The Role of **substitution** in understanding the costs of **climate change** policy

Prepared for the Pew Center on Global Climate Change

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Foreword *Eileen Claussen, President, Pew Center on Global Climate Change*

The U.S. economy has proven both resilient and adaptive over the past century. From the "bust" of the Great Depression to the current "boom" associated with information technology, the economy's ability to adapt stems largely from the substitution possibilities within it — that is, how businesses and households alter their behavior when a major economic change occurs.

Reducing greenhouse gases could alter future economic conditions, largely through increased energy prices. While these changes could be significant, the economy is rapidly becoming even more flexible and responsive as technology changes the way things are invented, produced, and distributed. Accordingly, the damages to the economy might be less. Yet, many economic models used in predicting the future costs of climate change policies do not adequately capture the economy's full range of substitution possibilities. A recent Pew Center report entitled, An Introduction to the Economics of Climate Change Policy, identified substitution assumptions as one of five key factors having the largest influence on modeling results. The other factors are: how baseline greenhouse gas (GHG) projections are measured; what policy regime is considered; how technological progress is represented; and whether GHG reduction benefits are included.

This analysis by Dale Jorgenson, Richard Goettle, Peter Wilcoxen and Mun Sing Ho explores the role of substitution in adapting to economic change. It begins with what is considered a "flexible" model (a top-down, computable general equilibrium model of the U.S. economy) and then constrains the flexibility parameters within this model to observe its new results. In essence, the authors use the same model to behave both "flexibly" and "inflexibly" in order to observe the effect of this pivotal assumption on model outcomes.

The most striking conclusion of this work is that the failure to depict the full range of historically-observed substitution possibilities (as many economic models do) can lead to as much as a doubling of the estimated costs of a climate change policy, an overestimate that is wholly attributable to this one pivotal assumption. This overestimation may be even more pronounced since the economy appears more flexible today than in the post-war period when these observations were made. Another interesting finding is that varying the flexibility households have in choosing to work more or fewer hours can be as important in predicting carbon prices and economic outcomes as the assumptions about flexibility in all of production. In summary, economic models of climate change must represent the full range of flexibility that is achievable or risk significant errors in estimating economic benefits and costs.

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Executive Summary

The U.S. economy's reaction both to climate change itself and to the policies designed to avoid climate change depends largely upon the abilities of consumers and producers to adapt to these changes and move forward under new conditions. In turn, these abilities depend on the ease with which consumers and producers can alter their purchasing behavior without sacrificing welfare, income, and production. This ease is reflected largely in the economy's "substitution possibilities" — the options available to consumers and producers to change what they buy and sell in response to changes in the prices of particular goods and services. If the cost of economic substitution is low, and the range of substitution possibilities is wide, then mitigation costs — the damages to welfare, income and production — are likely to be low and the burden on the economy is likely to be small. If the cost of substitution is high, and range of substitutability is narrow, then mitigation costs are likely to be high. The purpose of this paper is to examine the economy-wide impacts of reduced substitution opportunities when the economy must adjust to a constraint on carbon emissions.

This analysis uses an economic model that, compared to other models, depicts a relatively complete set of substitution possibilities for consumers and producers. Simulation results from the model portray the economy's response to an emissions reduction schedule that is implemented through a system of tradable emissions permits. The first model simulation used substitution possibilities that were estimated from historical data. Next, the authors systematically replaced key parameters (i.e., coefficients or multipliers of selected mathematical relationships embedded in the model) in a manner that drastically reduced the substitution possibilities of producers and consumers. Each of these simulations defined a different world or economy. The authors then simulated each economy's reaction to proportionally identical emissions constraints. In this manner, the model produced measures of the economic responsiveness both with and without flexibility and the analysis quantified the benefits and costs of substitution.

Three areas of substitution are most important to the overall economic reaction to climate change. These are:

- flexibility in production, meaning the ability of firms to substitute labor, capital, or other materials for energy or each other when the price of energy rises;
- flexibility in consumption, meaning the ability of households to change the mix of goods and services they buy in response to higher energy prices; and
- flexibility between *labor* (and, hence, income and consumption) and *leisure*, as households allocate their scarce time between the two.

The principal conclusions emerging from this analysis are:

1. When allowable substitutions reflect the observed behavior of the past, constraining carbon emissions to around 70 percent of their projected base-case levels costs the economy about a one and one-quarter percent loss in real Gross Domestic Product (GDP) and a one-tenth of one percent loss in economic welfare. For perspective, at current levels, this loss in GDP corresponds to an annual loss in income of $430 per person living in the United States and the welfare loss is equivalent to a tax, payable today, of $3,175 per person.

2. Constraining carbon emissions is generally more costly when substitutability in consumption or production is restricted. Thus, flexibility within the economy significantly reduces the adverse impacts of climate change and climate change policies. Real GDP losses are slightly larger when consumption is less flexible, and are doubled when production is less flexible. *Failing to account for the full range of substitution possibilities in consumption and production will lead to overestimation of the negative effects of climate change policy.*

3. Just as "rigidity" magnifies economic costs, it can also magnify economic benefits under certain circumstances. For example, inflexibility in consumption or production is beneficial to economic performance when: (a) climate change policies lead to additional tax revenues, and (b) the tax policy for reusing these additional revenues is economically advantageous. In fact, the benefit is magnified the more inflexibility is introduced (assuming a and b hold).

4. Differences among models' treatment of the substitutability between consumption and leisure are likely to be every bit as important in predicting emissions permit prices and economic outcomes as are the models' underlying details of technology, consumption, or production. The more *inflexible* households are with respect to their consumption-leisure tradeoff, the *lower* the costs of reducing emissions. Contrary to what occurs when substitution is constrained in production or consumption, rigidity in this instance appears beneficial. However, this rigidity can also prove harmful. The combination of an emissions constraint, inflexibility in consumption and production, and more favorable tax treatment leads to economic benefits (point 3 above). Add inflexibility in consumption and leisure, and the combination leads to economic costs. *Rigidities in household choices between consumption and leisure substantially limit the observed economic outcomes from climate change policy: either the adverse impacts are smaller or the potential benefits never materialize.*

This analysis is important not only because of its results, but also because it explores this topic in a detailed and systematic manner within a single methodology. It is among but a few efforts to fundamentally change the character of a model in developing a sensitivity analysis. The numerous and well-documented outcomes of other policy experiments have informed the policy process. There now are fewer surprises when a particular policy design is subjected to the scrutiny of a broad range of models. But the quest for understanding does not end here. A model's outcomes depend on interactions among the various components that govern its behavior, and thus analysts need to identify and examine these components in both isolation and combination. The intent of this exercise is to increase understanding of the nature and magnitude of the benefits and costs of substitution by exploring the key features of one particular model and the economy it can portray. The hope is that this exercise makes a modest contribution to the formulation of environmental and economic policies that are beneficially robust over the broadest possible range of economic circumstances.

I. Introduction

The easier it is for producers and consumers to make substitutions among goods and services, the less the economic burden of carbon emissions reductions. This analysis measures the magnitude of the U.S. economy-wide benefits and costs of substitution in such a systematic fashion. The objective is to measure the extent to which observed flexibility on the part of firms and households helps to insulate the economy from the potential costs of a carbon mitigation regime.[1]

This analysis used a comprehensive economic model to examine the economy's response to a hypothetical carbon emissions reduction scheme. First, the model was run using substitution possibilities that were estimated from historical data. Next, the modelers replaced model parameters so as to limit the substitution possibilities of producers and consumers relative to those estimated from historical data. These model runs provided a set of base-cases. For each of the base-cases, the modelers then simulated the economy's reaction to proportionally identical carbon emissions reductions. The benefits and costs of substitution were measured by comparing the model's results with and without flexibility.

The analytical community is quick to identify the attributes of an economy, like substitution, that are of central importance to the outcomes of various policy schemes or external shocks. Invariably the magnitudes of the outcomes depend upon empirical estimates of these attributes. Analytical issues arise because of differences in empirical estimates of parameters and because of differences in the ways models map or summarize the economy. The typical response to these issues is to assemble around a common task an array of models or model results, each offering a different worldview. Then by comparison, either through inference (Weyant [2000]) or quantifying analysis (Repetto and Austin [1997]), a sense of the relative importance of this or that attribute emerges. Unfortunately, this approach only weakly measures this importance because each worldview is so different in so many dimensions.

This analysis takes an alternative approach. Instead of inferences drawn from a set of differing portrayals and accounting schemes, this effort draws such inferences by creating different worlds within a single framework — one that is highly detailed and comprehensive in its representation of actual economic phenomena. By isolating various aspects of substitution within a single model structure, this analysis is among the relatively few to systematically analyze the effects of broadly different types of substitution on the nature and magnitude of economic response.

The remainder of this report is organized as follows. Section II explains what substitution is. Section III discusses the model methodology and experiment developed for this exercise. Section IV presents the results for this experiment using the model with parameters based on historical experience. Sections V and VI examine the results when model parameters limit the substitutions within production and consumption and the substitution between consumption and leisure. Section VII contains a brief discussion on the interaction between alternatives for the recycling of tax revenues and the economy's substitution possibilities. Finally, Section VIII summarizes the major results of this analysis with a view toward identifying the magnitudes of various substitution effects and clarifying the role of substitution in analyzing climate change.

II. What is Substitution?

The U.S. economy is remarkably adaptive, resourceful, and resilient, largely from the possibilities of substitution within it. Its ability to change with circumstances can be seen with only a brief survey of changes and events over the last five decades. The economy has absorbed and experienced the benefits of the four technological revolutions identified by Gordon (1999): inventions that relate to electrification (motors, lighting, electronic equipment, and appliances); transportation (motor and air transport); "rearranging molecules" (petrochemicals, plastics, and pharmaceuticals); and communications (telecommunications, radio, television, and movies). Add to this the changes arising from the mobilizations to support wars in Korea and Vietnam; space exploration in the 1960s; the defense initiatives of the 1980s; intermittent energy shocks; the regulation of air, water, and land quality; rounds of inflation and recession; the decline and reconfiguration of the industrial landscape; the growth of high technology and international trade; changing demographics; and the emergence of the "service" economy, and it becomes clear just how important substitution is to economic growth, adjustment, and progress.

This resilience is important when considering how the U.S. economy would respond to a constraint on carbon emissions. Such a constraint inevitably raises the prices of fossil fuels in proportion to their carbon content. This occurs whether the constraint is implemented through domestic or international regulations, a carbon tax, or a system of tradable carbon permits (leading to a "carbon price" determined in the marketplace). Households, businesses, governments, and international trading partners react to these price increases by substituting away from more expensive to less expensive goods and services. These direct "substitution effects" mean comparatively lower demands for energy, and for goods and services that require substantial amounts of energy in their production or use. The direct effects also mean comparatively higher demands for substitute goods and services. In turn, these direct effects give rise to indirect effects, as adversely affected firms curtail their purchases and positively affected firms increase their activity. Through these direct and indirect substitution effects, society shifts its resources from more carbon-intensive activities to less carbon-intensive activities, and adjusts to its new circumstances.

When all adjustments are completed, the economy is either smaller or bigger than it otherwise would be in the absence of the emissions constraint. In this analysis, real Gross Domestic Product (GDP) is used to measure the size of the economy. It is, equivalently, the inflation-adjusted spending on, or income earned from, the domestic production of finished goods and services. However, real GDP is only one measure of economic well-being. Changes in household welfare, defined as the cumulative consumption of goods, services, and leisure, offer another way to ascertain if the nation is collectively harmed or helped by a carbon emissions constraint.

There are numerous substitution possibilities in the economy for producers and consumers. In the face of higher fossil fuel prices, for example, producers substitute among the inputs into production. To the extent permitted by available technology, producers substitute:

- less carbon-intensive fuels for more carbon-intensive fuels (for example, gas for coal);
- non-fossil energy sources for fossil fuels (nuclear, hydropower, geothermal, solar, and wind for coal, oil, and gas);
- non-energy inputs (materials, labor, and capital) for energy inputs (installing automation and process control equipment);
- energy-conserving inputs for highly energy-using inputs (more energy-efficient vehicles, lighting, cooling, heating, production and computing equipment);
- less energy-intensive goods for more energy-intensive goods (greater use of high strength plastics and products made from recycled aluminum and steel); and
- more competitive imported goods and services for the now more expensive domestic ones.

Consumers, governments, and foreigners purchasing U.S. exports react to higher energy prices with similar substitutions of their own.

Households act on two additional important fronts. First, people allocate their time between work and leisure (here meaning the uncompensated use of time), substituting more of one for the other as consumer prices change relative to labor compensation rates. For example, increases in the costs of commuting, wardrobe, and other job-related expenses, healthcare, and childcare prompt some individuals to seek part-time rather than full-time employment. Second, people make choices regarding the allocation of spending over time, shifting spending between the present and the future by borrowing or saving in the interim. The direct and indirect consequences of all the above decisions alter the composition of production and consumption, the overall magnitude of income and spending, the size of the labor supply, and the levels of saving and wealth.

U.S. contributions to the world's anthropogenic carbon emissions arise from the energy used within production, by households, and by governments. These then are the most important areas in which to investigate the role of substitution. Accordingly, this analysis first addresses the input or "factor" substitutions that take place within production, and then substitutions among goods and services in household consumption. These substitutions reflect the reactions of businesses and households to the emissions constraints and energy prices facing them. Systematically altering the observed patterns of substitution in otherwise identical modeling experiments allows measurement of the benefits to income, production, and welfare afforded by flexibility.

Equally important in shaping the growth and structure of the economy is the substitutability of consumption and leisure by households, for this lies at the heart of the labor supply and saving and investment decisions. As household members choose whether or not they will work, at how many jobs they will work, and how much discretionary overtime they will pursue, they are simultaneously determining the labor supply, their incomes from work, and the amount of leisure they will "consume." Also, as they decide how much they will spend on goods and services, they are also determining their saving decisions which, along with that from businesses, determines the level of investment and the rate of capital formation in the economy. Because of its importance, this analysis examines separately limits on the consumption-leisure tradeoff.

III. The Model Experiment

The objective of this analysis is to show how incorporating flexibility (or choice) into various types of economic behavior affects the way models estimate the effects of climate change policy. As stated earlier, the three kinds of flexibility examined in this report are:

- flexibility in production, meaning the ability of firms to substitute labor, capital, or other materials for energy or each other when the price of energy rises;
- flexibility in consumption, meaning the ability of households to change the mix of goods and services they buy in response to higher energy prices; and
- flexibility between labor (and, hence, income and consumption) and leisure, as households allocate their scarce time between the two.

