to consume in each period. As in the intertemporal allocation, we simplify the representation of household preferences between goods and leisure by the use of a representative consumer. The representative consumer has a translog intraperiod indirect utility function which depends on the prices of leisure and an aggregate consumption good. (We take the price of leisure to be the after-tax wage rate and the price of the aggregate consumption good to be a price index based on the commodities consumed.) From this we derive the consumer's demands for leisure and goods in each period as a function of prices and the amount of full wealth allocated to the period. This produces an allocation of the household's time endowment, which is given exogenously, between leisure time and the labor market. Thus, the second stage of the consumer model determines labor

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19. The Euler equation approach to modeling intertemporal consumer behavior was originated by Hall (1978). Our application follows Jorgenson and Yun (1986).

supply.

The third stage of the household optimization problem is the allocation of consumption expenditures among capital, labor and the 35 commodities. At this stage, we abandon the representative consumer assumption and instead follow the methodology of Jorgenson, Lau and Stoker (1982) by formulating a system of individual household demand systems which can be aggregated. We then distinguish between 672 household types based attributes such as the number of household members and the geographic region in which the household is located. For each of these households, we follow the approach of Jorgenson and Slesnick (1987) by using a nested translog tier structure to represent demands for individual commodities.[20]

As with production, all behavioral equations in all stages of the consumer model are econometrically estimated. This includes the Euler equation, the allocation equations for leisure and personal consumption, and the equations governing the allocation of consumption among commodities.[21] Thus, our household model incorporates historical substitution shown by consumers. Moreover, an important feature of our specification is that we do not require household demands to be homothetic. Thus, as incomes rise the pattern of consumption will shift, even in the absence of price changes. This captures an important and often noted feature of historical data which is usually ignored in general equilibrium modeling.

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20. This allows our model of personal consumption to be used to represent the behavior of individual households as in Jorgenson and Slesnick (1985). Further details on the econometric methodology are given by Jorgenson (1984, 1990).

21. See Wilcoxen (1988) and Ho (1989) for more details.

2.3. Investment and Capital Accumulation

As noted above, an important feature of the model is that it is based on intertemporal optimization by households, which is the source of our savings supply function. In addition, we also assume intertemporal behavior on the part of investors. Both types of intertemporal behavior are very important for greenhouse abatement simulations as much of the impact of regulation occurs far in the future. Since many of these effects will be anticipated by households and firms, future events will have consequences for current decisions. Saving, for example, depends on households' expectations of future earnings and interest rates, while investment depends on firms' expectations of future wages and prices. Changes in saving and investment affect the rate of capital accumulation, and hence the rate of economic growth.

Our investment model is based on the Q theory of Tobin (1969). In particular, we require that the price of new investment goods always be equal to the present discounted value of the returns expected on an extra unit of capital [22] For tractability, we assume there is a single capital stock in the economy which is perfectly malleable and can be reallocated between industries at zero cost.[23] The total supply of capital, however, is fixed at any time by past investment behavior. This implies that the return on a unit of capital in a given period is precisely equal to the economy-wide rental price of capital goods. In addition, we assume that new capital goods are produced out of individual commodities according to a production function estimated from historical data, so the price of new capital will depend on commodity prices. Thus, the price of capital goods and the discounted value of future rental prices must be brought into equilibrium by adjustments in the term structure of interest rates. Finally, the quantity of investment done in each period is determined by the amount of savings made available by households.

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22. In order to make this assertion, we assume that there are no internal costs of adjusting the capital stock.
23. More accurately, between the industries themselves and between industries and final demand categories. Households, in particular, purchase a considerably amount of capital services.

The production function for new capital goods was estimated using final demand data for investment over the period 1947-1985. Thus, our model incorporates substitution between different inputs in the composition of the aggregate capital good. This feature sometimes plays an important role. In our earlier work on environmental regulation, for example, we found that a substantial drop in the price of automobiles would shift investment toward motor vehicles and away from other durable goods.

In sum, capital accumulation is the outcome of intertemporal behavior on the part of households and firms. Households determine the amount of savings available in each period through intertemporal utility maximization. Firms, for their part, invest until the returns on additional investment are driven to the cost of new capital goods. Finally, savings and investment are equilibrated by the interest rate.

2.4. Government and Foreign Trade

The two remaining final demand categories are the government and the foreign sector. Beginning with the government, we determine final demands for government consumption from the income-expenditure identity for the government sector. The first step is to compute total tax revenue by applying exogenous tax rates to appropriate transactions in the business and household sectors. We then add the capital income of government enterprises (determined endogenously) and nontax receipts (exogenous) to tax revenue to obtain total government revenue.

Next, we make a important assumption about the government budget deficit; namely that it can be specified exogenously.[24] We add the deficit to total revenue to obtain total

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24. Without a model of Congressional decision-making, we must take either the level of government expenditures or the size of the budget deficit to be exogenous.

government spending. To arrive at government purchases of goods and services, we subtract interest paid to domestic and foreign holders of government bonds together with government transfer payments to domestic and foreign recipients. We allocate the remainder among commodity groups according to fixed shares constructed from historical data. Finally, we determine the quantity of each commodity by dividing the value of government spending on the good by the its price.

Foreign trade, on the other hand, has two components: imports and exports. Imports are handled by assuming that they are imperfect substitutes for similar domestic commodities.[25] To implement this, we assume the goods actually purchased by households and firms are translog aggregates of domestic and imported products, where parameters of the aggregation function are determined by estimation. Thus, each commodity is governed by a separate elasticity of substitution between foreign and domestic goods. The result is that intermediate and final demands implicitly determine imports of each commodity. The prices of imports are given exogenously in each period.

Exports, on the other hand, are modeled by a set of explicit foreign demand equations, one for each commodity, which depend on foreign income (given exogenously) and the foreign price of US exports. Foreign prices are computed from domestic prices by adjusting for subsidies and the exchange rate. The demand elasticities appearing in these equations were estimated from historical data.[26]

The final important part of the foreign trade submodel is our treatment of the current account and the exchange rate. Without an elaborate model of international trade (far beyond the scope of this study) it is impossible to determine both the current account and the exchange

25. This is the Armington approach.
26. See Wilcoxen (1988) or Ho (1989) for more details.

rate endogenously. Thus, in the simulations reported below, we take the current account balance to be exogenous and the exchange rate to be endogenous.

25. Computing Carbon Emissions

The most important remaining feature of the model is the way in which carbon dioxide emissions are calculated. For tractability, we assume $C0_2$ is emitted in fixed proportion to fossil fuel use. This implicitly assumes that nothing can be done to reduce the $C0_2$ produced by any given combustion process, but in practice that is largely the case.[27] For comparability with other studies, we measure $C0_2$ emissions in tons of contained carbon.[28]

We calculated the carbon content of each fossil fuel in the following way. From the Department of Energy we obtained the average heat content of each fuel in millions of BTU per quantity unit (Department of Energy, 1990). Next, we obtained data from the Environmental Protection Agency on the amount of carbon emitted per million BTU produced from each fuel.[29] Multiplying EPA's figures by the heating value of the different fuels gives the carbon content of a unit of each fuel. Total carbon emissions can then be calculated using figures on total fuel production. Table 2.2 shows data for each fuel in 1987.

27. Unlike ordinary pollutants, carbon dioxide is one of the natural products of combustion. Little can be done to change the amount of it produced when burning any particular fuel.
28. To convert to tons of carbon dioxide, multiply by 3.67.
29. Environmental Protection Agency (1990) internal memoranda.

Table 2.2: Carbon Emissions Data for 1987

Item	Fuel		
	Coal	Oil	Gas
Unit of Measure	ton	bbl	kcf
Heat Content			
(10^6 *BTU per unit)*	21.94	5.80	1.03
Emissions Rate			
(kg per 10^6 BTU)	26.9	21.4	14.5
(kg per unit)	590.2	124.1	14.9
Total Domestic Output			
(10^9 *units)*	0.9169	0.3033	17.8
Total Carbon Emissions			
(10^6 *tons)*	595.3	414.1	268.6

Our simulation model, however, is normalized so that all prices are equal to one in 1982. Thus, its quantities do not correspond directly to physical units. Moreover, the model has a single aggregate sector for oil and gas. To convert the figures above into a form appropriate for the model's quantity units, we summed carbon production for oil and gas and divided by the model's output for industry 4 (oil and gas extraction) in 1987. This gave the carbon coefficient for that industry. Similarly, the coefficient for coal was computed by dividing total carbon production from coal by the model's 1987 value for coal output. These coefficients were then used to compute carbon emissions in each simulation. We now turn to a brief discussion of the model's base case.

2.6. The Base Case

In order to solve the model, we must provide values for all exogenous variables in all periods. We accomplish this in two steps. First, we develop a set of default assumptions about the values each exogenous variable will have over time in the absence of changes in government policy. This is used to generate a simulation called the "base case". The second step is to change certain exogenous variables to reflect a proposed policy and then solve the model again to produce a "revised case". We can then compare the two simulations to assess the effects of the policy. Thus, the assumptions underlying the base case are of some importance in understanding the model's results.

Since the model includes agents with perfect foresight, we must solve it far into the future. In order to do that, we project values for all exogenous variables over the period 1990-2050. After 2050 we assume the variables will remain constant at their 2050 values, which allows the model to converge to a steady state by the year 2100. Some of the most important or interesting projections are noted briefly below; a more detailed discussion appears in Jorgenson and Wilcoxen (1990c).

First, we set all tax rates to their values in 1985, the last year in our sample period. Next, we assume that foreign prices of imports (in foreign currency and before tariffs) remain constant in real terms at 1985 levels. Third, we project a gradual decline in the government deficit through the year 2025, after which the deficit is held at four percent of the nominal value of the government debt. This has the effect of maintaining a constant ratio of the value of the government debt to the value of the national product when the inflation rate is four percent (as it is in our steady state). Fourth, we project that the current account deficit will fall gradually to zero by the year 2000. After that we project a small current account surplus sufficient to produce a stock of net claims on foreigners by the year 2050 equal to the same proportion of national wealth as in 1982.

