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Carbon Taxes and Economic Welfare

THE POSSIBILITY THAT INCREASED concentrations of carbon dioxide in the atmosphere might lead to global warming has emerged as a leading environmental concern. Many nations, including the United States, are considering policies to reduce emissions of carbon dioxide.[1] The policy instrument for reducing carbon dioxide emissions most often recommended by economists is a carbon tax.[2] A carbon tax, levied on fossil fuels in proportion to the amount of carbon dioxide they produce during combustion, would stimulate firms and households to reduce fossil fuel use and shift the fuel mix toward less-carbon-intensive fuels, such as natural gas.

A carbon tax would internalize the externality associated with carbon

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[1] Overviews of the economics of global warming have been given by Nordhaus (1991) and Schelling (1992).

[2] A carbon tax was first analyzed by Nordhaus (1979) and has recently been discussed by the Congressional Budget Office (1990) and Poterba (1991b). Alternative policy options for stabilizing the global climate are described in detail by the Environmental Protection Agency (1989).

dioxide emissions.[3] However, this externality affects the whole planet, while carbon taxes are the responsibility of individual governments. Furthermore, carbon taxes would interact with taxes levied to achieve other objectives, such as taxes on motor fuels used to generate revenues for highway construction and maintenance. The design of an appropriate level for carbon taxes would involve international coordination and consideration of interactions among different tax and expenditure programs within each nation. Finally, benefits of a carbon tax would have to be weighed against losses in efficiency resulting from distortions in resource allocation.

Jorgenson and Wilcoxen have measured the efficiency cost to the U.S. economy of carbon taxes required to achieve alternative restrictions on carbon dioxide emissions.[4] For this purpose they simulated U.S. economic growth under different tax regimes by means of an intertemporal general equilibrium model of the U.S. economy. In this paper we analyze the distributional effect of carbon taxes that would stabilize U.S. carbon dioxide emissions at 1990 levels. To achieve this objective, we disaggregate the overall economic effect of carbon taxes to the level of individual households.

An evaluation of the impact of taxes to reduce carbon emissions must consider not only the resulting efficiency losses, but also the effects of these taxes on equity in the distribution of welfare among households. A carbon tax has potentially significant distributional consequences because it would affect the relative prices faced by consumers. The impact of this change in relative prices could vary widely among consumer groups with different expenditure patterns. For example, an increase in the price of energy, resulting from the imposition of a carbon tax, would adversely affect those consumers who devote a large share of their total expenditures to energy.

Our paper is not the first to examine the distributional impact of carbon taxes. Poterba has employed a static, partial equilibrium ap-

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[3] The use of Pigouvian taxes to internalize environmental externalities is discussed by Laffont (1977) and Sandmo (1975). A very lucid exposition is provided by Laffont (1988, pp. 6–32).

[4] Jorgenson and Wilcoxen (1992). Many estimates of the efficiency effect of restrictions on carbon dioxide emissions are now available. Detailed surveys are given by Hoeller, Dean, and Nicolaisen (1991) and Nordhaus (1990).

proach to estimate the effect of a $100-per-ton carbon tax on U.S. households with different levels of total expenditure.[5] He concludes that such a tax would be regressive. DeWitt, Dowlatabadi, and Kopp have conducted a similar study for a range of carbon taxes, using a detailed econometric model of U.S. household energy consumption to estimate the response of energy consumption patterns to the tax.[6] They find that there would be substantial differences in the economic effect among regions of the United States.

Our analysis of the welfare effect of carbon taxes differs from these previous studies in two important ways. First, we employ a general equilibrium approach in analyzing these taxes. A partial equilibrium analysis is limited to the effects of changes in energy prices. As Poterba and DeWitt, Dowlatabadi, and Kopp point out, nonenergy prices will also change, so a general equilibrium approach is required to assess the full impact.[7] Second, because a carbon tax will alter saving, investment, and interest rates, as well as relative prices, we measure changes in economic welfare throughout the lifetime of consumers. Jorgenson and Wilcoxen have shown that it is essential to incorporate changes in the U.S. economy over time into the evaluation of a carbon tax.[8]

To estimate the distributional effects of carbon taxes on the lifetime welfare of consumers, we consider a population of infinitely lived households. We refer to different household types, cross-classified by demographic characteristics and levels of wealth, as ''dynasties.'' Each household type is linked to a similar household type in the future through intergenerational altruism in preferences.[9] We evaluate the effect of carbon taxes on each dynasty through willingness to pay to avoid the consequences of the tax. Our measures of willingness to pay are var-

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[5] Poterba (1991b).

[6] DeWitt, Dowlatabadi, and Kopp (1991). This model was developed by Jorgenson, Slesnick, and Stoker (1987, 1988) and is similar in many respects to the model of the household sector used in this paper.

[7] Poterba (1991b); and DeWitt, Dowlatabadi, and Kopp (1991).

[8] Jorgenson and Wilcoxen (1992).

[9] Barro (1974) demonstrates the equivalence between a single consumer with an infinite time horizon and successive generations of consumers linked by intergenerational altruism. Laitner (1991) shows how similar household types are linked through time by assortative mating.

iations in dynastic wealth that are the monetary equivalent of changes in dynastic welfare.[10] We consider the distributional effect of carbon taxes on more than 16,000 different types of households.

The measurement of welfare levels of individual households is an essential first step in the evaluation of policies to control carbon dioxide emissions. An overall evaluation, however, must combine individual welfare levels into a measure of social welfare.[11] We define a social welfare function on distributions of individual welfare over households. An explicit social welfare function facilitates the decomposition of changes in social welfare into two components: changes in efficiency and changes in equity. Our social welfare function is consistent with principles of consistent social choice under measurability and comparability of individual preferences. It is sufficiently flexible to incorporate alternative normative assumptions for ranking distributions.

In this paper we first describe the intertemporal general equilibrium model of the U.S. economy employed in our evaluation of the effect of carbon taxes. We next outline the framework for measuring the welfare of individual households and combining these measures into an overall measure of social welfare. The effects of taxes required to hold U.S. carbon dioxide emissions constant at 1990 levels are then analyzed, and the growth of the U.S. economy with these taxes is compared with a "base case" with no controls on emissions. Finally, we evaluate the distributional effect of carbon taxes and summarize our conclusions.

An Overview of the Model

Our analysis of the incidence of carbon taxes is based on simulations of U.S. economic growth, using an intertemporal general equilibrium model of the U.S. economy described in detail by Jorgenson and Wil-

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[10] Our approach exemplifies the "lifetime incidence" approach discussed by Poterba (1989). Poterba (1991a) provides estimates of the lifetime incidence of gasoline taxes and references to the literature.

[11] It is well known that unweighted or weighted sums of equivalent variations in wealth are inappropriate for this purpose. See Slesnick (1991) and the references given there.

coxen.[12] This model has been used to measure the cost of all U.S. environmental regulations imposed at the federal level before 1990.[13] Here we outline the key features of the model and describe its application to policies for the control of carbon dioxide emissions.

Producer Behavior

Our submodel of producer behavior is disaggregated into 35 industrial sectors, listed in figure 1. The model determines levels of output for 35 separate commodities, each produced by one or more industries. The industries correspond, roughly, to two-digit industry groups in the Standard Industrial Classification (SIC). This level of industrial detail makes it possible to measure the effect of changes in tax policy on relatively narrow segments of the economy. Because carbon dioxide emissions are generated by fossil fuel combustion, a disaggregated model is essential for modeling sectoral differences in the response to policies for controlling these emissions.

We represent the technology of each of the 35 industries in our model by means of a hierarchical tier structure of models of producer behavior. At the highest level, the price of output in each industry is represented as a function of prices of energy, materials, and capital and labor services. Similarly, the price of energy is a function of prices of coal, crude petroleum, refined petroleum, electricity, and natural gas; the price of materials is a function of the prices of all other intermediate goods. We derive demands for inputs of capital and labor services and inputs of the 35 intermediate goods into each industry from the price function for that industry.

We have estimated the parameters of production models for the 35 industries econometrically. For this purpose we have constructed a set of consistent interindustry transactions tables for the U.S. economy for the period 1947 through 1985.[14] Our econometric method for parameterization stands in sharp contrast to the calibration method used in

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[12] Jorgenson and Wilcoxen (1990b).

[13] Jorgenson and Wilcoxen (1990a).

[14] Data on interindustry transactions are based on input-output tables for the United States constructed by the Bureau of Economic Analysis (1984). Income data are from the U.S. national income and product accounts, also developed by the Bureau of Economic Analysis (1986). The data on capital and labor services are described by Jorgenson (1990b). Additional details are given by Wilcoxen (1988, app. C) and Ho (1989).

Figure 1. Industries Used in the Model

Agriculture, forestry, and fisheries
Metal mining
Coal mining
Crude petroleum, natural gas extraction
Nonmetallic mineral mining
Construction
Food and kindred products
Tobacco manufactures
Textile mill products
Apparel and other textile products
Lumber and wood products
Furniture and fixtures
Paper and allied products
Printing and publishing
Chemicals and allied products
Petroleum refining
Rubber and plastic products
Leather and leather products
Stone, clay, and glass products
Primary metals
Fabricated metal products
Machinery, except electrical
Electrical machinery
Motor vehicles
Other transportation equipment
Instruments
Miscellaneous manufacturing
Transportation and warehousing
Communication
Electric utilities
Gas utilities
Trade
Finance, insurance, and real estate
Other services
Government enterprises

almost all applied general equilibrium models. Calibration involves choosing parameters to replicate the data for a particular year.[15]

The econometric approach to parameterization has several advantages over the calibration approach. First, by using an extensive time series of data rather than a single data point, we are able to derive the response of production patterns to changes in prices from historical evidence.[16] The calibration approach imposes these responses on the data through the choice of functional forms. Elasticities of substitution, for example, are set equal to unity by imposing the Cobb-Douglas functional form or equal to zero by imposing the Leontief form. Similarly, all elasticities of substitution are set equal to each other by imposing the constant elasticity of substitution functional form.

A second advantage of the econometric approach is that parameters estimated from time series are much less likely to be affected by the peculiarities of the data for a particular time period. By construction, parameters obtained by calibration are forced to absorb all the random errors present in the data for a single benchmark year. This poses a

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[15] See Mansur and Whalley (1984) for more detail. An example of the calibration approach is given by Borges and Goulder (1984), who present a model of energy policy calibrated to data for the year 1973. Surveys of applied general equilibrium modeling are given by Bergman (1985, 1990).

[16] A detailed discussion of our econometric methodology is presented by Jorgenson (1984, 1986).

severe problem when the benchmark year is unusual in some respect. Parameters calibrated to data for 1973, for example, would incorporate into the model all the distortions in energy markets that resulted from price controls and rationing of energy during the first oil crisis. Econometric parameterization greatly mitigates this problem by reducing the influence of random errors for any particular time period.

The third important feature of our producer submodel is the endogenous determination of productivity growth.[17] Other models used to study global warming, for example, that of Manne and Richels, take productivity growth to be exogenous.[18] In our model the rate of productivity growth for each industry is determined endogenously, as a function of input prices. In addition, an industry's productivity growth can be biased toward some inputs and away from others. Biased productivity growth is a common feature of historical data but is often excluded from models of production. By allowing for biased productivity growth, our model is able to capture the evolution of input patterns much more accurately.

In summary, the salient features of our production model are, first, that it is disaggregated into 35 industries. Second, all parameters of the model are estimated econometrically from an extensive historical data base developed specifically for this purpose. Third, the model determines rates of productivity growth endogenously and allows for biased productivity change in each industry. Fourth, the model incorporates extensive historical evidence on the price responsiveness of input patterns, including changes in the mix of fossil fuels. We turn next to a brief discussion of our modeling of final demands—consumption, investment, government expenditure, and foreign trade.

Consumption

Our model of household behavior is generated by a three-stage optimization process. At the first stage each household allocates full wealth, defined as the sum of human and nonhuman wealth, across different

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[17] Our approach to endogenous productivity growth was originated by Jorgenson and Fraumeni (1981). A general equilibrium model of production that incorporates both substitution among inputs and endogenous productivity growth is presented by Jorgenson (1984). This model has been analyzed in detail by Hogan and Jorgenson (1991).

[18] Manne and Richels (1990).

time periods. We formalize this decision by introducing a representative agent who maximizes an additive intertemporal utility function, subject to an intertemporal budget constraint. The optimal allocation satisfies a sequence of necessary conditions that can be summarized by means of a Euler equation.[19] This allocation is determined by the rate of time preference and the intertemporal elasticity of substitution.

After households have allocated full wealth to the current time period, they proceed to the second stage of the optimization process—choosing the mix of leisure and goods. We represent household preferences for leisure and goods by means of a representative agent with an indirect utility function that depends on the prices of leisure and goods. We derive demands for leisure and goods as functions of these prices and the wealth allocated to the period. This implies an allocation of the household's exogenously given time endowment between leisure time and the labor market, so that this stage of the optimization process determines labor supply.

The third stage of the household optimization problem is the allocation of total expenditure among capital and labor services and the 35 commodity groups included in the model. At this stage, we replace the representative consumer approach with the approach of Jorgenson, Lau, and Stoker for deriving a system of demand functions for each household.[20] We distinguish among household types cross-classified by attributes such as the number of household members and the geographic region in which the household is located. For each type of household, we employ a hierarchical tier structure of models of consumer behavior to represent demands for individual commodities.[21] These features of our household model are described in greater detail in the following sections.

As with production, the parameters of the behavioral equations for all three stages of our consumer model are estimated econometrically.[22]

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

[20] Jorgenson, Lau, and Stoker (1982).

[21] Our model of personal consumption expenditures can be used to represent the behavior of individual households or the behavior of the household sector as a whole, as in Jorgenson and Slesnick (1987) and Jorgenson, Slesnick, and Stoker (1987, 1988).

[22] Details on the econometric methodology are given by Jorgenson (1984, 1990a). Additional details are provided by Wilcoxen (1988) and Ho (1989).