The importance of these phenomena can only be understood by using a model that allows each to be altered. The Intertemporal General Equilibrium Model, or IGEM, developed by Ho, Jorgenson, and Wilcoxen is such a model. IGEM is a so-called "computable general equilibrium" model of the economy, meaning that it computes the "equilibrium" prices and quantities in the markets for 35 broad classes of goods and services in each time period. Equilibrium means that prices adjust so that supply equals demand in all of the markets represented in the model. Formal descriptions of the model appear in Ho (1989), Jorgenson and Slesnick (1985, 1987), Jorgenson *et al.* (1992), and Wilcoxen (1988). The model is described in greater detail in Appendix A of this report.

By understanding how the model incorporates each of the three forms of "flexibility," one can understand how that particular feature of the model can be "turned off" and the model's results compared with and without the feature in question. For example, consider the first type of flexibility — the way producers choose inputs into production. The model represents this kind of flexibility in the following way. Using data from 1947 to the late 1980s, the model computes how firms in each of 35 industry groups use labor, capital, energy, and other materials to produce output. Energy demand is divided among five fuel types; materials demand is divided among the 30 remaining commodities. The combination of resources that firms choose is determined by equations in the model. The model also includes whatever technological trends are discerned in the data. The equations of the model that link a change in the price of energy to a change in, for example, the use of capital in a particular industry, are constructed so that they vary according to the situation. For example, when the price of energy is very low, an increase in energy prices might not lead to a rapid shift toward energy-saving machinery, but that shift might be pronounced if energy prices are already very high. The opposite also is possible. Thus, IGEM goes to great lengths to specify fully the way firms might adjust their mix of inputs.

For the purposes of this experiment, the model can be set to “artificially” restrict the degree to which producers substitute between, for example, energy and capital (or any other resources) by “freezing” the parameter that links the use of these two resources (in economic terms, the cross-elasticity) at a specified value. By comparing the model’s predictions with and without this producer flexibility, one can estimate the importance of producer flexibility in the economy’s response to climate change policy.

A similar process occurs within the model for consumption. Households divide their consumption among five broad classes of goods and services (energy, food, non-durable goods, the capital services arising from housing and consumer durables, and consumer services) based on the relative prices of each — higher prices for energy, for example, lead to less consumption of some types of goods and more of others. Again, the model contains estimates from historical data that describe these relationships (cross-elasticities) in a way that most fully captures the possibilities of shifting spending between goods and services. By “freezing” these parameters at a specific value, the model is capable of showing how the economy would behave if households had more limited “flexibility,” or choice. And by comparing the results with full consumer flexibility to the results with this artificial limitation, one can estimate the importance of consumer flexibility in the economy’s response.

The third type of flexibility is between labor and leisure. While some people often work standard work weeks, many people in the economy regularly make important decisions about how much labor they offer and time they work. They decide whether to seek a job, to retire, to work and go to school, or whether to seek part-time work, overtime work or an additional job. When aggregated, these are far from trivial decisions. By determining how much labor they will offer, people decide how much the economy will be capable of producing and how much income they will have to buy what ends up being produced.

IGEM captures this trade-off by allowing the economy's working-age population to divide their time between work (labor) and other activities (generally called "leisure," although this includes time lost to commuting, illness, and the like). The division depends on prevailing wages and prices of the things wages buy, on the expected values of these wages and prices in the future, and on the interest rate that can be earned by saving (since not all income is immediately consumed). As in the examples above, household substitution between labor and leisure will depend on the starting point: when wages are low, for example, an increase in wages might lead to much more labor being offered, but when they are high, an increase might even lead some people to work less. And, once again, one can examine the role of substitution between labor and leisure by limiting dramatically the model parameters that govern it. Running the model with and without this limitation reveals the role that labor-leisure choice plays in the economy's response to climate change policy.

The progression of this analysis is as follows:

- first, to forecast the economy using IGEM;
- second, to impose a carbon constraint on that forecast;
- third, to forecast the economy again, but each time changing one of the forms of flexibility considered here; and
- last, to impose over each of these new "base-cases" a carbon constraint proportionally identical to the one originally computed.

For each of the three flexibility cases, the modelers introduce a constraint into IGEM simulations and observe the economy's responses under alternative assumptions about the substitution possibilities among producers and consumers.

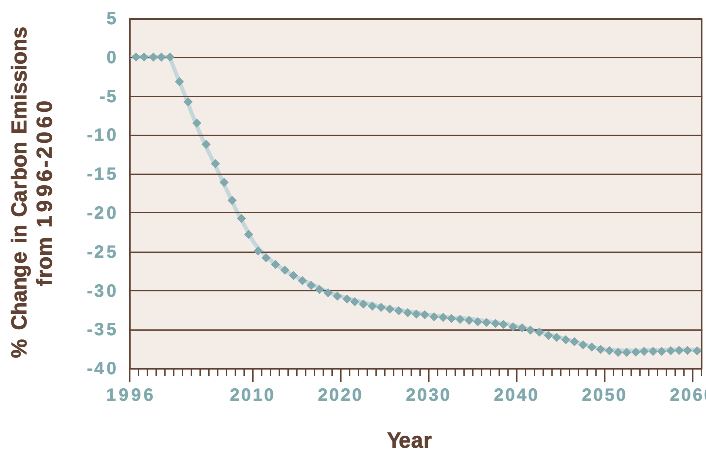
The first step is to perform a simulation of the economy in which all IGEM parameter values remain flexible, i.e., as they were estimated from historical data. This is the base model or full-flexibility simulation. This simulation, as are all others, covers the period 1996-2060. Against this base, climate change policy is represented by imposing a hypothetical constraint that reduces carbon emissions beginning in the year 2000. The constraint returns carbon emissions to the 1990 level of 1,324 million metric tons (mmt) by the year 2010 and holds them at this level through 2060. From 2000 to 2010, emissions decrease rapidly in comparison to the base-case. From 2010 to 2050, emissions continue to decrease in comparison to the base-case, but at a slower rate. By 2050 emissions in both the base and carbon constrained cases have stabilized. The carbon constrained emissions stabilize at 38 percent below the base-case emissions levels. The average reduction is 28 percent over the whole period (1996-2060).

In the model, the carbon constraint is accomplished through a system of tradable emissions permits in which firms achieving excess carbon emissions reductions sell their extra permits to firms unable to meet the current year's emissions constraint. Permits may be traded both within and across economic sectors, but there are no international permit trades or credits.

This carbon emissions constraint is depicted graphically in Figure 1. These are percentage reductions relative to the base-case and are the percentages applied to the emissions levels arising in each of the alternative flexibility cases.

Figure 1

Carbon Emissions Reductions for Base-case Projections



It is important to note that this environmental constraint and the mechanism employed to achieve it are hypothetical and do not represent the specifics of the Kyoto Protocol. The constraint and permit market is domestic only. Energy imports require carbon emissions permits. Energy exports also are affected in that U.S. energy prices reflect the imposition of the constraint on domestic energy production. Permit trading occurs only within the United States between those having permits they are willing to sell and those bidding on permits they are willing to buy. The annual permit price is that which secures the requisite carbon emissions reduction and which "clears" the market, equating permit supply with permit demand. There is no "banking" of permits for future periods as the emissions constraint is assumed to be binding and satisfied in each year.[2] Moreover, the precise mechanism by which the emissions constraint is achieved is not directly observable within the model. This is because the model cannot provide details on trading transactions, whether they occur within sectors, across sectors, or through specific technological substitutions. Thus, one only can infer net buyers and sellers of permits by comparing the final and initial permit distributions across sectors.

All revenues raised in the permit market are assumed to accrue to households, as they are the ultimate owners of the economy's capital stock, either as stockholders or as proprietors. There are no specific financial instruments in IGEM and financial behavior is not differentiated among households, businesses, governments, or the foreign sector. The assumed permit market involves a private auction in which the annual rights to emit carbon are distributed by the U.S. government to emitting firms. Excess or unused permits then are auctioned privately and the resulting revenues are distributed to owner-households in "lump-sum" fashion.[3] (It should be noted that this is equivalent to government ownership, a public auction, and lump-sum recycling.) There are no distributional consequences arising from the permit market because there is no basis within IGEM to distinguish behavioral differences among low-income versus high-income recipients of the permit revenues. The final distribution of carbon emissions and emissions permits in any given year is the same regardless of the initial distribution of permits to various persons, industries, or emissions sources in that year. Thus, the initial distribution of permits, whether it is on the basis of emissions levels, equity considerations (giving the permits to those likely to be most adversely affected), or ownership (private auction versus government auction), has no effect on the simulation results. In reality, it may make a difference to the outcomes whether the permit revenues accrue, for example, to the shareholders of manufacturing firms and electric utilities, or to coal miners. This is because equity considerations may vary across these groups, or each group may behave differently with respect to their choices on labor and leisure, consumption and saving, and the allocation of their consumption expenditures. However, within this modeling framework there is nothing that informs this difference.

After simulating the model with estimated parameters based on historical experience, three alternative model simulations were performed. As discussed above, these reduce the substitution possibilities within the economy, making it more difficult and more expensive to react to the imposed emissions constraint. Again, the alternative sets of parameters involve:

- the ability of firms to substitute away from energy and between different types of energy and, more generally, to substitute the inputs of capital, labor, and materials (or, *reduced producer flexibility);*

- the ability of households to substitute away from energy in its various forms and, more generally, between their purchases of food products, non-durable goods, capital, and services (or, *reduced consumer flexibility*); and

- the ability of households to substitute between consumption and leisure (*reduced consumption-leisure flexibility*).

Changing each of these flexibility behaviors changes the forecast of the model. If, for example, producers have limited flexibility in changing their inputs, then the economy's forecasted behavior from now to 2060 will be different from that forecasted using historical flexibility rates. As discussed above, the degree of flexibility in IGEM depends not only on model parameters but also on prevailing market conditions, either simulated or historical. Using an example discussed earlier, people might substitute leisure for work in a different fashion if their wages are low than they would if their wages were high. This means that the model will compute different substitution possibilities according to market prices and quantities even though the model's equations and parameters do not change.

Each of the three "flexibility" simulations involve two simulations or model "runs." In the first, the model is changed to limit some type of flexibility in the economy, but not to limit emissions. In the second, there is a corresponding run with the same limitations on flexibility, but with an imposed emissions constraint.

Insofar as each of these base-case simulations offers a new view of the growth and structure of the economy, each has a somewhat different time path for carbon emissions. In order to make all of these cases pair-wise comparable, emissions under each of the reduced flexibility alternatives decrease by the same *percentages* as in the full flexibility simulation shown in Figure 1.

The carbon constraint is represented in proportional terms because that is the only way to allow meaningful comparisons across the various flexibility alternatives. Because emissions levels and atmospheric concentrations of carbon dioxide (CO_2) in each of the base-cases will differ, imposing an identical *absolute* constraint across simulations would allow the *relative* stringency of the constraint to differ. If making the economy less flexible leads to lower carbon emissions compared to full flexibility, then imposing identical *absolute* targets across simulations leads to an underestimation of carbon mitigation costs in the inflexible cases, and an underestimation of the benefits of flexibility. By using *proportional* constraints (e.g., identical percentage reductions in emissions), these base-case biases are reduced but probably not eliminated. Given the specific non-linear structure of IGEM, preserving the same relative stringency across cases offers the best measure of the "work" the economy must do, given its circumstances, to secure environmental improvements. Using proportional emissions constraints is an essential step in minimizing the base-case biases and isolating the contributions of flexibility.

It is important to emphasize the absence of any comparisons across the unconstrained simulations themselves. First, the theoretical discipline in economics does not permit value judgments or the ranking of one set of flexibility parameters over another. Second, measuring the impacts of substitution depends only on what happens when an emissions constraint is imposed on each case. Since each unconstrained simulation involves only variations in underlying consumer preferences and/or production technologies, comparisons among them shed no light on the economy's ability to absorb reductions in carbon emissions.

Substitution possibilities are measured in the model by *elasticities,* which portray the relative responsiveness of the demand for a good or service to a proportional change in the price of that or some other good or service. This measurement assumes that all other factors affecting demand are unchanged. For the first two of the flexibility cases (i.e., *reduced producer flexibility* and *reduced consumer flexibility*), price elasticities of approximately zero (at base-case prices) were used. This means that model parameters were set so that demands are nearly perfectly inelastic (i.e., unresponsive to price). In these cases, producers' demands for energy, capital, labor, and aggregate materials do not vary with price changes. For consumers, energy commodity demands are equally insensitive to price, as are the demands for total energy, food products, non-durable goods, capital services (from housing and consumer durable goods), and consumer services. Thus, these replacements of the model's historically estimated parameters mean that inputs to production (or consumer demands) are less sensitive to price changes at all price levels.

For the third category — consumption and leisure — model parameters were reduced to around 10 percent of their estimated values, not zero. At the prices and quantities of the base-case, this still allows some flexibility between consumption and leisure. Substitution was made to be very inelastic, but not perfectly so, because the consumption-leisure decision is so important to the determination of the economy's labor supply and, through saving and investment, to the process of capital formation.

The comparative measures of substitution presented in subsequent sections draw information from five base-case model simulations, each of which then adjust to a proportionally identical constraint on carbon emissions. In addition to using the historically determined flexibility parameter base-case, base-case simulations are developed for each of the three flexibility cases and for a combined case with reduced flexibility in production and in consumption and leisure. Table 1 summarizes this set of analytical starting points.

Table 1

Summary of the Base Model Simulations before Carbon Emissions Constraint

Title	Description
Base-case (full flexibility)	Historically observed rates of flexibility
Reduced consumer flexibility	Base model with price elasticities for consumers set to approximately 0% (at base-case prices)
Reduced producer flexibility	Base model with price elasticities for producers set to approximately 0% (at base-case prices)
Reduced consumption-leisure flexibility	Base model with consumption-leisure price elasticities reduced by approximately 90% (at base-case prices)
Reduced production and consumption-leisure flexibility	Base model with price elasticities for producers set to approximately 0% and consumption-leisure price elasticities reduced by 90% (at base-case prices)

IV. The Energy and Economic Consequences of Reducing Carbon Emissions

This section describes the effects of reducing U.S. carbon emissions to their 1990 level by 2010 and stabilizing them at this level through 2060. The implications of this constraint for energy use are presented in Table 2. This simulation uses the IGEM model parameters as estimated from historical data (i.e., assuming full flexibility).