Finally, the most important exogenous variables are those associated with US population growth and the corresponding change in the economy's time endowment. We project population by age, sex and educational attainment through the year 2050 using demographic assumptions consistent with Social Security Administration forecasts.[30] After 2050 we hold population

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30. Our breakdown of the US population by age, educational attainment, and sex is based on the system of demographic accounts compiled by Jorgenson and Fraumeni (1989). The population projections are discussed in detail by Wilcoxen (1988), Appendix B.

constant, which is roughly consistent with Social Security projections. In addition, we project educational attainment by assuming that future demographic cohorts will have the same level of attainment as the cohort reaching age 35 in the year 1985. We then transform our population projection into a projection of the time endowment used in our model of the labor market by assuming that relative wages across occupations are constant at 1985 levels. Since capital accumulation is endogenous, these population projections effectively determine the size of the economy in the more distant future.

3. THE IMPACT OF DIFFERENT EMISSIONS TARGETS

We now turn to our results on the effects of using a carbon tax to achieve different CO2 emissions goals. All together, we ran three simulations in addition to the base case, one for each of the following policies:

[1] Stabilizing carbon emissions at the 1990 base level beginning immediately.

[2] Decreasing carbon emissions gradually over 1990-2005 until they are 20% below the 1990 base level.

[3] Doing nothing until 2000, then gradually increasing the carbon tax over 2000-2010 to stabilize emissions at the year 2000 base level.

These policies vary considerably in stringency. In 1990, base case fossil fuel use produced 1576 million tons of carbon. Policy I would keep that level constant forever, even in the face of rapid GNP growth. Policy 2, however, is even more restrictive: it requires emissions to drop to 1261 million tons by 2005 and remain at that level forever. Policy 3, on the other hand, is the least restrictive: it allows emissions to rise to the base case year 2000 level of 1675 million tons.

In each simulation, we constrained total carbon emissions and allowed the level of the carbon tax to be determined endogenously. The tax was applied to primary fuels (industries 3 and 4) in proportion to carbon content. Since even the least stringent policy produces substantial tax revenue, it was also necessary to make an assumption about how the revenue would be used. In these simulations, we held the real value of government spending constant at its base case

level and allowed the average tax on labor to adjust to keep the difference between government spending and government revenue equal to the exogenous budget deficit. At the same time, we held the *marginal* tax on labor constant, so adjustments in the average rate reflect changes in the implicit zero-tax threshold.

3.1. Long Run Effects

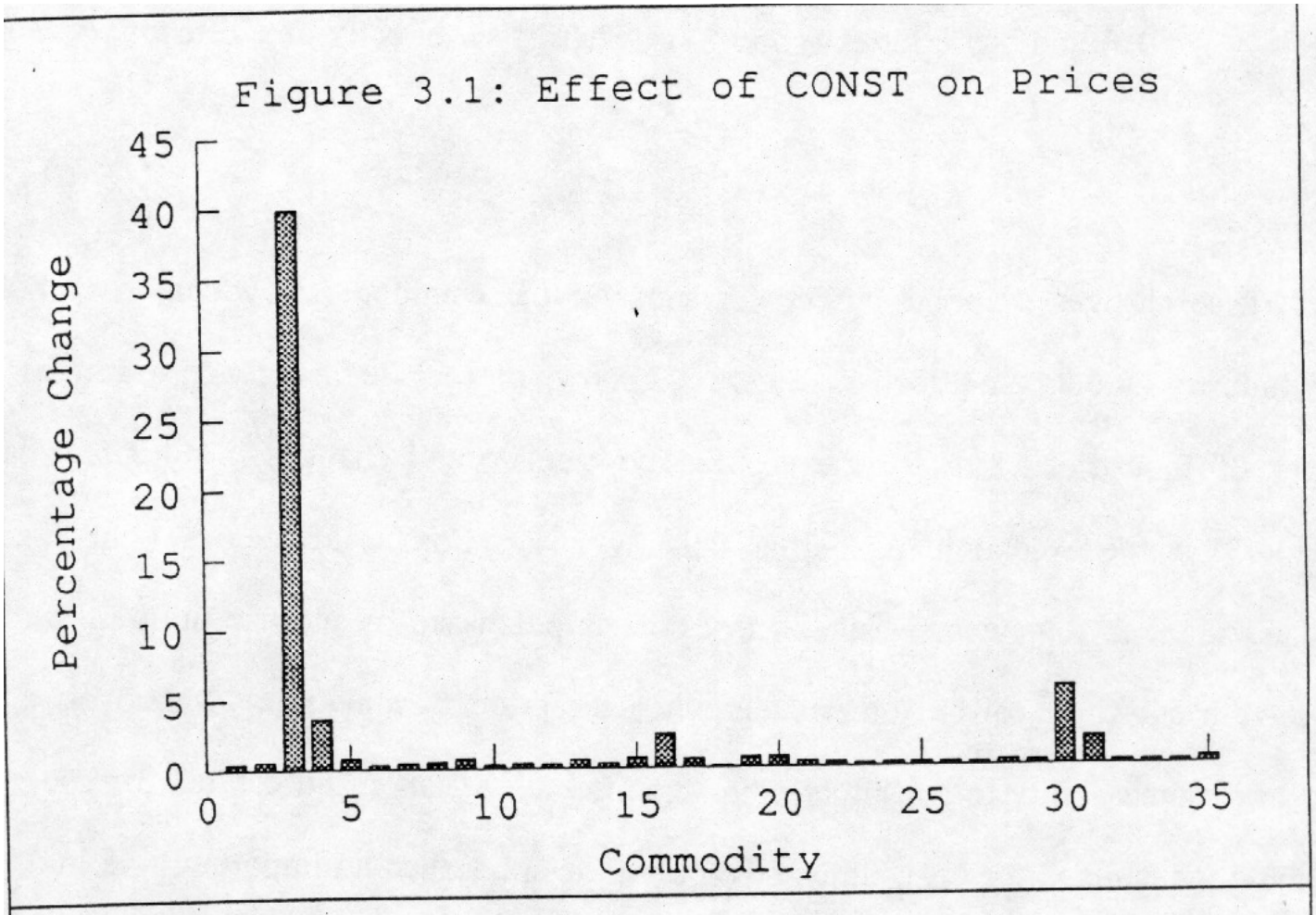
The principal direct consequence of all three carbon control strategies is to increase purchasers' prices of coal and crude oil. This can be seen most clearly by examining the model's results for each simulation at a particular point in time, so in this section we present detailed results for the year 2020. Our model is most suitable for medium run analysis (periods of 2030 years), so for our purposes 2020 is the long run.

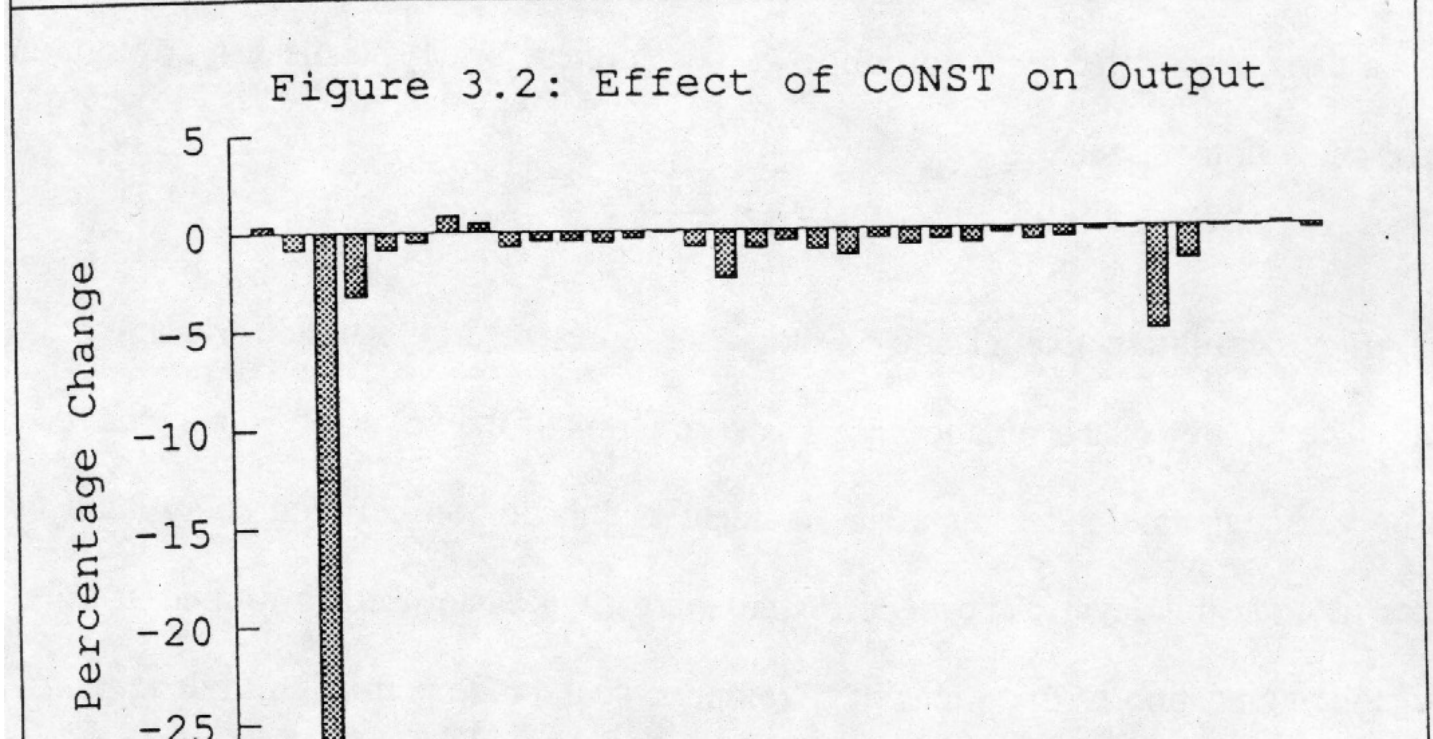
We begin with results for the first experiment: holding emissions at 1990 levels. By the year 2020, maintaining 1990 emissions will require a tax of $16.96 per ton of carbon contained in primary fuels.[31] Using the data in Table 2.2, it can be shown that this amounts to a tax of about $11.01 per ton of coal, $2.32 per barrel of oil or $0.28 per thousand cubic feet of gas. The tax would generate revenue of $26.7 billion annually.