This includes the Euler equation, demand functions for leisure and personal consumption expenditures, and demand functions for individual commodities. Our household model incorporates extensive time series data on the price responsiveness of demand patterns by consumers and detailed cross-section data on demographic effects on consumer behavior. An important feature of our household model is that demands need not be homothetic. As levels of total expenditure increase, patterns of expenditure on individual commodities change, even in the absence of price changes. This captures an important feature of cross-section data on household expenditure patterns that is usually ignored in applied general equilibrium modeling.

Investment and Capital Formation

Our investment model is based on perfect foresight, or rational expectations. In particular, we require that the price of new investment goods is always equal to the present value of future capital services.[23] The return on a unit of capital is determined by the economy-wide rental price of capital services. The price of investment goods and the discounted value of future rental prices are brought into intertemporal equilibrium by adjustments in prices and the term structure of interest rates. This intertemporal equilibrium incorporates the forward-looking dynamics of asset pricing by producers.

For tractability, we assume there is a single capital stock in the economy that is perfectly malleable, so that it can be reallocated among industries and between industries and final demand categories at zero cost. Under this assumption, imposition of a carbon tax can affect the distribution of capital and labor supplies among sectors, even in the short run. In each time period, the supply of capital in our model is completely inelastic, since the stock of capital is determined by past investment. Investment during the period is determined by the savings made available by households. The relationship between capital stock and past investment incorporates backward-looking dynamics into our model of intertemporal equilibrium.

We assume that new capital goods are produced from individual

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[23] The relationship between the price of investment goods and the rental price of capital services is discussed in greater detail by Jorgenson (1989).

commodities, so that the price of new capital depends on commodity prices. We have estimated the price function for new capital goods using final demand data for investment over the period 1947–85. Thus, our model incorporates substitution among inputs in the composition of the capital. This feature can play an important role in the evaluation of environmental policies. Jorgenson and Wilcoxen have found, for example, that an increase in the price of automobiles resulting from mandatory installation of pollution control devices shifts investment away from motor vehicles and toward other types of capital.[24]

In summary, capital formation in our model is the outcome of intertemporal optimization by households and firms. Optimization by households is forward-looking and incorporates expectations about future prices, wages, and interest rates. Optimization by producers is also forward-looking and depends upon these same expectations. Both types of optimization are important for modeling the effect of future restrictions on carbon dioxide emissions. The effects of these restrictions will be anticipated by households and firms, so that future policies will have important consequences for current decisions.

Government and Foreign Trade

The two final demand categories remaining in our model are the government and foreign sectors. 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, determined exogenously, to tax revenue to obtain total government revenue.

We assume the government budget deficit can be specified exogenously. We add the deficit to total revenue to obtain total 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

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[24] Jorgenson and Wilcoxen (1990a).

determine the quantity of each commodity by dividing the value of government spending on the good by its price.

Foreign trade has two components—imports and exports. We assume that imports are imperfect substitutes for similar domestic commodities.[25] The goods actually purchased by households and firms reflect substitution between domestic and imported products. The price responsiveness of these purchases is estimated econometrically from historical data. In effect, each commodity is assigned a separate elasticity of substitution between domestic and imported goods. Because the prices of imports are given exogenously, intermediate and final demands implicitly determine imports of each commodity.

Exports, on the other hand, are determined by a set of export demand equations, one for each commodity, that depends on exogenously given foreign income and the foreign price of U.S. exports. Foreign prices are computed from domestic prices by adjusting for subsidies and the exchange rate. The demand elasticities in these equations are estimated from historical data. Without an elaborate model of international trade, it is impossible to determine both the current account balance and the exchange rate endogenously. In the simulations reported below, we take the current account to be exogenous and the exchange rate to be endogenous.

Estimating Carbon Emissions

The most important remaining feature of the model is the way in which carbon dioxide emissions are calculated. For tractability, we assume that carbon dioxide is emitted in fixed proportion to fossil fuel combustion. This implicitly assumes that nothing can be done to reduce the carbon dioxide produced by a given combustion process.[26] For comparability with other studies, we measure carbon dioxide emissions in tons of contained carbon. To convert to tons of carbon dioxide, the reader can multiply contained carbon by 3.67.

We have calculated the carbon content of each fossil fuel by mul-

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[25] This is the Armington (1969) approach. See Wilcoxen (1988) and Ho (1989) for further details on our implementation of this approach.

[26] This is largely the case in practice, since carbon dioxide is one of the natural products of combustion. Little can be done to change the amount produced when burning a particular fuel.

Table 1. Carbon Emissions Data, 1987

Item	*Coal (tons)*	*Oil (barrels)*	*Gas (thousands of cubic feet)*
Heat content			
(million BTUs per unit)	21.94	5.80	1.03
Emissions rate			
(kilograms per million BTUs)	26.9	21.4	14.5
(kilograms per unit)	590.2	124.1	14.9
Total domestic output			
(billion units)	0.9169	0.3033	17.8
Total carbon emissions			
(million tons)	595.3	414.1	268.6

Source: Authors' calculations; Energy Information Administration (1990); and Environmental Protection Agency (1988).

tiplying the heat content of the fuel by the carbon emitted. From the Energy Information Administration, we obtained the average heat content of each fuel in millions of British thermal units (BTUs) per quantity unit.[27] We then obtained data from the Environmental Protection Agency on the amount of carbon emitted per million BTUs generated from each fuel.[28] Multiplying the emissions figures by the heating value gives the carbon content of each fuel. Total carbon emissions can then be calculated from data on fuel production. Table 1 gives data for each fuel in 1987.

All prices in our model are normalized to unity in a common base year, so quantities do not correspond directly to physical units. Moreover, the model has a single sector for oil and gas extraction. To convert the data for this industry into a form appropriate for the model, we have added carbon production for crude petroleum and natural gas and divided by the industry's output for 1987 to obtain the carbon coefficient for this industry. Similarly, the coefficient for coal was obtained by dividing total carbon production from coal by the model's 1987 value for coal mining output. These coefficients were used to estimate carbon emissions in each simulation. We now turn to a brief discussion of the model's base case.

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[27] Energy Information Administration (1990).

[28] Environmental Protection Agency (1988).

The Base Case

To simulate the U.S. economy, we must provide values of the exogenous variables for all time periods. We have accomplished this in two steps. First, we have adopted a set of default assumptions about the time path of each exogenous variable in the absence of changes in government policy. These assumptions are used in generating a simulation of U.S. economic growth called the "base case." The second step is to change certain exogenous variables to reflect the introduction of a carbon tax and then to simulate U.S. economic growth again to produce an "alternative case." We then compare the two simulations to assess the effect of the policy change. Obviously, the assumptions underlying the base case are important in interpreting the results.

Because our model is based on agents with perfect foresight, we must solve the model indefinitely far into the future. To do this, we project values for all exogenous variables over the period 1990–2050. After 2050 we assume the variables remain constant at their 2050 values, which allows the model to converge to a steady state by the year 2100.[29] 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 remain constant in real terms at 1985 levels before U.S. tariffs are applied.

We project a gradual decline in the government deficit through the year 2025, after which the nominal value of the government debt is maintained at a constant ratio to the value of the national product. Finally, we project the current account deficit by allowing it to fall gradually to zero by the year 2000. After that, we project a 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 that existed in 1982.

The most important exogenous variables are those associated with growth of the U.S. population and corresponding changes 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 projections.[30] We hold

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[29] A more detailed discussion of these projections is given by Jorgenson and Wilcoxen (1992).

[30] Our breakdown of the U.S. population by age, sex, and educational attainment is

population constant after 2050, which is approximately in line with these projections. In addition, we project the educational composition of the population by holding the level of educational attainment constant, beginning with the cohort reaching age 35 in 1985. We transform our population projection into a projection of the time endowment by holding relative wages across different types of labor input constant at 1985 levels. Because capital formation is endogenous in our model, our projections of the time endowment effectively determine the size of the economy in the more distant future.

Welfare Economics

In assessing the welfare effects of a carbon tax, we have focused on three closely related questions. First, how does the tax affect the welfare of different types of households? Second, how can these individual effects be aggregated to provide a summary measure of the effect of the tax? Third, is the tax progressive or regressive? This section presents the analytical framework used to answer each of these questions.

Dynastic Welfare

We begin by assuming that the household sector comprises a number of infinitely lived households, which we refer to as dynasties. Each household takes commodity prices and rates of return as given and is endowed with perfect foresight. All dynasties face the same vector of consumer goods prices at time t, p_t, and the same nominal interest rate, r_t. The quantity of commodity n consumed by dynasty d in period t is x_{ndt}, and the total expenditure of dynasty d on consumption in period t is M_{dt}.

$$M_{dt} = \sum_{n=1}^{N} p_{nt} x_{ndt},$$

where N is the number of commodities.

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based on the system of demographic accounts compiled by Jorgenson and Fraumeni (1989). The population projections are discussed in detail by Wilcoxen (1988, app. B).

We assume that each dynasty maximizes an additive intertemporal utility function of the form

$$(1) \qquad V_d = \sum_{t=0}^{\infty} \delta^t \ln V_{dt},$$

where $\delta = 1/(1 + \rho)$ and ρ is the subjective rate of time preference. The intratemporal indirect utility function V_{dt} is taken to be of the form

$$(2) \qquad \ln V_{dt} = \alpha_p' \ln p_t + \frac{1}{2} \ln p_t' B_{pp} \ln p_t - D(p_t) \ln(M_{dt}/N_{dt}).$$

In this representation, α_p and B_{pp} are unknown parameters, $N_{dt} = K_{dt}\, m_0(p_t, A_d)$ is the number of household equivalent members in the dynasty at time t, and $D(p_t)$ has the form $D(p_t) = -1 + \iota' B_{pp} \ln p_t$. The number of household equivalent members is

$$\ln m_0(p, A_d) = \frac{\ln m(A_d)'\alpha_p + 1/2 \ln m(A_d)' B_{pp} \ln m(A_d) + \ln m(A_d)' B_{pp} \ln p}{D(p)},$$

where the function $\ln m(A_d) = B_{pp}^{-1} B_{pA} A_d$ is a vector of commodity-specific equivalence scales.[31] We allow dynasties to differ by a vector of attributes A_d. These attributes allow for differences in preferences among households.

The dynasty maximizes the intertemporal utility function V_d over the time path of the intratemporal utility levels $\{V_{dt}\}$ subject to the budget constraint:

$$\sum_{t=0}^{\infty} \gamma_t M_{dt}(p_t, V_{dt}, A_d) = \Omega_d,$$

where

$$\gamma_t = \prod_{s=0}^{t} (1 + r_s)^{-1},$$

and Ω_d is the wealth of the dynasty. In this representation, $M_{dt}(p_t, V_{dt}, A_d)$ is the intratemporal expenditure function and takes the form

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[31] Further details are given by Jorgenson and Slesnick (1987).

$$\ln M_{dt}(p_t, V_{dt}, A_d) = \frac{\alpha_p' \ln p_t + 1/2 \ln p_t' B_{pp} \ln p_t - \ln V_{dt}}{D(p_t)} + \ln(N_{dt}). \tag{3}$$

The necessary conditions for a maximum of the intertemporal utility function, subject to the wealth constraint, are given by the discrete time Euler equation:

$$\ln V_{dt} = \frac{D_t}{D_{t-1}} \ln V_{dt-1} + D_t \ln\left(\frac{D_{t-1}\gamma_t N_{dt} P_t}{\delta D_t \gamma_{t-1} N_{dt-1} P_{t-1}}\right), \tag{4}$$

where we have used D_t to denote $D(p_t)$, and

$$P_t = \exp\left(\frac{\alpha_p' \ln p_t + 1/2 \ln p_t' B_{pp} \ln p_t}{D_t}\right).$$

The Euler equation implies that the current level of utility of the dynasty can be represented as a function of the initial level of utility and the initial and future prices and interest rates:

$$\ln V_{dt} = \frac{D_t}{D_0} \ln V_{d0} + D_t \ln\left(\frac{D_0 \gamma_t N_{dt} P_t}{\delta^t D_t N_{d0} P_0}\right). \tag{5}$$

Equation 5 enables us to represent dynastic utility as a function of wealth and initial and future prices and interest rates. We begin by rewriting the intertemporal budget constraint as

$$\sum_{t=0}^{\infty} \gamma_t N_{dt} P_t V_{dt}^{-1/D_t} = \Omega_d. \tag{6}$$

Substituting equation 5 into equation 6 and simplifying yields the following:

$$\ln V_{d0} = -D_0 \ln\left(\frac{\Omega_d}{N_{d0} R}\right), \tag{7}$$

where

$$R = \frac{P_0}{D_0}\left(\sum_{t=0}^{\infty} \delta^t D_t\right).$$

This enables us to evaluate dynastic utility in terms of dynastic wealth:

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\begin{aligned}
(8) \qquad V_d &= \sum_{t=0}^{\infty} \delta^t \ln V_{dt}, \\
&= \sum_{t=0}^{\infty} \delta^t \left[\frac{D_t}{D_0} \ln V_{d0} + D_t \ln \left(\frac{D_0 \gamma_t N_{dt} P_t}{\delta^t D_t N_{d0} P_0} \right) \right], \\
&= \sum_{t=0}^{\infty} \delta^t \left[-D_t \ln(\Omega_d / R) + D_t \ln \left(\frac{D_0 \gamma_t N_{dt} P_t}{\delta^t D_t P_0} \right) \right], \\
&= S \ln R - S \ln \Omega_d + \sum_{t=0}^{\infty} \delta^t D_t \ln \left(\frac{\gamma_t N_{dt} P_t D_0}{\delta^t D_t P_0} \right),
\end{aligned}
$$

where

$$S = \sum_{t=0}^{\infty} \delta^t D_t .$$

Solving for wealth as a function of prices and utility yields the intertemporal expenditure function[32] of the dynasty:

$$(9) \quad \ln \Omega_d(\{p_t\}, \{\gamma_t\}, V_d) = \frac{1}{S} \left[S \ln R + \Sigma \delta^t D_t \ln \left(\frac{\gamma_t N_{dt} P_t D_0}{\delta^t D_t P_0} \right) - V_d \right],$$

where $\{p_t\}$ indicates a profile of prices and $\{\gamma_t\}$ is a profile of discount factors. We employ this expenditure function in measuring the monetary equivalent of a change in welfare resulting from the imposition of a carbon tax. We let $\{p_t^0\}$ and $\{\gamma_t^0\}$ be the profiles of prices and interest rates under the base case and V_d^0 be the resulting level of welfare. If the welfare of the dynasty after the imposition of a carbon tax is denoted V_d^1, the equivalent variation in dynastic wealth is

$$(10) \qquad \Delta W_d = \Omega_d(\{p_t^0\}, \{\gamma_t^0\}, V_d^1) - \Omega_d(\{p_t^0\}, \{\gamma_t^0\}, V_d^0).$$

The equivalent variation in wealth in equation 10 is the wealth required to attain the welfare associated with imposition of a carbon tax at prices in the base case, less the wealth required to attain the welfare of the base case at these prices. If this equivalent variation is positive, the carbon tax produces a gain in welfare; otherwise, the policy change results in a welfare loss. Equivalent variations in wealth enable us to

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[32] The intertemporal expenditure function was introduced by Jorgenson and Yun (1991).

rank the policy of the base case and any number of alternative policies in terms of a money metric of dynastic welfare.

