CHAPTER 8

Energy, the Environment and US Economic Growth

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Abstract

The point of departure for the study of the impact of energy and environmental policies is the neoclassical theory of economic growth formulated by Cass (1965) and Koopmans (1967). The long-run properties of economic growth models are independent of energy and environmental policies. However, these policies affect capital accumulation and rates of productivity growth that determine the intermediate-run trends that are important for policy evaluation. Heterogeneity of different energy producers and consumers is critical for the evaluation of energy and environmental policies. To capture this heterogeneity it is necessary to distinguish among commodities, industries and households. Econometric methods are essential for summarizing information on different industries and consumer groups in a form suitable for general equilibrium modeling. In this chapter, we consider the application of econometric general equilibrium modeling to the US — the economy that has been studied most intensively. The framework for our analysis is provided by the Intertemporal General Equilibrium Model (IGEM) introduced by Jorgenson and Wilcoxen (1998). The new version of the IGEM presented in this paper is employed for the evaluation of proposed legislation on climate policy by the US Environmental Protection Agency (2012b).

Keywords

Econometric modeling, energy, environment, general equilibrium, heterogeneity, policy evaluation

JEL classification codes

C51, C68, D58, E13, O41, O51, Q43, Q50

8.1 INTRODUCTION

Economic growth is a critical determinant of US demand for energy. Emissions from the combustion of fossil fuels are an important source of US requirements for pollution abatement. An essential first step in modeling the impact of energy and environmental policies is to analyze the growth of the US economy. The appropriate point of departure for modeling economic growth is the neoclassical theory of economic growth, originated by Solow (1956, 2005). The form of this theory appropriate for modeling the

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inter-relationships among energy, the environment and US economic growth was developed by Cass (1965) and Koopmans (1967).[1]

Maler (1974) and Uzawa (1975) have presented neoclassical theories of economic growth with pollution abatement. A recent survey by Brock and Taylor (2005) summarizes the extensive literature on this topic. Solow (1974a, 1974b) has provided a theory of economic growth that includes an exhaustible resource. The classic textbook treatment of this topic remains that of Dasgupta and Heal (1979), who also give a detailed survey of the literature. In this paper we focus on pollution abatement, since the US economy is relatively open to trade in natural resources, exporting coal and importing oil and natural gas.

In the neoclassical theory of economic growth wage rates grow at the same rate as productivity in the long run, while rates of return depend on productivity growth and the parameters that describe saving behavior. These long-run properties of economic growth are independent of energy and environmental policies. The neoclassical theory of economic growth also provides a framework for analyzing intermediate-run growth trends. These trends reflect the same determinants as long-run trends, but also depend on energy and environmental policies through their effects on capital accumulation and rates of productivity growth. In this context the "intermediate-run" refers to the time needed for the capital–output ratio to converge to a long-run stationary value. This often requires decades, so that the impact of energy and environmental policies on intermediate-run trends is critical for policy evaluation.

The slowdown of the US economy during the 1970s and 1980s, and the acceleration of growth during the 1990s and 2000s, are striking examples of changes in intermediate-run trends. Two events associated with the slowdown – the advent of more restrictive environmental policies and the increase in world petroleum prices – have led to a focus on the interactions of energy supplies and prices, environmental quality and its cost, and the sources of economic growth. Similarly, Jorgenson (2009a) has demonstrated that the rapid development of information technology is the key to more rapid growth in the 1990s and 2000s.

Nordhaus (2008, 2010) has applied the Cass–Koopmans theory of economic growth to the analysis of energy and environmental policies in his important studies of climate policy for the world economy.[2] The necessarily schematic modeling of technology limits consideration of issues that are very important in implementation of energy and environmental policies at the national level, such as the heterogeneity of different energy producers and consumers. To capture this heterogeneity we distinguish among commodities, industries and households. We employ an econometric approach to summarize information on different industries and consumer groups in a form

1 Barro and Sala-i-Martin (2004) provide a standard textbook treatment.
2 More details are given by Nordhaus (2012) in Chapter 16 of this Handbook.

suitable for general equilibrium modeling. We next consider the application of the econometric approach to the US economy.

The framework for our econometric analysis of the impact of energy and environmental policies is provided by the Intertemporal General Equilibrium Model (IGEM) introduced by Jorgenson and Wilcoxen (1998). The organizing mechanism of this model is an intertemporal price system balancing demand and supply for products and factors of production. The intertemporal price system links the prices of assets in every time period to the discounted value of future capital services. This forward-looking feature is essential in dealing with the critique of macroeconometric models by Lucas (1976).[3]

Forward-looking behavior of producers and consumers is combined with backward linkages among investment, capital stock and capital services in modeling the dynamics of economic growth. These mechanisms are also featured in the Cass–Koopmans neoclassical model of economic growth. The alternative time paths for economic growth depend on energy and environmental policies through the impact of these policies on intermediate-run trends.

In disaggregating the economic impacts of US energy and environmental policies, we preserve the key features of more highly aggregated IGEMs like those of Nordhaus. One important dimension for disaggregation is to distinguish among industries and commodities in order to measure policy impacts for narrower segments of the US economy. This makes it possible to model differences among industries in response to changes in energy prices and the imposition of pollution controls for different fuels.

A second avenue for disaggregation is to distinguish among households by level of wealth and demographic characteristics. This makes it possible to model differences in responses to price changes and environmental controls. Jorgenson *et al.* (1997, 2011) incorporate these differences in analyzing the distributional effects of energy and environmental policies. We begin our discussion of econometric intertemporal general equilibrium modeling by outlining the methodology.[4]

At the outset of our discussion it is necessary to recognize that the predominant tradition in general equilibrium modeling does not employ econometric methods. This tradition originated with the seminal work of Leontief (1951), beginning with the implementation of the static input-output model. Leontief (1953) gave a further impetus to the development of general equilibrium modeling by introducing a dynamic

[3] An important application of the econometric approach to general equilibrium is the G-Cubed model constructed by McKibbin and Wilcoxen (1999). A survey of applications of the G-Cubed model is presented by McKibbin and Wilcoxen in Chapter 15 of this Handbook.

[4] Econometric methodology for general equilibrium modeling is discussed in greater detail by Jorgenson *et al.* in Chapter 17 of this Handbook.

input-output model. This model can be regarded as an important progenitor of the intertemporal general equilibrium model described below. Empirical work associated with input-output analysis is based on determining the parameters that describe technology and preferences from a single interindustry transactions table.

The usefulness of the "fixed coefficients" assumption that underlies input-output analysis is hardly subject to dispute. By linearizing technology and preferences Leontief solved at one stroke the two fundamental problems that arise in practical implementation of general equilibrium models. (i) The resulting general equilibrium model can be solved as a system of linear equations with constant coefficients. (ii) The "input-output coefficients" can be estimated from a single data point. The data required are now available for all countries that have implemented the United Nations' *2008 System of National Accounts* (United Nations *et al.*, 2009).

An input-output approach to modeling environmental policy was introduced by Kneese *et al.* (1970). Their work was particularly notable for introducing a "materials balance" implied by conservation of mass for all economic activities. Materials balances bring out the fact that material not embodied in final products must result in emissions of pollutants. These emissions accumulate as solid waste or enter the atmosphere or hydrosphere and reduce air or water quality. The assumption that pollutants are generated in fixed proportions to output is a natural complement to the fixed-coefficients assumptions of Leontief's input-output models in implementing the materials balance approach.

The obvious objection to the fixed-coefficients approach to modeling energy and environmental policies is that the purpose of these policies is to change the input-output coefficients. For example, the purpose of many environmental regulations is to induce producers and consumers to substitute less polluting inputs for more polluting ones. A prime example is the substitution of low-sulfur coal for high-sulfur coal by electric utilities to comply with regulations on sulfur dioxide emissions. Another example is the dramatic shift from leaded to unleaded motor fuels in order to clean up motor vehicle emissions.

Johansen (1960, 1974) provided the first successful implementation of an empirical general equilibrium model without the fixed-coefficients assumption of input-output analysis. Johansen retained Leontief's fixed-coefficients assumption in determining demands for intermediate goods, including energy. However, he employed linear-logarithmic or Cobb–Douglas production functions in modeling the substitution between capital and labor services and technical change.