The rising price of fossil fuels provokes substitution toward other energy sources and away from energy in general. Total BTU consumption falls by 12% to about 68 quads. This substitution away from energy, and hence toward more expensive production techniques, results in a drop of 0.7% in the capital stock and 0.5% in real GNP. These figures are fairly small because they measure, in a loose sense, the welfare losses from introducing a small distortionary tax. Since revenue from the tax is returned to households through essentially lump sum adjustments in the income tax, social welfare falls purely due to the inefficiency of the tax.

At the commodity level the impact of the tax varies considerably. Figure 3.1 shows changes

in the supply price of the 35 commodities measured as percentage changes relative to the base case. The largest change occurs in the price of coal (commodity 3), which rises by





40%. This, in turn, increases the price of electricity (commodity 30) by about 5%. Electricity prices rise considerably less than coal prices because coal accounts for only about 13% of total utility costs. Other prices showing significant effects are those for crude and refined petroleum (goods 4 and 16) and gas utilities (good 31). These rise, directly or indirectly, because of the tax on oil.

These changes in prices affect demands for the commodities, which in turn determine how industry outputs are affected. Figure 3.2 shows percentage changes in quantities produced by the 35 industries. Most of the sectors show only small changes in output. Coal mining (sector 3) is the exception: its output falls by 26%. Coal is affected strongly because the demand for it is somewhat elastic. Most coal is purchased by electric utilities, which in our model can substitute toward other fuels when the price of coal rises. Moreover, the utilities also have some ability to substitute other inputs, such as labor and capital, for energy, further reducing the demand for coal. Since electric utilities play such an important role in determining how a carbon tax affects coal mining, we now digress briefly to discuss how the utilities are represented in the model.

Electric utilities, like all other sectors, are represented by a nested translog unit cost function. The top tier of the function gives cost in terms of the prices of four inputs: capital, labor, an energy aggregate and a materials aggregate. Substitution between energy and other inputs takes place at this level. The price of the energy aggregate itself is formed at a lower tier by translog aggregation of the prices of five inputs: coal, crude petroleum, refined petroleum, electricity, and natural gas from gas utilities. Substitution between fuels takes place at that level.

Estimated parameters govern the ease of substitution at both the KLEM and energy tiers of the cost function. At the KLEM level, substitution between energy and capital is very inelastic (an elasticity of -0.15), substitution between energy and labor is moderately inelastic (-0.64), and substitution between energy and materials is slightly elastic (-1.16). Thus, increases in the relative price of energy will, for the most part, induce substitution toward materials. In addition, substitution possibilities also exist at the energy tier. The elasticity of substitution between coal and refined petroleum is -0.7, although between coal and natural gas it is only -0.1. Thus, an increase in the relative price of coal will produce some substitution toward other fuels. Overall, the parameters appearing in the cost function for electric utilities imply that an increase in the relative price of coal will lead to substitution toward other fuels and toward non-energy inputs.

The second policy we considered was a 20% reduction below 1990 emission rates, to be phased in gradually over 15 years. By 2020, this would amount to a drop of 32% below base case emissions, and would require a tax of $60.09 per ton of carbon. Using the data in Table 2.2, this is equivalent to a tax of $39.01 per ton of coal, $8.20 per barrel of oil, or $0.98 per thousand cubic feet of gas. The tax would produce $75.8 billion in revenues. Comparing these results to those for maintaining 1990 emissions shows that the tax would more than triple, from $17 to $60. At equilibrium, the tax gives the marginal cost of reducing emissions by an additional ton of carbon, so it is clear that further reductions are becoming significantly more difficult.

Tighter carbon regulations also lead to a reduction in total fossil fuel BTU production to 57 quads, a drop of 27% from the base case. This, in turn, reduces the capital stock by 2.2% and real GNP by 1.6%. These figures are about triple the values obtained for holding emissions at 1990 levels. Although the changes in capital and GNP appear small, recall that they are measures of deadweight loss associated with fairly large marginal changes in the energy sector.

At the commodity and industry level, results for this experiment are qualitatively similar to those for maintaining 1990 emissions, although they are numerically somewhat different. Figure 3.3 shows percentage changes in commodity prices relative to the base case. The price of coal more than doubles, rising by 137% from its base case value. The price of oil rises by 13%, while that of electricity rises by about 18%. The prices of refined petroleum and natural gas also rise, but by somewhat less. Comparing Figures 3.3 and 3.1 shows how this simulation compares with the previous one. In particular, commodity prices rise roughly in proportion to the increase in the carbon tax: the tax rises by a factor of 3.5, and so do most of the percentage changes in commodity prices.

The quantity results, shown in Figure 3.4, display a similar pattern except that they scale up in proportion to the change in carbon reductions rather than the change in taxes. That is, reducing emissions to 20% below 1990 levels requires a cut of about twice the size needed to reach 1990 levels. Thus, percentage changes in quantities from the base case are about twice those of the previous experiment. The most important results are the 53% drop in coal production and the 15% drop in electricity produced.

In contrast, the looser restrictions implied by maintaining emissions at year 2000 levels produce much smaller effects on the economy. The tax required is only $8.55 per ton of carbon, which implies charges of $5.55 per ton of coal, $1.17 per barrel of oil, or $0.14 per thousand cubic feet of gas. The tax would produce $14.4 billion annually in revenue. Aggregate effects are also considerably smaller than in the two previous scenarios. The capital stock will fall by 0.4%, and GNP will drop by 0.3%, about half the value obtained in the 1990 simulation. This is quite reasonable since the cut in emissions is about half as deep. The industry results look qualitatively

so similar to those of the previous experiments that we omit the graphs. The principal numerical result is that coal prices rise by 20% while coal output shrinks by about 16%.

Figure 3.3: Effect of CUT20 on Prices

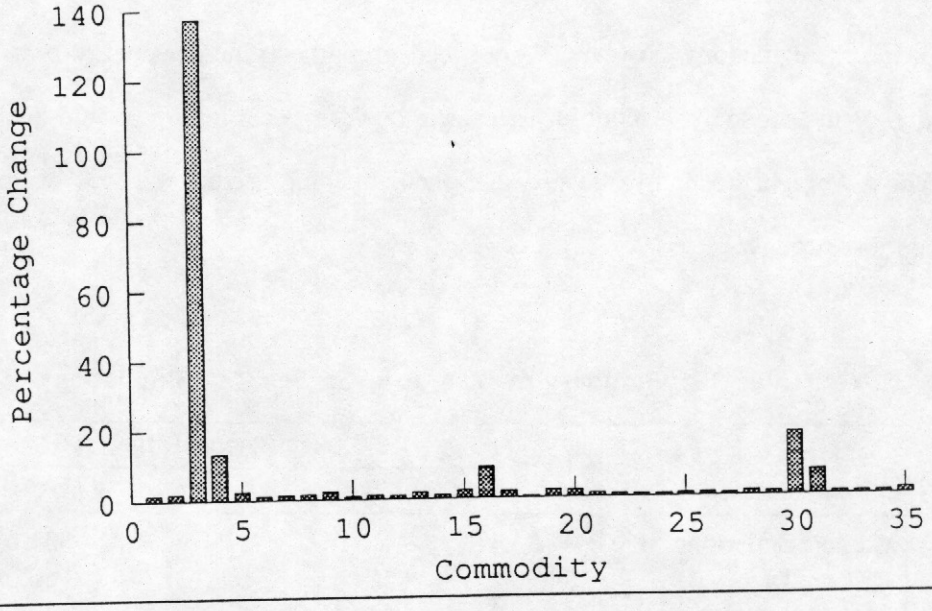
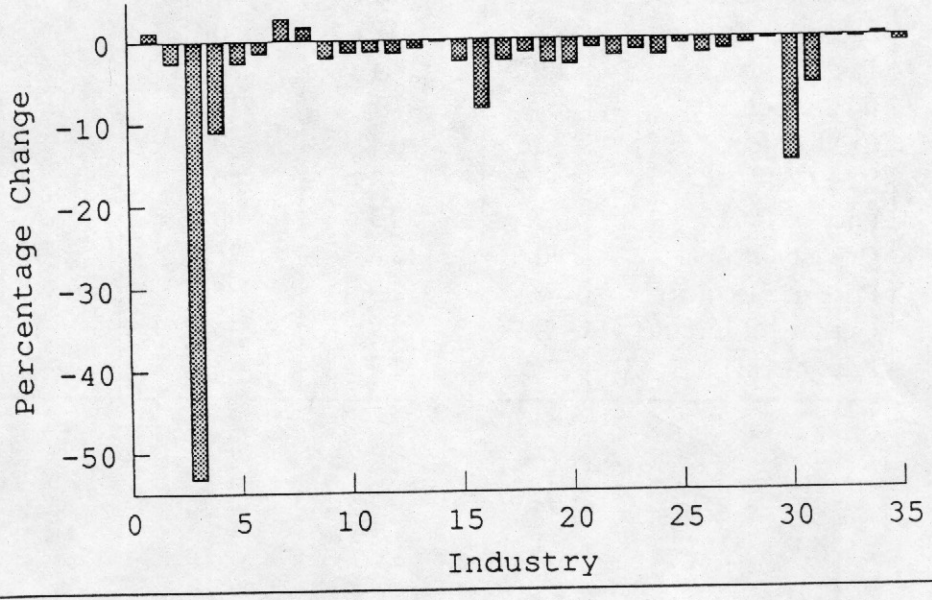


Figure 3.4: Effect of CUT20 on Output



The results of all three carbon tax simulations are summarized in Table 3.1, in which the policies are listed in order of increasing stringency. From these results it appears that maintaining emissions at the year 2000 base-case level can be accomplished with a very low carbon tax and minimal disturbance of the economy. The strongest effect would be felt by the coal mining industry, which would see its demand fall as electric utilities substituted toward other fuels. More stringent regulations, however, would lead to markedly higher energy prices and greater disruption of the economy. Under any scenario, however, coal mining would bear the brunt of the changes brought about by the tax. Of the remaining sectors, electric utilities would be affected most strongly.