In the base-case simulation, carbon emissions increase from 1,467 to 1,549 million metric tons (mmt) (about 1.4 percent annually) between 1996 and 2000. They continue to rise, but at a continually decreasing rate through 2050, at which point they stabilize. By 2020 and 2050 (also 2060), base-case carbon emissions are 1,918 and 2,124 mmt, respectively.

The assumed carbon constraint is a phased reduction in carbon emissions beginning in 2000. From 2000 through 2010, allowable emissions decline from 1,549 to 1,324 mmt, the latter being equal to 1990 emissions. Emissions are held at 1,324 mmt from 2010 through 2060. Over the period 1996-2060, emissions are reduced by an average of 28 percent below the base-case, while fossil fuel usage declines by an average of 25 percent.

Table 2

Energy Market Results of a Carbon Emissions Constraint with Full Flexibility

	Average Price, 1996-2060
Carbon Permit Fee ($ per metric ton)	$99.42
Price to users of:	
Coal ($ per short ton)	$53.35
Petroleum ($ per barrel)	$9.07
Natural gas ($ per 10^3 cubic feet)	$1.48
Carbon emissions % change (relative to base-case)	-28%
Fossil-fuel use % change (relative to base-case)	-25%

	2020 Price (% change in prices relative to base-case)	2020 Production (% change in U.S. production relative to base-case)
Coal	129	-52
Petroleum refining	7	-8
Gas utilities	21	-26
Electric utilities	16	-13

Note: All dollar figures are in 1999 U.S. dollars.

The price that equates permit demand with permit supply averages around $100 per metric ton (mt) of carbon for the period 1996-2060, roughly equal to about 22 cents per gallon of refined petroleum product. (All dollars reported here are 1999 U.S. dollars.) The emissions constraint has a significant impact on energy markets. Permit fees raise consumer prices on the primary energy inputs of coal, oil, and gas from both domestic and imported sources, and higher prices for energy inputs lead to price increases for all energy and non-energy goods and services and for the price of capital. Reduced domestic oil consumption, however, reduces marginal production costs, which offsets some of the increase in domestic oil prices (simply put, there is a supply curve effect for domestic oil and gas extraction within IGEM).[4] By the year 2020 and compared to the base-case, coal prices are 129 percent higher, and petroleum, gas, and electric utility prices 7, 21, and 16 percent higher, respectively.

The patterns of energy demand and supply respond as expected to price changes. For the economy in 2020 as a whole, domestic coal production decreases by 52 percent, refinery output is down by 8 percent, and gas and electric utility outputs decline by 26 and 13 percent, respectively. On balance, coal and gas use are affected proportionally more than oil use. This follows from the observed consequences for their prices. As oil prices are least affected due to lower production costs (that follow from lower domestic oil production), oil demand and supply reductions are proportionally the smallest. This is counterintuitive in light of the high energy-carbon ratio for natural gas as compared to oil and coal. It arises because of the aforementioned oil supply curve effect and because of the historical patterns of oil and gas use within their respective model sectors (i.e., oil use being too little and gas use being too much). In the relative sense, petroleum and gas behavior is consistent in these simulations, but in the absolute sense, oil reductions most likely are underestimated while gas reductions are overestimated.

Table 3

Macroeconomic Consequences of a Carbon Emissions Constraint with Full Flexibility

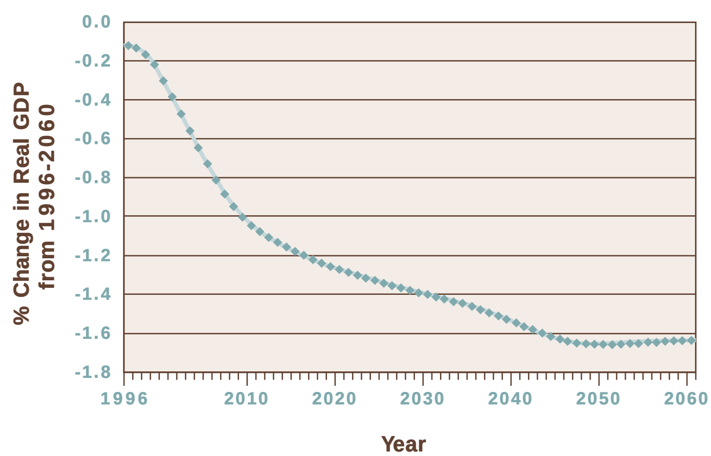
	Average % change, 1996-2060
Household Welfare	-0.12
Real GDP	-1.25
Consumption	-0.86
Investment	-1.88
Government Purchases	0.03
Exports	-3.00
Imports	-0.50
Capital Stock	-1.36
Labor Supply (and Demand)	-0.78
Leisure Demand	0.21
Price of Consumption*	1.29
Price of Investment*	0.79

*Prices based on Bureau of Economic Analysis (BEA) data.

The macroeconomic results for this analysis are summarized in Table 3. When compared to the base-case, real GDP is, on average, 1.25 percent lower over the period 1996-2060. There are three important time intervals that characterize this decline. These are depicted in Figure 2.

Figure 2

Impacts on Real GDP Assuming Full Flexibility



In the first interval, from 1996 to 2000, GDP declines somewhat in comparison to the base-case. Because the model assumes perfect foresight, economic actors foresee the future imposition of carbon constraints and begin taking carbon-reducing actions in 1996. The emissions targets are imposed in 2000. From 2001 through 2010, the emissions constraint binds increasingly tightly as base-case emissions rise and ever larger emissions reductions are required. However, from 2010 to 2050, the 1990-level emissions constraint binds at a decreasing rate, since projected emissions rise more slowly in the base-case simulation, consequently GDP declines more slowly relative to the base-case. From 2050 on there is no further decline in GDP relative to the base-case.

From a comprehensive welfare perspective, one that includes the consumption of not only goods and services but also leisure (but one that ignores changes in the distribution of income), constraining carbon emissions to their 1990 level imposes a burden of 0.12 percent on households. This means that households lose an equivalent of just over one-tenth of one percent of the value of their lifetime expenditure on goods, services, and leisure as a result of higher energy prices and restricted energy use owing to the carbon constraint. This is a smaller loss than the reduction in GDP because it includes the offsetting value of added leisure.

Real GDP declines because of reductions in all three of its private components: consumption, investment, and net exports. But, as shown later, the manner in which any revenues resulting from the sale of carbon permits are returned to households is pivotal in determining this outcome.

The IGEM model estimates the reduction in real GDP by balancing several sometimes conflicting effects. Higher energy prices lead to higher prices for all goods and services. If everything else were unchanged, households would substitute away from consumption (which has become more expensive) and toward leisure (which is now relatively less expensive). This is the *substitution effect* on leisure. But everything else is not unchanged. On the one hand, households receive permit revenues via lump-sum rebates that restore some of their income. Receiving these permit revenues does not affect the relative price of work and leisure but rather reinforces the substitution effect on leisure by adding to income. This leads households, on average, to increase their demand for leisure. At the same time, real (inflation-corrected) household income is permanently reduced by higher prices for the goods and services households consume. This is called the *income effect* on leisure, and it leads to reductions in *full* consumption (comprising goods, services, and leisure); by reducing people's incomes, it leads them to demand less leisure and supply more labor. Also, since future price increases are larger than those in the nearer term, there is some substitution of present for future full consumption, which amplifies this income effect in future periods.

On balance, real consumption declines while leisure demand increases. Higher prices for goods and services, even with the added permit revenues, lead people to offer less labor to the economy (since the effective buying power of their wages is now lower). Since there is a reduction in the real wage, workers respond by supplying less labor and demanding more leisure. In essence, the real (inflation-adjusted) returns on labor services are lower. As labor income declines and as consumer spending rises (higher prices more than offset lower quantities), private saving declines. This adversely affects investment and capital availability. When all these effects are taken into account, there is less labor and capital available to the economy, and slower productivity growth due to higher prices and inflation. In combination, all of this reduces national output and income, or GDP. The household sector is worse off in that the costs of foregone consumption are offset only partially by the benefits of more leisure.

In this simulation, the level and structure of government purchases and net tax receipts are constrained by assumption to be those of the base-case. This ensures fiscal neutrality or the absence of any government influence on private investment (so-called "crowding out"). It has the added feature of rendering government completely inflexible in its response to the emissions constraint. This is because the level and composition of purchases are not allowed to change.

All the model simulations here assume that the emissions constraint only applies to the United States. Thus, exports fall because higher energy prices lead to higher prices for domestic goods and services relative to the rest of the world, and U.S. goods and services become less competitive in world markets.

Foreign demand for U.S. exports responds more than proportionally. United States spending on imports declines as energy imports decline, as U.S. national income falls, and as the substitution toward lower-priced imports occurs. In IGEM, exchange rate adjustments restore the trade balance to that of the base-case, again ensuring neutrality and avoiding the crowding-out of private investment. Thus, the dollar strengthens as the reduction in U.S. spending on imports exceeds the decrease in foreign purchases of U.S. exports. All told, the reductions in consumption, investment, and net exports (exports minus imports) account for the reduction in real GDP.

Table 4 shows the changes in industry prices and domestic output for the year 2020. Though differing in magnitude in each year of the simulation, the structural pattern of impacts on the industrial sectors are qualitatively identical for other years. Clearly, some industries are affected more than others, although only the energy and energy-intensive industry changes are larger than 2 percent. As seen earlier, finished energy products — coal, petroleum refining, electricity, and gas — experience the largest price increases and quantity reductions. The energy-intensive industries — the extractive sectors, chemicals and plastics, stone, clay and glass, and primary metals — are the next most affected as energy is a more significant portion of their costs. In addition, these sectors are important to the capital goods industries such as machinery, motor vehicles, and instruments, all of which contract due to reductions in investment spending. The impacts on investment also affect construction, the lumber and furniture sectors, and electrical equipment; but to lesser degrees as they face smaller price increases. The agriculture and food sectors actually benefit under the emissions constraint as consumers substitute food products for other manufactured goods. Finally and not surprisingly, communications, trade, finance, and the services industries either benefit from or remain unaffected by either the large-scale energy changes or the related restructuring of the economy.

It is important to note that intuitive findings about the structure of the economy may or may not be borne out in these results. Intuitively, one would expect households to increase their purchases of clothing as a substitute for using energy to keep warm or cool. However, for these industries as a whole, such substitution does not occur. Textile production is a comparatively energy-intensive sector. When energy prices rise, its costs rise and so too its output price. Import substitution does occur but is not sufficient to offset overall price increases. As textile prices rise, apparel prices follow and consumers substitute away from these commodities as well. It is possible and indeed likely that within apparel purchases (as within furniture and appliance purchases), consumers are making decisions based on prevailing climate and energy market conditions. However, these details cannot be determined within IGEM; instead, higher prices, lower production, and reduced demand are observed. On the other hand, other intuitions are supported. One would expect communications to substitute for transportation equipment and travel as energy prices rise, and this is precisely what occurs, although perhaps not to the degree expected. Motor vehicles, other transportation equipment, and transportation services all decline while telecommunications services increase in relative importance. Together, these patterns all arise in line with the economy's substitution possibilities and as direct and indirect consequences of the energy price increases that are necessary to achieve emissions reduction.

Table 4

Industrial Market Consequences in 2020 of a Carbon Emissions Constraint

Industry description	Price (% change)*	Domestic Production (% change)*
Agriculture, forestry, and fisheries	1.2	1.7
Metal mining	2.3	-3.7
Coal mining	128.7	-52.1
Crude petroleum, natural gas extraction	-6.1	-4.5
Non-metallic mineral mining	2.6	-2.9
Construction	1.1	-1.3
Food and kindred products	1.2	3.0
Tobacco manufactures	1.2	2.1
Textile mill products	2.1	-2.2
Apparel and other textile products	0.5	-1.8
Lumber and wood products	0.9	-1.2
Furniture and fixtures	0.9	-1.4
Paper and allied products	2.2	-1.9
Printing and publishing	1.0	-0.2
Chemicals and allied products	2.0	-2.8
Petroleum refining	7.3	-7.5
Rubber and plastic products	1.9	-2.6
Leather and leather products	0.0	-2.1
Stone, clay, and glass products	2.6	-3.8
Primary metals	2.4	-4.5
Fabricated metal products	1.2	-1.4
Non-electrical machinery	0.8	-2.4
Electrical machinery	0.5	-1.7
Motor vehicles	0.5	-2.0
Other transportation equipment	0.8	-1.7
Instruments	0.8	-2.0
Miscellaneous manufacturing	0.3	-1.7
Transportation and warehousing	1.2	-1.1
Communications	0.7	0.1
Electric utilities (services)	16.4	-12.8
Gas utilities (services)	21.4	-25.6
Wholesale and retail trade	1.0	-0.3
Finance, insurance, and real estate	0.7	0.2
Other personal and business services	0.9	0.2
Government enterprises	1.9	-1.0

*% change in price and domestic production relative to the base-case

V. Reducing Carbon Emissions When Substitution Is Less Flexible

Having examined the effects of a carbon constraint in the absence of any restrictions on economic flexibility, this section reports on simulations in which the model parameters are changed so as to reduce the magnitudes of key elasticities in consumption and production.