Johansen also replaced Leontief's fixed coefficients assumption for household behavior by a system of demand functions originated by Frisch (1959). Finally, he developed a method for solving the resulting nonlinear general equilibrium model for growth rates of sectoral output levels and prices and implemented this model for Norway, using data from the Norwegian national accounts. Johansen's multisectoral growth

(MSG) model of Norway is another important progenitor for the IGEM described below.[5]

Linear logarithmic production functions have the obvious advantage that the capital and labor input coefficients respond to price changes. Furthermore, the relative shares of these inputs in the value of output are fixed, so that the unknown parameters can be estimated from a single data point. In describing producer behavior Johansen employed econometric modeling only in estimating constant rates of productivity growth. Similarly, the unknown parameters of the demand system proposed by Frisch can be determined from a single point, except for a single parameter estimated econometrically.

Dixon and Parmenter (1996) and Dixon and Rimmer (2012) have surveyed the literature on Johansen-type models. The unknown parameters describing technology and preferences in these models are determined by "calibration" to a single data point. Data from a single interindustry transactions table are supplemented by a small number of parameters estimated econometrically. An important advantage of the Johansen approach, like input-output analysis, is the capacity to absorb the enormous amounts of detail available for a single data point. Dixon and Parmenter describe a model of Australia with 120 industries, 56 regions, 280 occupations and several hundred family types.

The obvious disadvantage of the calibration approach is the highly restrictive assumptions on technology and preferences required to make calibration feasible. Almost all general equilibrium models retain the fixed-coefficients assumption of Leontief and Johansen for modeling the demand for intermediate goods. However, this assumption is directly contradicted by massive empirical evidence of price-induced energy conservation in response to higher world energy prices beginning in 1973.

British Petroleum's (2011) *Energy Outlook 2030* shows that world energy use per unit of GDP peaked in the early 1970s and has fallen by more than 50% through 2010. The reductions in energy utilization induced by successive energy crises in the 1970s and the higher level of energy prices prevailing in the 1980s has been documented in great detail by Schipper *et al.* (1992). This extensive survey covers nine Organization for Economic Cooperation and Development (OECD) countries, including the US, for the period 1970–1989 and describes energy conservation in residential, manufacturing, other industry, services, passenger transport and freight transport sectors. Reductions in energy–output ratios for these activities average 15–20%.

Fixed coefficients for intermediate goods also rule out a very important response to environmental regulations by assumption. This is the introduction of pollution control equipment to treat wastes after they have been generated, substituting capital for other inputs, such as energy and materials. This is commonly known as end-of-pipe abatement

5 Holmøy (2012) describes the current version of the MSG model of Norway. Holmøy and Strøm present applications of this model to financial sustainability of the Norwegian economy in Chapter 3 of this Handbook.

and is frequently the method of choice for retrofitting existing facilities to meet environmental standards.

A typical example of end-of-pipe abatement is the use of electrostatic precipitators to reduce emissions of particulates from combustion. Regulations promulgated by regulators like the US Environmental Protection Agency encourage the use of this approach by setting standards for emission on the basis of the "best available technology." Bergman (2005) surveys computable general equilibrium (CGE) models of energy and the environment.

A representation of technology and preferences that overcomes the limitations of the Johansen approach requires econometric methods. A common extension of Johansen's methodology employs constant elasticities of substitution between two inputs into production. A less restrictive approach is to generate complete systems of equations for the inputs of capital, labor, energy, materials and services (KLEMS). The current version of IGEM discussed in this chapter employs the state-space model of technical change introduced by Jin and Jorgenson (2010) and discussed in Chapter 17 of this Handbook.

As in the descriptions of technology by Leontief and Johansen, production in the econometric approach of Jin and Jorgenson is characterized by constant returns to scale in each sector. As a consequence, commodity prices can be expressed as functions of factor prices, using the non-substitution theorem of Samuelson (1951). The non-substitution theorem permits a substantial reduction in the dimensionality of the space of prices determined by the model. This greatly facilitates the solution of the new version of IGEM.

Constant returns to scale and the non-substitution theorem have been exploited in solving Johansen models by the "fixed point" methods pioneered by Scarf (1973). Johansen (1960, 1974) introduced a method of linearizing the MSG model and solving it by matrix inversion. Dixon *et al.* (1982) extended this to the "Johansen—Euler" method that eliminated the linearization errors. Dixon and Parmenter (1996) survey the extensive applications of this method. Dixon *et al.* (1992) surveys methods for solving intertemporal general equilibrium models like the IGEM model of Jorgenson and Wilcoxen (1998).

Similarly, econometric models of consumer behavior can overcome the limitations of the Frisch (1959) model of consumer demand. A common approach is to use systems of equations that incorporate the theory of consumer behavior by utilizing the notion of a representative consumer employed by Frisch. Aggregate demand functions are treated as if they could be generated by a single utility-maximizing individual. The difficulty with this approach is that aggregate demand functions must be expressed as sums of individual demand functions.

Jorgenson *et al.* (1997a) have constructed an aggregate model of consumer behavior based on Lau's (1977) theory of exact aggregation. The exact aggregation model included the demographic characteristics of individual households, as well as prices and household expenditures, as determinants of consumer behavior. The model was implemented from aggregate time series and individual household data. The demographic characteristics of the households successfully capture the enormous heterogeneity of the US population reflected in census and survey data and emphasized by Browning *et al.* (1999).

Jorgenson and Slesnick (2008) have recently extended the exact aggregation approach to include labor supply, as well as the intertemporal allocation of full wealth. Full wealth includes the value of the household's human wealth, as well as the household's tangible and financial wealth. Jorgenson and Slesnick (2008) implement this model of aggregate demand for goods and leisure for the US using 150,000 individual household observations from the consumer expenditure survey (CEX) and price data from the consumer price index (CPI) for US regions at different points of time (Bureau of Labor Statistics, 2012a, 2012b).

The exact aggregation approach to econometric modeling of data for individual households generates a model of aggregate behavior. The fact that individual demand functions can be recovered from the aggregate demand functions makes it possible to evaluate energy and environmental policies in terms of measures of individual welfare, as demonstrated by Jorgenson *et al.* (1997b). We extend these measures of household welfare to incorporate labor supply, using the model of Jorgenson and Slesnick (2008) discussed in Chapter 17 of this Handbook.

8.2 IGEM

In this section we describe the main features of the IGEM used in this chapter for analyzing energy, the environment and US economic growth.[6] The core of the supply side of the model is the domestic production sector modeled by Jin and Jorgenson (2010). This is augmented by models of imports from the rest-of-the-world sector. The core of the demand side is the household sector modeled by Jorgenson and Slesnick (2008). This is supplemented by models of investment and government demand and models of exports to the rest of the world.

We distinguish among 35 industries and commodities listed in Table 8.1, including the five energy-producing sectors – coal mining, petroleum and natural gas mining, petroleum refining, electric utilities, and gas utilities. Each commodity is the primary product of one of the industries. Non-comparable imports (NCIs) are a 36th commodity that is not produced domestically, but enters as an input into production. We describe the main agents in the model in turn, beginning with the household sector.

[6] A summary of the model is given by Environmental Protection Agency (2012b). http://www.epa.gov/climatechange/economics/modeling.html.

Table 8.1 Industry output, energy use in 2005 and historical growth

		Output (billion $)	Energy share (% output)	Output growth 1960–2005 (% p.a.)	TFP growth 1960–2005 (% p.a.)
1	Agriculture, forestry, fisheries	424	4.4	2.00	1.40
2	Metal mining	25	9.8	0.67	−0.60
3	Coal mining	26	12.5	2.21	1.17
4	Crude oil and gas extraction	260	7.6	0.40	−0.58
5	Non-metallic mineral mining	24	12.3	1.56	0.27
6	Construction	1356	2.7	1.60	−0.61
7	Food products	595	1.8	2.01	0.52
8	Tobacco products	31	0.7	−0.83	−1.52
9	Textile mill products	60	3.2	1.17	1.56
10	Apparel and other textile products	36	1.4	−0.28	0.97
11	Lumber and wood products	130	2.9	2.03	0.15
12	Furniture and fixtures	101	1.9	3.27	0.69
13	Paper and allied products	168	4.4	2.04	0.47
14	Printing and publishing	230	1.1	1.83	−0.15
15	Chemicals	521	4.9	2.81	0.55
16	Petroleum refining	419	51.3	1.63	0.08
17	Rubber and plastic products	188	2.5	4.21	0.87

18	Leather and leather products	6	2.7	−2.36	0.33
19	Stone, clay and glass products	129	5.9	1.90	0.54
20	Primary metals	251	5.1	0.84	0.32
21	Fabricated metal products	296	2.2	1.94	0.51
22	Industrial machinery	424	1.3	5.92	2.65
23	Electrical machinery	331	1.4	6.50	3.81
24	Motor vehicles	442	0.9	3.22	0.27
25	Other transportation equipment	227	1.3	1.91	0.28
26	Instruments	207	1.0	4.32	1.10
27	Miscellaneous manufacturing	61	1.8	2.18	0.88
28	Transportation and warehousing	668	13.1	3.01	0.99
29	Communications	528	0.8	5.65	1.16
30	Electric utilities (services)	373	14.2	2.94	0.30
31	Gas utilities (services)	77	55.0	−0.45	−0.86
32	Wholesale and retail trade	2488	3.2	3.72	0.84
33	Finance, insurance and real estate (FIRE)	2752	1.2	4.19	0.77
34	Personal and business services	4354	1.7	3.93	−0.27
35	Government enterprises	328	7.8	2.43	0.19

"Energy share" includes feedstocks.