Table 3.1: Summary of Long Run Carbon Tax Simulations

Variable	Unit	Emissions Target		
		2000 Level	1990 Level	80% of 1990
Carbon Emissions	%0	-8.4	-14.4	-31.6
Carbon Tax	$/ton	8.55	16.96	60.09
Tax on Coal	$/ton	5.55	11.01	39.01
Tax on Oil	$/bbl	1.17	2.32	8.20
Tax on Gas	$/kcf	0.14	0.28	0.98
Labor Tax Rate	0	-0.25	-0.45	-1.22
Tax Revenue	Bil.$	14.4	26.7	75.8
BTU Production	%0	-7.1	-12.2	-27.4
Capital Stock	%A	-0.4	-0.7	-2.2
Real GNP	%0	-0.3	-0.5	-1.6
Price of Coal	%A	20.3	40.0	137.4
Quantity of Coal	%0	-15.6	-26.3	-53.2
Price of Electricity	%0	2.9	5.6	17.9
Quantity of Electricity	%A	-2.9	-5.3	-15.3
Price of Oil	%0	1.8	3.6	13.3

3.2. Intertemporal Results

Carbon restrictions adopted today will have effects far into the future. At the same time, anticipated future restrictions will have effects today. To assess the intertemporal consequences of carbon taxes, we now turn to the model's dynamic results. As with the long run results, we begin by discussing a carbon tax designed to maintain emissions at 1990 levels. Following that, we examine the dynamic behavior of other experiments.

The path of the carbon tax needed to maintain 1990 emissions is shown in Figure 3.5. Base case emissions increase over time, so the tax grows gradually, about $0.70 per year, over the next few decades. It reaches a peak around the year 2020 when our forecast of the US population crests.[32] The tax produces significant reductions in carbon emissions which are shown in Figure 3.6 as percentage changes from the base case. Emissions begin dropping immediately and by 2020 are about 14% below their unconstrained level.

As suggested by the long run results, the principal effect of the tax is to reduce coal mining. This is shown clearly in Figure 3.7, which gives percentage changes in coal output from the base case. Production gradually slows as the tax is introduced. It does not, however, fall all the way back to its 1990 level-some of the reduction in emissions comes about through reductions in oil consumption. This can be seen in Figure 3.8, which gives percentages changes in crude petroleum and natural gas extraction over time.

The increasing price of energy raises costs and reduces household income. This, in turn, changes the rate of capital accumulation. The outcome is shown in Figure 3.9, which gives percentage changes in the capital stock from the base case. Unlike variables in the preceding

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32. As noted in Section 2, our population forecast is based on work done by the Social Security Administration. Two notable features are that the US population stabilizes early in the next century, and that educational attainment (and hence labor quality) stabilizes as well.