Table 5 provides a summary of the major results for the permit and energy markets with reduced flexibility. In each simulation, the carbon emissions are reduced by an average of 28 percent, and fossil fuel use is reduced by 25 percent, relative to the corresponding base-case. When consumption is made inflexible but production remains flexible, the average permit price for carbon rises from $100 to $135 per metric ton and energy prices and demand and supply patterns are qualitatively similar to those reported in Section IV. However, when production flexibility is limited and consumption remains flexible, the average permit price increases dramatically to $394 per metric ton. In this case, substitution possibilities within the economy are severely limited and energy prices must rise significantly to achieve the annual emissions targets. Coal price increases approach 500 percent while gas and electricity price increases are around

Table 5

Energy Market Consequences of a Carbon Emissions Constraint with Varying Flexibility

	Base-case full flexibility	Reduced consumer flexibility	Reduced producer flexibility
	Averages for 1996-2060		
Carbon Permit Fee ($ per metric ton)	$99.42	$135.28	$393.80
Price burden on users of:			
Coal ($ per short ton)	$53.35	$72.59	$211.31
Petroleum ($ per barrel)	$9.07	$12.34	$35.91
Natural Gas ($ per 103 cubic feet)	$1.48	$2.02	$5.87
	2020 Price (% change relative to corresponding base-case)		
Coal	129%	164%	502%
Petroleum refining	7%	5%	2%
Gas utilities	21%	21%	57%
Electric utilities	16%	19%	45%
	2020 U.S. Production (% change relative to corresponding base-case)		
Coal	-52%	-53%	-49%
Petroleum refining	-8%	-6%	-10%
Gas utilities	-26%	-26%	-16%
Electric utilities	-13%	-10%	-22%

Note: All dollar figures are in 1999 U.S. dollars.

60 and 45 percent, respectively. The patterns of coal and oil use are quantitatively comparable to the simulations in which production is more flexible, but it takes larger price increases to produce the same result. On the other hand, there are comparatively smaller reductions in natural gas use and comparatively larger reductions in electricity use. This occurs because the increased rigidity in production leads to greater changes in the composition of demand, which changes the required inputs into production.

The impacts on real GDP appear graphically in Figure 3, which depicts GDP changes over time, and Figure 4, which shows the average annual change.

As noted in the previous section, even with flexibility, the imposition of an emissions constraint imposes an economic cost. There is more leisure demand, less labor supply, less saving, less investment, and less capital (see Table 6). Household welfare is lower because lower consumption more than offsets greater leisure. With less flexibility in consumption or production, these results and the details of adjustment are amplified. Less elastic responses mean that permit prices need to be higher to satisfy proportionally identical emissions constraints. Hence, the costs are greater in terms of foregone income and production.

Figure 3

Impacts on Real GDP from Reduced Producer and Consumer Flexibility

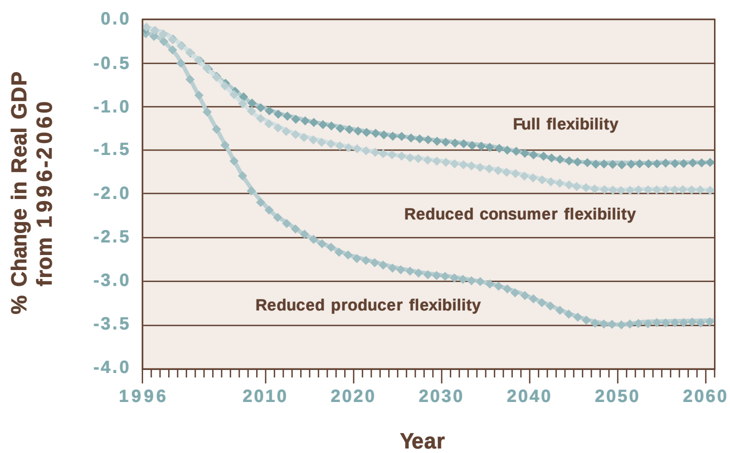


Figure 4

Average Real GDP Impacts from Reduced Producer and Consumer Flexibility

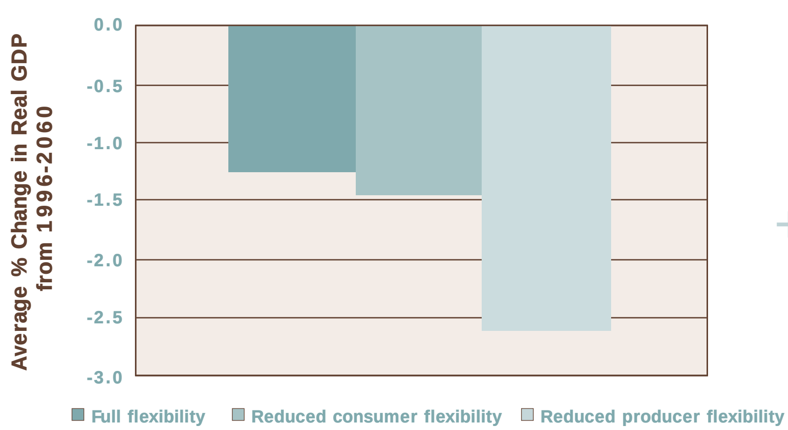


Table 6

Macroeconomic Impacts of a Carbon Emissions Constraint with Varying Flexibility in Consumption and Production (Average percent change, 1996-2060)

	Base-case full flexibility	Reduced consumer flexibility	Reduced producer flexibility
Household Welfare	-0.12	-0.11	-0.15
Real GDP	-1.25	-1.46	-2.61
Consumption	-0.86	-1.24	-1.63
Investment	-1.88	-0.47	-3.65
Government Purchases	0.03	0.11	0.67
Exports	-3.00	-5.05	-9.19
Imports	-0.50	-1.00	-1.81
Capital Stock	-1.36	-0.41	-2.59
Labor Supply (and Demand)	-0.78	-1.88	-1.89
Leisure Demand	0.21	0.42	0.50
Price of Consumption	1.29	2.03	2.56
Price of Investment	0.79	0.52	1.72

Limiting the substitution possibilities within consumption leads to only slightly higher costs in adjusting to the new emissions requirements. With flexibility, the burden of adjustment falls proportionally more on capital goods and export producers than it does on consumers and the suppliers of consumption goods (see Tables 6 and 7). With rigidity in consumption, export markets are even more adversely affected as higher permit prices lead to higher energy prices, which further erode U.S. competitiveness abroad. However, inflexibility within consumption alters the observed impacts on consumption and investment. Here, the burden of adjustment falls more heavily on consumers as their options for substitutability are narrowed; the resulting higher prices lower their real incomes even more than occurs under full flexibility. This disproportionately erodes the returns to work and leads to disproportionate declines in labor supply. Investment and capital availability, while adversely affected, account for a much smaller portion of the overall economic adjustment. When substitutions within consumption are limited, the economy becomes less labor-intensive and more capital-intensive under the emissions constraint; this is the exact opposite of what is observed with the model when full flexibility is assumed. This rigidity also accounts for the slightly lower impact on household welfare. In both cases, welfare declines because consumers give up more in goods and services than they gain in additional leisure. With flexibility in consumption, household welfare declines by 0.12 percent in terms of foregone goods, services, and leisure over a household's lifetime. With rigidity in consumption, this loss is 0.11 percent, which is a small but measurable improvement. This improvement occurs because the ensuing higher prices lead more households to substitute leisure for consumption. The household choices that follow leave the net welfare loss ever so slightly smaller.[5]

Constraining substitutability within production as opposed to consumption has a huge impact on the response to carbon emissions mitigation (see Table 6). Here, the adverse impacts on real GDP and many of its components are more than doubled and households experience an even greater welfare loss. This is not surprising since the average permit price necessary to achieve the emissions constraint rises by a factor of nearly four. Reaching these emission targets, absent the full range of production flexibility, ultimately is accomplished through a combination of very expensive, but limited, input substitutions and significant reductions in domestic non-agricultural outputs. That is, since producers of relatively energy-intensive products such as capital goods and other durable goods cannot adopt better ways of making these products (see Appendix C), the only way to reach emissions targets is for prices to rise so high that they discourage the production of them. This tendency works against investment and exports, which again account for proportionally more of the overall adjustment, while consumption contributes proportionally less.

Table 7

Economic Sectors Most Affected from Varying Consumer and Producer Flexibility

	Base-case full flexibility	Reduced consumer flexibility	Reduced producer flexibility
Capital Goods	x		x
Export Producers	x	x	x
Consumer Goods		x	
Labor Market		x	

When only producer flexibility is limited, the capital intensity of the economy changes very little while its labor intensity increases. As discussed in Section III, higher energy prices and the redistribution of permit revenues encourage more leisure demand. Higher consumer prices lead to reduced consumption, but full consumer flexibility allows consumers to manage this burden (as in the full flexibility case). As a result, the decline in labor supply is proportionally less. Saving declines, and with it, investment, as higher consumer spending claims available income. All told, the resulting decline in the capital stock is commensurate with the decline in real GDP. Qualitatively, the patterns of adjustment in factor and industry composition that take place under rigid production are nearly identical to those arising under full flexibility. The differences are matters of scale. They are not matters of differing incentives as occurred when only consumption was made less flexible, which disproportionately disfavored consumption and favored investment.

These two simulations give rise to one of the central conclusions of this analysis. *When subjecting the economy to far-reaching and substantial changes, the more flexible consumption and production are, the smaller are the resulting losses to income and spending.* In mitigating carbon emissions, rigidity in consumption increases the magnitudes of GDP loss by 17 percent while rigidity in production more than doubles these losses. Clearly, inflexibility, taken to mean the narrowing of the economy's substitution possibilities, makes matters worse and, sometimes, much worse. The good news here is that the rigidities just analyzed represent departures from the observed behavior of consumers and producers over the last 50 years. Thus, it is virtually assured that the economy is a good deal more resilient to dramatic change than is generally acknowledged. Moreover, this resourcefulness is evident in both the short and long runs. It cannot be ignored when considering the challenges inherent in climate change policies. Thus, models that fail to capture the full range of flexibility in production and consumption in the economy risk overstating the adjustment costs imposed on the economy by a policy that relies on those adjustments as much as climate change does.

VI. The Consumption-Leisure Choice: A Dominating Influence

Many economic models currently employed in climate change policy analysis are based on maximizing household welfare as the driving force underlying economic activity over time. In IGEM (and, for example, Goulder [1994]) household welfare depends on "full consumption," which comprises goods, services, and leisure. Welfare is specified in a manner that allows the substitution of goods and services for leisure (and vice versa). An equally common specification is a narrower household welfare measure that depends only on the consumption of goods and services (for example, Nordhaus [1994]).

In such models, the behavioral parameters in these consumption "functions" are of overwhelming importance to the economic outcomes portrayed in any given simulation. This is not surprising in that these choices govern the overall availability of labor and capital in the economy. With a fixed amount of time available to allocate between work and leisure, the choice concerning leisure demand simultaneously determines labor supply and employment income. From a given income, the choice of how much to consume determines the saving available to finance investment and add to the capital stock. Since labor, capital, and productivity are the determinants of supply (or so-called potential output), decisions affecting them ultimately establish the size of the economy. This presumes that in the long-run, markets clear and there is no "unemployment" or "excess capacity." It also presumes that the work-leisure choice is unconstrained by other time demands, such as illness or commuting.

This section examines the role of the consumption-leisure choice in the economy's response to imposed carbon emission reductions. To accomplish this, two additional simulations were performed. In the first of these, rigidity in the consumption-leisure choice was introduced with all other parameters for consumption and production remaining as estimated from historical data. In the second, rigidity in consumption-leisure was accompanied by inflexibility within production. The key comparisons of the results are presented in Table 8 and Figures 5 and 6.

Table 8

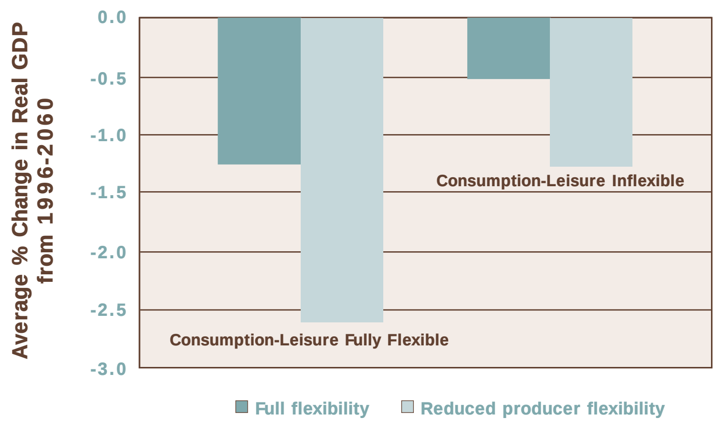
The Economic Impacts from Reduced Consumption-Leisure Flexibility
(Average percent change (except permit fee), 1996-2060)

	Base-case full flexibility	Reduced producer flexibility	Reduced consumption-leisure flexibility	Reduced consumption-leisure and producer flexibility
Permit Fee (1999 U.S. $ per metric ton)	$99.42	$393.80	$101.81	$411.48
Household welfare	-0.12%	-0.15%	-0.04%	-0.01%
Real GDP	-1.25%	-2.61%	-0.52%	-1.27%
Consumption	-0.86%	-1.63%	-0.13%	-0.21%
Investment	-1.88%	-3.65%	-0.94%	-1.90%
Capital Stock	-1.36%	-2.59%	-0.69%	-1.35%
Labor Supply (and Demand)	-0.78%	-1.89%	0.05%	-0.27%
Leisure Demand	0.21%	0.50%	-0.01%	0.07%
Price: Consumption	1.29%	2.56%	1.50%	3.16%
Price: Investment	0.79%	1.72%	0.98%	2.29%

As the demands for consumption and leisure become increasingly inflexible, the economy becomes far less responsive to the imposition of carbon emissions constraints, even though the carbon permit prices required to achieve them are slightly higher. Inflexibility in the consumption-leisure tradeoff reduces the real GDP losses by more than half under both sets of assumptions concerning flexibility within production. With consumption and leisure less responsive, the labor-leisure changes are less dramatic. There is a uniformly smaller impact on saving and investment and, hence, on capital availability. Household welfare also is much less affected by the emissions constraints. This is not surprising in that welfare depends on consumption and leisure, which are now less substitutable for one another and respond less to the price effects arising from the emissions constraint.[6]

Figure 5

Real GDP Effects

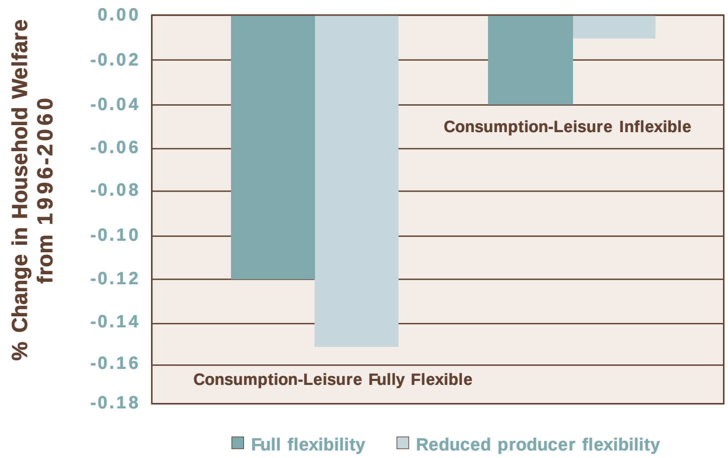


The results from the simulations have important implications for the modeling and analysis of climate change. As seen before, when all of production is made less flexible, the real GDP losses of imposed emissions reductions are twice as great as GDP losses under historical flexibility. However, when consumption and leisure are made less flexible, the real GDP losses are half as great compared to losses under historical flexibility. This means that this single substitution parameter has as much to do with the outcomes of environmental policy as do the combined parameters relating to input substitutions within the 35 sectors of production. It also means that differences among models' substitutability between consumption and leisure are likely to be every bit as important in predicting permit prices and economic outcomes as are their underlying details of technology, consumption, or production. This is well understood by economists, but not widely appreciated by policy-makers.