Social Welfare

Although the distribution of equivalent variations across dynasties is useful for policy analysis, it is also important to assess the change in social welfare that results from the imposition of a carbon tax. For this purpose we define an intertemporal social welfare function over the distribution of dynastic welfare functions given in equation 8. Following Jorgenson and Slesnick,[33] we take the intertemporal social welfare function to be a weighted sum of the average dynastic welfare and a measure of deviations from the average:

$$W = \bar{V} - \eta\left(\sum_{d=1}^{D} a_d \lvert V_d - \bar{V}\rvert^{-\mu}\right)^{-1/\mu}, \tag{11}$$

where

$$\bar{V} = \sum_{d=1}^{D} a_d V_d .$$

In this representation of the social welfare function, the parameter η is chosen to ensure that social welfare is increasing in the levels of individual welfare; this is the familiar Pareto principle. The parameter μ is a measure of social aversion to inequality and can take values ranging from minus one to minus infinity. The maximum value of minus one gives the greatest weight to equity relative to efficiency. Allowing this parameter to go to minus infinity generates a utilitarian social welfare function and gives the least relative weight to equity considerations.

If we require that all transfers of wealth from rich dynasties to poor dynasties must increase social welfare, then the weights on the individual welfare levels must be given by

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[33] Jorgenson and Slesnick (1990).

$$a_d = \frac{\exp\left\{\left[\sum_t \delta^t D_t \ln(N_{dt})\right]/S\right\}}{\sum_{l=1}^{D} \exp\left\{\left[\sum_t \delta^t D_t \ln(N_{lt})\right]/S\right\}}.$$

The maximum level of social welfare for fixed prices and fixed total wealth is attained by reallocating wealth among dynasties to equalize dynastic welfare. This occurs when the wealth of dynasty d is $\Omega_d^* = a_d\Omega$, where Ω is total wealth.

The maximum level of social welfare can be represented as

$$(12) \quad W_{\max} = S\ln R - S\ln\Omega + S\ln N + \sum_{t=0}^{\infty} \delta^t D_t \ln\left(\frac{\gamma_t P_t D_0}{\delta^t D_t P_0}\right),$$

where

$$N = \sum_{l=1}^{D} \exp\left\{\left[\sum_t \delta^t D_t \ln(N_{lt})\right]/S\right\}.$$

This is a representative agent version of equation 8 and can be interpreted as the welfare level of a dynasty with size equal to the number of household equivalent members in the whole population.

To derive a money measure of social welfare, we define the social expenditure function as the minimum level of total wealth required to attain a specified level of social welfare at given prices and interest rates:

$$\Omega(\{p_t\}, \{\gamma_t\}, W) = \min\left[\Omega: W(u, x) \geq W; \Omega = \sum_{d=1}^{D} \Omega_d\right].$$

Our representation of the social expenditure function is obtained by solving the welfare function for the representative agent shown in equation 12 for aggregate wealth as a function of social welfare and the initial and future prices and interest rates:

$$(13) \quad \ln\Omega(\{p_t\}, \{\gamma_t\}, W) = \frac{1}{S}\left[S\ln R + S\ln N + \Sigma\delta^t D_t \ln\left(\frac{\gamma_t P_t D_0}{\delta^t D_t P_0}\right) - W\right].$$

This is the expenditure function of a representative agent with welfare level given by equation 12.

The social expenditure function enables us to evaluate the monetary equivalent of the change in social welfare that results from the imposition of a carbon tax. Let W^0 be the level of social welfare under the base case, and let W^1 be the corresponding level of social welfare after the imposition of a carbon tax. The monetary measure of the change in social welfare is given by

$$(14) \qquad \Delta W = \Omega(\{p_t^0\}, \{\gamma_t^0\}, W^1) - \Omega(\{p_t^0\}, \{\gamma_t^0\}, W^0).$$

This is the variation in wealth equivalent to imposition of the tax. If this equivalent variation is positive, then social welfare has increased as a result of the tax. Otherwise, the tax decreases social welfare or leaves it unaffected.

Policies for control of carbon dioxide emissions are often evaluated solely in terms of their impact on economic efficiency. Accordingly, we can define the change in efficiency to be the change in social welfare at a perfectly egalitarian distribution of wealth. For this distribution, social welfare is a maximum for a given level of wealth and corresponds to the potential level of welfare associated with a particular policy. This measure of efficiency is independent of the distribution of welfare among dynasties. If $W_{\max}^0$ is the maximum level of social welfare in the base case and $W_{\max}^1$ is the corresponding level after the imposition of a carbon tax, our monetary measure of the change in efficiency is

$$(15) \qquad \Delta E = \Omega(\{p_t^0\}, \{\gamma_t^0\}, W_{\max}^1) - \Omega(\{p_t^0\}, \{\gamma_t^0\}, W_{\max}^0).$$

The definition of the change in efficiency shown in equation 15 suggests a decomposition of the change in social welfare, shown in equation 14, into efficiency and equity components:

$$(16) \qquad \Delta W = \Delta E + \Delta EQ,$$

where ΔEQ is a monetary measure of the change in equity. The difference between the level of potential welfare and the level of actual welfare is the loss due to an inequitable distribution of dynastic welfare. Our measure of equity is the monetary value of the change in this welfare loss due to a carbon tax:

$$(17) \qquad \begin{aligned} \Delta EQ = {} & [\Omega(\{p_t^0\}, \{\gamma_t^0\}, W^1) - \Omega(\{p_t^0\}, \{\gamma_t^0\}, W_{\max}^1)] \\ & - [\Omega(\{p_t^0\}, \{\gamma_t^0\}, W^0) - \Omega(\{p_t^0\}, \{\gamma_t^0\}, W_{\max}^0)]. \end{aligned}$$

A positive value of ΔEQ indicates that equity has increased due to the imposition of the carbon tax.

Tax Progressivity

We have developed a framework for evaluating the effect of a carbon tax on the level of social welfare. A separate but closely related issue is the progressivity of such a tax. Following Slesnick,[34] we can classify a tax as progressive if it induces greater equality in the distribution of welfare. Equality, however, can be measured in absolute or relative terms. In the context of the model presented above, an absolute index of equality is given by

$$(18)\quad AEQ(\{p_t^0\}, \{\gamma_t^0\}, W, W_{\max}) = [\Omega(\{p_t^0\}, \{\gamma_t^0\}, W) - \Omega\{p_t^0\}, \{\gamma_t^0\}, W_{\max})].$$

This measure of equality is the monetary value of the loss in social welfare due to an inequitable distribution of welfare. It is nonpositive and invariant to equal absolute additions to the money measures of potential and social welfare.

A relative measure of equality can be defined as the ratio of money metric social welfare to the monetary measure of potential welfare:

$$(19)\quad REQ(\{p_t^0\}, \{\gamma_t^0\}, W, W_{\max}) = \Omega(\{p_t^0\}, \{\gamma_t^0\}, W)/\Omega(\{p_t^0\}, \{\gamma_t^0\}, W_{\max}).$$

This measure of equality lies between zero and one and attains the value of unity when the actual distribution of welfare is the perfectly egalitarian distribution. The measure of relative equality is invariant to equal proportional changes in money metric potential and social welfare. This will occur with equal proportional changes in the wealth of all dynasties.

An absolute measure of progression of a carbon tax is the change in the absolute measure of equality:

$$(20)\quad AP = AEQ(\{p_t^0\}, \{\gamma_t^0\}, W^1, W_{\max}^1) - AEQ(\{p_t^0\}, \{\gamma_t^0\}, W^0, W_{\max}^0).$$

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[34] Slesnick (1986).

The measure of absolute progressivity is identical to the measure of the change in equity, shown in equation 17. A positive value indicates that the carbon tax is absolutely progressive. A negative value indicates absolute regressivity. The corresponding relative measure of progressivity is defined similarly:

$$(21)\quad RP = REQ(\{p_l^0\}, \{\gamma_l^0\}, W^1, W_{\max}^1) - REQ(\{p_l^0\}, \{\gamma_l^0\}, W^0, W_{\max}^0).$$

It is easily demonstrated that a carbon tax that is absolutely progressive need not be relatively progressive, and vice versa.

The Impact of a Carbon Tax

We next consider the economic effect of adopting a sequence of carbon taxes that holds U.S. carbon dioxide emissions constant at the 1990 level of 1,576,000,000 tons. To measure this effect, we have constructed two alternative simulations of U.S. economic growth. The base case simulates U.S. economic growth without a carbon tax. The alternative case simulates growth with emissions of carbon dioxide held constant.[35]

To hold the level of carbon dioxide emissions constant, we introduce an endogenous tax applied to primary fuels in proportion to their carbon content. Because this tax produces substantial revenue, we hold government spending constant at its base-case level and allow the average tax rate on labor income to adjust to keep the government deficit constant. We hold the marginal tax rate on labor income constant, so that adjustments in the average rate reflect changes in the implicit zero-tax threshold. This tax adjustment is equivalent to a lump-sum transfer to the household sector.

Long-Run Effects

The direct effect of introducing a carbon tax is to increase purchasers' prices of coal and crude oil. In the year 2020, for example, the tax

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[35] Jorgenson and Wilcoxen (1992) have considered the efficiency effect of imposing a number of alternative limits on carbon dioxide emissions by different sequences of carbon taxes.

needed to hold emissions at 1990 levels is \$17.65 per ton of carbon.[36] Using the data in table 1, this amounts to a tax of \$11.46 per ton of coal, \$2.41 per barrel of oil, or \$0.29 per thousand cubic feet of gas. The rising price of fossil fuels results in substitution away from fossil fuels toward other energy and nonenergy commodities by both firms and households. Total energy consumption falls to about 68 quadrillion BTUs, or by 12 percent, relative to the base case. This substitution toward nonenergy inputs results in a drop of 0.7 percent in the capital stock and of 0.5 percent in the national product by the year 2020.

The impact of a carbon tax differs considerably among different types of fossil fuels. Figure 2 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, which rises by 40 percent. This, in turn, increases the price of electricity by about 5.6 percent. Electricity prices rise considerably less than coal prices because coal accounts for only about 13 percent of total electric utility costs. Other prices showing significant effects are those for crude and refined petroleum and gas utilities. These rise, directly or indirectly, because of the tax on the carbon content of oil and natural gas.

Changes in relative prices affect demands for energy and nonenergy commodities and lead to a restructuring of industry outputs. Figure 3 gives percentage changes in quantities produced by the thirty-five industries by the year 2020. Although most sectors show only small changes in output, the output of coal falls by 25 percent. Coal is strongly affected because its demand is elastic. Most coal is purchased by electric utilities. In our model these utilities can substitute other fuels for coal when its price rises. Moreover, the utilities also have some ability to substitute other inputs for energy, such as labor and capital services, further reducing the demand for coal. Finally, users of electricity reduce their demands substantially when the price of electricity rises.