Figure 3.5: Carbon Tax Under CONST

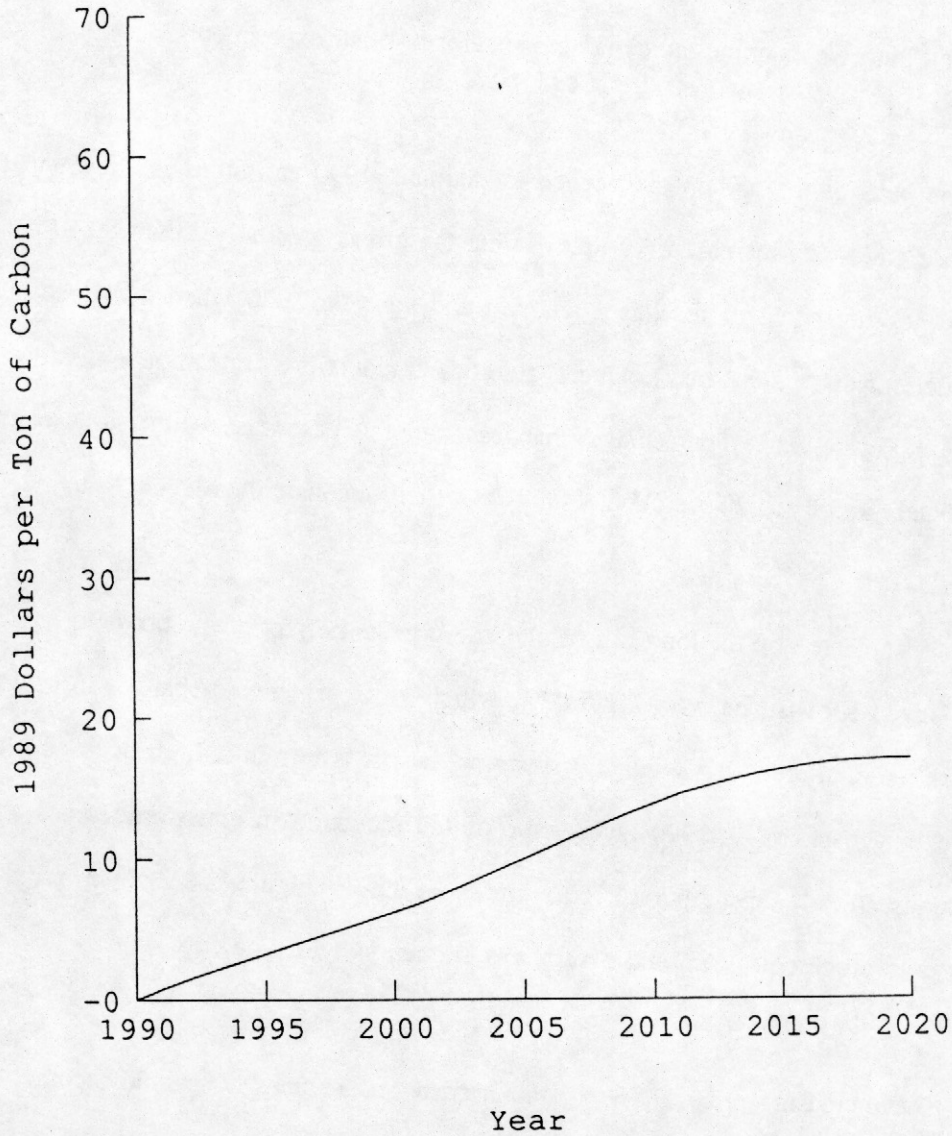


Figure 3.6: Carbon Emissions Under CONST

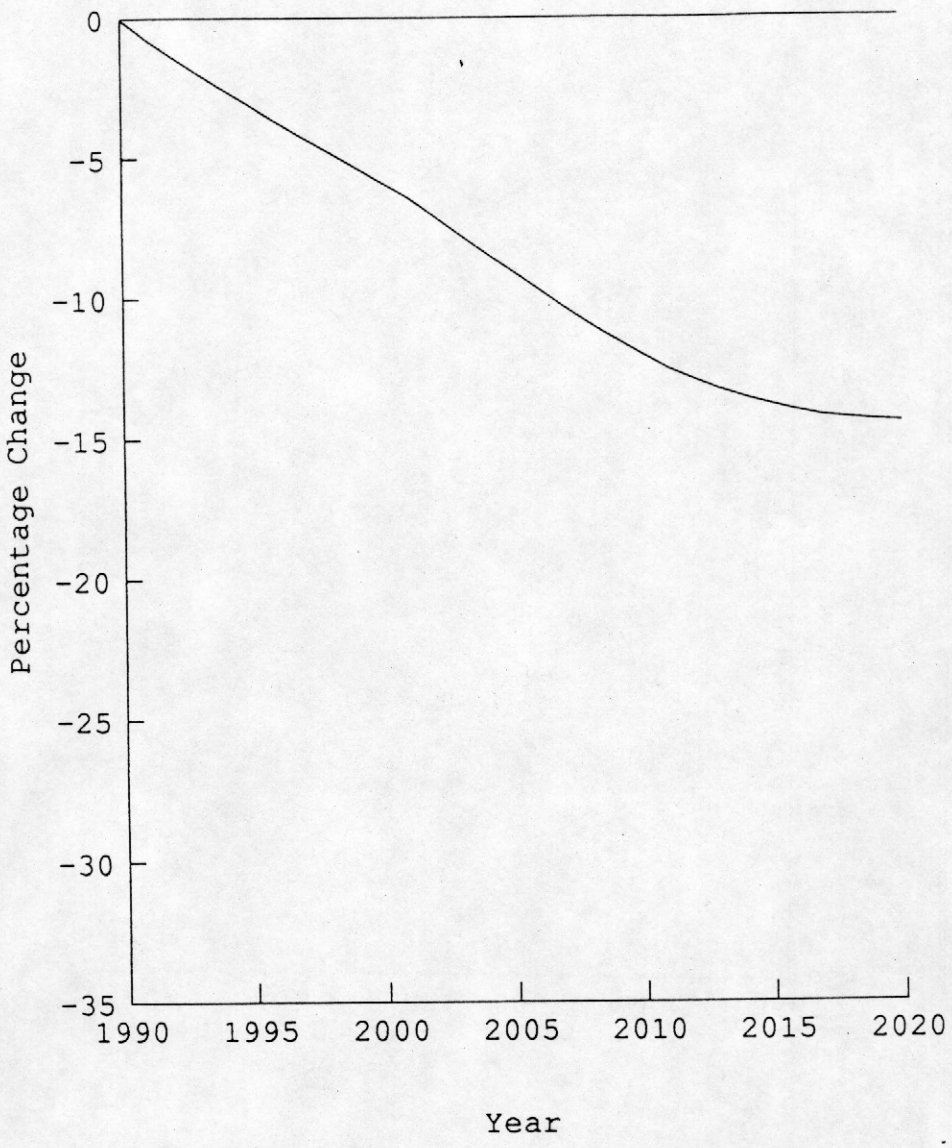


Figure 3.7: Coal Production Under CONST

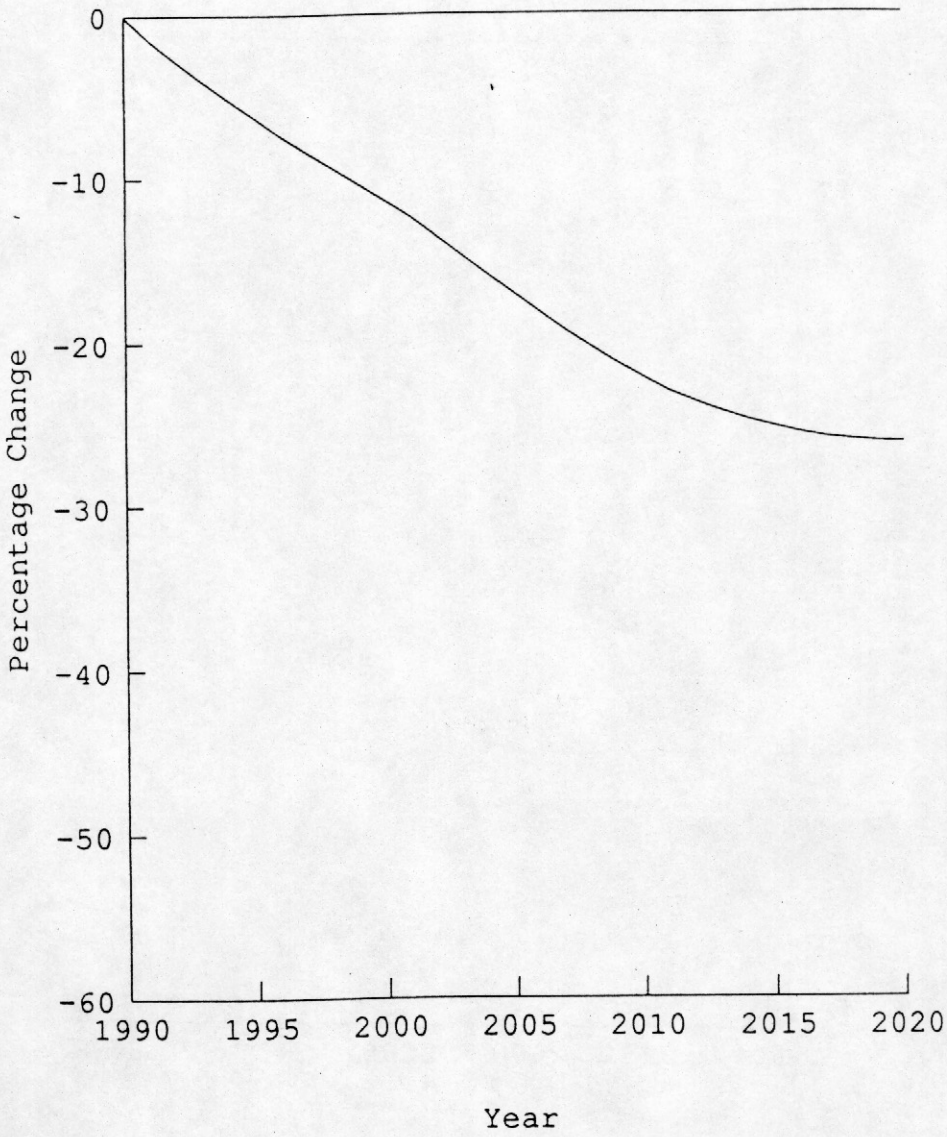


Figure 3.8: Oil and Gas Extraction Under CONST

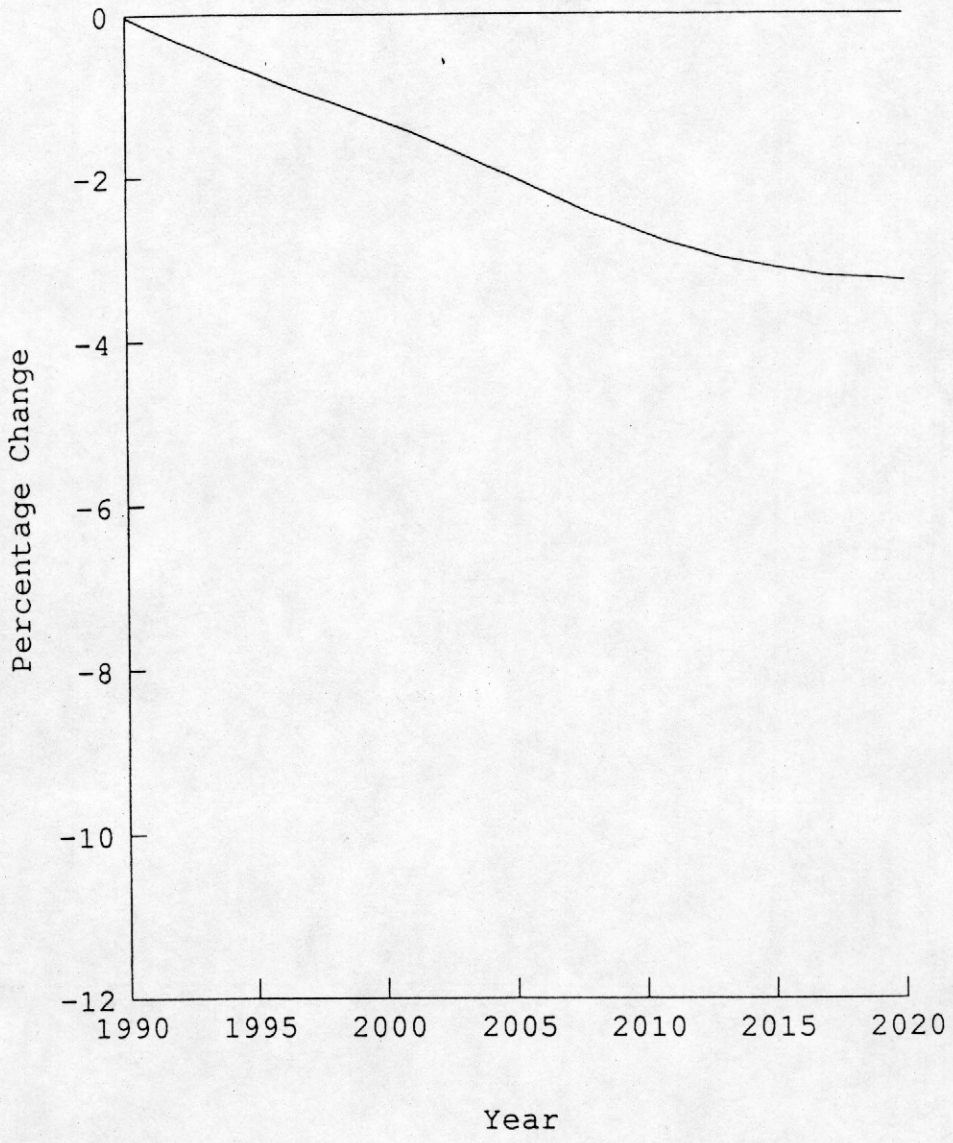
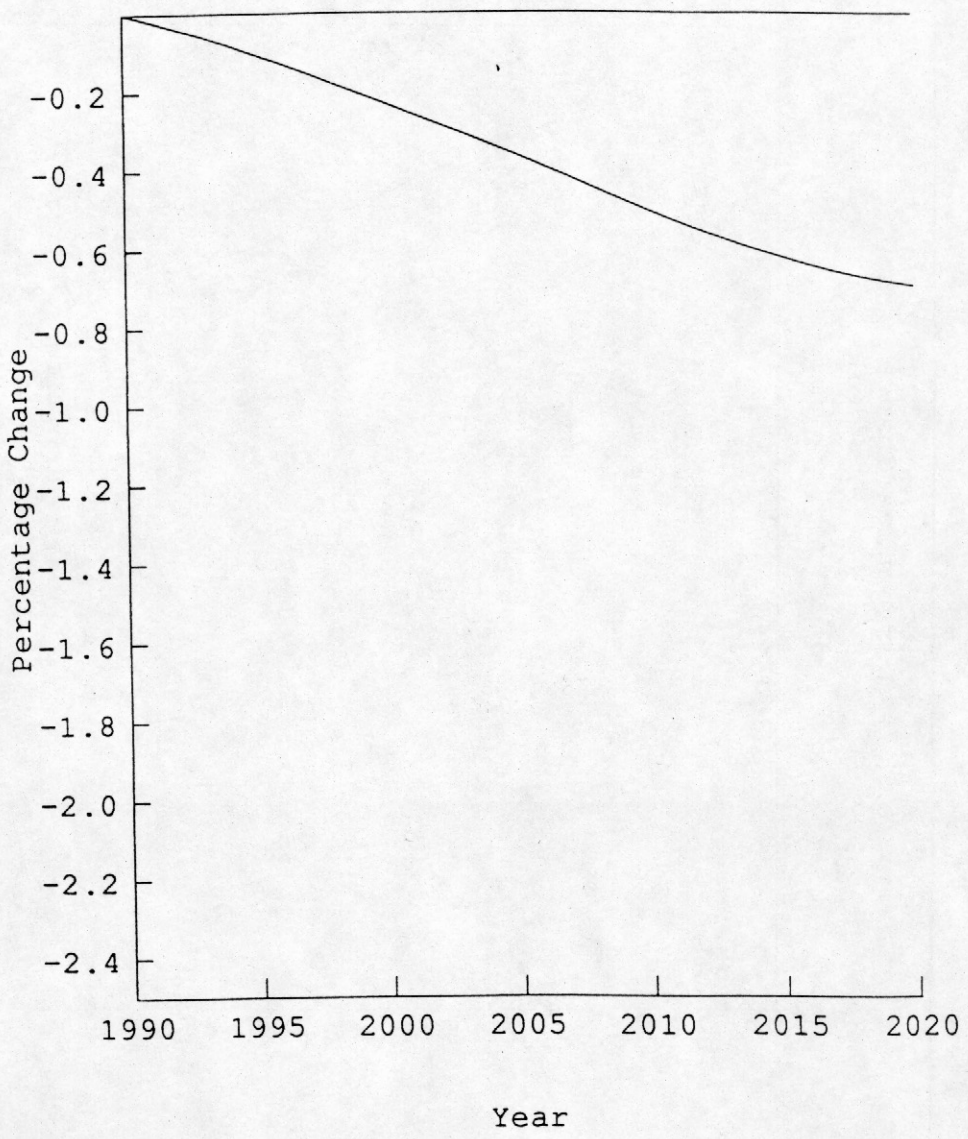