Figure 6

Percentage Change in Household Welfare

from Reducing Consumption-Leisure and Producer Flexibility



VII. The Economic Impact of Revenue Recycling

Carbon taxes and permit fees can generate substantial revenues from any meaningful carbon emissions reductions. Thus, analysts must make assumptions regarding the disposition of these revenues. Economists long have known that taxes, like all prices, provide incentives to do some things and not others. In short, taxes influence or "distort" behavior. As examples, income taxes reduce incentives for work, saving, and investment; sales taxes on clothing but not on food bias purchasing decisions; and taxes on gasoline, cigarettes, and alcoholic beverages discourage their use. Clearly, there are economic consequences associated with the level and structure of the nation's tax codes. Equally clearly, there are possible economic benefits from using the revenues raised under various climate change mitigation schemes to reduce the burdens of other non-environmental taxes. Model analyses indicate that there are better and worse ways to distribute any proceeds from climate change policies. (See, for example, Goulder [1994], Jorgenson *et al.* [1995, 1998], Nordhaus [1994], Norland and Ninassi [1998], and Repetto and Austin [1997].)

In the preceding analyses, the operational assumption is that permit revenues accrue to shareholders and business owners. In IGEM, these are households, the ultimate owners of the nation's private stock of capital goods. This assumption is equivalent to distributing permit revenues from either private or public auctions in a lump-sum fashion. Lump-sum distributions are those in which the transfers are independent of taxpayer behavior. For example, the personal exemptions in income taxes are lump-sum transfers. As reported in Goulder (1994) and Jorgenson *et al.* (1995, 1998), and in Repetto and Austin (1997), lump-sum distributions are among the least attractive mechanisms available for re-introducing carbon tax or permit revenues into the economy. This is because the permit price or carbon tax "distorts" or affects economic behavior by favoring certain activities over others. In other words, the carbon tax, while revenue-neutral, reduces national income and wealth through its impacts on labor and capital availability and on productivity. Since lump-sum distributions are "neutral" — i.e., they do not affect behavior — they cannot counteract this distortion. This section considers an alternative permit ownership and revenue-recycling scheme that redistributes the tax revenue by correcting pre-existing tax distortions in other parts of the economy.

In this alternative scheme, permits are publicly rather than privately owned. The U.S. government auctions them and the revenues are used to reduce the marginal tax rates on that portion of household income arising from work. It must be emphasized that it is the recycling scheme — lump sum versus reduced tax rate — and not the ownership assumption that drives these results. The timing and magnitudes of emissions reductions are proportionally identical to those considered earlier; only the recycling plan is altered. To determine the impact of this change, four of the previous simulations are revisited. These are the experiments with the model based on observed experience, with inflexibility in production, with inflexibility in consumption and leisure, and with inflexibility in consumption-leisure and in production. Table 9 reports key results from these new simulations. Figure 7 shows the impacts on real GDP. Both the table and the figure display the corresponding results from previous sections.

Table 9

The Effects of Lowering Marginal Tax Rates
(Average percent change (except permit fee), 1996-2060)

Results from Lump-Sum Distributions	**Base-case full flexibility**	**Reduced producer flexibility**	**Reduced consumption-leisure flexibility**	**Reduced consumption-leisure and producer flexibility**
Permit Fee (1999 U.S. $ per mt)	$99.42	$393.80	$101.81	$411.48
Household Welfare	-0.12%	-0.15%	-0.04%	-0.01%
Real GDP	-1.25%	-2.61%	-0.52%	-1.27%
Consumption	-0.86%	-1.63%	-0.13%	-0.21%
Investment	-1.88%	-3.65%	-0.94%	-1.90%
Capital Stock	-1.36%	-2.59%	-0.69%	-1.35%
Labor Supply (and Demand)	-0.78%	-1.89%	0.05%	-0.27%
Leisure Demand	0.21%	0.50%	-0.01%	0.07%
Price: Consumption	1.29%	2.56%	1.50%	3.16%
Price: Investment	0.79%	1.72%	0.98%	2.29%
Results from Lowering Marginal Tax Rates	**Base-case full flexibility**	**Reduced producer flexibility**	**Reduced consumption-leisure flexibility**	**Reduced consumption-leisure and producer flexibility**
Permit Fee (1999 U.S. $ per mt)	$101.80	$422.68	$98.79	$374.05
Household Welfare	0.11%	0.49%	-0.04%	-0.04%
Real GDP	1.22%	5.92%	-0.27%	-0.45%
Consumption	1.45%	5.81%	0.03%	0.27%
Investment	1.19%	6.64%	-0.61%	-0.54%
Capital Stock	0.94%	5.31%	-0.42%	-0.51%
Labor Supply (and Demand)	2.00%	8.26%	0.31%	0.68%
Leisure Demand	-0.53%	-2.18%	-0.08%	-0.17%
Price: Consumption	-2.39%	-9.68%	-1.53%	-5.99%
Price: Investment	-2.79%	-10.09%	-1.95%	-6.50%

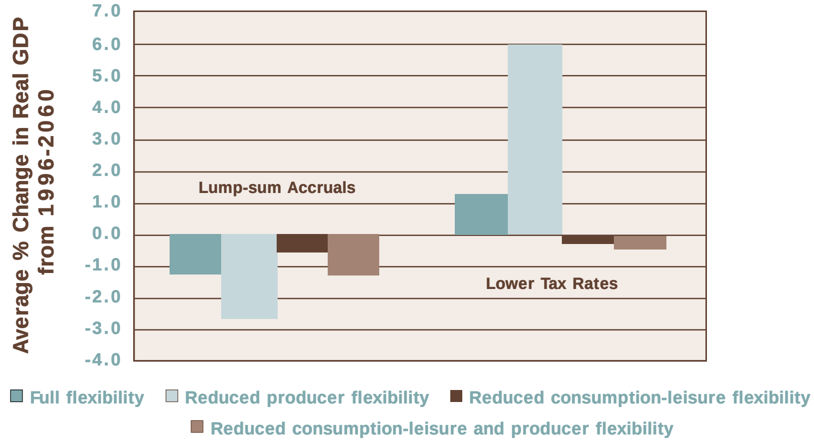
The most striking difference here is that the economy performs measurably better when the permit revenues are used to reduce marginal tax rates on labor income. (Other recycling schemes involving taxes on capital income also prove more favorable than lump-sum redistributions. See Jorgenson *et al.*, [1995, 1998].) On a case-by-case basis, incomes and production are higher when tax rates are lowered.

When revenues from a carbon tax are used to reduce tax rates, the distorting influence on energy prices replaces an even greater distorting influence both on the price of labor to producers, and on the income from work for consumers. Under these simulations, the emissions constraint still raises energy prices to producers and consumers and permit revenues again are returned to households as in the earlier simulations, but now they are returned in the form of tax rate reductions that alter the relative price of labor. Since a significant fraction of total household income arises from work, this plan increases the "opportunity cost" of choosing more leisure. Households substitute toward consumption and away from leisure. Equivalently, households offer additional labor services at a reduced *before-tax* rate of compensation. Gross compensation per employee need not be as high because tax rates now are lower. Producers absorb this additional, now lower-cost labor, by restructuring inputs toward labor. Unit production costs and non-energy commodity prices fall as the pre-tax wage paid by producers falls (relative to the simulation with no tax rate reduction).

Figure 7

Average Real GDP Impacts

with Reduced Flexibility and Revenue Recycling



This recycling scheme favors work and consumption because of lower costs and lower commodity prices, and because of the substitution away from leisure. However, saving and investment also are favored. Saving is higher because the stimulus to income from a greater labor supply is greater than the stimulus to consumption due to lower prices. Investment is higher because of more saving and because the decline in commodity prices permits more capital goods to be purchased from each dollar of saving. Additional investment adds to capital availability so that the economy now has more labor and capital. Nevertheless, the capital-labor ratio declines due to increased labor. Households are better off as the costs of foregone leisure are more than offset by the benefits of higher consumption. On the basis of real GDP, income, consumption, and welfare, actions under this plan are favorable to the economy compared to the lump-sum distribution. Using revenues from a carbon tax to reduce taxes on income from work substitutes a less-distorting scheme (permit fees) for a substantially more-distorting one (taxes on labor income). The lump-sum distribution, on the other hand, does nothing to offset the distorting effect of the permit fees because it directly affects income and not prices.

With full flexibility, using the permit revenues to reduce tax rates secures an economic benefit to GDP and household welfare that is approximately equal and opposite to the costs that arise under lump-sum accruals. This is the so-called “double dividend” or “win-win” condition for the environment and the economy. The possibility of a double dividend is controversial in both theoretical and applied research (See Box 1). In theory, a double dividend can occur only if there are sufficiently large tax distortions prior to the introduction of the permit system, and only if the introduction of the permit system combined with revenue recycling significantly reduces these distortions. Hence, its existence becomes an empirical issue and, as discussed below, is very sensitive to the economy’s underlying substitution possibilities.

Paradoxically, when production is made less flexible, the beneficial effects associated with tax rate reductions increase by a factor of five. As indicated earlier, less substitutability among inputs to production means that permit prices must be substantially higher to satisfy proportionally identical emissions constraints. Accordingly, the economic costs of mitigation become larger under lump-sum transfers while the economic benefits become significantly larger with lower marginal tax rates. Inflexibility makes a “bad” situation much worse and a “good” situation much, much better.

As discussed in Section VI, substitutability between consumption and leisure again is of great importance to the results. As this substitution becomes increasingly inflexible, the economy becomes far less responsive to the emissions constraints irrespective of the recycling mechanism. Under lump-sum redistributions, inflexibility in consumption-leisure reduces GDP losses by more than half, from -1.25 percent to -0.52 percent. When producer flexibility also is reduced, inflexibility in consumption-leisure reduces GDP losses from -2.61 percent to -1.27 percent. These findings appear on the left half of Figure 7 and in Table 9.

Although inflexibility in consumption-leisure lessens the impact of the carbon constraint when revenues are distributed through lump-sum payments, this inflexibility is detrimental when permit revenues are used to reduce tax rates on income from work. The emissions constraints unambiguously give rise to economic damages and, again, these damages double when accompanied by inflexibility within production. These results appear on the right half of Figure 7 and in Table 9. The GDP reductions are about one-fifth the magnitude of those occurring under lump-sum redistributions and full flexibility, but they are losses nevertheless. With consumption and leisure less responsive, the substitutions that give rise to the "double dividend" are limited and the economic benefits never materialize. *This strongly suggests that a "win-win" for the environment and the economy depends as much on the economy's substitution possibilities for consumption and leisure as it does on pre-existing, large tax distortions.*

Box 1

The "Double Dividend"

The term "double dividend" refers to the idea that environmental taxes (or, equivalently, auctioned permits) can simultaneously improve both the tax system and environmental quality. To achieve a double dividend, a revenue-neutral environmental tax must reduce some pre-existing distortion associated with an existing tax in a way that more than offsets the efficiency costs associated with the environmental tax itself.

The potential for a double dividend has enormous implications for environmental policies. The extent to which it exists provides a rationale for the use of so-called "green" taxes (even apart from the environmental benefits) and strengthens the case for using price-based polices to achieve environmental goals. Literature on this topic has tended to raise doubts as to how often the double dividend can occur. However, this analysis shows the double dividend can occur more frequently than expected, and raises important questions for future research.

For any environmental tax, there are three key determinants of the existence of a double dividend: the coverage, the method of revenue recycling, and the tax-interaction.

1. Coverage: It is a general principle of taxation that the narrower the tax base (i.e., what is being taxed — labor, capital, or pollution), the less efficient and more distorting the tax is in raising a given amount of revenue. Energy and environmental taxes fall on a relatively narrow range of activities and therefore lead to relatively high economic efficiency losses. To achieve a double dividend, an environmental tax must yield large enough benefits to more than offset the efficiency cost arising from the policy's narrower base.

2. Method of revenue recycling: Environmental tax revenues may be used either to reduce pre-existing distortions, or to redistribute the revenues to households in lump-sum fashion. Welfare gains arise from reducing pre-existing distortions. A strong "recycling effect" exists when the new environmental taxes are less distortionary than the ones they displace. The size of this effect depends on how revenue collected from an environmental tax is recycled back into the economy. Recycling via reductions in personal income taxes or taxes on capital or labor may produce a double dividend since these taxes produce an efficiency cost on the economy. In addition, there is evidence that reducing taxes on capital is preferred to reducing taxes on labor; that is, the welfare costs of capital taxes are higher than those of labor taxes so capital's recycling effect is stronger than labor's (Jorgenson and Yun [1991]).

3. Tax interaction: It is this third determinant, tax interaction, that drives doubts about the existence of a double dividend. Tax-interaction means that markets do not work independently — higher environmental taxes lead to higher production costs, higher product prices, and reduced real returns to work (and saving). Until recently, much of the literature supported the conclusion that, for environmental taxes, the welfare *costs* due to the combination of the narrow tax base and tax interaction exceed the *benefits*

Box 1 continued

of revenue recycling. Those who are pessimistic about the double dividend have focused on this "tax-interaction effect." However, these interactions come into play when personal income taxes are *reduced* as well — i.e., producers do not need to pay as high a wage to attract labor.