8.2.1 Household behavior and demographic characteristics

Our household model has three stages. In the first stage, *lifetime full income* is allocated between consumption and savings. Full income includes leisure as well as income from the supply of capital and labor services. Consumption consists of commodities and leisure and we refer to this as *full consumption*. In the second stage, full consumption is allocated to leisure and three commodity groups — non-durables, capital services and services. In the third stage, the three commodity groups are allocated to the 36 commodities, including the five types of energy. We next describe the three stages of the household model.

8.2.1.1 Stage 1: intertemporal optimization

Let V_{kt} denote the utility of household k derived from consuming goods and leisure during period t. In the first stage household k maximizes the expectation of an additively separable intertemporal utility function:

$$\max_{F_{kt}} U_k = E_t\left\{ \sum_{t=1}^{T} (1+\rho)^{-(t-1)} \left[\frac{V_{kt}^{(1-\sigma)}}{(1-\sigma)} \right] \right\}, \tag{8.1}$$

subject to the lifetime budget constraint:

$$\sum_{t=1}^{T} (1+r_t)^{-(t-1)} PFF_{kt} \leq W_k, \tag{8.2}$$

where PFF_{kt} is the value of full consumption in period t, the value of goods and leisure, r_t is the nominal interest rate, W_k is full wealth, σ is an intertemporal curvature parameter, and ρ is the subjective rate of time preference. The expectation based on the dataset at time t is denoted $E_{t.}$

The term full wealth refers to the present value of future earnings from the supply of tangible assets and labor, plus transfers from the government, and imputations for the value of leisure. Tangible assets include domestic capital, government bonds and net foreign assets. Equations (8.1) and (8.2) are standard in growth models found in macroeconomics textbooks.[7] In describing the second stage of the household model below, we show that V_{kt} is a function of the prices of goods and leisure and may be regarded as the quantity of full consumption, $V_{kt} = F_{kt}$. The price of full consumption is the value of full consumption, divided by this quantity index, $PF_{kt} = PFF_{kt}/F_{kt}$.

[7] See, e.g. Barro and Sala-i-Martin (2004).

The first-order condition for intertemporal optimality is expressed in the Euler equation:

$$\Delta \ln PF_{k,t+1}F_{k,t+1} = (1-\sigma)\Delta \ln V_{k,t+1} + \Delta \ln\Big(-D\Big(p_{k,t+1}\Big)\Big) + \ln(1+r_{t+1}) - \ln\Big(1+\rho\Big) + \eta_{kt}, \tag{8.3}$$

where $D(p_{kt})$ is a function of the prices of goods and leisure. This arises from expressing V_{kt} as a function of these prices (see (8.13) below); η_{kt} is an expectational error. Jorgenson *et al.* in Chapter 17 of this Handbook describe how the household Euler equation is estimated from data for synthetic cohorts obtained by adding over all households in each cohort. From these household Euler equations we derive an aggregate Euler equation. This Euler equation is forward-looking, so that the current level of full consumption incorporates expectations about all future prices and discount rates.

In the simulations reported below we use a simplified version of the aggregate Euler equation with the curvature parameter σ equal to one. This is used in the version of IGEM given in Jorgenson and Wilcoxen (1998), and is written simply as:

$$\frac{F_t}{F_{t-1}} = \frac{(1+n_t)(1+r_t)}{1+\rho}\ \frac{PF_{t-1}}{PF_t}, \tag{8.4}$$

where n_t is the rate of growth of population.

8.2.1.2 Stage 2: goods and leisure

In the second stage of the household model, full consumption is divided between leisure time and personal consumption expenditures on commodities. Given the time endowment of the household sector, the choice of leisure time also determines the supply of labor. The allocation of full consumption employs a very detailed household demand model that incorporates demographic characteristics of the population. The database for this model includes the CEX and the CPI, and is described in greater detail in Chapter 17. Since the model is based on the National Income and Product Accounts (NIPAs), we need to distinguish the concept of personal consumption expenditures (PCE) employed there from the concept employed in the CEX. We use the "X" superscript to denote variables associated with the CEX.

Conceptually, we determine the consumption C_{ik}^X of commodity i for household k by maximizing a utility function $U(C_{1k}^X, \ldots C_{ik}^X \ldots C_{Rk}^X; A_k)$, where C_{Rk}^X is leisure and A_k denotes the demographic characteristics of household k, such as the number of children and region of residence. We arrange the 35 distinctly identified inputs into a tier structure. This is shown in Table 8.2 along with the values of the inputs in 2005. The names of the nodes of the tier structure are capitalized. At the top tier, the utility function

Table 8.2 Tier structure of consumption function, 2005 (billion $)

Full consumption	23,423	Non-durables	2715	Energy	503	gasoline and oil	284		
						fuel-coal	21	coal	0.3
								fuel-oil	21
						electricity	133		
						gas	65		
				Food	1270	food	720		
						meals	449		
						meals-emp	12		
						tobacco	88		
				Consumer goods	942	clothing-shoe	342	shoes	55
								clothing	287
						household articles	181	toilet articles; cleaning	138
								furnishings	43
						drugs	265		
						miscellaneous goods	154	toys	66
								stationery	20
								imports	7
								reading materials	61
		Capital Services	1972						
		Consumer Services	4303	Housing	536	rental housing	334		
						owner maintenance	202		
				Household operation	281	water	64		
						communications	133		
						domestic service	20		
						other household	64		
				Transportation	324	own transportation	263		
						transportation services	62		
				Medical	1491	medical services	1350		
						health insurance	141		
				Miscellaneous services	1670	personal services	116		
						business services	646	financial services	499
								other business services	147
						recreation	458	recreation	358
								foreign travel	100
						education and welfare	451		
		Leisure	14,432						

depends on Non-durables, Capital Services, Consumer Services and Leisure; in the second tier, the Non-durables node is a function of three other subaggregates (Energy, Food and Consumer goods) and the Consumer Services node is a function of five other subaggregates:

$$U = U\left(C_{ND,k}, C_{K,k}, C_{SV,k}, C_{R,k}; A_k\right); C_{ND} = C\left(C_{EN}, C_{FD}, C_{CG}\right); C_{SV} = C\left(C_{\text{housing}}, \ldots C_{\text{misc svcs}}\right). \tag{8.5}$$

A major difference between our classification system and PCE from the US NIPAs is the treatment of consumers' durables. Purchases of new housing are included in investment in the NIPAs, while only the annual rental value of housing is included in PCE. Purchases of consumers' durables such as automobiles are treated as consumption expenditures in the PCE, but in the new architecture for the national accounts they are treated symmetrically with housing. Investment in housing and consumers' durables are included in investment and annual rental values are treated as consumption.

We first describe how the parameters of the top tier of the household model are estimated from the CEX. We then indicate how the model for individual households is aggregated to obtain the model of the household sector in IGEM. Summation over all households gives the total demand for commodity i:

$$PC_{it}^{X} C_{it}^{X} = \sum_{k} P_{ikt}^{CX} C_{ikt}^{X} \quad i = 1, 2, \ldots, R. \tag{8.6}$$

The price P_{ik}^{CX} is the price of good i faced by household k. Similarly, total leisure demand, $PC_R C_R^X$, is the sum over all leisure demands, and the sum of goods and leisure gives full consumption:

$$PF_t F_t = \sum_{i} PC_{it}^{X} C_{it}^{X} + PC_R C_R^X. \tag{8.7}$$

In order to characterize substitutability among leisure and the commodity groups, we find it convenient to derive household k's demands from a translog indirect utility function $V(p_k, m_k; A_k)$, where:

$$-\ln V_k = \alpha_0 + \alpha^{H} \ln \frac{p_k}{m_k} + \frac{1}{2} \ln \frac{p_k}{m_k}' B^{H} \ln \frac{p_k}{m_k} + \ln \frac{p_k}{m_k}' B_A A_k, \tag{8.8}$$

p_k is a vector of prices faced by household k, σ^{H} is a vector of parameters, B^{H} and B_{A} are matrices of parameters that describe price, total expenditure and demographic effects.[8] The value of full expenditure on leisure and the three commodity groups is:

$$m_k = P_{ND}^{C} C_{NDk} + P_{K}^{C} C_{Kk} + P_{SV}^{C} C_{SVk} + P_{R}^{C} C_{Rk}. \tag{8.9}$$

8 This indirect utility function satisfies the restrictions implied by exact aggregation over households to obtain aggregate demand. These restrictions are discussed in more detail in Jorgenson and Slesnick (2008) and Chapter 17.