Economic Dynamics

Carbon restrictions adopted today will have effects far into the future through their influence on capital formation. At the same time, anticipated future restrictions will have effects today through expectations

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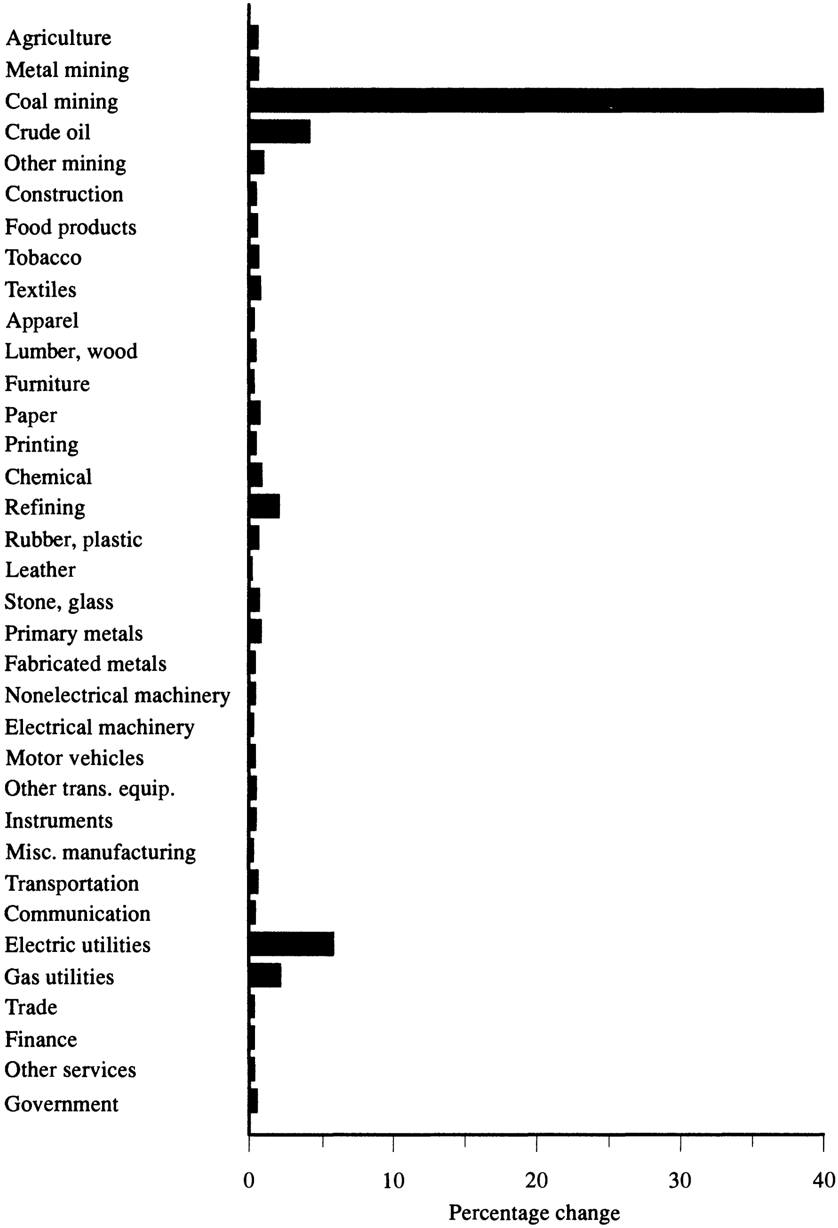
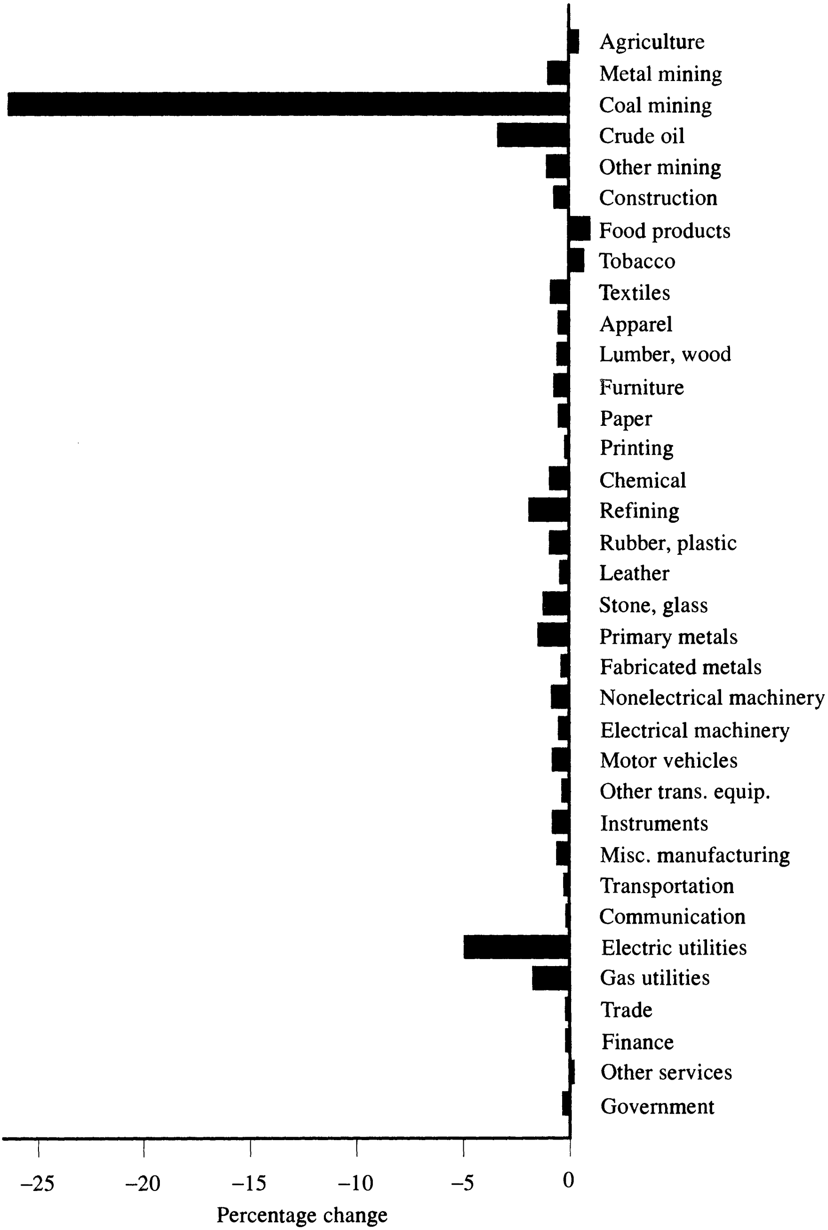
[36] All dollar amounts are in 1990 prices.

Figure 2. Effect of a Carbon Tax on Prices in 2020



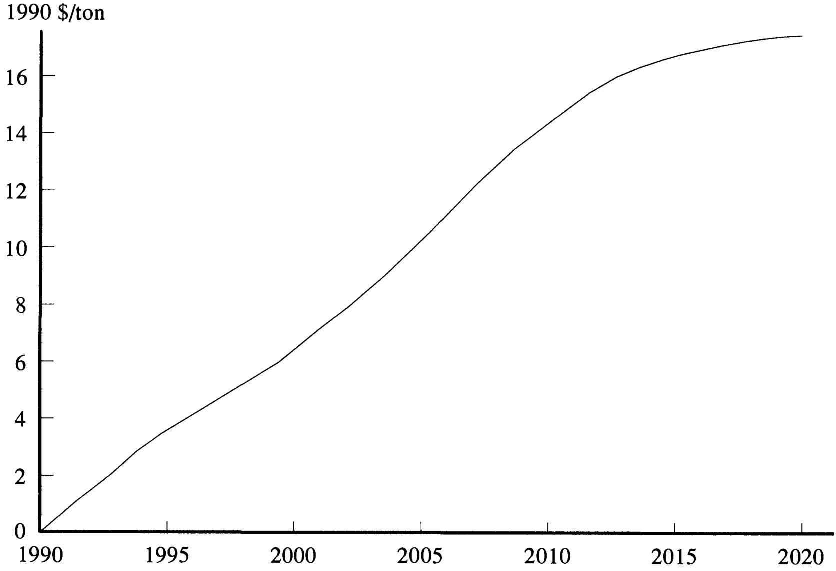
Source: Authors' calculations.

Figure 3. Effect of Carbon Tax on Quantities in 2020



Source: Authors' calculations.

Figure 4. Carbon Tax Required to Maintain 1990 Emission Levels, 1990–2020



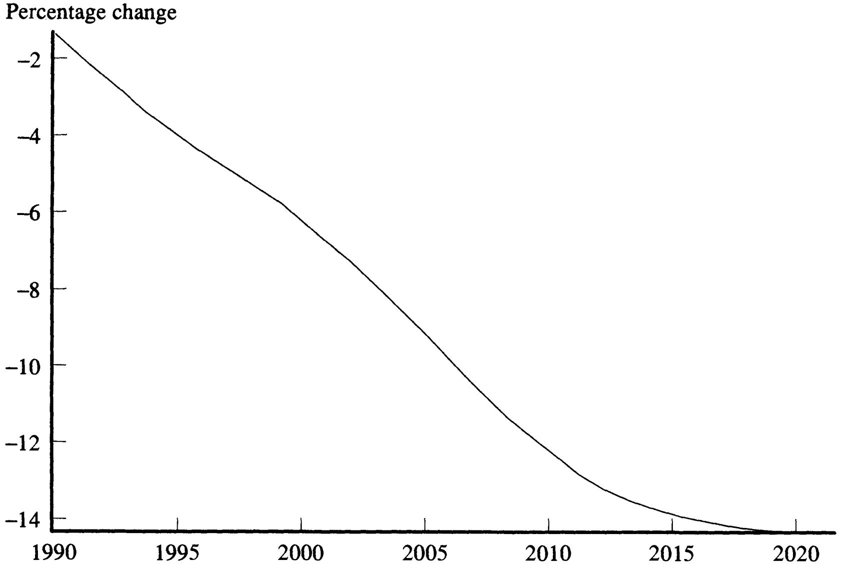
Source: Authors' calculations.

of future prices, wages, and interest rates incorporated into current prices of investment goods. To assess the intertemporal effects of carbon taxes, we now examine the dynamics of the transition to an economy with lower emissions of carbon dioxide.

The time path of the carbon taxes needed to maintain 1990 emissions is shown in figure 4. Base-case emissions increase over time, so the tax grows gradually over the next several decades. Holding carbon dioxide emissions constant lowers emissions relative to the base case, as shown in figure 5. By the year 2020, emissions are about 14 percent lower than they would have been without the tax.

The rising price of energy reduces the rate of capital formation. The outcome is shown in figure 6, which gives percentage changes in the capital stock from the base case. The capital stock does not decline immediately; instead, it remains near its base-case level for the first few years. This reflects intertemporal optimization by households. The household regards carbon taxes as reductions in future earnings and

Figure 5. Change in Carbon Emissions as a Result of a Carbon Tax, 1990–2020

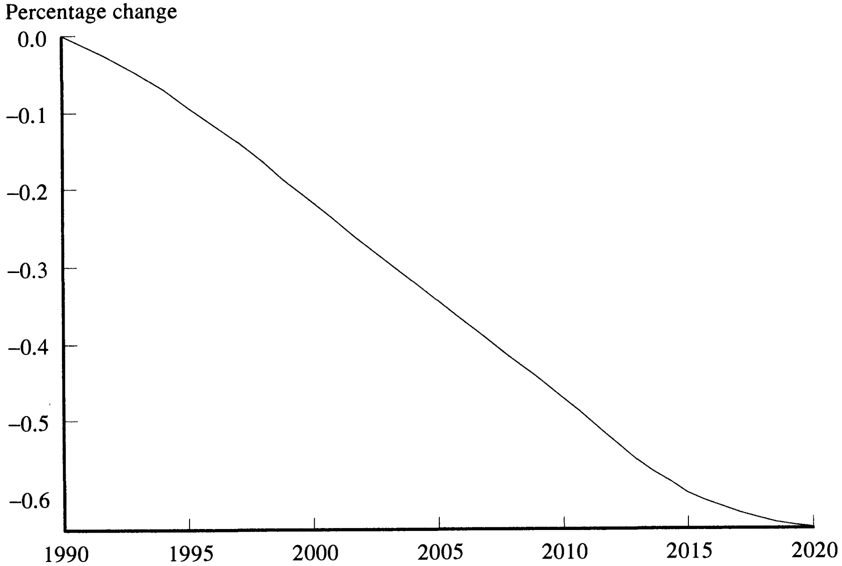


Source: Authors' calculations.

reacts by lowering consumption in all periods. In the early years, household income is largely unaffected. However, the drop in consumption leads to an increase in saving and helps to maintain capital formation. Eventually, the impact of the tax reduces capital stock relative to the base case.

The decline in growth of the capital stock leads to a drop in economic growth, as shown in figure 7. The national product falls gradually, relative to the base case, by about half a percent. The capital stock, however, is not the only factor contributing to the decline. Higher energy prices reduce the rate of productivity growth, leading to slower growth of output. Under the carbon tax, average annual growth of output between 1990 and 2020 is 0.02 percentage points lower than in the base case. About half of this is due to slower productivity growth and half to reduced capital formation.

Figure 6. Change in Capital Stock as a Result of a Carbon Tax, 1990–2020



Source: Authors' calculations.

The Effect on Welfare

We now evaluate the welfare impact of the carbon tax, using the framework we have presented above. Within each period households allocate total expenditure among five broad commodity groups:

Energy: expenditures on electricity, natural gas, heating oil, and gasoline.

Food: expenditures on all food products, including tobacco and alcohol.

Consumer goods: expenditures on all other nondurables.

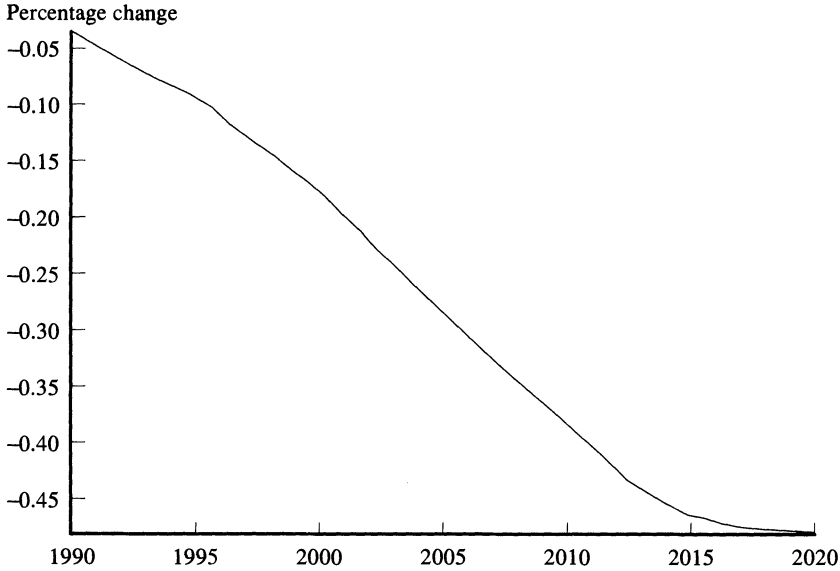
Capital services: the service flow from consumer durables and housing.

Consumer services: expenditures on consumer services.

Each of these commodity groups is an aggregate of several consumer goods and services.

Our model contains 35 consumer goods and services, as shown in figure 8. Each consumer good is produced from the primary output of

Figure 7. Change in Real GNP as a Result of a Carbon Tax, 1990–2020



Source: Authors' calculations.