Results from the IGEM model depart from the literature by using a full, instead of partial, accounting of the tax-interaction effect. When environmental taxes are imposed and the revenues are recycled in lump sum, IGEM has similar results to most models. The adverse effects of higher production costs and product prices augment the welfare costs of the taxes. Since lump-sum redistributions do not alter the formation and evolution of IGEM's price incentives, there are only welfare costs as the new distorting taxes displace a non-distorting one. There is no recycling effect to counter the tax-interaction effect. However, when revenues are recycled through reducing the marginal tax rate on labor income, two tax-interactions should be considered — one with and one without the effects of lower labor taxes. Lowering the marginal tax rate on labor income stimulates labor demand by reducing the pre-tax compensation paid by producers. With energy costs now higher and labor costs now lower, labor substitution leads to *lower* overall production costs and product prices, not higher as predicted in other models. These price reductions affect consumer and investment goods alike so that capital also becomes relatively less expensive. Lower-cost capital substitution further amplifies the beneficial price effects and the strong double dividend emerges. Labor supply and the capital stock increase because price reductions now make the real returns to work and saving higher, not lower.

IGEM pays close attention to how households supply labor. The more elastic the supply of labor, the more likely is the double dividend because of the greater benefits arising from the lower prices associated with lower labor taxes. With a more elastic labor supply and less elastic energy demands, the double dividend is amplified because it takes higher taxes to achieve the same proportional carbon reductions, and these higher revenues then are used to even further reduce the tax distortions in the labor market. However, when the labor supply elasticity is relatively low, the strong double dividend disappears. It remains preferable to recycle via labor-tax reductions as opposed to lump-sum redistributions (i.e., the weak double dividend remains) but, because labor supply is now less price-responsive, the tax-interaction and revenue recycling effects no longer dominate the welfare costs of higher environmental taxes. IGEM is therefore unique in identifying how lower marginal tax rates lead to a larger supply of labor which allow it to capture these double dividend effects.[7]

Several features of IGEM may have a smaller, though still significant, impact on the existence and size of the double dividend than tax interaction. They include the following:

- **Marginal tax rates:** IGEM uses both average and marginal rates of taxation instead of the proportional tax rate used in most models. There are both average and marginal rates of labor taxation, the average being lower and representing the existence of a zero-tax income bracket. This treatment identifies greater pre-existing distortions in the labor market and makes the marginal tax rate on labor an even more attractive recycling instrument than it would be were labor taxes proportional.
- **Treatment of capital:** The varying treatments of capital in the IGEM model allow it to be more reactive to changes in the economy. Capital is either short- or long-lived and is owned by corporations, non-corporate enterprises, or households. Each category has its own tax treatment, its own price, its own demands (by industry and sector), and, hence, its own market. In comparison to models with a single capital good, this degree of disaggregation alters not only the relative welfare costs of each form of taxation but also the time path of capital accumulation as determined by prevailing (general equilibrium) conditions. These observations clearly merit additional analysis and research.

Finally, along similar lines, recent and preliminary analyses by Parry and Bento (1998) indicate the importance of household tax deductions (e.g., for housing and health care). When household income declines, households will choose to carry less mortgage debt and shift assets into more productive assets. This can lead to significantly higher recycling gains than obtained from models that do not represent these distortions. Indeed, the authors illustrate the possibilities of strong double dividends from environmental taxes that reduce pollution by between 20 and 40 percent.

As more and more of the economy's current tax distortions find their way into theoretical and empirical models, more is learned about the costs and benefits of tax reform and tax recycling. The early optimism for the double dividend has been challenged in the literature and researchers are now undertaking a more systematic exploration of the circumstances driving its existence and size.

VIII. Conclusions

The U.S. economy is characterized by numerous influences on consumers and producers, and by a myriad of substitution possibilities. Many of these are represented in the model employed in this analysis. The consequences of planned or unplanned changes in economic circumstances depend on interactions that reflect the quantifiable characteristics of consumer preferences and production technologies. The model uses parameters to describe these characteristics. This analysis demonstrates the importance of these parameters in evaluating the effects of a constraint on carbon emissions. The emissions constraint imposes costs on the economy when allowable substitution possibilities reflect the historical patterns of the last 50 years. It imposes greater costs when substitutability is reduced artificially, either within household purchases of goods and services or within the input structure of U.S. producing industries. The inherent flexibility of the economy makes a valuable contribution to mitigating the adverse impacts of climate change policy. This is entirely intuitive and predictable. Moreover, it means that failure to recognize this flexibility can lead to a serious overstatement of the costs of a mitigation policy from any given change or disturbance.

There is another major finding emerging from this analysis. Not all rigidities are harmful in all situations. Inflexibilities in consumption or production are harmful when permit revenues are distributed in lump-sum fashion. However, less responsiveness is beneficial to economic performance when the revenue redistribution mechanism itself is favorable. These rigidities amplify the direct consequences of both the emissions policy and the revenue redistribution, so that favorable impacts become even more so.

Inflexibility in consumption-leisure operates somewhat differently in the economy. Under lump-sum distributions, inflexibilities in consumption and production are harmful to the economy, but the harm is less when accompanied by rigidities in household decisions regarding the tradeoff between consumption and leisure. The economic damages from the emissions reductions are smaller if households are less sensitive to changes in the relative prices of consumption and leisure; hence, this rigidity appears beneficial. Yet, when permit revenues are recycled using a more favorable policy instrument, rigidity in consumption and leisure proves harmful, and can completely erode the benefits of the better redistribution mechanism. This finding prompts the need to identify and examine key sensitivities and modeling assumptions not only in isolation but also in combination.

Because models are incomplete representations of the real world, the modeling community long has emphasized the dependence of model outcomes on distinctive features and modeling assumptions. These dependencies are key to understanding the consequences of change. Model features determine the responses to identically formulated changes. Cross-model comparisons inform the analytical process by showing the effect of features relating to a model's time horizon, its level of national, regional, industrial, and technological detail, its ease and range of substitutability and its behavioral treatment of expectations. But this only goes so far. Within each model, there are important components and related sets of parameters that govern its behavior. It is imperative to examine more fully these sub-structures and their interactions. The preceding analysis focuses on just such an examination. Its intent is to increase understanding of the nature and magnitude of the benefits and costs of substitution by exploring the key features of a portrayal of the economy in one particular model. Other researchers can extend this effort to models that are either similar or different in content and structure. After all, the goal of climate change analysis is to find that combination of environmental and economic policies that maximize the net benefits of emissions reductions over the broadest possible range of economic circumstances.

Endnotes

1. Non-carbon greenhouse gases are not included in this analysis.

2. In this respect, this simulation is less flexible relative to other model experiments and relative to the Kyoto Protocol, which allows emissions averaging over time.

3. Lump-sum distributions are those in which the transfers are independent of taxpayer behavior. For example, the personal exemptions in income taxes are lump-sum transfers.

4. Currently, net oil imports are around 56 percent of domestic consumption while net gas imports are around 15 percent of domestic consumption. Because model simulations involve lower import levels than currently observed, the magnitude of the supply-curve effect, while directionally correct, is overstated (i.e., domestic production is too large a share of total supply and so the model shows smaller price increases for petroleum products than would probably actually occur as a result of lower domestic production costs).

5. Table 7 shows the welfare loss associated with an imposed emissions constraint under two different sets of parameters. Each set reflects household preferences for various categories of goods and services. The two sets are distinguished by their degrees of flexibility. There are no welfare comparisons as to whether households are better off or worse off when preferences reflect less flexible consumer demands. The table merely shows that the welfare loss associated with proportional emissions reductions is smaller when consumption is less flexible and larger when production is less flexible. Stated another way, the table shows the relative responsiveness of three different economies to identically stringent emissions constraints. The analysis makes comparative statements about the magnitudes of responsiveness, but does not make comparative statements about the underlying economies, because one cannot compare different economies when their underlying preferences are different.

6. The losses to household welfare arising from the emissions constraint are smaller when households are less responsive to price changes at this price level. Since welfare is a function of both consumption and leisure, and both are unresponsive to relative price changes, it is not surprising that welfare changes very little. This is not the same as saying that households are better off or worse off when their preferences are more or less flexible; the economics discipline avoids such value judgments. Nor, for the same reason, does it follow that public policy should be directed toward promoting one or the other flexibility regime.

7. In IGEM the (base-case) compensated elasticity of labor supply is 0.65. Labor supply is measured in terms of quality-adjusted person-hours and the seemingly high estimated elasticity is the result of the very rapid expansion of the quality-adjusted labor supply over the 40-year period through the mid-1980s. The compensated elasticity of labor supply under reduced consumption-leisure flexibility is 0.06, or nearly inelastic. These elasticities are high and low, respectively, in comparison to those of the double dividend literature. In this literature, the magnitudes are in the range of 0.30 to 0.50 (not quality-adjusted) and there is evidence that numbers toward the lower end are more realistic for the current U.S. economy (even for the quality-adjusted labor supply). In light of these figures and given the results, a small but positive (i.e., strong) double dividend appears most likely for reduced labor tax rates.

References

Böhringer, C., A. Pahlke and T. Rutherford. 1997. "Environmental Tax Reforms and the Prospects for a Double Dividend: An Intertemporal General Equilibrium Analysis for Germany." Working paper, Department of Economics, University of Colorado.

Goettle, R.J., and E.A. Hudson. 1984. *The Thirty-six Sector Dynamic General Equilibrium Model.* Washington, DC: U.S. Federal Emergency Management Agency. Prepared by Dale W. Jorgenson Associates, Cambridge, MA.

Goulder, L.H. 1994. "Energy Taxes: Traditional Efficiency Effects and Environmental Implications." *Tax Policy and the Economy*, Vol. 8. National Bureau of Economic Research (NBER). Edited by J.M. Poterba. The MIT Press, Cambridge, MA.

Gordon, R.J. 1999. "U.S. Economic Growth Since 1870: One Big Wave?" Pp.123-128 in *The American Economic Review: Papers and Proceedings,* May 1999.

Ho, M.S. 1989. *The Effects of External Linkages on U.S. Economic Growth: A Dynamic General Equilibrium Analysis.* Ph.D. Dissertation, Harvard University.

Hudson, E.A., and D.W. Jorgenson. 1974. "U.S. Energy Policy and Economic Growth, 1975-2000." in *The Bell Journal of Economics and Management Science* 5(2): 461-514.

Jorgenson, D.W. 1984. "Econometric Methods for Applied General Equilibrium Analysis." Pp.139-203 in *Applied General Equilibrium Analysis,* edited by E. Scarf and J.B. Shoven. Cambridge University Press, Cambridge.

___ 1986. "Econometric Methods for Modeling Producer Behavior." Pp.1842-1915 in *Handbook of Econometrics,* Vol. 3, edited by Z. Griliches and M.D. Intriligator. Amsterdam, North-Holland.

___ 1989. "Capital as a Factor of Production." Pp.1-36 in *Technology and Capital Formation,* edited by D.W. Jorgenson and R. Landau. The MIT Press, Cambridge, MA.

___ 1990. "Aggregate Consumer Behavior and the Measurement of Social Welfare." *Econometrica,* 58, 3.

___ 1990. "Productivity and Economic Growth." Pp.19-118 in *Fifty Years of Economic Measurement,* edited by E. Berndt and J. Triplett. University of Chicago Press, Chicago, IL.

Jorgenson, D.W., and B.M. Fraumeni. 1981. "Relative Prices and Technical Change." Pp.17-47 in *Modeling and Measuring Natural Resource Substitution,* edited by E. Berndt and B. Field. The MIT Press, Cambridge, MA.

___ 1989. "The Accumulation of Human and Nonhuman Capital, 1948-1984." Pp.17-47 in *The Measurement of Saving, Investment and Wealth,* edited by R.E. Lipsey and H.S. Tice. University of Chicago Press, Chicago, IL.

Jorgenson, D.W., R.J. Goettle, D.E. Gaynor, D.T. Slesnick and P.J. Wilcoxen. 1993. *The Clean Air Act and the U.S. Economy.* Washington, DC: U.S. Environmental Protection Agency. Prepared by Dale W. Jorgenson Associates, Cambridge, MA.

___ 1995. *Social Cost Energy Pricing, Tax Recycling and Economic Change.* Washington, DC: U.S. Environmental Protection Agency. Prepared by Dale W. Jorgenson Associates, Cambridge, MA.

Jorgenson, D.W., R.J. Goettle, D.T. Slesnick and P.J. Wilcoxen. 1998. *Carbon Mitigation, Permit Trading and Revenue Recycling.* Washington, DC: U.S. Environmental Protection Agency. Prepared by Dale W. Jorgenson Associates, Cambridge, MA.

Jorgenson, D.W., L.J. Lau, and T.M. Stoker. 1982. "The Transcendental Logarithmic Model of Aggregate Consumer Behavior." Pp.9-238 in *Advances in Econometrics,* Vol. 1, edited by R.L. Basmann and G. Rhodes. JAI Press, Greenwich, CT.

Jorgenson, D.W., and D.T. Slesnick. 1985. "General Equilibrium Analysis of Economic Policy." Pp.293-370 in *New Developments in Applied General Equilibrium Policy,* edited by J. Piggott and J. Whalley. Cambridge University Press, Cambridge.

___ 1987. "Aggregate Consumer Behavior and Household Equivalence Scales." *Journal of Business and Economic Statistics* 5(2): 219-232.

Jorgenson, D.W., D.T. Slesnick and P.J. Wilcoxen. 1992. "Carbon Taxes and Economic Welfare." Pp.393-454 in *Brookings Papers on Economic Activity: Microeconomics,* edited by M.N. Baily and C. Winston. Washington, DC.

Jorgenson, D.W., and P.J. Wilcoxen. 1990. "Environmental Regulation and U.S. Economic Growth." *The Rand Journal of Economics* 21(2): 314-340.

___ 1990. "Intertemporal General Equilibrium Modeling of U.S. Environmental Regulation." *Journal of Policy Modeling,* December.

___ 1991. "Reducing U.S. Carbon Dioxide Emissions: An Assessment of Different Instruments." Unpublished manuscript.

Jorgenson, D.W., and K.Y. Yun. 1986. "The Efficiency of Capital Accumulation." *Scandinavian Journal of Economics* 88(1): 85-107.

___ 1991. "The Excess Burden of Taxation in the United States." *Journal of Accounting, Auditing and Finance* 6(4): 487-508.

Nordhaus, W.D. 1994. *Managing the Global Commons: The Economics of Climate Change.* The MIT Press, Cambridge, MA.