In (8.8) the demands are allowed to be non-homothetic, so that full expenditure elasticities are not constrained to be equal to unity.

The commodity groups in (8.5) and (8.9) represent consumption of these commodities by household k. The leisure consumed by household k takes into account the different opportunity costs of time of different members of the household. To do this we use the after-tax wage p_{Rk}^m. We assume that the effective quantity of leisure of person m $\left(R_k^m\right)$ is non-work hours multiplied by the after-tax wage relative to the base wage, that is, multiplied by an effectiveness index: $q_k^m = p_{Rk}^m / p_R^0$.

We assume a time endowment of $\bar{H} = 14$ hours a day for each adult. The annual leisure of person m is the time endowment, less hours worked LS; thus, effective leisure is:

$$R_k^m = q_k^m\left(\bar{H}_k^m - LS_k^m\right) = q_k^m\left(14 * 365 - \text{hours worked}_k^m\right). \tag{8.10}$$

The quantity of leisure for household k is the sum over all adult members:

$$C_{Rk} = \sum_m R_k^m, \tag{8.11}$$

and the value of household leisure is:

$$P_R^C C_{Rk} = p_R^0 \sum_m R_k^m = \sum_m p_{Rk}^m\left(\bar{H}_k^m - LS_k^m\right). \tag{8.12}$$

The demand functions for commodities and leisure are derived from the indirect utility function (8.8) by applying Roy's Identity:

$$\mathbf{w}_k = \frac{1}{D(p_k)}\left(\alpha^{\mathrm{H}} + B^{\mathrm{H}} \ln p_k - \iota' B^{\mathrm{H}} \ln m_k + B_A A_k\right), \tag{8.13}$$

where $\mathbf{w}_k$ is the vector of shares of full consumption, ι is a vector of ones and $D(p_k) = -1 + \iota' B^{\mathrm{H}} \ln p_k$. For example, the demand for consumer non-durables is:

$$w_{ND,k} = -\frac{1}{D(p_k)}\left(\alpha_{ND}^{\mathrm{H}} + B_{ND\cdot}^{\mathrm{H}} \ln p_k - \iota B^{\mathrm{H}} \ln m_k + B_{A,ND\cdot} A_k\right), \tag{8.14}$$

where $B_{ND\cdot}^{\mathrm{H}}$ denotes the top row of the B^{H} matrix of share elasticities.

The parameters of the translog indirect utility function must satisfy the restrictions:

$$B^{\mathrm{H}} = B^{\mathrm{H}'}; \iota' B^{\mathrm{H}} \iota = 0, \iota' B_A = 0, \iota' \alpha^{\mathrm{H}} = -1, \tag{8.15}$$

where B^{H} are the share elasticities, $\iota' B^{\mathrm{H}}$ represents the full expenditure effect and the kth column of B_{A} determines how the demands of demographic group k differ from the base group. These restrictions are implied by the theory of individual consumer behavior and the requirement that individual demand functions can be aggregated exactly to obtain the aggregate demand functions used in the model. The demographic characteristics of individual households employed in the model are given in Table 8.3.

Table 8.3 Demographic groups identified in household consumption model

Number of children	0, 1, 2, 3 or more
Number of adults	1, 2, 3 or more
Region	Northeast, Midwest, South, West
Location	urban, rural
Gender of head	male, female
Race of head	white, nonwhite

Table 8.4 Price and income elasticities

	Uncompensated price elasticity	Compensated price elasticity	Expenditure elasticity
Non-durables	−0.727	−0.651	0.673
Capital services	−1.192	−1.084	0.902
Consumer services	−0.561	−0.490	1.067
Leisure	0.014	−0.305	1.063
Labor supply	−0.032	0.713	−2.486

The estimated price and income elasticities are reported in Table 8.4. The elasticities are calculated for the reference household type — two adults, two children, Northeast, urban, male head, white. They are computed at $100,000 of full consumption in 1989. The compensated own-price elasticities are negative for all goods and services, as well as for leisure.

Capital services are price elastic, while non-durables, consumer services, and leisure are price inelastic. The uncompensated wage elasticity of household labor supply is negative but close to zero, a common finding in modeling labor supply, while the compensated wage elasticity is 0.7. The full consumption elasticity for leisure is greater than one, so that leisure is classified as a luxury. Non-durables and capital services are necessities with full consumption elasticities less than one, while services are a luxury.

Table 8.5 gives the fitted shares of the four commodity groups at different levels of full consumption for the reference household. The share allocated to non-durables falls

Table 8.5 Full expenditures and household budget shares

Full expenditures	Non-durables	Capital	Services	Leisure
7500	0.208	0.151	0.055	0.586
25,000	0.164	0.137	0.06	0.626
75,000	0.123	0.124	0.065	0.693
150,000	0.098	0.116	0.068	0.713
275,000	0.075	0.108	0.071	0.718
350,000	0.066	0.106	0.072	0.716

rapidly as expenditures rise while the share allocated to services rises a little. Leisure value is hours multiplied by wage rates and the share rises substantially with rising wage rates of the higher income households.

To incorporate the econometric model of household behavior in IGEM we derive an aggregate version of the household demand functions (8.13). Let n_k be the number of households of type k. Then the vector of consumption shares for the US economy:

$$SC^{\mathrm{X}} = \left(\frac{P_{ND}^{\mathrm{CX}} C_{ND}^{\mathrm{X}}}{MF^{\mathrm{X}}}, \frac{P_{K}^{\mathrm{CX}} C_{K}^{\mathrm{X}}}{MF^{\mathrm{X}}}, \frac{P_{SV}^{\mathrm{CX}} C_{SV}^{\mathrm{X}}}{MF^{\mathrm{X}}}, \frac{P_{R}^{\mathrm{CX}} C_{R}^{\mathrm{X}}}{MF^{\mathrm{X}}}\right)',$$

is obtained by aggregating over all types of households:

$$\begin{aligned} SC &= \frac{\sum\limits_k n_k m_k \mathbf{w}_k}{\sum\limits_k n_k m_k} \\ &= \frac{1}{D(p)} \left[\alpha^{\mathrm{H}} + B^{\mathrm{H}} \ln p - \boldsymbol{\iota} B^{\mathrm{H}} \xi^d + B_A \xi^{\mathrm{L}}\right], \end{aligned} \tag{8.16}$$

where the distribution terms are:

$$\xi^d = \sum_k n_k m_k \ln m_k / M; \quad M = \sum_k n_k m_k \tag{8.17}$$

$$\xi^{\mathrm{L}} = \sum_k n_k m_k A_k / M. \tag{8.18}$$

The national value of full consumption expenditures in CEX units is given by:

$$MF^{\mathrm{X}} = \sum_k n_k m_k = P_{ND}^{\mathrm{CX}} C_{ND}^{\mathrm{X}} + P_{K}^{\mathrm{CX}} C_{K}^{\mathrm{X}} + P_{SV}^{\mathrm{CX}} C_{SV}^{\mathrm{X}} + P_{R}^{\mathrm{CX}} C_{R}^{\mathrm{X}}. \tag{8.19}$$

By constructing an aggregate model of consumer demand through exact aggregation over individual demands, we are able to incorporate the restrictions implied by the theory of individual consumer behavior. In addition, we incorporate demographic information through the distribution terms (8.17) and (8.18). For the sample period we estimate the values of these distribution terms from microeconomic data. For the period beyond the sample we project the distribution terms, using projections of the population by sex and race. More formally, we project the number of households of type k, n_{kt}, by linking the age and race of the head of household to the projected population.