Figure 8. Consumer Goods Used in Model

Food
Meals
Employee meals
Shoes
Clothing
Gasoline
Coal
Fuel
Tobacco
Cleaning
Furnishings
Drugs
Toys
Stationery
Imports
Reading
Rental
Electricity
Gas
Water
Communications
Labor
Other household
Own transportation
Transportation
Medical services
Medical insurance
Personal services
Financial services
Other services
Recreation
Foreign travel
Private education
Housing maintenance
Durables

one or more industries. Gasoline, for example, is produced by combining the output of petroleum refining with outputs of transportation services and retail trade. The price changes consumers face are a transformation of the changes in the prices of industry outputs. Figure 9, for example, gives changes in prices of consumer goods and services in the year 2020.

In figure 10 we present the percentage changes of prices of the five commodity groups resulting from the imposition of carbon taxes. Although all prices increase relative to the base case, the changes are quite small except for energy prices, which exhibit the largest price increases over the entire period. The next largest increase is in the price of capital services. This demonstrates the importance of analyzing the general equilibrium effects of carbon taxes rather than focusing exclusively on the change in energy prices.

In figure 11 we present the time path of the change in nominal total expenditure under the carbon tax relative to the base case. In every year there is an increase in total expenditure after the imposition of the carbon taxes. As with the prices, however, the changes are quite small. The percentage increase in nominal total expenditure is smaller than the increase in commodity prices in most years. This implies that carbon taxes induce a decrease in efficiency.

Carbon Taxes and Dynastic Welfare

Given the projections of commodity prices and total expenditure, we can evaluate the welfare changes induced by imposition of a carbon tax at various levels of aggregation. We begin by considering dynasties distinguished by the following demographic characteristics:

Family size: One, two, three, four, five, six, and seven or more persons.

Age of household head: 16–24, 25–34, 35–44, 45–54, 55–64, and 65 and over.

Region of residence: Northeast, Midwest, South, and West.

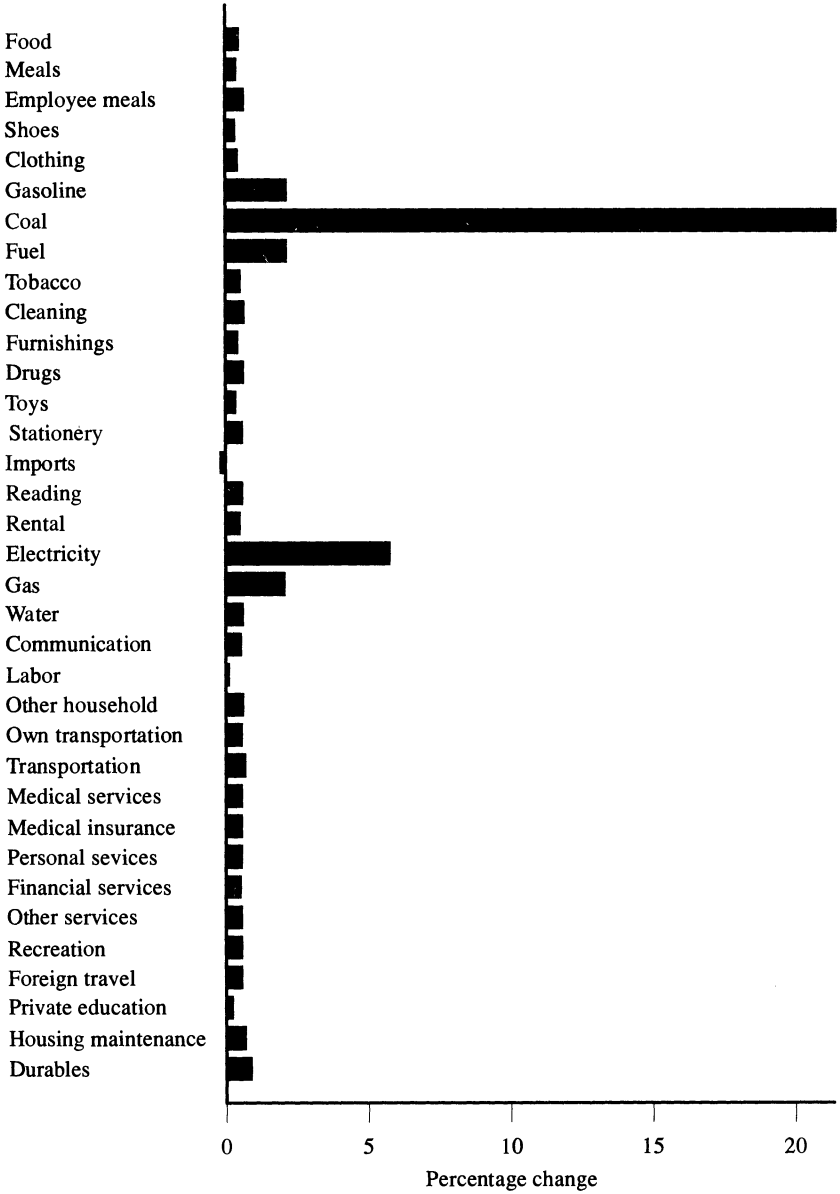
Race: White, nonwhite.

Type of residence: Nonfarm, farm.

Sex of household head: Male, female.

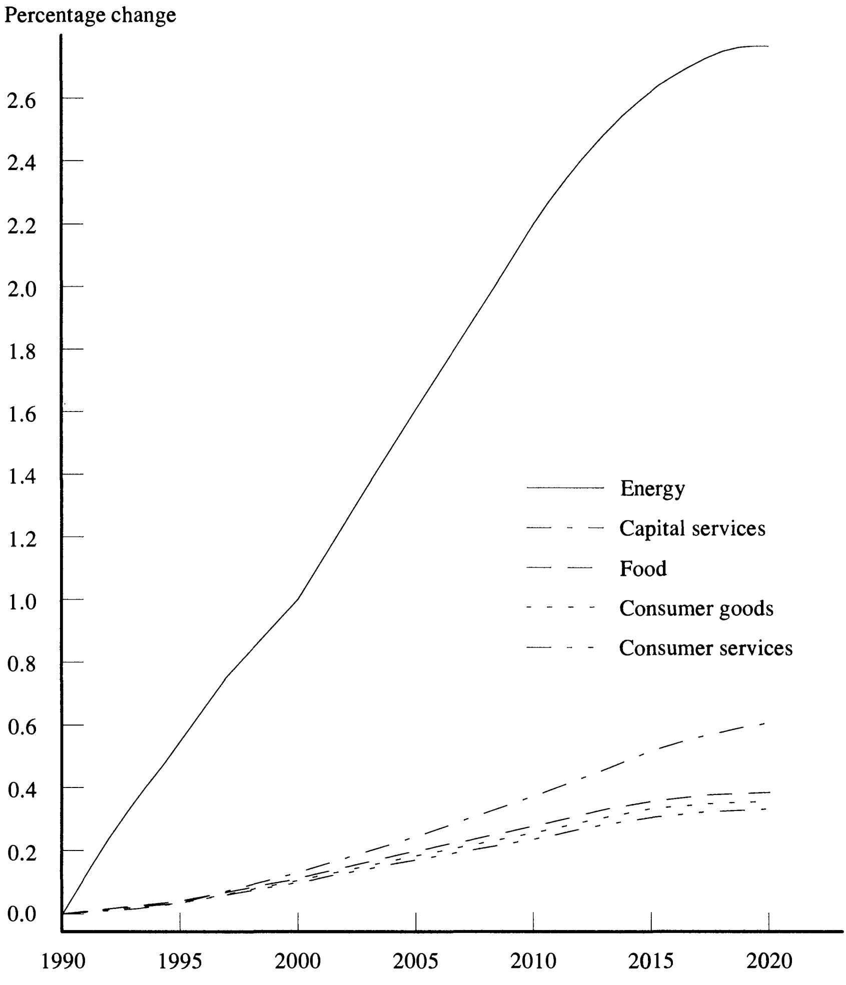
We consider 1,344 distinct types of households and 12 wealth categories within each household type, for a total of 16,128 household groups.

Figure 9. Effect of a Carbon Tax on Consumer Prices in 2020



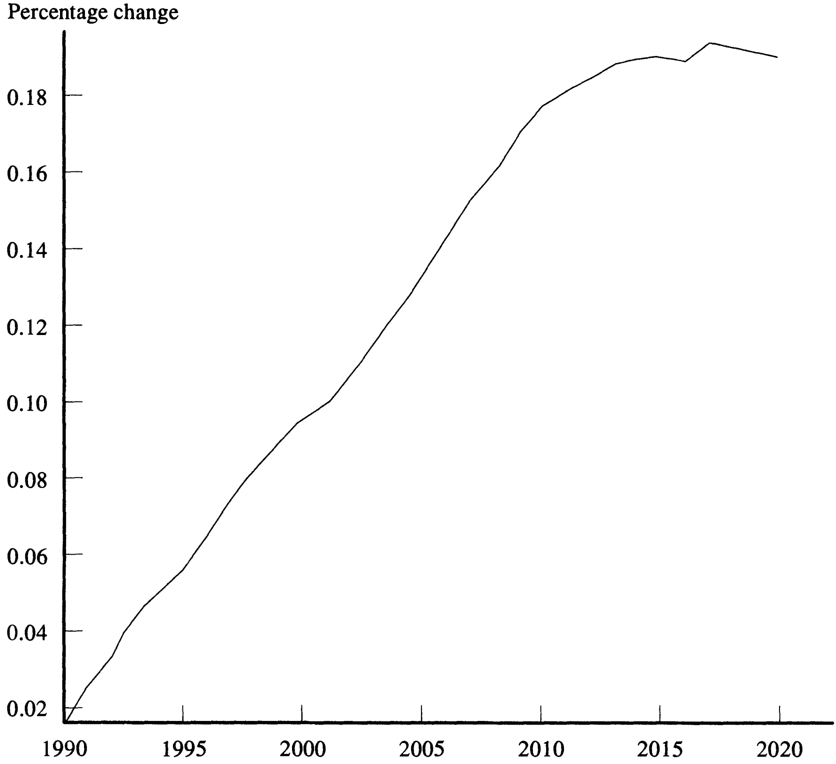
Source: Authors' calculations.

Figure 10. Change in Prices of Aggregate Goods as a Result of a Carbon Tax, 1990–2020



Source: Authors' calculations.

Figure 11. Change in Consumer Expenditure as a Result of a Carbon Tax, 1990–2020



Source: Authors' calculations.

We require projections of the distribution of total expenditure over time across dynasties. For this purpose we assume that the distribution of total expenditure within each of the 1,344 household types is the same as in the Bureau of Labor Statistics' *Consumer Expenditure Survey* for 1989.[37] The expenditure level of each dynasty increases at the rate given by the discrete time Euler equation 4.

We are now in a position to evaluate the welfare effects of a carbon tax for individual households. Because it is obviously impossible to present equivalent variations for each of the 16,128 household groups, we have chosen a single reference household with a family size of four,

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[37] Bureau of Labor Statistics (1990).

and a white, male head of household, aged 35 to 44, living in the urban Northeast. We present equivalent variations in wealth for the imposition of a carbon tax for this household type and other household types that differ in one of the demographic characteristics. We also evaluate these equivalent variations for low, medium, and high levels of wealth. The results are presented in table 2.

The medium and high wealth levels correspond to time paths of total expenditure equal to average and double-the-average wealth levels. Households with low wealth have a time path of expenditure that is one-half average wealth. In table 2 we see that the equivalent variation in wealth is negative for all households. For a household of one member with a low level of wealth, the carbon tax is equivalent to a loss of $1,396. The equivalent variations increase with wealth, but less than in proportion to wealth. As an illustration, for a household of one member, the equivalent variation for medium wealth households is less than twice that of low wealth households but more than half that of high wealth households.

The demographic pattern of the equivalent variations is also of interest. The equivalent variations generally increase with family size. For a medium level of wealth, households of one member have an equivalent variation of −$2,545. Households of seven members with the same level of wealth have an equivalent variation of −$2,913. Thus, larger households are more adversely affected by imposition of a carbon tax than smaller households. The absolute size of the equivalent variations also decreases with the age of the head of household. For a medium wealth household, the equivalent variation is −$2,976 for heads of household under age 25 and −$2,845 for those aged 65 and above. Households in the West are affected least by the carbon tax, while those living in the Midwest have the greatest loss. Farm households experience substantially lower losses than do nonfarm households. Finally, nonwhite households and those headed by males have higher losses from imposition of a carbon tax.

Although the demographic pattern of equivalent variations in wealth from imposition of a carbon tax is interesting, an important feature of table 2 is that all of the losses are small. This can be seen more clearly in table 3 where the equivalent variations are divided by the corresponding wealth. For our reference dynasty—a four-member household with medium wealth—imposition of a carbon tax is equivalent to a loss

Table 2. Equivalent Variations in Wealth upon Imposition of a Carbon Tax
(1990 dollars)

Wealth	*Size 1*	*Size 2*	*Size 3*	*Size 4*	*Size 5*	*Size 6*	*Size 7+*
Low	−1,396.22	−1,527.30	−1,570.84	−1,564.30	−1,586.36	−1,561.91	−1,580.02
Medium	−2,544.95	−2,807.17	−2,894.26	−2,881.19	−2,925.31	−2,876.39	−2,912.62
High	−4,594.80	−5,119.36	−5,293.58	−5,267.42	−5,355.69	−5,257.82	−5,330.29

Wealth	*Age 16–24*	*Age 25–34*	*Age 35–44*	*Age 45–54*	*Age 55–64*	*Age 65+*
Low	−1,611.60	−1,590.93	−1,564.30	−1,595.77	−1,600.36	−1,546.28
Medium	−2,975.80	−2,934.45	−2,881.19	−2,944.14	−2,953.30	−2,845.12
High	−5,456.68	−5,373.97	−5,267.42	−5,393.35	−5,411.69	−5,195.28

Wealth	*Northeast*	*Midwest*	*South*	*West*	*Nonfarm*	*Farm*
Low	−1,564.30	−1,646.41	−1,621.97	−1,514.02	−1,564.30	−1,471.77
Medium	−2,881.19	−3,045.43	−2,996.54	−2,780.60	−2,881.19	−2,696.08
High	−5,267.42	−5,595.98	−5,498.19	−5,066.21	−5,267.42	−4,897.12

Wealth	*White*	*Nonwhite*	*Male*	*Female*
Low	−1,564.30	−1,741.19	−1,564.30	−1,446.60
Medium	−2,881.19	−3,235.04	−2,881,19	−2,645.72
High	−5,267.42	−5,975.29	−5,267.42	−4,796.40

Source: Authors' calculations. Reference dynasty: size 4, age 35–44, Northeast, nonfarm, white, male.