Norland, D.L. and K.Y. Ninassi. 1998. *Price It Right: Energy Pricing and Fundamental Tax Reform.* Washington, DC: Alliance to Save Energy. In cooperation with Dale W. Jorgenson and Dale W. Jorgenson Associates, Cambridge, MA.

Parry, I.W.H. 1998. "The Double Dividend: When You Get It and When You Don't." Presented at the National Tax Association Meetings in Austin, Texas, December.

Parry, I.W.H. and A.M. Bento. 1998. "Tax Deductions, Environmental Policy, and the 'Double Dividend' Hypothesis." Discussion paper, Resources for the Future, Washington, DC.

Repetto, R. and D. Austin. 1997. *The Costs of Climate Protection: A Guide for the Perplexed.* World Resources Institute, Washington, DC.

Weyant, J.P. 2000. *An Introduction to the Economics of Climate Change Policy.* The Pew Center on Global Climate Change, Arlington, VA.

Wilcoxen, P.J. 1988. *The Effects of Environmental Regulation and Energy Prices on U.S. Economic Performance.* Ph.D. Dissertation, Harvard University.

Appendix A: A Description of the Intertemporal General Equilibrium Model (IGEM)

The results of this analysis are based on simulations conducted with the Intertemporal General Equilibrium Model or IGEM developed by Ho, Jorgenson, and Wilcoxen. This is a multi-sector, multi-period model of the U.S. economy. It is one of a class of models called computable general equilibrium (CGE) models because it solves for the market-clearing prices and quantities of each sector and market in each time period. The parameters (or coefficients) of the equations in IGEM are estimated statistically from historical data spanning the last 50 years. The model consists of 35 producing sectors, the household or consumer sector, a business investment sector, the federal, state and local governments sector, and a foreign sector. Formal descriptions of the methodology and its components are numerous and appear in Ho (1989), Jorgenson and Slesnick (1985, 1987), Jorgenson *et al.* (1992) and Wilcoxen (1988).

In the IGEM model, production is disaggregated into 35 separate commodities produced by one or more of 35 industries. The industries (see Table 4 in the text) generally match two-digit sectors in the Standard Industrial Classification (SIC). Each industry or producing sector produces one primary product and may produce one or more additional goods or services. Each producing sector is modeled by a set of equations that fully represent possible substitutions among its inputs or factors — i.e., capital, labor, non-competing imports, and the 35 commodities.

Within each producing sector, changes in input demand (i.e., substitutions) occur because relative prices change, encouraging more or less use of that input. In addition, historical data invariably reveal trends (or biases) in input use that are independent of input price. This means there is either increasing or decreasing input usage over time, even after accounting for the changes arising from relative price incentives. For example, historical data may indicate that particular industries are increasingly labor-saving, energy-saving, or capital-using over time, independent of relative prices. The equations used to model production in IGEM account for both price- and trend-related substitution effects. Industry-level productivity growth also is part of the specification for each of the 35 producing sectors estimated statistically from observed changes in input prices and observed technological trends.

These equations, along with others in the model, are organized in an inter-industry framework in which the demands for and supplies of each commodity, as well as those of capital and labor, must balance in terms of both quantity and value (i.e., price times quantity). The organization of annual "use" and "make" tables is illustrated in Figure A.1. These are "spreadsheets" at the industry and commodity level of detail. The "cells" in each use table depict commodity purchases (the rows) by each industry and final demand (the columns). The "cells" in each make table show the commodities produced by each industry. Figure A.1 also shows the inputs of capital and labor into each producing and consuming sector.

Figure A-1

Organization of the **Use and Make Tables**

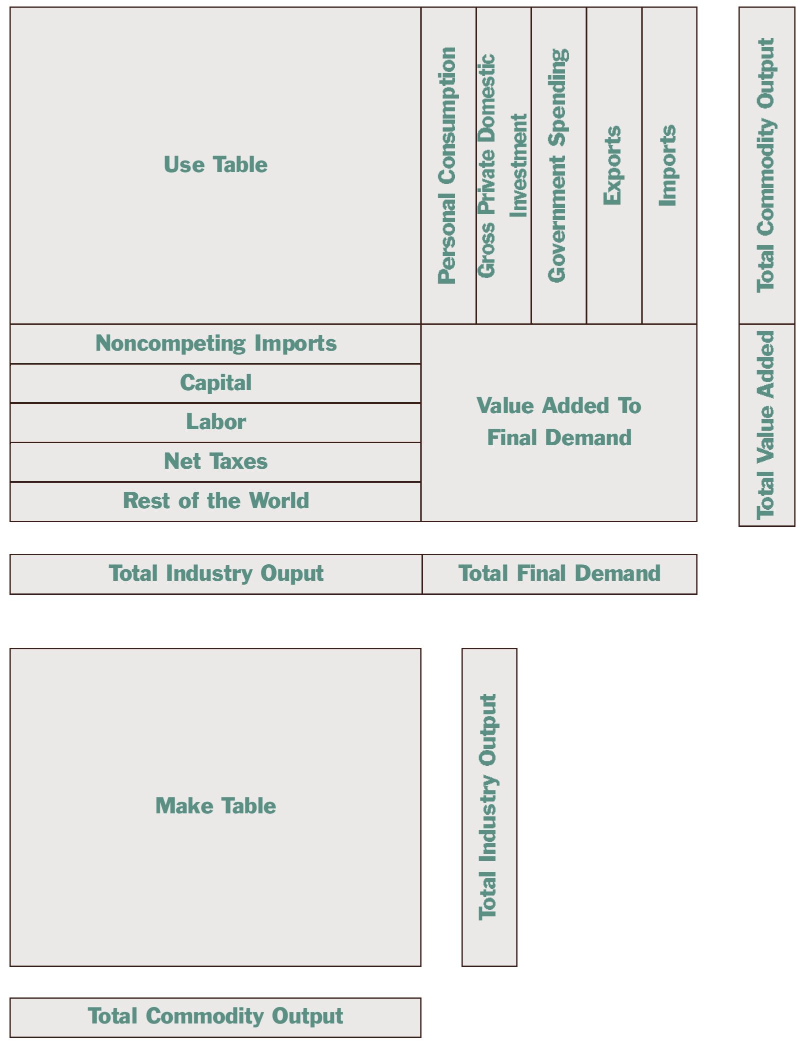
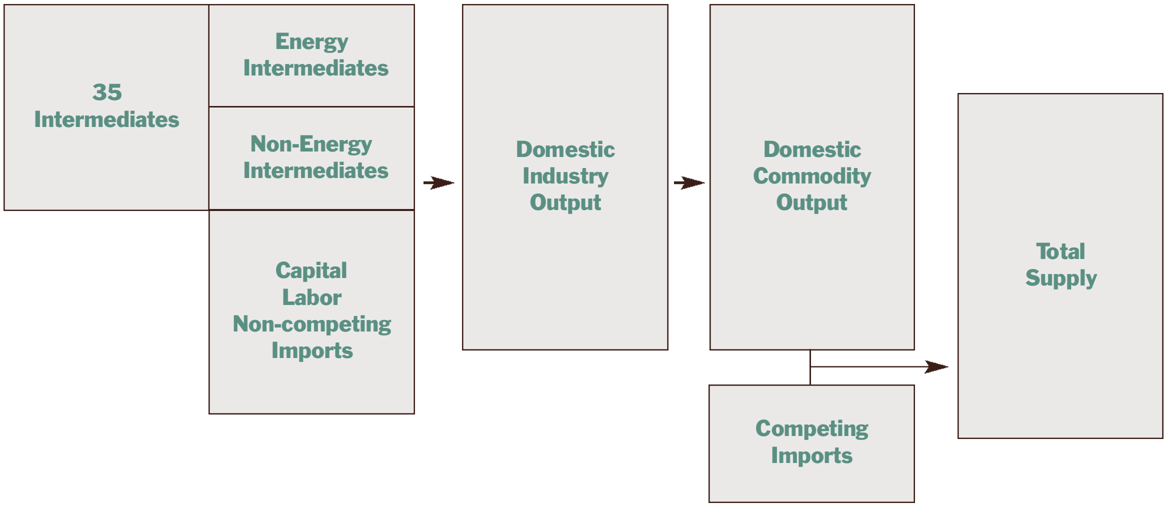


Figure A.2 depicts production and supply. Inputs of the 35 commodities plus capital, labor, and non-competing imports are combined to produce domestic industrial outputs. In turn, these outputs are mapped into domestic commodity outputs through the use and make table. Combining the domestic commodities with competitive foreign imports gives rise to the available supplies, which are purchased as intermediate inputs or finished goods (final demand).

The model is solved iteratively until the prices of all commodities and inputs are such that demand equals supply in all product and factor (input) markets. Model solutions depict, among other

Figure A-2

The Model Flows of **Production and Commodity Supply**



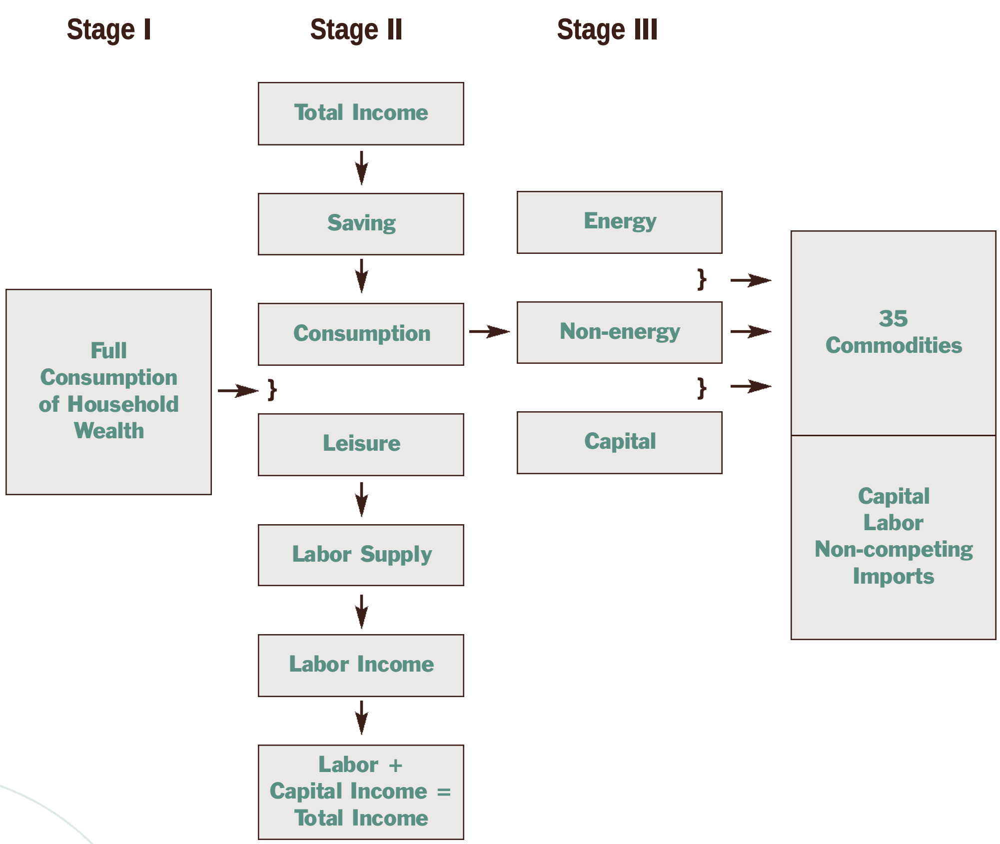
things, all prices and quantities, the complete structure of inputs to production, and industry-level rates of technological change. As a result, economy-wide changes in energy or capital intensity, for example, are calculated by adding up industry-level details. There are none of the so-called autonomous "economy-wide" energy efficiency improvements (i.e., assumed declines in the amount of energy required to produce a given level of output over time, with labor and capital unchanged), except those arising from the assumed continuation of independent technological trends. (Experimentation has shown that these technological trends in the use of such factors as energy or capital comprise around 20 percent of the overall adjustment to new energy conditions, with substitution or relative price effects explaining the remaining 80 percent [Jorgenson *et al.*, 1993].)

Household consumption by commodity is the result of a three-stage, multi-period decision process (see Figure A.3) involving price and demand equations like those of the producing sectors. First, households decide their levels of "full consumption" over time. Full consumption, comprising goods, services, *and* leisure, is the amount of financial wealth "consumed" in each period and is dependent on relative prices, current and future, and the time path of interest rates (both of which are known to households with perfect foresight). Financial wealth is the (present) value of household capital wealth (private, government and foreign) and the household time endowment.

The household time endowment is a population-based, monetary estimate of the amount of time available to the working-age population (those 14 through 74 years old) for work and leisure. It assumes that there are 14 hours per day of discretionary time for work and leisure with appropriate allowances for weekends, holidays, and hours spent in school. The time endowment is evaluated at the prevailing wage or after-tax rate of labor compensation, including benefits and is adjusted for quality (i.e., educational attainment and experience). Leisure is defined as the uncompensated use of time (i.e., that portion of the 14 hours that people use for activities other than paid work). (This is not the ideal measure of leisure in that it includes commuting, illness, and many other uses of time that would not be considered "leisure" in the usual sense of the word. However, construction of a pure measure of leisure is probably beyond available data.)

Figure A-3

The Model Flows of **Household Behavior**



Once households decide each period's full consumption, they then decide the split between the consumption of goods and services and the demand for leisure. This decision is based on the price of consumption relative to the wage rate (the opportunity cost, or price of leisure). When households decide their leisure demand, they simultaneously determine their labor supply and, so too, their labor income. Finally, households choose the allocation of total consumption among capital, labor, and the various categories of goods and services. Like production, these stages of household behavior are estimated statistically from historical data, and the equations capture both price- and income-driven changes in observed spending patterns.

In the model, capital accumulation is the outcome of a series of decisions over time by households and firms. Households and businesses determine the amount of saving available in each period as the difference between their income and expenditures. Households and firms invest until the returns on additional investment are no longer greater than the cost of new capital goods. Capital is assumed to be perfectly mobile across households and corporate and non-corporate enterprises; in other words, capital flows to where it is needed. (In the real world, there are, most likely, severe constraints on the near-term mobility of capital.) Investment is structured according to a statistically estimated model allowing substitutions among different types of capital goods. The total supply of capital at any time is fixed by the accumulated investment in these capital goods.