A final step deals with the difference between the CEX and PCE measures of consumption. The difference in the value of expenditures on non-durables is

$PN^{\mathrm{ND}}N^{\mathrm{ND}} - P_{ND}^{\mathrm{CX}}C_{ND}^{\mathrm{X}}$, where N^{ND} denotes the quantity on non-durable consumption in PCE units and PN^{ND} denotes its price.[9] The CEX omits many items in the PCE, such as employer-paid health insurance. Given the rising gap between these two measures of consumption we express the gap as an AR(1) process and project this forward. The value of full consumption is the sum of expenditures on non-durables, capital, services and leisure; this sum is the same in both CEX and PCE units and it is the value that appears in the Euler Equation (8.4) in the first stage:

$$PF_tF_t = PN^{\mathrm{ND}}N^{\mathrm{ND}} + PN^{\mathrm{K}}N^{\mathrm{K}} + PN^{\mathrm{CS}}N^{\mathrm{CS}} + PN^{\mathrm{R}}N^{\mathrm{R}} = MF^{\mathrm{X}}. \tag{8.20}$$

8.2.1.3 Stage 3: allocation of demands for commodities

In the third and final stage of the household model we allocate the quantities of non-durables, capital services, and other services (N^{ND}, N^{K} and N^{CS}) to the 35 commodities, NCIs and capital services, such as housing and consumers' durables. We do not employ demographic characteristics of households for this stage and allocate aggregate consumption, using a hierarchical model with the 17 nodes shown in Table 8.2. At each node m we represent the demand by a translog indirect utility function, $V^m(P^{\mathrm{H}m}, m_m; t)$:

$$-\ln V^m = \alpha_0 + \alpha^{\mathrm{H}m} \ln \frac{P^{\mathrm{H}m}}{m_m} + \frac{1}{2}\ln \frac{P^{\mathrm{H}m}}{m_m}' B^{\mathrm{H}m} \ln \frac{P^{\mathrm{H}m}}{m_m} + f^{\mathrm{H}m} \ln \frac{P^{\mathrm{H}m}}{m_m}. \tag{8.21}$$

$$\ln P^{\mathrm{H}m} \equiv \left(\ln PN_{m1}, \ldots, \ln PN_{mi}, \ldots, \ln PN_{m,im}\right)', \; i \in \text{node } m.$$

There are im inputs at node m and the value of aggregate expenditures at m is:

$$m_m = PN_{m1}N_{m1} + \ldots + PN_{m,im}N_{m,im}. \tag{8.22}$$

The shares of full consumption derived from (8.21) are similar to (8.13), but exclude demographic characteristics and impose homotheticity. Formally, we require $\iota' B^{\mathrm{H}m} = 0$. In order to model the changes in budget shares not explained by price movements we include latent variables, $f_t^{\mathrm{H}m}$, to represent changes in preferences. These latent variables are discussed in greater detail for the production model presented in Section 8.2.2 below.

The shares of consumption at node m simplify to an expression that is independent of the level of expenditures (m_m):

$$SN^m = \begin{bmatrix} PN_{m1}N_{m1}/PN^mN^m \\ \cdots \\ PN_{m,im}N_{m,im}/PN^mN^m \end{bmatrix} = \alpha^{\mathrm{H}m} + B^{\mathrm{H}m} \ln PN^{\mathrm{H}m} + f^{\mathrm{H}m}. \tag{8.23}$$

[9] For more detail, see Fixler and Jaditz (2002).

Under homotheticity the indirect utility function reduces to:

$$-\ln V^m = \alpha^{\mathrm{H}m} \ln P^{\mathrm{H}m} + \frac{1}{2} \ln P^{\mathrm{H}m\prime} B^{\mathrm{H}m} \ln P^{\mathrm{H}m} + f^{\mathrm{H}m} \ln P^{\mathrm{H}m} - \ln m_m. \tag{8.24}$$

We define the price for consumption at node m as:

$$\ln PN^m = \alpha^{\mathrm{H}m} \ln P^{\mathrm{H}m} + \frac{1}{2} \ln P^{\mathrm{H}m\prime} B^{\mathrm{H}m} \ln P^{\mathrm{H}m} + f^{\mathrm{H}m} \ln P^{\mathrm{H}m}. \tag{8.25}$$

The quantity of consumption in node m is an index of utility and the value of expenditures is the price multiplied by this quantity:

$$m_m = PN^m N^m. \tag{8.26}$$

As an example, for $m=3$ the energy aggregate is a function of N_6 (gasoline), N^{FC} (fuel-coal aggregate), N_{18} (electricity) and N_{19} (natural gas). The demand shares are functions of the prices of these four components and the state variables representing the non-price trends:

$$SN^{m=3} = \begin{bmatrix} PN_6 N_6 / PN^{m=3} N^{m=3} \\ \cdots \\ PN_{19} N_{19} / PN^{m=3} N^{m=3} \end{bmatrix} = \alpha^{\mathrm{H3}} + B^{\mathrm{H3}} \ln PN^{\mathrm{H3}} + f^{\mathrm{H3}}. \tag{8.27}$$

The value of energy purchases that appears in the next higher node for non-durables ($m=2$) is:

$$PN^{\mathrm{EN}} N^{\mathrm{EN}} = PN_6 N_6 + PN^{\mathrm{FC}} N^{\mathrm{FC}} + PN_{18} N_{18} + PN_{19} N_{19}. \tag{8.28}$$

A full set of estimates of unknown parameters of the household model for all 17 nodes is given by Jorgenson *et al.* (2009b). Most of the estimated share elasticities ($\beta_{ii}^{\mathrm{H}m}$) are between −0.1 and 0.1. About half are negative, i.e. the price elasticity is greater than one. The latent variables $f_t^{\mathrm{H}m}$ representing changes in preferences have noticeable trends in the sample period. For example, the term for electricity rises between the late 1960s and 1990 but has flattened since then.

The final step is to convert the model of household behavior based on PCE categories in the NIPAs to categories employed in the interindustry transactions tables. A major difference is that PCE is based on purchasers' prices whereas the input-output values are producers' prices and exclude trade and transportation. The PCE values are converted to input-output values by using the bridge table provided with the official benchmark input-output tables.[10] Denote the bridge matrix by $\mathbf{H}$, where H_{ij} is the share of input-output commodity i in PCE item j. The value of total demand for commodity i is:

$$VC_i = \sum_j H_{ij} PN_j N_j. \tag{8.29}$$

A similar link is required for the input-output commodity prices (PS_i) and the PCE prices (PN_j).

8.2.1.4 Leisure and household disposable income

The demand for leisure is given by the fourth element of the vector of shares of full consumption (8.16). Individual leisure is related to hours supplied to the labor market in (8.10). We construct an aggregate version of this equation by defining the aggregate time endowment LH_t as an index number of the population, where individuals are distinguished by gender, age and educational attainment. Let POP_{kt} denote the number of people in group k at time t and the price of time is the after-tax hourly wage of person k, $(1 - tl_t^m)P_{kt}^{\mathrm{L}}$. The value of the aggregate time endowment, allocating 14 hours a day to each person, is:

$$P_t^{\mathrm{h}} LH_t = VLH_t = \sum_k \left(1 - tl_t^m\right) P_{kt}^{\mathrm{L}} * 14 * 365 * POP_{kt}. \tag{8.30}$$

The value of time endowment is the product of the quantity LH and the price of hours, P^{h}. The Tornqvist index for the quantity of the time endowment is:

$$d \ln\ LH_t = \sum_k \frac{1}{2}\left(v_{kt}^{\mathrm{L}} + v_{kt-1}^{\mathrm{L}}\right) d \ln \left(14 * 365 * POP_{kt}\right), \tag{8.31}$$

where v_{kt}^{L} are the value shares and the k index runs over gender, age and educational attainment. In a similar manner, the quantity of aggregate leisure, N_t^{R}, is a Tornqvist index of the leisure hours in each population group, H_{kt}^{R}. The price of aggregate leisure, PN_t^{R}, is given by the value and the quantity index:

$$VR_t = PN_t^{\mathrm{R}} N_t^{\mathrm{R}} = \sum_k \left(1 - tl_t^m\right) P_{kt}^{\mathrm{L}} * H_{kt}^{\mathrm{R}} * POP_{kt}. \tag{8.32}$$

The price of aggregate time endowment (P_t^{h}) is not the same as the price of aggregate leisure due to the differences in aggregation weights and we relate the two with an aggregation coefficient:

$$PN_t^{\mathrm{R}} = \psi_{Ct}^{\mathrm{R}} P_t^{\mathrm{h}}. \tag{8.33}$$

[10] For the 1992 Benchmark in the *Survey of Current Business*, November 1997, this is given in table D, "Input-Output Commodity Composition of NIPA Personal Consumption Expenditure Categories."