Table 3. Equivalent Variations as a Percentage of Wealth

Wealth	*Size 1*	*Size 2*	*Size 3*	*Size 4*	*Size 5*	*Size 6*	*Size 7+*
Low	−0.2608	−0.2853	−0.2935	−0.2922	−0.2964	−0.2918	−0.2952
Medium	−0.2377	−0.2622	−0.2704	−0.2691	−0.2733	−0.2687	−0.2721
High	−0.2146	−0.2391	−0.2472	−0.2460	−0.2501	−0.2456	−0.2490

Wealth	*Age 16–24*	*Age 25–34*	*Age 35–44*	*Age 45–54*	*Age 55–64*	*Age 65+*
Low	−0.3011	−0.2972	−0.2922	−0.2981	−0.2990	−0.2889
Medium	−0.2780	−0.2741	−0.2691	−0.2750	−0.2759	−0.2658
High	−0.2549	−0.2510	−0.2460	−0.2519	−0.2528	−0.2426

Wealth	*Northeast*	*Midwest*	*South*	*West*	*Nonfarm*	*Farm*
Low	−0.2922	−0.3076	−0.3030	−0.2829	−0.2922	−0.2750
Medium	−0.2691	−0.2845	−0.2799	−0.2597	−0.2691	−0.2518
High	−0.2460	−0.2614	−0.2568	−0.2366	−0.2460	−0.2287

Wealth	*White*	*Nonwhite*	*Male*	*Female*
Low	−0.2922	−0.3253	−0.2922	−0.2703
Medium	−0.2691	−0.3022	−0.2691	−0.2471
High	−0.2460	−0.2791	−0.2460	−0.2240

Source: Authors' calculations. Reference dynasty: size 4, age 35–44, Northeast, nonfarm, white, male.

Table 4. Change in Social Welfare

Inequality aversion parameter	*Change in social welfare*			*Change in social welfare as a proportion of wealth*		
	Welfare	*Efficiency*	*Equity*	*Welfare*	*Efficiency*	*Equity*
	(billions of 1990 dollars)				*(percent)*	
−1	−187	−234	47	−0.1495	−0.1871	0.0376
−∞	−249	−234	−15	−0.1991	−0.1871	−0.0120

Source: Authors' calculations.

of slightly more than one-fourth of 1 percent (0.269 percent) of lifetime wealth. By this measure, nonwhite households with low levels of wealth are most affected by the tax—a loss of 0.325 percent of wealth—while unattached individuals with high wealth are affected least—a loss of 0.215 percent.[38]

Carbon Taxes and Social Welfare

The evaluation of policies to stabilize carbon dioxide emissions requires combining measures of changes in individual welfare into a measure of change in social welfare. For this purpose we estimate the changes in social welfare for two different representations of the social welfare function presented above. We take the inequality aversion parameter μ to be minus one and minus infinity, in turn. A value of minus one gives the greatest weight to equity, while a value of minus infinity gives the least weight to equity. The corresponding estimates of changes in social welfare are given in table 4.

Our first conclusion is that social welfare decreases as a result of imposing a carbon tax that would stabilize emissions of carbon dioxide at 1990 levels. This conclusion is independent of the choice of the inequality aversion parameter, since changes in social welfare are dominated by changes in efficiency. When inequality aversion is equal to minus one, its maximum value, money metric social welfare decreases by $187 billion (in 1990 dollars). When the inequality aversion parameter goes to minus infinity, the loss is $249 billion. These losses are

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[38] The results presented in table 3 are typical of findings for all 16,128 household types. For example, the minimum percentage loss is 0.186 percent of wealth and the maximum loss is 0.330 percent for all medium wealth households.

very small proportions of aggregate wealth, 0.149 percent and 0.199 percent, respectively.

We can decompose the changes in social welfare into changes in efficiency and changes in equity. Our measure of efficiency is independent of the degree of aversion to inequality and is the same for both measures of social welfare. Imposition of a carbon tax reduces money metric efficiency by $234 billion, or 0.187 percent of total wealth. Our measures of equity vary from a gain of $47 billion, or 0.0376 percent of total wealth, for the maximum value of aversion to inequality to a loss of $15 billion, or −0.0120 percent of total wealth, for a utilitarian social welfare function.

Is the carbon tax regressive? The answer depends critically on whether equality is measured in absolute or relative terms and on the inequality aversion parameter used in the social welfare function. The absolute measure of progression shown in equation 20 corresponds to the changes in equity reported in table 4. When the inequality aversion parameter is minus one, equity increases, indicating that the carbon tax is absolutely progressive. When the social welfare function is utilitarian, however, equity decreases, indicating that the same carbon tax is absolutely regressive. For both social welfare functions, the change in equity induced by the carbon tax is small relative to the efficiency change.

The relative measure of progression shown in equation 21 indicates that the carbon tax is regressive for both social welfare functions. When the inequality aversion parameter is minus one, the index of relative progression is −0.0004. The utilitarian social welfare function implies an index of relative progression equal to −0.0005. The base-case measure of relative equality is equal to 0.58 so that, although a carbon tax is regressive in the relative sense, the effect on the relative distribution is extremely small.

In summary, the direct effect of imposing carbon taxes that would stabilize carbon dioxide emissions at 1990 levels is to increase the prices of fossil fuels. This increase induces changes in relative prices for all commodity groups in our model and results in changes in the industry composition of output through substitution away from fossil fuels by firms and households. Imposition of a carbon tax reduces carbon dioxide emissions quite substantially and depresses economic growth by a modest amount. These changes are spread over time, reflecting the backward-looking dynamics of capital accumulation and the forward-looking dynamics of intertemporal optimization by producers and consumers.

We have measured the impact of a carbon tax on social welfare and decomposed this impact into equity and efficiency components. The efficiency changes greatly predominate in the overall effect of the tax on social welfare. The equity changes are much smaller and depend on the degree of aversion to inequality in the social welfare function. In addition, we find that the carbon tax is either mildly progressive or mildly regressive, depending on the degree of inequality aversion and the measure of progression used.

Comments and Discussion

Comment by Paul L. Joskow: Concerns about the global effects of the accumulation of carbon dioxide (CO_2) and other greenhouse gases in the atmosphere have intensified interest by both developed and developing countries in public policies designed to constrain emissions of these gases. The policy debate has focused primarily on CO_2 emissions. Since the vast bulk of the CO_2 emissions result from the combustion of fossil fuels, there is a close relationship between policies regarding CO_2 and the future evolution of the supply and demand for energy. Among the control policies under consideration are carbon taxes, energy taxes, tradable allowance schemes, subsidies for conservation and renewable energy technologies, and a variety of command and control regulations affecting both the production and use of energy.

Economists have been drawn into these policy discussions to examine the likely costs of alternative CO_2 emissions constraints, to evaluate alternative policy instruments for achieving them, and, to a much smaller extent, to measure the societal benefits that are likely to flow from reducing CO_2 emissions and slowing global warming. Because CO_2 emissions are so intimately related to the combustion of fossil fuels, it should come as no surprise that economists interested in examining the costs of alternative emissions constraint policies have either dusted off the energy models of the 1970s and 1980s as a platform for performing their analysis or built new models that are centered around interactions between energy and CO_2. These models generally simulate the costs of achieving a variety of CO_2 emissions constraints by introducing taxes

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on the carbon content of fossil fuels sufficient to meet a given carbon emissions constraint target. In some cases the analysis is meant to analyze the impacts of carbon taxes per se, while in other cases carbon taxes are merely used as a modeling convenience to generate estimates of "the costs of controlling CO_2 emissions."

Dale Jorgenson and his collaborators (in particular Peter Wilcoxen and Daniel Slesnick) have been major players in the "cost of controlling CO_2" game. The paper before us expands upon their previous analyses of the costs to the U.S. economy of achieving various U.S. CO_2 constraints using a carbon tax. It examines the implications for the United States of achieving a particular CO_2 target, (apparently) immediate stabilization of CO_2 emissions at 1990 levels, using a carbon tax. The analysis produces the values for the carbon tax required to achieve this target and the effects of the tax on prices and quantities for 35 producing sectors, gross national product (GNP), aggregate U.S. welfare, and the distribution of wealth. It does so by using a highly disaggregated general equilibrium model of production, consumption, investment, and economic growth that the authors have developed over the past several years. All of the relevant parameters of the model are estimated econometrically based on post–World War II time series data. I will refer to the model simply as "JSW" in what follows.

Overall, the model is an impressive machine that applies basic neoclassical production, consumption, and growth theory to the nines. It allows for virtually all of the relevant input and product substitutions that in theory one would like to examine for these purposes. In addition, the inclusion of 1,344 distinct household types with various demographic characteristics and 12 wealth categories within each type allows for more refined estimates of the welfare consequences of alternative constraint policies and their distributional implications.

It is important to address, however, a number of questions about the JSW model and how it is being used here and elsewhere. Let me begin by observing that for someone whose ambition in life is not to become an expert on the JSW model, it is very difficult to figure out what is going on from the information provided in this paper or the other recent papers on the same subject by Jorgenson and his collaborators that I reviewed. None of the papers that I reviewed reports the relevant coefficient estimates, their standard errors, or the relevant elasticities in a clear and consistent way. Perhaps more important, given the complexity of the model, none of the papers ever presents the *levels* for all of the key quantity and price variables of interest over the simulation period either for the base case or the constraint cases. Instead, the papers report primarily percentage changes from unreported base-case levels for some of the variables of interest resulting from imposing carbon taxes that achieve alternative CO_2 constraint targets. This makes it extremely difficult to relate the results generated by the JSW model to those generated by other models or to conventional (or unconventional) wisdom about how key variables and production sectors are likely to evolve in the future both with and without regulations on CO_2 emissions. While the detail of the JSW model is impressive compared with the much simpler models used by other analysts, this detail is not without its costs, at least from the perspective of this casual consumer. The underlying parameters and how they interact are much more transparent in other models that are often used to evaluate the economic consequences of carbon taxes. And although the parameters in these models are often not estimated econometrically based on historical data, at least we know what the parameters are and can change them to see how sensitive the results are to key parameter values.

The mysteries associated with the JSW machine and what comes out of it are important for a number of reasons. First, for those who rely on respectable economic models of one sort or another to generate estimates of the costs of controlling CO_2 emissions, the JSW models almost always yield carbon tax rates and GNP losses that are significantly lower than those generated by other models to meet otherwise similar constraints.

To see this, let's look at table 1, which is taken from another recent paper using the JSW model. Table 1 presents the results from three simulations produced by the JSW model, including the one presented in this paper. The first column is a simulation of a policy that does nothing until the year 2000, then gradually imposes increasing carbon taxes until CO_2 emissions are stabilized at year 2000 levels by 2010. The second column reports the results for a policy that stabilizes CO_2 emissions at the 1990 levels immediately. This appears to be identical to the constraint case presented in this paper. The final column is a simulation of a policy that constrains CO_2 emissions gradually over the 1990–2005 period until they are 80 percent of 1990 levels. The resulting carbon taxes required to meet these CO_2 constraints are $8.55, $17,

Table 1. Summary of Jorgenson/Wilcoxen Long-Run Carbon Simulations for 2020
Percent change, unless otherwise indicated

	Emissions target		
Variable	*2000 level*	*1990 level*	*80% of 1990*
Carbon emissions	−8.4	−14.4	−31.6
Carbon tax (1989 dollars per ton)	8.55	16.96	60.09
Tax on coal (1989 dollars per ton)	5.55	11.01	39.01
Tax on oil (1989 dollars per barrel)	1.17	2.32	8.20
Tax on gas (1989 dollars per thousand cubic feet)	0.14	0.28	0.98
Labor tax rate	−0.25	−0.45	−1.22
Tax revenue (billions of dollars)	14.4	26.7	75.8
BTU production	−7.1	−12.2	−27.4
Capital stock	−0.4	−0.7	−2.2
Real GNP	−0.3	−0.5	−1.6
Price of coal	20.3	40.0	137.4
Quantity of coal	−15.6	−26.3	−53.2
Price of electricity	2.9	5.6	17.9
Quantity of electricity	−2.9	−5.3	−15.3
Price of oil	1.8	3.6	13.3

Source: Dale W. Jorgenson and Peter J. Wilcoxen. 1991. "Reducing U.S. Carbon Dioxide Emissions: The Cost of Different Goals," Discussion Paper 1575, Harvard Institute of Economic Research, October, Table 3.1. Percent changes are from base-case values for unconstrained case in 2020.

and $60 per ton carbon, respectively, in 1989 dollars (or roughly 2.8 cents, 5.5 cents, and 20 cents per gallon of gasoline for those of you who don't think in terms of tons of carbon or coal). These carbon tax rates are associated with a loss of GNP of 0.3 percent, 0.5 percent, and 1.6 percent respectively in 2020.

In comparison, for a U.S. constraint case similar to Jorgenson and Wilcoxen's 80 percent of 1990 case, the Manne-Richels model yields a carbon tax of $375 and a loss of GNP of 3.2 percent. For a similar constraint case applied to a world model, Manne-Richels produces a carbon tax of about $300 and a loss in GNP of 2 to 3 percent. Most of the other models that have analyzed similar CO_2 constraints yield tax rates and GNP losses between these extremes.