Government purchases are calculated to balance the available government revenues and a predetermined budget deficit. Government revenues arise by applying tax rates, both historical and projected, to the levels of income and wealth generated by the model. The composition of government spending — for example, spending on automobiles, computers, highways, schools, and employees — is fixed by assumption.

Finally, the international exchange rate of the dollar against other currencies adjusts to bring net exports (exports less imports) into line with a predetermined trade balance in goods and services. This means that net foreign saving is insensitive to changes in U.S. prices and interest rates. Imports are considered imperfect substitutes for similar domestic commodities and compete on price, which in turn depends on the value of the relevant foreign currency. Export demands depend on assumed foreign incomes and the foreign prices of U.S. exports, which, in turn, are determined by domestic prices and the exchange rate.

The assumptions regarding the budget and trade deficits drive important aspects of the process of capital formation. In combination, they imply that no "crowding-out" of private investment occurs as a result of changes in investment by either the government or foreign sectors. Holding the budget and trade deficits constant across simulations means that neither governments nor foreigners influence the level of investment spending beyond what is assumed for the base-case. As a result, investment changes from one simulation to another depend entirely on changes in saving by households and businesses.

On the supply side, overall economic growth in IGEM, as in the real world, arises from three sources. These are productivity, accumulated capital, and the availability of labor. The model itself determines two of these — productivity and capital. Productivity depends on emerging trends in relative prices combined with the continuation of observed technological trends. Capital accumulation occurs as a result of the saving and investment behavior of producers and consumers. Labor supply is determined as households allocate their discretionary time between work and leisure. All of these, therefore, are products of the model. U.S. population growth by age, race, sex, and educational attainment is projected through 2050 using demographic assumptions consistent with U.S. Social Security Administration forecasts; after 2050, population is held constant. As indicated above, the population projection is used to calculate a projection of the economy's "time endowment" in dollar terms by applying historical wage patterns to estimates of the working-age population. Since the model largely determines productivity and capital accumulation, these population projections effectively determine the size of the economy in the distant future.

Models are necessarily an abstraction of the environment they portray, and IGEM is no exception. In characterizing the results from this methodology, three features merit consideration. Two of these are assumptions, while the third derives from the source of the model's parameters. First, as indicated above, consumers and producers in IGEM are assumed to have perfect foresight and are able to react today to expected future price changes. This means that they behave according to so-called "rational expectations." There are no surprises in the form of price shocks. Since producers and consumers immediately plan for and adopt new technologies, there are no losses associated with equipment becoming prematurely obsolete when technology or relative prices change repeatedly. Second, capital income and the corresponding stock of capital goods and services are assumed to be perfectly mobile among industries, households, and governments. This implies that capital can migrate from sector to sector with little or no adjustment cost. Moreover, there are no capacity shortages or supply-demand imbalances associated with this migration. Instead, equipment is effortlessly transformed into some other use.

Finally, the model parameters in IGEM are based on 50 years of historical data. Much has changed in these 50 years and these parameters reflect and embody these changes. Hence, model adjustments and reactions to changing economic conditions are based on observed long-term trends and any short-run constraints on or lags in adjustment behavior that are part of this history.

Taken together, these features imply that IGEM is more likely than other models are to produce "best" case outcomes (least losses or greatest gains) when confronted with significant economic changes. Households and businesses are fully aware of these changes through perfect foresight, substitution possibilities are long-run in nature and occur quickly and easily, and capital readily migrates and mutates to new uses. Conversely, myopia, inflexibility in production and consumption, and low capital stock turnover are conditions that lead to "worst" case outcomes (greatest losses or least gains). In comparing model estimates of the economy's response to climate change and climate change policies, those from IGEM will appear less damaging (or more beneficial) than those from models in which there are more rigidities or higher adjustment costs (see Weyant [2000] and Repetto and Austin [1997]).

Appendix B: Introducing Inflexibility into IGEM

The estimating equations (formally, the transcendental logarithmic or *translog* function) common in IGEM have the feature that substitution and demand elasticities in any given period are functions of: (1) the historically estimated parameters unique to each equation and (2) the historical or simulated value shares for the commodities being analyzed. Specifically,

$$\ln(P) = \alpha_0 + \sum\alpha_i * \ln(p_i) + {}^1/_2 * \sum\sum \beta_{ij} * \ln(p_i) * \ln(p_j) + f(t,p)$$

$$\sigma_{ij} = (\beta_{ij} + Share_i * Share_j) / Share_i*Share_j$$

$$\sigma_{ii} = (\beta_{ii} + (Share_i)^2 - Share_i) / (Share_i)^2$$

P = aggregate or industry price

p = input prices to the aggregate or industry

σ = elasticities of substitution

ln = natural logarithm

α and β = parameters estimated from historical data

f(t,p) = function of time and prices representing induced technical change

Value shares are defined as the nominal expenditure (that is, price times quantity) on a given commodity relative to the total expenditure on a relevant group of commodities.

Mathematically, the value share for commodity "i" is given by:

$$Share_i = p_i * q_i / \sum p_i*q_i$$

For producers, the relevant commodity groups are energy commodities within total energy expenditure; and capital, labor, energy, and materials within total cost. For consumers, the relevant commodity groups are energy commodities within total energy expenditure; energy, food, non-durable goods, capital, and services within total expenditure; and consumption and leisure within full consumption. To get demand elasticities that are near zero simply involves resetting the historically estimated parameters within IGEM to numbers computed from simulated value shares. For cross-price elasticities (that is, the percent change in quantity "i" with respect to a percent change in price "j"), the new parameter is given by:

$$\beta_{ij} = -Share_i * Share_j$$

For own-price elasticities (that is, the percent change in quantity "i" with respect to a percent change in price "i"), the new parameter is given by:

$$\beta_{ii} = Share_i * (1-Share_i)$$

Using these formulas, new model parameters were determined from the average of the simulated value shares for the period 1996-2060. As a result, demand elasticities at the base-case prices and quantities are unlikely to be zero in any given period but are likely to be near zero at base-case prices in all periods. It must be emphasized that this computed inflexibility changes as simulated prices, quantities and value shares change. The new parameters lead to more limited substitution possibilities at all simulated values but to near-complete inflexibility only at base-case simulated values.

Appendix C: Selected Industry Output and Price Changes

Table C-1

Industrial Market Consequences in 2020 of a Carbon Emissions Constraint
(% change in domestic production)

Industry	Description	Reduced consumer flexibility	Reduced producer flexibility
1	Agriculture, forestry and fisheries	0.0	2.2
2	Metal mining	-3.5	-15.0
3	Coal mining	-53.0	-49.4
4	Crude petroleum, natural gas extraction	- 3.7	4.2
5	Non-metallic mineral mining	-3.0	-7.7
6	Construction	-0.5	-3.0
7	Food and kindred products	-0.3	3.8
8	Tobacco manufactures	-0.3	2.4
9	Textile mill products	-2.5	-11.8
10	Apparel and other textile products	-5.2	-4.5
11	Lumber and wood products	-1.3	-4.2
12	Furniture and fixtures	-0.6	-4.1
13	Paper and allied products	-3.0	-9.8
14	Printing and publishing	33.5	-1.5
15	Chemicals and allied products	-3.1	-6.9
16	Petroleum refining	-6.4	-9.7
17	Rubber and plastic products	-3.8	-11.3
18	Leather and leather products	-2.4	-6.0
19	Stone, clay and glass products	-4.4	-11.4
20	Primary metals	-5.5	-20.7
21	Fabricated metal products	-1.4	-5.5
22	Non-electrical machinery	-3.1	-8.4
23	Electrical machinery	-1.8	-5.7
24	Motor vehicles	-1.5	-6.0
25	Other transportation equipment	-2.4	-5.7
26	Instruments	-3.1	-6.6
27	Miscellaneous manufacturing	-1.3	-4.9
28	Transportation and warehousing	-1.3	-1.4
29	Communications	1.9	-0.4
30	Electric utilities (services)	-10.5	-22.2
31	Gas utilities (services)	-26.2	-16.0
32	Wholesale and retail trade	-0.6	-1.1
33	Finance, insurance and real estate	-17.5	0.1
34	Other personal and business services	-0.6	-0.2
35	Government enterprises	-0.3	-2.9

Note: Output changes correspond to the simulations of Section V.

Table C-2

Industrial Market Consequences in 2020 of a Carbon Emissions Constraint

(% change in prices)

Industry	Description	Reduced consumer flexibility	Reduced producer flexibility
1	Agriculture, forestry and fisheries	1.0	2.1
2	Metal mining	2.0	5.0
3	Coal mining	164.4	502.1
4	Crude petroleum, natural gas extraction	-7.7	-38.4
5	Non-metallic mineral mining	2.6	6.5
6	Construction	1.0	2.4
7	Food and kindred products	1.0	3.0
8	Tobacco manufactures	1.0	3.0
9	Textile mill products	2.1	7.2
10	Apparel and other textile products	-0.1	0.8
11	Lumber and wood products	0.6	1.7
12	Furniture and fixtures	0.6	2.3
13	Paper and allied products	2.2	7.0
14	Printing and publishing	0.9	2.8
15	Chemicals and allied products	1.6	3.4
16	Petroleum refining	5.1	2.1
17	Rubber and plastic products	1.7	5.2
18	Leather and leather products	-0.9	-1.5
19	Stone, clay and glass products	2.6	7.7
20	Primary metals	2.4	10.5
21	Fabricated metal products	1.1	3.9
22	Non-electrical machinery	0.6	2.2
23	Electrical machinery	0.1	1.0
24	Motor vehicles	-0.1	0.8
25	Other transportation equipment	0.7	2.1
26	Instruments	0.5	1.8
27	Miscellaneous manufacturing	-0.4	-0.2
28	Transportation and warehousing	1.0	1.7
29	Communications	0.6	1.7
30	Electric utilities (services)	18.6	57.4
31	Gas utilities (services)	21.1	44.8
32	Wholesale and retail trade	1.0	2.3
33	Finance, insurance and real estate	0.6	1.4
34	Other personal and business services	0.9	2.3
35	Government enterprises	1.8	4.5

Note: Price changes correspond to the simulations of Section V.

Table C-3

Industrial Market Consequences in 2020 of a Carbon Emissions Constraint, Base-case (full flexibility) (% change in domestic production)

Industry	Description	Lump-sum Accruals	Lower Marginal Tax Rates
1	Agriculture, forestry and fisheries	1.7	4.0
2	Metal mining	-3.7	-1.8
3	Coal mining	-52.1	-52.5
4	Crude petroleum, natural gas extraction	-4.5	-4.0
5	Non-metallic mineral mining	-2.9	-0.7
6	Construction	-1.3	1.4
7	Food and kindred products	3.0	5.3
8	Tobacco manufactures	2.1	4.5
9	Textile mill products	-2.2	0.6
10	Apparel and other textile products	-1.8	0.8
11	Lumber and wood products	-1.2	1.9
12	Furniture and fixtures	-1.4	1.7
13	Paper and allied products	-1.9	0.7
14	Printing and publishing	-0.2	2.8
15	Chemicals and allied products	-2.8	-0.2
16	Petroleum refining	-7.5	-7.1
17	Rubber and plastic products	-2.6	0.6
18	Leather and leather products	-2.1	1.2
19	Stone, clay and glass products	-3.8	-1.0
20	Primary metals	-4.5	-2.0
21	Fabricated metal products	-1.4	1.4
22	Non-electrical machinery	-2.4	0.7
23	Electrical machinery	-1.7	1.4
24	Motor vehicles	-2.0	0.7
25	Other transportation equipment	-1.7	0.5
26	Instruments	-2.0	1.0
27	Miscellaneous manufacturing	-1.7	1.3
28	Transportation and warehousing	-1.1	0.9
29	Communications	0.1	2.9
30	Electric utilities (services)	-12.8	-11.8
31	Gas utilities (services)	-25.6	-25.4
32	Wholesale and retail trade	-0.3	2.3
33	Finance, insurance and real estate	0.2	3.3
34	Other personal and business services	0.2	3.5
35	Government enterprises	-1.0	1.9

Note: Column 1: Output changes correspond to the simulation of Section IV. Column 2: Output changes correspond to the simulation of Section VII.

Table C-4

Industrial Market Consequences in 2020 of a Carbon Emissions Constraint, Base-case (full flexibility) (% change in prices)

Industry	Description	Lump-sum Accruals	Lower Marginal Tax Rates
1	Agriculture, forestry and fisheries	1.2	-2.8
2	Metal mining	2.3	-1.3
3	Coal mining	128.7	127.7
4	Crude petroleum, natural gas extraction	-6.1	-8.3
5	Non-metallic mineral mining	2.6	-1.3
6	Construction	1.1	-2.9
7	Food and kindred products	1.2	-2.6
8	Tobacco manufactures	1.2	-2.8
9	Textile mill products	2.1	-1.8
10	Apparel and other textile products	0.5	-2.8
11	Lumber and wood products	0.9	-3.0
12	Furniture and fixtures	0.9	-2.8
13	Paper and allied products	2.2	-1.5
14	Printing and publishing	1.0	-3.1
15	Chemicals and allied products	2.0	-1.5
16	Petroleum refining	7.3	4.9
17	Rubber and plastic products	1.9	-1.9
18	Leather and leather products	0.0	-2.9
19	Stone, clay and glass products	2.6	-1.1
20	Primary metals	2.4	-1.1
21	Fabricated metal products	1.2	-2.6
22	Non-electrical machinery	0.8	-3.0
23	Electrical machinery	0.5	-3.0
24	Motor vehicles	0.5	-2.8
25	Other transportation equipment	0.8	-3.1
26	Instruments	0.8	-3.0
27	Miscellaneous manufacturing	0.3	-2.8
28	Transportation and warehousing	1.2	-2.7
29	Communications	0.7	-3.3
30	Electric utilities (services)	16.4	13.0
31	Gas utilities (services)	21.4	18.9
32	Wholesale and retail trade	1.0	-3.2
33	Finance, insurance and real estate	0.7	-3.5
34	Other personal and business services	0.9	-3.3
35	Government enterprises	1.9	-2.2

Note: Column 1: Price changes correspond to the simulation of Section IV. Column 2: Price changes correspond to the simulation of Section VII.

notes