Taking this aggregation coefficient into account, aggregate labor supply is time endowment less leisure:

$$LS = LH - \psi_C^{R} N^{R}. \tag{8.34}$$

The value of labor supply is equal the gross payments by employers less the marginal tax on labor income (tl^m). The payment by industry j ($PLD_j LD_j$) is given below (Equation 8.42). Summing over industry j gives the value of the labor supply:

$$P^{h} LS = P^{h} LH - PN^{R} N^{R} = \left(1 - tl^m\right) \sum_j PLD_j LD_j. \tag{8.35}$$

We next describe the household financial accounts. Household tangible income, Y_t, is the sum of after-tax capital income (YK^{net}), labor income (YL) and transfers from the government (G^{TRAN}):

$$Y_t = YK_t^{net} + YL_t + G_t^{TRAN} - TLUMP_t - twW_{t-1}. \tag{8.36}$$

The term twW_{t-1} represents taxes on wealth, and $TLUMP_t$ represents lump-sum taxes that are zero in the base case but may be different from zero for specific energy and environmental policies.

Labor income is the main source of household income. Labor income is employer payments less the average tax rate:

$$YL = P^{h} LS \frac{1 - tl^a}{1 - tl^m} = (1 - tl^a) \sum_j PLD_j LD_j. \tag{8.37}$$

We distinguish between marginal and average tax rates. The price of the time endowment and leisure refers to the marginal price, the wage rate reduced by the marginal tax rate, while income is reduced by average income taxes.

Capital income is the sum of dividend income (DIV) from the private stock of physical assets and financial assets in the form of claims on the government and rest of the world.

$$YK_t^{net} = DIV - YK^{gov} + \left(1 - tk\right)\left(GINT_t + Y_t^{row}\right). \tag{8.38}$$

The components of capital income are explained in more detail below. Private household saving is income less consumption, non-tax payments to the government (R_t^{N}) and transfers to rest of the world (CR):

$$S_t = Y_t - P_t^{CC} CC_t - CR_t - R_t^{N}. \tag{8.39}$$

8.2.2 Producer behavior and endogenous technical change

A key feature of IGEM is a specification of producer behavior that captures substitution among inputs in response to price changes and changes in technology. Modeling price substitution is especially important for analyzing the economic impacts of energy and environmental policies that induce substantial price changes. However, production patterns also depend on changes in output per unit of input or *total factor productivity (TFP)* and *biases of technical change* or changes in the composition of inputs unrelated to price changes. For example, energy use may decline in intensity due to energy-saving changes in technology, as well as substitution away from higher-priced energy.

We employ a production function for each of the 35 industries in IGEM. These industries are listed in Table 8.1 and include the five energy producers. The output of each industry is produced by using capital, labor and intermediate inputs. The value of capital services consists of all property-type income − profits and other operating surplus, depreciation and taxes on property. The price of capital services is the price of the corresponding asset, multiplied by an annualization factor that we denote as the *cost of capital*. The cost of capital consists of the rate of return, the rate of depreciation, less capital gains or plus capital losses, all adjusted for taxes.

The construction of the price of capital services and the cost of capital is described in Jorgenson *et al*. (2005, Chapter 5), and is based on the detailed development in Jorgenson and Yun (2001). The quantity of capital services for each industry is an aggregate of the service flows from all asset types. Our database identifies 62 asset categories including land and inventories. We emphasize that the price of capital services is distinct from the price of capital stock. The price of capital services is an annualized rental, while the capital stock price is the price for acquiring an asset.

Similarly, the quantity of labor input for each industry is a Tornqvist aggregate over the hours of work for different demographic categories, where the weights are the hourly compensation of workers, including wages and salaries and benefits. Our database identifies seven age groups, six education groups and the two genders. The construction of the labor input indices is described in Jorgenson *et al.* (2005, Chapter 6).

The construction of capital and labor indices is a critical feature of our historical dataset. Simple sums of hours worked or asset quantities would not fully capture the substitution possibilities within each aggregate. For example, a simple sum of computers and industrial buildings would fail to reflect the impact on capital input of substitution toward information technology equipment and software as prices of these inputs decline relative to buildings. Similarly, a simple sum of hours worked would not adequately characterize the impact on labor input of the substitution toward more highly educated workers as the educational attainment of the labor force increases.

Intermediate inputs are the 35 commodity groups consisting of domestically produced goods and competitive imports. There is a 36th input consisting of NCIs, defined in the official input-output tables to include goods not produced in the US, such as coffee, natural rubber and foreign port services. The generation of our data on industry-level outputs and intermediate inputs is described by Jorgenson chapter (2005, Chapter 4).

The output of the production sector is divided among 35 commodities, each the primary product of one of the 35 industries. Many industries produce secondary products as well, e.g. the petroleum-refining industry produces refined petroleum products and secondary products that are the primary outputs of the chemicals industry. The relation between industries and commodity output is given by the *make* matrix (or supply matrix) in the official input–output accounts. We model joint production of primary and secondary products as well as substitution among inputs and technical change for each industry.

8.2.2.1 Top-tier production function

The production function represents output from capital services, labor services and intermediate inputs. Output also depends on the level of technology t, so that for industry j:

$$QI_j = f\left(KD_j, LD_j, QP_1^j, QP_2^j, \ldots, QP_{35}^j, QP_{\mathrm{NCI}}^j, t\right), \quad j = 1, 2, \ldots, 35. \tag{8.40}$$

The dimensionality of this production function is intractable. We assume that the production function is separable in energy and materials inputs, so that output at the first stage of the production model depends on quantities of energy input and input of non-energy materials, as well as inputs of capital and labor services:

$$\begin{aligned} QI_j &= f\left(KD_j, LD_j, E_j, M_j, t\right) \\ E_j &= E\left(QP_3^j, QP_4^j, QP_{16}^j, QP_{30}^j, QP_{31}^j\right) \\ M_j &= M\left(QP_1^j, QP_2^j, QP_5^j, \ldots, QP_{35}^j, QP_{\mathrm{NCI}}^j\right). \end{aligned} \tag{8.41}$$

In the second stage of the production model the energy and non-energy inputs depend on the components of each of the aggregates. For example, energy input depends on inputs of coal, crude oil, refined petroleum products, natural gas, and electricity. Similarly, non-energy input depends on all the non-energy commodities listed in Table 8.1, plus NCIs. Energy and materials inputs are further allocated among the detailed commodity groups by means of the tier structure of the production model is given in Table 8.6. There is a total of 13 nodes in the tier structure with 11 of them describing non-energy material input.

We assume constant returns to scale and competitive markets, so that the production function (8.41) is homogeneous of degree one and the value of output is equal to the sum of the values of all inputs:

$$\begin{aligned} PO_{jt}QI_{jt} &= PKD_{jt}KD_{jt} + PLD_{jt}LD_{jt} + P_{Ejt}E_{jt} + P_{Mjt}M_{jt} \\ P_{Ejt}E_{jt} &= PS_{3t}QP_{3t}^j + PS_{4t}QP_{4t}^j + \ldots + PS_{31t}QP_{31t}^j \\ P_{Mjt}M_{jt} &= PS_{1t}QP_{1t}^j + PS_{2t}QP_{2t}^j + \ldots + PNCI_{jt}QP_{\mathrm{NCI},t}^j. \end{aligned} \tag{8.42}$$

Table 8.6 Tier structure of industry production function

	Symbol	Name	Components
1	Q	Gross output	Capital, Labor, Energy, Materials Q = *f*(K,L,E,M)
2	E	Energy	Coal mining, Petroleum and gas mining, Petroleum refining, Electric utilities, Gas utilities E = *f*(X3,X4,X16,X30,X31)
3	M	Materials (non-energy)	Construction, Agriculture materials, Metallic materials, Non-metallic materials, Services materials M = *f*(X6,MA,MM,MN,MS)
4	MA	Agriculture materials	Agriculture, Food manufacturing, Tobacco, Textile-apparel, Wood-paper MA = *f*(X1,X7,X8,TA,WP)
5	MM	Metallic materials	Fabrication-other metals, Machinery materials, Equipment MM = *f*(FM,MC,EQ)
6	MN	Non-metallic materials	Non-metal mining, Chemicals, Rubber, Stone, Miscellaneous manufacturing MN = *f*(X5,X15,X17,X19,X27)
7	MS	Services materials	Transportation, Trade, FIRE, Services, OS MS = *f*(X28,X32,X33,X34,OS)
8	TA	Textile-apparel	Textiles, Apparel, Leather TA = *f*(X9,X10,X18)
9	WP	Wood-paper	Lumber-wood, Furniture, Paper, Printing WP = *f*(X11,X12,X13,X14)
10	OS	Other services	Communications, Government enterprises, NCIs OS = *f*(X29,X35,X_NCI)
11	FM	Fabricated-other metals	Metal mining, Primary metals, Fabricated metals FM = *f*(X2,X20,X21)
12	MC	Machinery materials	Industrial machinery, Electric machinery MC = *f*(X22,X23)
13	EQ	Equipment	Motor vehicles, Other transport equipment, Instruments EQ = *f*(X24,X25,X26)

Each industry j is composed of many firms, each maximizing profits independently. In order to simplify the characterization of substitution and technical change for the industry we assume that these firms face the same price for commodity i, PS_{it}. Under this assumption, it is more convenient to work with the price function, rather than the production function (8.41).[11] The price function expresses the price of output as a function of the input prices and technology.