I was quite surprised the first time I saw the JSW results. One of the special, and controversial, characteristics of the JSW framework is that (endogenous) productivity growth is negatively correlated with energy prices, a correlation that generally does not appear in other models. Since carbon taxes increase energy prices, higher energy prices would tend to reduce productivity growth and *increase* the cost of CO_2 constraints. In an earlier paper, Hogan and Jorgenson write that ''this ignored productivity effect could be the largest component of a complete cost analysis.'' Despite the negative effect of higher energy prices on productivity growth, the JSW results continue to be the low field among the ''respectable'' players in the game of modeling the cost of controlling CO_2.

There are, of course, many reasons why these models could yield different results. In comparing different models, however, it is important to keep in mind the nature of the constraint that is generally being analyzed. Specifically, the target CO_2 reduction is typically specified in terms of proportional changes from emissions in *some historical base year* CO_2 (1990, for example) rather than in terms of a reduction in a specific number of tons of CO_2 (300 million tons a year, for example). This means that models that project rapidly rising base-case CO_2 emissions must work a lot harder to meet a constraint based on 1990 emissions than models that project slow growth in CO_2 emissions. As a result, the equilibrium tax rates and GNP losses derived from different models are very difficult to interpret unless the base cases are quite similar or, at the very least, we understand how and why they differ. Unfortunately, Jorgenson and his collaborators have not generally presented base or constraints case values for the *levels* of the key economic variables in their papers. Instead, they report their results as percentage changes from base-case values that are not revealed. This makes interpretation of the results and comparisons with other analysts' projections quite difficult.

To try to gain a better understanding of the differences in the baseline cases being used by different analysts, I asked Peter Wilcoxen to provide me with the values for several quantity and price variables for 1990, 2020, and 2050 for the base case in this paper and for the constraint cases in table 1. He was kind enough to provide me with most of what I asked for, and, I hope, this has been helpful in improving my understanding of what is going on here.

Turning to table 2, the first thing to note is that in the JSW base case, U.S. carbon emissions do not grow very quickly in the absence

Table 2. Base-Case Values, 1990–2020

Variable	*JSW* *1990 values*	*JSW* *2020 simulated values*	*JSW* *Annual growth rate (%)*	*EIA 2010 annual growth rate (%)*
GNP (1990 dollars)	5,981.34	9,226.01	1.5	2.20
Fossil fuels consumed (quads)	69.14	78.04	0.4	1.00
Oil and gas consumed (quads)	48.05	47.82	0.0	0.90
Coal consumed (quads)	20.98	30.05	1.2	1.50
Electricity (billions of kilowatt hours)	2,259.4	3,170.43	1.1	1.90
Carbon emissions (millions of tons)	1,576.82	1,842.31	0.5	1.10
Oil and gas imports (quads)	12.09	7.21	−1.7	2.80
Domestic oil/gas price (dollars per million BTUs)	4.53	4.92	0.3	3.20
Imported oil/gas price (dollars per million BTUs)	3.59	9.08	3.1	2.20
Electricity price (cents per kilowatt hours)	5.92	4.74	−0.7	0.20

Source: Computed from data provided by Peter Wilcoxen, December 9, 1991, and from data in the Department of Energy, U. S. Energy Information Administration, *Annual Energy Outlook*, Washington, D.C., March 1991.

of any controls. From 1990 to 2020, CO_2 emissions increase by only about 17 percent (0.5 percent a year) without any special CO_2 emissions constraints. These are very low baseline values compared with those generated by other models. The Manne-Richels model projects that U.S. CO_2 emissions increase by about 60 percent by 2025 and 230 percent by 2100. The Office of Technology Assessment model projects about a 50 percent increase in U.S. CO_2 emissions by 2015. The Department of Energy's Energy Information Administration (EIA) projections of energy consumption imply carbon emissions increases of 25 percent (reference) to 50 percent (high growth) by 2010. The annual growth rates for the relevant variables for the EIA reference case (which only goes to 2010) are presented in the last column of table 2 for comparison purposes. So, the JSW model does not have to work too hard to keep CO_2 emissions at 1990 levels since emissions do not rise all that much above 1990 levels even without any special constraints being imposed.

Just because the JSW model produces unusually low rates of growth in CO_2 emissions over the next 30 years absent any constraints, however, does not mean that the projections are implausible. After all, U.S.

CO_2 emissions increased by only about 17 percent between 1970 and 1990 (0.8 percent a year), while GNP grew by 70 percent (2.7 percent a year). Nevertheless, it is useful to understand why the JSW baseline CO_2 emissions are so low compared with other unconstrained projections. Unfortunately, the paper does not present the information necessary to do so. The additional information Peter Wilcoxen provided to me, however, does begin to answer this question.

Perhaps most important, table 2 indicates that, for the period 1990–2020, the model generates an unconstrained base case with a very low (endogenous) rate of growth in GNP and a low marginal energy-to-GNP ratio. The time path of these endogenous variables appears to account for a significant fraction of the difference in baseline CO_2 emissions levels compared with other models. The model also generates some base-case values that are, at least to me, surprising. Oil and gas imports fall, rather than rise as they do in most other medium-term projections. Oil and gas consumption does not increase as it does with most other models. Electricity prices fall rather than rise as they do in most other projections. This raises questions in my mind about the underlying parameter estimates that drive the results.

When we turn to what happens in the base case from 2020 to 2050 (table 3), we see that the JSW base-case economy goes into a sort of suspended animation sometime early in the next century. Nothing changes very much at all between 2020 and 2050. The economy appears to go into a close-to-zero growth equilibrium, and CO_2 emissions actually fall slightly between 2020 and 2050 without any help from government regulators. This presumably reflects the combination of the stabilization of the size of the U.S. population, slow endogenous productivity growth, a low marginal energy-to-GNP ratio, and the way the model has been simulated. The economic growth characteristics of the base case are so different from those used by other analysts that their credibility deserves at least some discussion by the authors.

Overall, in evaluating the JSW results it is important to understand that the baseline against which the carbon taxes must constrain behavior is one of slow economic growth, slow increases in energy consumption, and slow increases in carbon emissions. In the JSW world the good news is that the United States does not have nearly as much of a CO_2 problem as some think because, even if we do nothing, CO_2 emissions will stabilize by the middle of the next century at a level not much

Table 3. JSW Base-Case Values, 2020–2050

Variable	*2020 simulated values*	*2050 simulated values*	*Annual growth rate (%)*
GNP (1990 dollars)	9,226.01	9,502.18	0.10
Fossil fuels consumed (quads)	78.04	77.63	−0.02
Oil and gas consumed (quads)	47.82	47.97	0.01
Coal consumed (quads)	30.05	29.47	−0.06
Electricity (billions of kilowatt hours)	3,170.43	3,232.56	0.06
Carbon emissions (millions of tons)	1,842.31	1,828.77	−0.02
Oil and gas imports (quads)	7.21	7.45	0.11
Domestic oil/gas price (dollars per million BTUs)	4.92	4.80	−0.08
Imported oil/gas price (dollars per million BTUs)	9.08	10.67	0.54
Electricity price (cents per kilowatt hour)	4.74	4.58	−0.11

Source: Computed from data provided by Peter Wilcoxen, December 9, 1991.

higher than the level in 1990. The bad news is that we can look forward to slow economic growth.

A lot of action associated with carbon taxes affects the electric power sector, a sector that is near and dear to my heart. The largest direct effects in the simulations reported in table 1 are large increases in the price of coal and large reductions in the quantity of coal consumed. Since the electric utility sector consumes 80 percent of the coal produced in the United States, and coal accounts for 60 percent of the electricity produced, the second largest price and quantity effects are associated with electricity. An especially good model of future electricity supply opportunities, electricity demand, and regulatory policies affecting both seems to be in order. However, I am quite dubious about the ability of JSW's econometric production or cost function approach that relies on the time series data for the 1947–85 period to make accurate projections of input choices and productivity growth for the U.S. electricity sector over the next 30 to 100 years.

Why am I dubious? Primarily because I don't think that the future supply, demand, and regulatory conditions affecting the electric power industry are going to be much like those of the past. The historical period from which the data are drawn to estimate the parameters in the

JSW model includes long periods when gas was cheap but not available to utilities, the growth of the nuclear sector from zero to 20 percent of electricity generation, a large increase in hydroelectric capacity, the exhaustion of thermal efficiency improvements and economies of scale associated with conventional steam cycles, and continually changing environmental regulations. The generation technologies being built and planned today are frequently much more efficient thermodynamically than the Rankine steam cycle and rely heavily on gas rather than coal. Nuclear energy does not seem very promising in the medium term. Various renewable energy options are becoming much more economical due to technological change, and more likely to be selected by utilities due to changing environmental constraints and regulatory requirements. Amendments to the Clean Air Act were recently passed that will increase electricity costs considerably as electricity suppliers meet tighter SO_2 and NOX constraints. I have no reason to believe that JSW's econometric model picks up any of these structural changes. Nor am I thrilled with a key modeling assumption that capital is freely and costlessly mobile between sectors. There are very significant sunk capital costs associated with the production of electricity. Perhaps much of the stock will turn over by 2020, but these sunk costs should at least play a role in determining the transition path from here to there. I have more faith in the engineering-economic models used by other analysts to provide a useful framework for evaluating the full array of policy alternatives affecting the electric power sector than in the econometric model used here. In any case, not enough information is available (in the paper or from the authors) about how the electricity sector evolves in JSW's base and constraint cases to compare JSW's electricity future with those produced by other analysts.

The authors' extension of their previous modeling and policy simulations to examine aggregate welfare and, in particular, the distributional consequences of a carbon tax are quite interesting and innovative. This may be where the real payoff to disaggregation at the industry and household level lies. It is a shame, however, that this paper limited itself to the particular CO_2 constraint selected here since the tax rate, price, quantity, and welfare effects are (apparently) so small. The case reported in the last column of table 1 would have been a more interesting one to examine for exploring distributional issues.

Let me move quickly now from models and what they spit out to

CO_2 policy. All of the economic models that I have referred to generate numbers for the costs of meeting alternative CO_2 constraints by imposing carbon taxes on fossil fuels. They may do this because the analysts believe that carbon taxes are the most likely environmental policy instrument to be chosen to control CO_2 emissions. Alternatively, carbon taxes may be used simply as a modeling convenience to generate the price, quantity, and investment responses necessary to calculate the costs to the economy of meeting a particular CO_2 constraint. In either case, however, it is very important to recognize that the costs spit out by the models in this way are not likely to be good predictions of the *actual* costs of controlling CO_2 emissions to various levels *unless regulatory policies are adopted that have the same efficiency attributes as carbon taxes*. The way the models work, the assumption that carbon taxes alone are used to meet a specific CO_2 target is equivalent to assuming that a specific emissions constraint will be achieved *as efficiently as possible*, that is, at least cost. (Marginal cost of CO_2 control equals the carbon tax; the marginal cost of CO_2 control is equated across all sources.)

It would be very exciting if the U.S. government decided to rely on a carbon tax to control CO_2 emissions. As a student of the history of U.S. environmental regulation, however, I must ask why we should assume either that the favored policy instrument will be a carbon tax in the United States or anywhere else, or that alternative constraint policies will be adopted that yield a least-cost solution to the carbon constraint specified. I hear much more talk about subsidies for conservation and renewables, CAFE standards, mandatory fuel switching, building efficiency standards, and the like than I do about CO_2 taxes from the people who seem to matter most in the policy process. In general, why should we expect that we will adopt least-cost policies generally for CO_2 emissions when we have not done so for almost any other environmental problem?

Historically, U.S. environmental policies have generally relied on inefficient command and control mechanisms that cost 2, 4, 10, or even 20 times the cost of the least-cost control strategy for achieving a particular emissions level. Rather that taxing gasoline, we have applied CAFE standards that increase the efficiency of new cars, leave old dirty cars on the road, and make it economical to drive both cars more miles a year. Rather than taxing SO_2, we imposed costly sulfur removal technologies (scrubbers) on electricity generators. If history repeats itself, the costs of controlling CO_2 produced by the models that assume that a carbon tax or policy with equivalent attributes will be relied upon will significantly underestimate the actual cost of real CO_2 constraint policies.

Indeed, I am struck by some of the similarities to the problems of controlling SO_2 and NOX from stationary and mobile sources and those we face with regard to CO_2. The effects of CO_2 constraints are concentrated on the coal, utility, and petroleum sectors. Even for the modest constraints and aggregate costs implied by the CO_2 emissions case reported in the JSW paper, which would maintain emissions at 1990 levels, the effect on the coal industry is devastating, once we recognize that there are sunk investments and immobile workers in that sector. The price effects on electricity are more than double those projected for the acid rain title of the 1990 Clean Air Act. These are the same industries that fought reforms of the Clean Air Act for more than a decade and have opposed all efforts to use emissions or energy taxes to internalize pollution externalities. Although a tradable SO_2 allowance system could be sold (barely) politically because it vested property rights in SO_2 emissions in the incumbents, an SO_2 tax would not have passed the laugh test politically. So, there is probably a lot to learn about the challenges associated with implementing *good* CO_2 constraint policies by examining the way we have dealt with other air emissions from similiar sources.

The political economy lesson of the efforts to control SO_2, NOX, and other air emissions is that it is not the average burden and distributional effects on *consumers* that matter so much as it is the interests of incumbent industries and workers that are likely to be harmed economically by new environmental constraints. We have tended to insulate existing sources from the full costs of environmental compliance by placing significantly tighter emissions constraints on new sources (NSPS, percent removal, and CAFE) than on existing sources. We have protected high sulfur coal suppliers by requiring utilities to remove at least 70 percent of the SO_2 from all coal regardless of how low the sulfur content is. We have avoided emissions taxes because the affected industries perceive the burden to them of controlling some emissions *and* paying for inframarginal emissions to be much larger than the burden of paying much too much to clean up marginal emissions reductions while paying nothing for inframarginal emissions. Finally, because of an irrational aversion to flexible incentive-based systems by most environmental groups, we have been slow to allow for intersource emissions trading that could reduce control costs substantially.