Figure 3.9: Capital Stock Under CONST



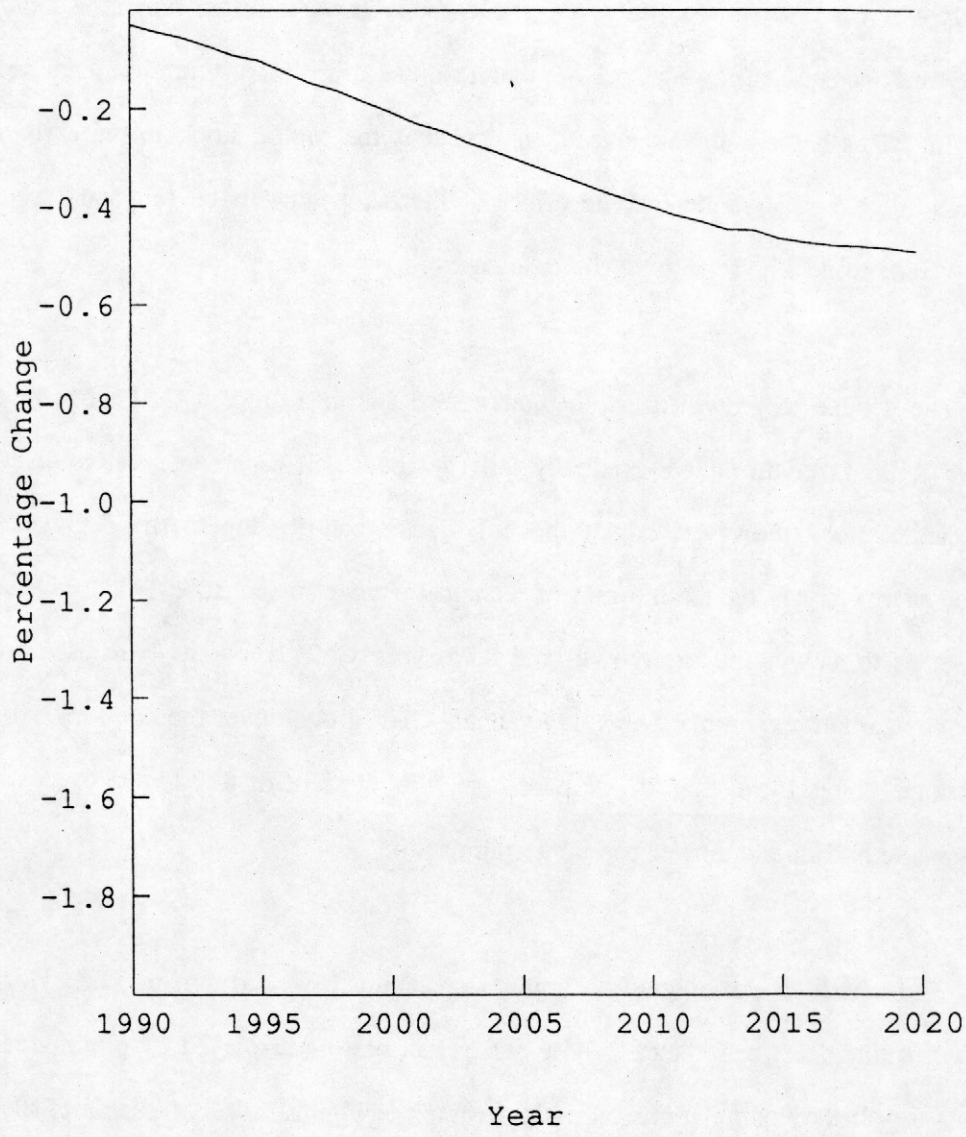
graphs, the capital stock does not start declining immediately; instead, it tends to remain near its base case level for the first few years. This comes about because of intertemporal optimization by households. From a household's point of view, the effect of the tax is to decrease its real income by an amount related to the tax's deadweight loss.[33] Thus, the household regards carbon taxes as reductions in future earnings, so it reacts by lowering consumption in all periods. In the early years, however, the carbon tax is minimal and household income is largely unaffected. During that period, therefore, the drop in consumption leads to an increase in saving. This helps maintain investment-and thus the capital stock-in the early years of the simulation. Eventually, the income effect of the tax begins to be felt and the capital stock finally starts to decline relative to the base case.

The decline in growth of the capital stock leads to a drop in GNP growth, as shown in Figure 3.10. Over time GNP gradually falls by about half a percent relative to the base case. The capital stock, however, is not the only factor contributing to the decline. In addition, higher energy prices reduce the rate of technical change in industries which are energy-using. This leads to slower income growth and helps keep GNP below its base case level. In fact, under the carbon tax simulation average annual GNP growth over the period 1990-2020 is 0.02 percentage points lower than in the base case.[34] About half of this is due to slowing technical change and half due to slower capital accumulation.

The other two carbon control targets we examined showed dynamic behavior qualitatively similar to that described above. These results can best be displayed by plotting each variable's values for all three simulations on a single graph.[35] Figure 3.11, for example, shows the paths

33. Since revenue earned by the tax is given back to households through a vertical shift in the labor tax schedule, the simulation is essentially the replacement of a lump sum tax (the labor tax) by a distorting one (the carbon tax).
34. The difference in two variables growing at rates differing by 0.02 percentage points is about 2% after a hundred years.
35. Recall that the targets were (1) maintaining 1990 emissions, (2) reducing emissions by *20%* below 1990 levels, and (3) gradually introducing taxes to stabilize at year 2000 emissions.

Figure 3.10: Real GNP Under CONST



of the carbon tax needed to achieve each of the targets. The highest path is the tax required to reduce emissions to 20% below their 1990 levels; the central path is that for maintaining 1990 emissions; and the lowest path is the tax needed to stabilize emissions at year 2000 levels. Similarly, Figure 3.12 shows the carbon reductions achieved under each of the policies.[36] Plotting three curves on each figure makes it easy to compare different targets. For example, many of the figures show that as the target becomes more stringent, the variable of interest is pushed further away from the base case. However, some of the figures show much more interesting behavior, and we will focus on these for the remainder of this section.

The first feature to note, which is apparent from Figure 3.12, is that the three targets require carbon reductions of roughly 8, 14 and 32 percent. (This was also noted in the section on long run results.) Keeping these reductions in mind, Figure 3.13 is quite interesting because it shows that coal production does not fall in proportion to the drop in emissions. This occurs because it becomes increasingly costly to drive coal production toward zero. Coal users, notably electric utilities, find it increasingly difficult to substitute away from coal as the amount they use of it decreases. This is reflected in Figure 3.14, which shows that oil extraction consequently more sharply as regulations become more stringent.

One of the most interesting results of our study is shown in Figure 3.15, a graph of the capital stock under the three policies. Figure 3.15 is a very clear example of the effects of intertemporal optimization by households. For the policy which has least effect and occurs furthest in the future (maintaining emissions at year 2000 levels), the early reduction in consumption actually leads to a temporary increase in the capital stock. As explained above, this comes about because households reduce consumption in anticipation of lower future earnings.