[11] The price function contains the same information about technology as the production function. For further details, see Jorgenson (2000).

We have chosen the translog form of the price function, so that substitutability in response to price changes can be characterized in a flexible manner and changes in technology can be represented by latent variables through the Kalman filter, as in Jin and Jorgenson (2010):

$$\ln PO_t = \alpha_0 + \sum_i \alpha_i \ln p_{it} + \frac{1}{2} \sum_{i,k} \beta_{ik} \ln p_{it} \ln p_{kt} + \sum_i \ln p_{it} f_{it}^{\mathrm{p}} + f_t^{\mathrm{p}} \tag{8.43}$$

$$p_i, p_k = \{PKD, PLD, P_{\mathrm{E}} P_{\mathrm{M}}\}.$$

α_i, β_{ik} and α_0 are parameters that are separately estimated for each industry, and we have dropped the industry "j" subscript for simplicity.

The "p" superscript on the f_{it}^{p} s denotes that these are latent variables for the production sector. There are similar variables for the consumption, investment and import demand functions. The vector of latent variables, $\xi_t = (1, f_{Kt}^{\mathrm{p}}, f_{Lt}^{\mathrm{p}}, f_{Et}^{\mathrm{p}}, f_{Mt}^{\mathrm{p}}, \Delta f_t^{\mathrm{p}})'$, is generated by a first-order vector autoregressive scheme:

$$\xi_t = F\xi_{t-1} + v_t. \tag{8.44}$$

An important advantage of the translog price function is that it generates equations for the input shares that are linear in the logarithms of the prices and the latent variables. Differentiating Equation (8.43) with respect to the logarithms of the prices, we obtain equations for the shares of inputs. For example, if we differentiate with respect to the price of capital services, we obtain the share of capital input:

$$v_K = \frac{PKD_t KD_t}{PO_t QI_t} = \alpha_K + \sum_k \beta_{Kk} \ln P_k + f_{Kt}^{\mathrm{p}}. \tag{8.45}$$

The parameters $\{\beta_{ik}\}$ are *share elasticities*, giving the change in the share of the *i*th input in the value of output with respect to a proportional change in the price of the *k*th input. These parameters represent the degree of substitutability among the capital (K), labor (L), energy (E), and non-energy (M) inputs. If the share elasticity is positive, the value share increases with a change in the price of the input, while if the share elasticity is negative, the share decreases with a change in the price. A zero share elasticity implies that the value share is constant, as in a linear-logarithmic or Cobb—Douglas specification of the technology.

The price function is homogeneous of degree one, so that a doubling of input prices results in a doubling of the output price. This implies that the row and column sums of the matrix of share elasticities must be equal to zero:

$$\sum_i \beta_{ik} = 0 \text{ for each } k; \quad \sum_k \beta_{ik} = 0 \text{ for each } i. \tag{8.46}$$

Symmetry of the price effects implies that the matrix of share elasticities is symmetric. Monotonicity and concavity restrictions on the price function are discussed along with further details on estimation in Jorgenson *et al.* in Chapter 17 of this Handbook.

The level of technology f_t^{p}, together with the biases of technical change $\{f_{it}^{\mathrm{p}}\}$, evolves according to equation (8.44). The latent variable f_t^{p} represents the level of technology, a declining value corresponding to a decline in output prices or positive growth in productivity. The first difference of the level of technology takes the form:

$$\Delta f_t^{\mathrm{p}} = F_{p1} + F_{pK} f_{K,t-1}^{\mathrm{p}} + F_{pL} f_{L,t-1}^{\mathrm{p}} + F_{pE} f_{E,t-1}^{\mathrm{p}} + F_{pM} f_{M,t-1}^{\mathrm{p}} + F_{pp} \Delta f_{t-1}^{\mathrm{p}} + v_{pt}. \tag{8.47}$$

The latent variables $\{f_{it}^{\mathrm{p}}\}$ describe the *biases of technical change*. For example, if the energy share declines, holding prices of all inputs constant, the bias with respect to energy is negative and we say that technical change is energy-saving. Similarly, a positive bias implies that technical change is energy-using. While the parameters describing substitution in response to price changes are constant, the biases of technical change may vary from time to time. Historical patterns of production involve both energy-using and energy-saving technical change.

The estimated parameters are given in a supplement to Jorgenson and Jin (2010).[12] The β_{EE} coefficients for almost all the 35 industries are positive; the value share of energy rises with the price of energy, so that the quantity of energy input falls by less than the percentage rise in price. The β_{LL} coefficients, on the other hand, show a more varied pattern, the value share of labor input may rise or fall with higher wage rates.

Table 8.7 gives the cumulative change in the bias terms for various sub-periods. A positive value in the f_{Kt} column, for example, indicates a capital-using bias over this period. Most industries, 29 out of 35, have a capital-using bias in this period, that is, an increase in the use of capital beyond that explained by the fall in the cost of capital. Two-thirds of the industries had labor-saving technical change, the major exception being the labor-intensive Services and Construction industries. Eleven of the 35 industries have energy-saving technical change, while 20 industries have material-saving bias.

The major energy-intensive industries – Paper, Chemical products, Electric utilities and Gas utilities – have energy-saving technical change, while Petroleum refining, Stone, clay and glass, Primary metals, and Transportation have energy-using change. In the energy group Electric utilities have labor- and energy-saving technical change, while Petroleum refining has labor- and material-saving change. Technical change in Gas utilities is energy-saving, and capital-, labor- and material-using, while change in Coal mining is capital-using and change in Petroleum and gas mining is energy-saving.

12 See: http://www.economics.harvard.edu/faculty/jorgenson/recent_work_jorgenson.

Table 8.7 Changes in the bias of technical change latent variable

		1960–2005			
		Δf_{Kt}	Δf_{Lt}	Δf_{Et}	Δf_{Mt}
1	Agriculture	0.0436	−0.0109	0.0619	−0.0946
2	Metal mining	0.0250	0.0679	−0.0004	−0.0925
3	Coal mining	0.2528	−0.1836	−0.0589	−0.0103
4	Petroleum and gas	0.1192	0.0178	−0.2093	0.0722
5	Non-metallic mining	0.0046	0.0279	0.0588	−0.0913
6	Construction	0.0309	0.0151	0.0155	−0.0614
7	Food products	0.0655	0.0524	−0.0012	−0.1166
8	Tobacco products	0.0434	0.0304	−0.0003	−0.0735
9	Textile mill products	0.0007	0.0041	0.0175	−0.0223
10	Apparel and textiles	0.0545	−0.0493	−0.0009	−0.0043
11	Lumber and wood	0.0444	−0.0509	0.0145	−0.0081
12	Furniture and fixtures	0.0252	−0.0384	0.0044	0.0089
13	Paper products	0.0176	0.0125	−0.0054	−0.0247
14	Printing and publishing	0.0370	−0.0119	0.0020	−0.0271
15	Chemical products	0.1094	0.1155	−0.0232	−0.2018
16	Petroleum refining	0.1058	−0.0453	0.0695	−0.1300
17	Rubber and plastic	0.0365	0.0181	0.0012	−0.0557
18	Leather products	0.0790	−0.0291	0.0132	−0.0631
19	Stone, clay and glass	0.0580	−0.0731	0.0097	0.0054
20	Primary metals	0.0325	−0.0369	0.0262	−0.0217
21	Fabricated metals	0.0874	−0.1150	0.0054	0.0223
22	Industrial machinery	−0.0038	−0.0034	0.0031	0.0041
23	Electronic and electric equipment	0.0849	−0.0897	0.0023	0.0025
24	Motor vehicles	−0.0317	0.0151	0.0022	0.0145
25	Other transportation equipment	0.0008	−0.0001	0.0008	−0.0015
26	Instruments	0.0426	−0.1127	0.0033	0.0667
27	Miscellaneous manufacturing	0.0635	−0.1275	0.0021	0.0619
28	Transport and warehouse	0.0458	−0.0903	0.0372	0.0073
29	Communications	−0.0436	0.0005	0.0018	0.0413
30	Electric utilities	0.1013	−0.0471	−0.0646	0.0104
31	Gas utilities	0.0161	0.0180	−0.0467	0.0125
32	Trade	−0.0057	−0.0471	−0.0096	0.0625
33	FIRE	−0.0272	−0.0006	0.0041	0.0237
34	Services	−0.0063	0.0040	0.0034	−0.0011
35	Government enterprises	0.1797	−0.0316	0.0376	−0.1857