I can assure you that there are indeed some very costly ways to control CO_2 emissions. Indeed, prototype designs for CO_2 scrubbers that could be fitted on power plants have already been commissioned. These studies suggest that CO_2 could be scrubbed from the combustion products of a pulverized coal generating unit at a cost of $350 to $450 per ton of carbon removed, or roughly 20 times the tax the JSW model simulates for stabilizing CO_2 emissions at 1990 levels.

The lesson that I take away from the history of environmental regulation in this country is that we need models that will allow us to evaluate the effects of a wide range of potential public policies that include but are not limited to carbon taxes and that do not assume that least-cost solutions to environmental problems are what Congress or the United Nations will give us. Modeling approaches that allow us to analyze the consequences of a wide variety of different policies arguably aimed at reducing CO_2 emissions are necessary to produce the information required to respond to those (at the Environmental Protection Agency, for example) who point to the JSW results to support their arguments that very restrictive constraints on CO_2 are cheap and then turn to a variety of much more costly and inefficient subsidies and command and control regulations, rather than carbon taxes, to meet these constraints. The JSW model does not seem to me to be up to this task, and its results can easily be misused by those with an interest in doing so.

Comment by Raymond Kopp: Certainly, one of the downsides of being the second discussant is that if you follow somebody like Paul Joskow who has a prepared handout and typewritten notes, you are necessarily going to look bad when you have just some miscellaneously collected thoughts.

The plus side, of course, is that I get a chance to dynamically adjust to whatever he said. That allows me to take out all the stuff that is duplicative so we can stay within a timeframe. I may only need about three minutes, now. But, perhaps, I will emphasize a few things that he didn't say and, maybe, correct things that he did say.

Certainly, Dale Jorgenson will take care of most of the necessary corrections. There is one thing that I feel I have to comment on, however, and that is this. The paper is not necessarily transparent to the user, and it cannot be so. Anyone who has ever designed these sorts of models and written them and sent detailed papers to editors and gotten them back by return mail would say thanks, but I wouldn't even think of imposing this on a referee. So, you put a referee's appendix, which is 90 pages long, and that doesn't even get sent out. No one really wants to know the details, when it comes right down to it, from the refereeing process. Of course, if you don't supply them, that is the first thing you get attacked on. So, to be able to use or interpret any of these results confidently you do have to go through a long laborious process of tracing back to year one or version 1.0 and then following it all up to the present. But that is just the way the game is played, and there is not much we can do about it.

I might as well not comment, then, on the macroeconomic applications of this model and look more to the distribution side. Since I seem to be a designated hitter for discussion of Wilcoxen and Jorgenson papers, anyway, I have already discussed the macro paper, which preceded this one. So, those comments are on record.

Let me just discuss the distributional side, which I think really is the interesting aspect of this particular paper. If you look at the two of these combined, if you are in favor of greenhouse taxes, this is the best of all possible worlds. There is virtually no macroeconomic impact of these things. Growth just continues on.

Secondly, the distribution of these things is small, and it is evenly distributed across all the households. So, politically, this seems to be the greatest thing since sliced bread.

The question is: Is it in fact true that, when we go from the modeling world, where this in fact is the case, to the policy world, both of these things will move over?

Paul has already discussed that perhaps the macro side may be a little suspect in the real world, and I just want to talk a little bit, perhaps, about the distributional side.

On the face of it, I guess I am not convinced. I mean, I started thinking about carbon taxes and their regressivity, and my initial thinking is that it just seemed fairly evident that these things were going to be regressive in some sense, that is, that very poor people—black folks living in urban Cleveland in the Midwest—are going to get hit worse than white affluent families living in the Pacific Northwest. A lot of the reasons have to do not so much with their income as to where they happen to live. But income also plays a part. We will talk about that in a little bit.

One thing that you do have to understand about this particular kind of model—again, it is not an indictment of the model—is that these sorts of general equilibrium models have perfect foresight. No regrets. No one ever makes a mistake, ever. Mistakes, unfortunately, occur a lot, and they are costly. If you pick the prices wrong or you invest in something wrong, you make these kinds of irreversible decisions, and they turn out bad, there is cost associated with that. There cannot be any of that sort of thing in this model.

But, more important, this model has perfect-factor mobility and malleability. What that means is that at any one point in time the model allows for only one kind of labor. Coal miners and rocket scientists are the exact same person. And there is only one kind of capital. Coal plants look just like heat pumps to the model when it does its reallocation. So, as soon as prices change and it wants to reallocate capital, it can do so instantaneously and costlessly.

Where do all those coal miners go, by the way, who get zapped when the coal industry declines by 30 percent? Well, they are turned into somebody else, without any particular cost. So, there is no distributional implication to the fact that those coal miners get disrupted.

Again, the model is very long run. It has got lots of flexibility in it. All of these things tend to diminish the impact of any one of these particular environmental shocks. But as long as you understand that, you have got a base case that you can compare against, and you can evaluate different sorts of things, knowing how that whole thing works.

What is important about this particular application is this. It is how the tax reenters the economy that really counts. The authors are talking about the distribution of welfare losses. This is not a distribution of a tax. The taxes are fairly substantial. Depending upon what assumptions you want to make about the elasticities of substitution that may exist in the short run and where you are in the country, it can vary from—according to the paper—$50 to $100 a year per household. So, these things are not trivial.

But all the households get the money back again. You take it out of one pocket; you give it back to them in a lump sum form. As a result, essentially, it is a wash. Again, there is some little income loss due to the dead-weight loss of removing a lump-sum tax. The authors change the income tax by putting in this distortionary tax. But, on net, things look pretty good.

I assume this is the case. What I generate out of my comments are a lot of questions that have to do with the dynasties. (For those of you who are not familiar with Dale-isms, this is households.) In the model all the households get back the money in the exact proportion in which they put it in. Given that, what is the difference between that sort of view of the world and the sort of view of the world that folks on Capitol Hill are going to have to deal with when it comes time to vote on actual carbon taxes?

Well, the first thing is that in the authors' model there is no space. So, there is a coal sector and there is an electricity sector and there is a natural gas sector. But there is one big supplier that supplies all the households. As a result, there is one electricity price. In the real world, however, there is not one electricity price or natural gas price or fuel oil price or gasoline price. Energy prices vary greatly across the United States, by as much as 50 percent for some different kinds of energy forms.

Why? For a variety of conditions. People use energy very differently. In some places you have to both heat and cool. In some places you don't have to either heat or cool.

Also, depending on how energy comes to you and in what sort of forms, prices are very different. People who live in the Pacific Northwest, who draw electricity off of the hydropower of the Bonneville Power System, or people in the Mid-Atlantic states, who draw it off of TVA, have fairly low electricity prices. If you live in the Midwest or in the central states, you have fairly high prices. If you use a lot of coal to generate your electric power, the impact of that tax is going to be much greater in your particular region than it is going to be in the Pacific Northwest.

So, the first thing you want to look at, when you look at the distribution of these burdens, essentially is the distribution of the taxes, and they are not going to be even. It is pretty clear that the folks in the Pacific Northwest and in areas where they have a lot of hydropower are going to pay low taxes, and individuals who use fuel oil for heating or whose electricity is generated by coal and who have to both air-condition and heat are going to pay substantial amounts. The model doesn't take these differences into account.

If that is not taken into account, then how do you rebate the taxes to these people equally? Let's face it—this money is not going back into the pockets of individuals. But if you wanted to put it back into the pockets of individuals, how would you do it? You have got to have some regional way of rebating all of these energy credits, and this is a nontrivial public finance problem and one that I think deserves some attention.

This leaves some questions that to me are still unresolved. The first one that is bothering me, of course, is that the analysis shows that there does not appear to be any real regressivity associated with the tax. The reason is that rich people buy a whole lot of other stuff also. The prices of those goods go up. And as those prices go up, energy prices go up, but somehow, on net, everything seems to work out. Okay. That may well be. And, again, I don't think any of us know, really, what the income elasticity of energy demand is by income class, but there still are some facts that we can look at.

If you look at the 1987 household energy survey that the Energy Information Administration did and if you look at the percentage of income by household class, there are some striking numbers that you have got to deal with. Families that earn less than $5,000 a year spend 25 percent of their income on energy. Those individuals in the $20,000 to $25,000 range spend 4 percent.

You have got to convince yourself that there is enough going on in those non-energy-related commodity categories—I didn't see any huge price shocks out there—to account for these huge differences in the components of the energy budget. Perhaps the model really doesn't capture very low-income individuals. This gets back to what exactly the model is capturing.

We have these dynasties out here, but are we to believe that if we have rich and poor dynasties, everyone is paid the same wage rate in the model? Everyone gets the same rate of return on wealth in the model. But, presumably, the authors have allocated expenditure across these dynasties, according to the 1989 Consumer Expenditure Survey. Is that how they arrived at rich dynasties and poor dynasties? And, if they did that, did they have enough very poor dynasties in there to say anything about those folks down at the low end of the line? Or, are the authors only starting where the bulk of individuals live, which is maybe the higher level of the income distribution, where essentially the amount of expenditures spent on energy is fairly flat, and it only really drops off when you get down to this very low-income group. I am not sure what is going on there.

The last thing that I am concerned about is how the authors are measuring the welfare. This is a technical issue, but it is one that is definitely not transparent in the paper and is confusing to me. This model sets up the consumer side, so that consumers make a whole host of hierarchical decisions, starting with this intertemporal decision about how they are going to spend their full wealth over their lifetime. How much are they going to spend now, and how much are they going to spend in the future? Once they have the amount they are going to spend now, they must decide how to divide that portion between leisure and goods and services.

Once the consumers have settled on an amount for goods and services, they must decide how to divide that between imports and exports. The domestic amount must be divided among all these commodities. So, there is a whole tree structure.

Each one of those can be identified as a little expenditure function or a little indirect utility function, and you can measure welfare changes anywhere you want in that tree. The lower you measure it, however, the less flexibility the household has to adjust to the shock that you are imposing and, as a result, the higher the welfare loss is going to be. So, keep that in mind.

It is said on the consumption side of the paper that at the first stage, each household allocates full wealth across different time periods according to its rate of time preference and its intertemporal elasticity of substitution. The authors formalize this decision using a representative agent who maximizes an intertemporal utility function subject to an intertemporal budget constraint. So, at the top level of the hierarchy, we have got a representative agent up there with an intertemporal utility function.

Now, on the welfare analytic side, it says: ''We assume that each dynasty''—read ''household''—''maximizes an additive intertemporal utility function. . . .'' Well, is this the same or a different intertemporal utility function?

According to the paper, "The intertemporal utility function forms the foundation for the analysis of the change in lifetime well-being. . . ." Here is where I am confused. It is clear we are making the welfare calculation. It is very high up the tree, so it is the place where the household has the most flexibility, up where they are making their intertemporal decisions. But, I am confused as to who is doing this. If in fact it is all these individual households where the demographics lie and where the income-distribution story lies, it seems to be inconsistent with the first statement that said it was a representative household. I didn't know that these dynasty households had ever been estimated over anything other than just static goods and services. I didn't know there was an estimation of how they allocate their intertemporal wealth. If there is, you have got intertemporal substitution elasticities that vary by demography, which would be fascinating information. I don't think I have ever seen that. So, again, it confuses me because that seems to be crucial to telling the story here about why the welfare loss is as low as it is. I know it is low because you have got it very high up in the tree, but I want to tie that to the distribution of these various kinds of households.

In closing, I have to go back to the remark that I criticized originally but which still holds a certain amount of validity, and that is that the paper itself isn't really transparent. We know you can't go out there and lay out the 6,000 coefficients with standard errors. I don't think anybody is asking you to. No one wants to see them, anyway. But how exactly the consumer side works in this case, how these different households actually link into the story and how you get a brighter light on the demographic side of this to convince those of us who still doubt why we should believe this story about progressivity—that I think would be important.

General Discussion: Several participants commented on the social welfare effects of a carbon tax. Linda Cohen questioned the authors' claim that a carbon tax would have political appeal because it would not be regressive. She said that the political feasibility of such a tax would more likely be connected to other issues, such as the geographic distribution of costs and benefits.

Richard Schmalensee also said that regressivity was not the correct equity measure surrounding the effects of a carbon tax. In noting the similarity between the new global warming issue and the slightly older acid rain problem, Schmalensee said that during the debate over reducing acid rain through reducing coal usage in electric power generation, there was little discussion over the regressive effect of increased prices for electricity, but much concern about the substantial effect on, for example, a relatively small number of coal miners. Schmalensee pointed out that the political importance of such an effect would be connected to the mobility of labor and capital in an industry hit hard by these measures. He noted that the model used in the paper did not take into account the existence of industry-specific human or physical capital.

Some discussion centered on the long-run projections about the U.S. economy that were made in the paper. Schmalensee said that projection of past productivity trends into the future might lead to serious problems when examining long time horizons. He wondered if one could make better predictions by moving away from the kind of standard modeling strategy used in the paper and toward actually talking to people with knowledge about the shape of future technologies.

Ariel Pakes argued that the effects on technology development of price increases brought about by a carbon tax must be examined more closely. He suggested that patents on technology dealing with reducing carbon emissions might shoot up within a few years after the imposition of a carbon tax. Pakes said that the development of these new technologies might have a substantial effect on long-run projections about the U.S. economy.

John Meyer argued that because the greenhouse problem from carbon emissions is worldwide, solutions should also be reviewed on this scale. He suggested that there might be some exceptionally inexpensive (at least partial) solutions to the carbon emission problem. For example, the economies of the communist and formerly communist nations (including China, the former Soviet republics, and Eastern Europe) make extremely inefficient use of energy resources, especially coal. According to Meyer, rationalizing energy prices in these economies almost certainly would lead to a large reduction in coal and, more generally, in total energy usage. Worldwide carbon emissions could thereby be reduced substantially while at the same time increasing economic efficiency.

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