36. Notice that target policies are drawn using the same line type in each graph. Maintaining 1990 emissions is always a solid line, [illegible] ots and

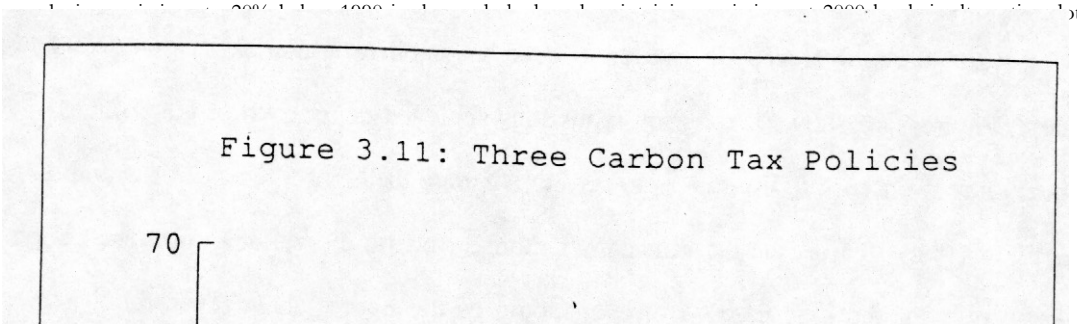


Figure 3.12: Carbon Emissions

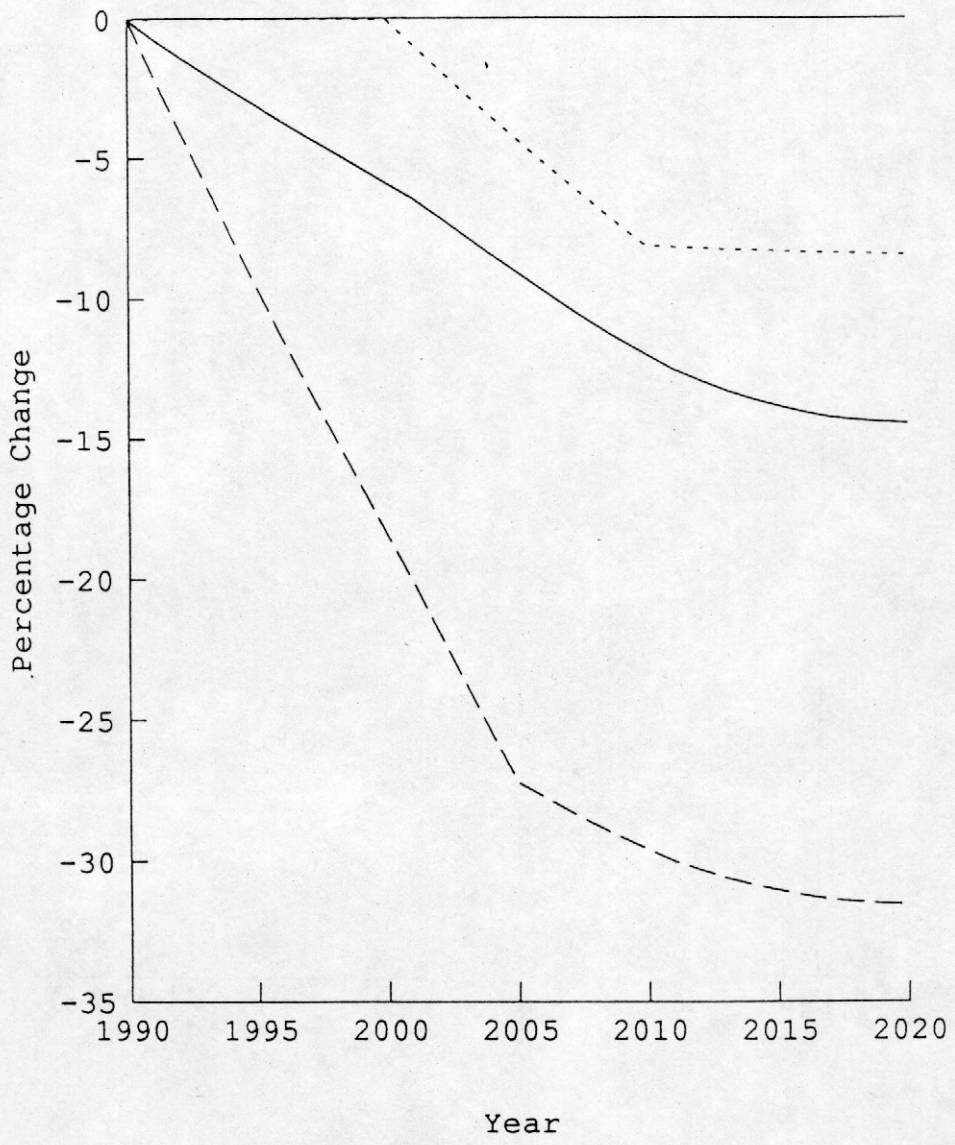


Figure 3.13: Coal Production

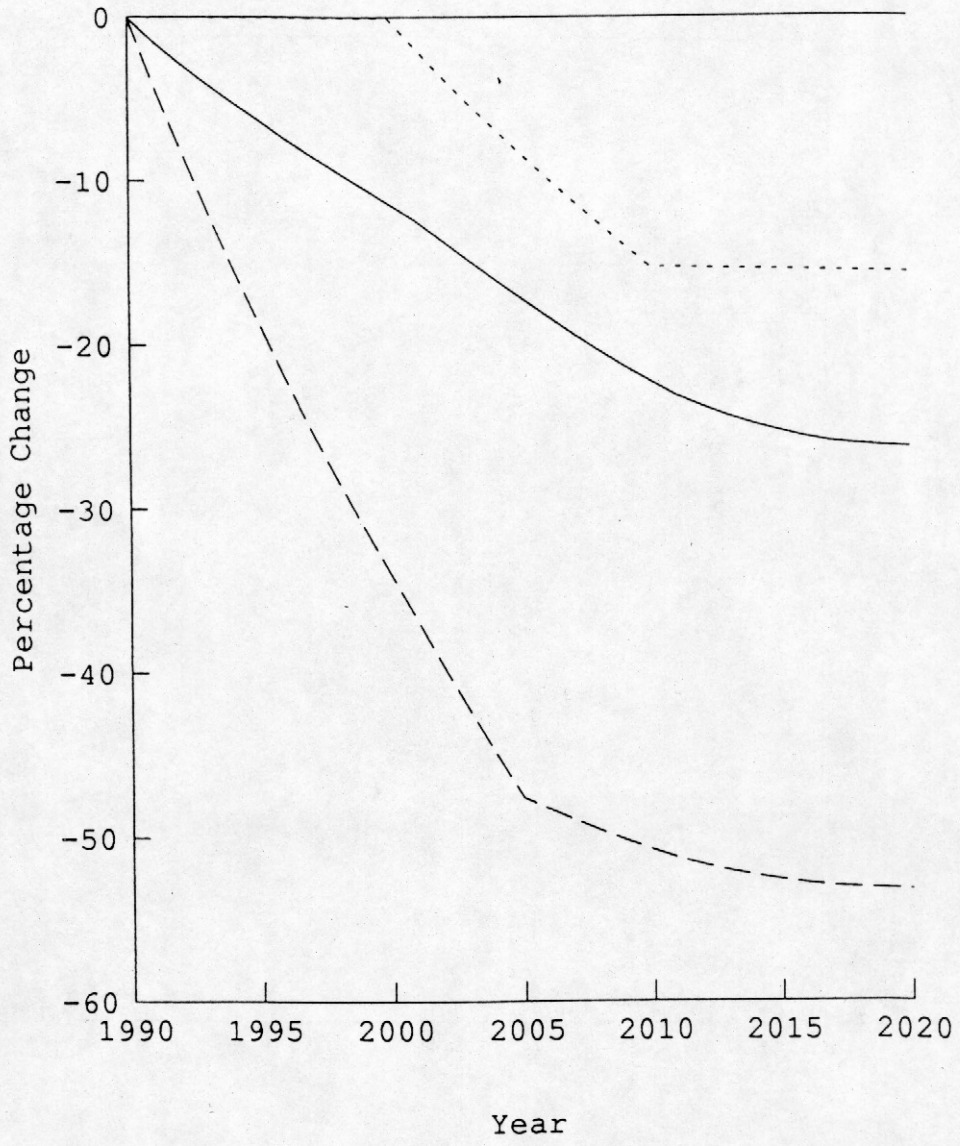


Figure 3.14: Oil and Gas Extraction

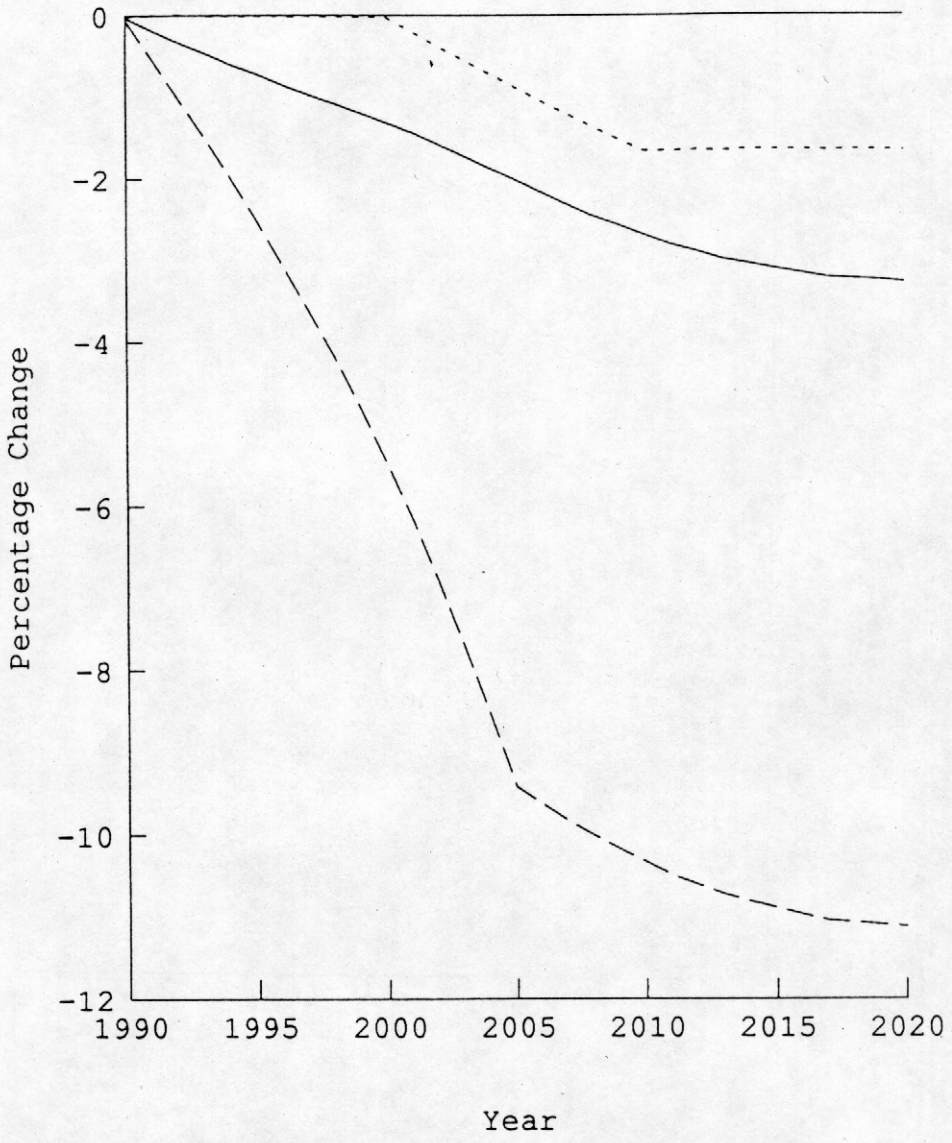
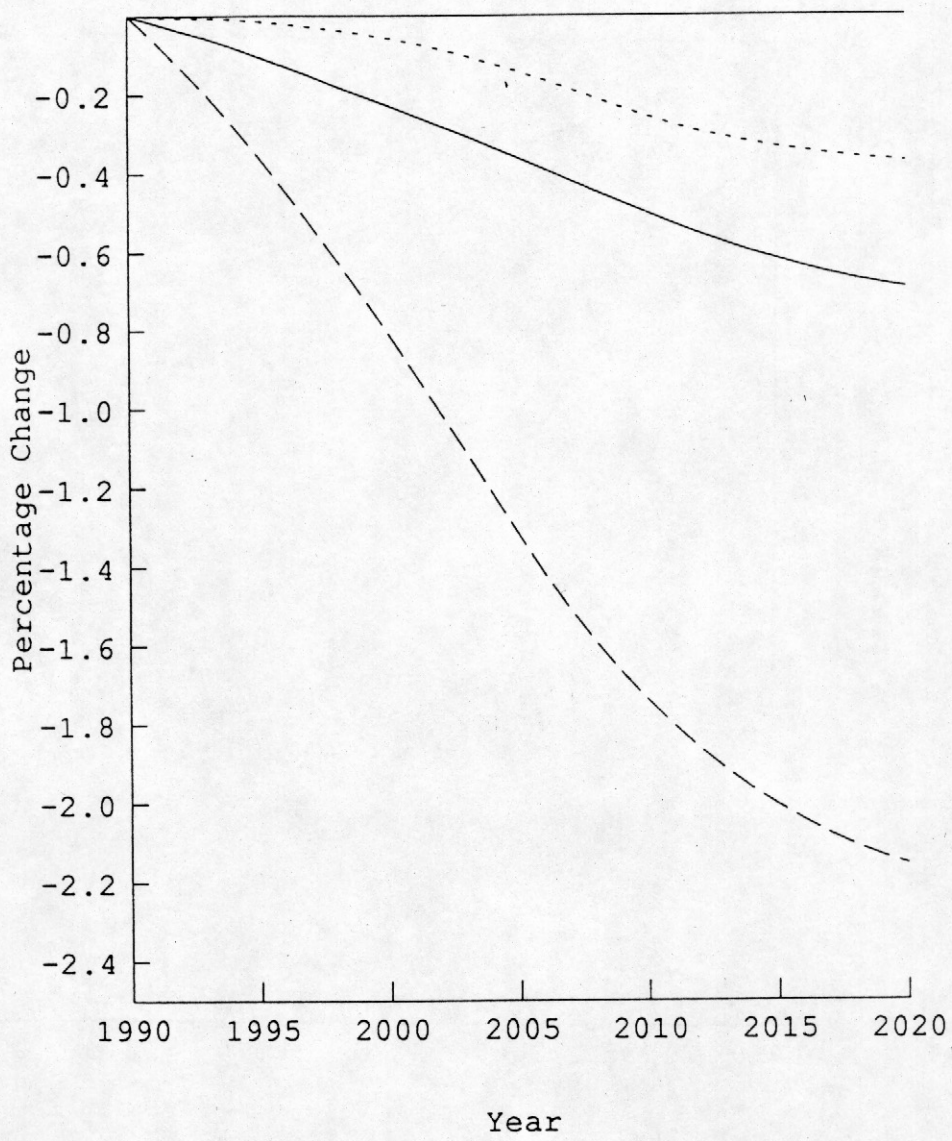
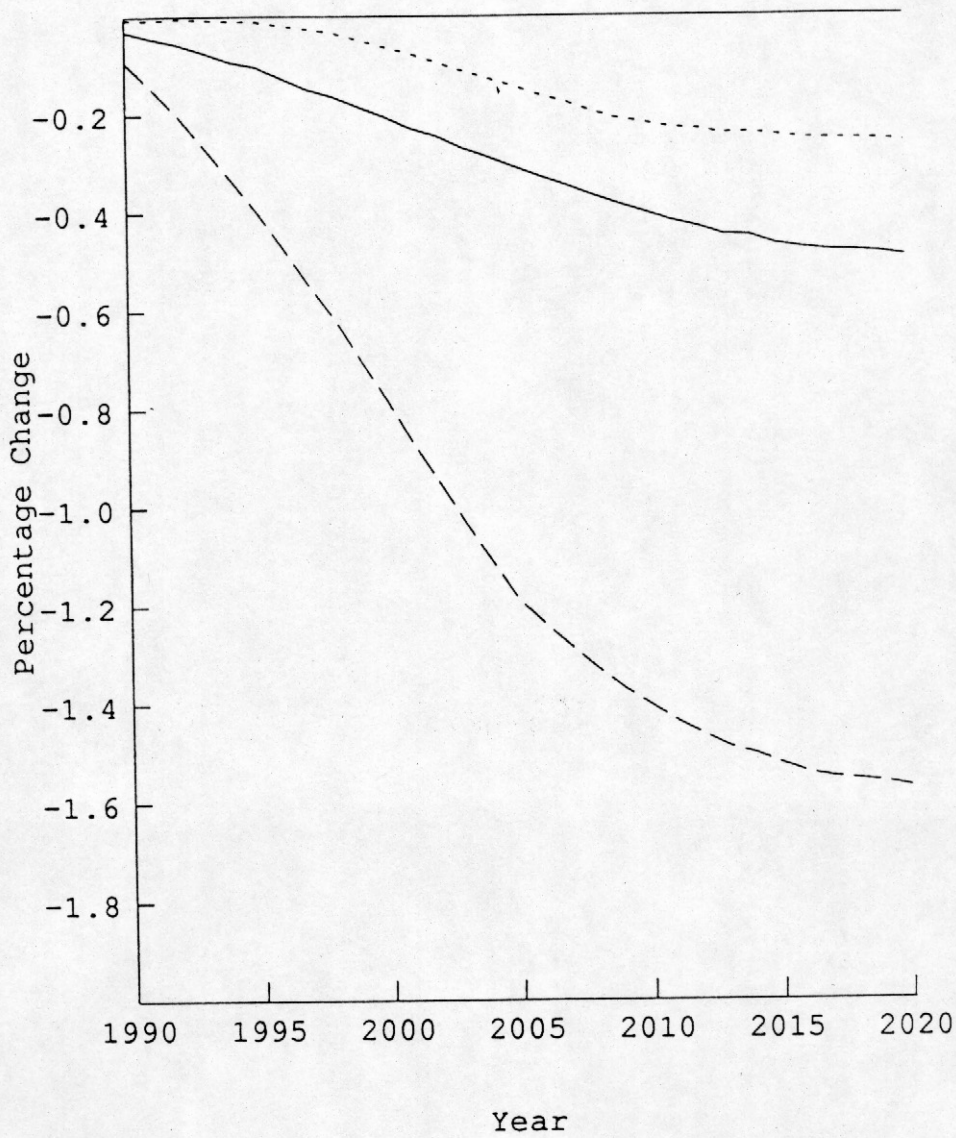


Figure 3.15: Capital Stock



only in under the most stringent policy (reducing emissions by 20% from 1990 levels) does the capital stock begin to fall immediately. Finally, the results for GNP, shown in Figure 3.16, echo those for the capital stock. As mentioned above, GNP falls in part because of the drop in capital accumulation and in part because higher energy prices reduce the rate of technical change.

Figure 3.16: Real GNP



4. CONCLUSION

Several important observations can be made about the carbon tax simulations presented in this paper. First, the principal effects of a carbon tax will be felt at the industry level. Coal mining, in particular, will be strongly affected. Even under the least restrictive policy, coal output will fall 16% from its base case value; more restrictive policies could lead to reductions of 50% or more. Electric utilities will also be affected, with output failing by as much as 15% under tighter emissions restrictions. At more aggregate levels, however, our results also show that the economy-wide effects of a carbon tax would be fairly modest. Thus, the effects of a tax would be concentrated in coal mining, although a handful of other sectors such as oil extraction would also be affected.

A second but no less important observation about these simulations is that the stringency and timing of the tax will determine how strongly the tax affects the economy. Comparing long run results of the three simulations considered here shows that increasingly stringent targets are increasingly costly. Thus it is essential that any serious national or international goal on carbon dioxide emissions be chosen by carefully comparing costs and benefits. Setting goals arbitrarily risks seriously under or over emphasizing carbon dioxide reductions. Since our model does not compute benefits, we cannot say which policy is most appropriate. We do urge, however, that careful consideration of benefits be given before any national or international policy is adopted.

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