The change in the level of technology is given for the 35 industries in Table 8.8. This is calculated for the entire 1960–2005 period, the most recent decade 1995–2005 and the first 20 years of the projection period 2005–2025. While the majority of industries had falling prices and improving technology, there are nine industries with negative productivity growth over the 1960–2005 period. These poor performers include three

Table 8.8 Changes in the level of technology, sample period and projections (negative of change in f_t)

		$-\Delta f_t$ per year		
		1960–2005	**1995–2005**	**2005–2025**
1	Agriculture	0.0129	0.0155	0.0316
2	Metal mining	−0.0059	−0.0264	−0.0055
3	Coal mining	0.0107	0.0237	0.0114
4	Petroleum and gas	−0.0058	−0.0147	−0.0528
5	Non-metallic mining	−0.0026	−0.0065	−0.0027
6	Construction	−0.0066	−0.0108	−0.0048
7	Food products	0.0051	0.0054	0.0035
8	Tobacco products	−0.0163	−0.0336	−0.0167
9	Textile mill products	0.0149	0.0187	0.0154
10	Apparel and textiles	0.0102	0.0167	0.0095
11	Lumber and wood	0.0013	0.0057	0.0010
12	Furniture and fixtures	0.0059	0.0101	0.0063
13	Paper products	0.0043	0.0125	0.0038
14	Printing and publishing	−0.0025	0.0033	−0.0046
15	Chemical products	0.0043	0.0047	−0.0147
16	Petroleum refining	−0.0024	−0.0341	−0.0053
17	Rubber and plastic	0.0082	0.0089	0.0074
18	Leather products	0.0034	0.0035	0.0015
19	Stone, clay and glass	0.0045	0.0055	0.0118
20	Primary metals	0.0024	0.0103	0.0078
21	Fabricated metals	0.0048	0.0040	0.0052
22	Industrial machinery	0.0261	0.0500	0.0338
23	Electronic and electric equipment	0.0375	0.0591	0.0522
24	Motor vehicles	0.0019	0.0092	0.0045
25	Other transportation equipment	0.0022	0.0042	−0.0021
26	Instruments	0.0101	0.0132	0.0172
27	Miscellaneous manufacturing	0.0088	0.0115	0.0151
28	Transport and warehouse	0.0088	0.0087	0.0123
29	Communications	0.0099	0.0083	0.0121
30	Electric utilities	0.0011	0.0033	0.0119
31	Gas utilities	−0.0078	−0.0119	−0.0046
32	Trade	0.0072	0.0063	0.0066
33	FIRE	0.0076	0.0082	0.0066
34	Services	−0.0035	−0.0011	−0.0041
35	Government enterprises	0.0007	0.0042	−0.0114

energy industries – Petroleum and gas Mining, Petroleum refining, and Gas utilities – and the large labor-intensive industries, Construction and Services. On the other extreme, the information technology industries – Industrial machinery and Electrical machinery, containing computers and semiconductors – have very rapid productivity growth.

8.2.2.2 Lower-tier production functions for intermediate inputs

In the lower tiers of the model, energy and non-energy materials inputs are allocated to the individual commodities, as summarized in Table 8.6. The energy and materials aggregates are represented in (8.41) above. As before, we work with the price dual to the production function. To illustrate the elements of the tier structure we consider the translog price function for energy input:

$$\ln P_{Et} = \alpha_0 + \sum_{i\in \text{energy}} \alpha_i \ln P_{it}^{\mathrm{P,E}} + \frac{1}{2}\sum_{i,k}\beta_{ik}\ln P_{it}^{\mathrm{P,E}}\ln P_{kt}^{\mathrm{P,E}} + \sum_{i\in \text{energy}} f_{it}^{\text{node=E}} \ln P_{it}^{\mathrm{P,E}}$$

$$P_i^{\mathrm{P,E}} \in \left\{PS_3, PS_4, PS_{16}, PS_{30}, PS_{31}\right\}. \tag{8.48}$$

The share equations are obtained by differentiating with respect to the log price, for the first input, the coal mining commodity, the share demand is:

$$v_3 = \frac{PS_3 QP_3}{P_E E} = \alpha_3 + \sum_{k\in \text{energy}} \beta_{3k}\ln P_k^{\mathrm{P,E}} + f_{3t}^{\text{node=E}}. \tag{8.49}$$

The other four input demands corresponding to crude petroleum, refined petroleum products, electricity and natural gas are derived in a similar manner.

The components of the non-energy materials input include the other thirty commodities identified in IGEM, in addition to NCIs. The price functions for the subtiers (8.48) differ from the price function (8.43), since there is no latent variable representing the level of technology. This reflects the fact that the price of energy is an index number constructed from the prices of the individual components, while the price of output is measured separately from the prices of capital, labor, energy, and non-energy materials inputs. As before, the β_{ik} s are share elasticities; in the case of the energy node they represent the degree of substitutability among the five energy commodities.

The latent variables $\{f_{it}^{\text{node}}\}$ represent the biases of technical change. For example, an increase in the latent variable $f_{30t}^{\text{node=E}}$ implies that the electricity share of total energy input is increasing, so that technical change is electricity-using, while a decrease in this latent variable implies technical changes in electricity-saving. The latent variables are generated by a vector autoregression, as in (8.44).

Our econometric method for estimating the input share Equation (8.49) is identical to that for the top tier. Homogeneity, symmetry, and concavity restrictions are imposed for the subtier price functions. As shown in Table 8.6 there are 12 nodes in the subtiers, giving a total of 106 independent parameters (α_i and β_{ik}) for each industry after imposing these constraints. Some inputs are zero and thus the number of estimated parameters is less than 106; however, with 35 industries, the total number of parameters to be estimated for the subtiers exceeds 3000.

To summarize the highlights of the results: there is a wide range of estimates for the share elasticities. For example, in the Electric utilities tier structure the most elastic own price term is in the Textile-apparel node with a coefficient of −0.397, and the most inelastic own-price term is in Machinery with a coefficient of 0.225. This implies that the Leontief framework, imposing fixed input-output coefficients, is far too inflexible and imposes an artificially high welfare cost for policy changes.

The contribution of the bias of technical change is sizable in most cases. In the Electric utilities industry, for example, the node for Service materials (MS) has five inputs − Transportation, Trade, FIRE, Services and Other services (OS). The shares of these five inputs in 1996 were 23%, 13%, 22%, 37% and 45% respectively. The latent variable f_{it}^{NI} for transportation fell by 0.274 over this period, while FIRE rose by 0.052 and Services rose by 0.244.

In concluding this section we emphasize that the state-space model of producer behavior is required to capture the changes in patterns of production revealed in the data. Overly simplified formulations like the fixed coefficients of the Leontief framework would lead to inaccurate estimates of the cost of policy changes, generating costs that are far too high. Latent variables representing biases of technical change are required to track the changes in inputs that are not explained by price changes. Finally, a latent variable representing the level of technology is needed to capture differences in productivity growth rates across industries and over time.

8.2.2.3 Commodities, industries and output taxes

Production or sales taxes may be proportional to the value of output or expressed as a tax per unit of the quantity. We represent all taxes on production as an *ad valorem* tax that is proportional to value. In the policy simulations we introduce additional *ad valorem* or unit taxes. PO_j is the seller's price given in (8.43), and we refer the post-tax price as the industry price, PI_j:

$$PI_j = \left(1 + tt_j^{\text{full}}\right) PO_j, \tag{8.50}$$

where the "full" superscript denotes that it is the sum of the taxes described in (8.63).

We have noted that each industry makes a primary commodity and many industries also make secondary products that are the primary outputs of other industries. We denote the price, quantity, and value of commodity i by PC_i, QC_i and V_i^{QC} respectively, all from the purchasers' point of view. The shares contributed by the various industries to commodity i (m_{ji}) are given by the make matrix, as are the shares of output of industry j to the various commodities $\left(m_{ji}^{\text{row}}\right)$. To model joint production we fixed these shares to the base year's make matrix.

We assume that the production function for each commodity is a linear logarithmic aggregate of the outputs from the various industries, with these base shares as weights.

That is, the price of commodity i as a linear logarithmic function of the component industry prices:

$$\ln\ PC_i = \sum\nolimits_{j=1}^{35} m_{ji} \ln\ PI_j, \quad i = 1, 2, \ldots, 35. \tag{8.51}$$

The value of commodity output is the sum of the contributions from all industries:

$$V_{it}^{\mathrm{QC}} = \sum_j m_{ji}^{\mathrm{row}} PI_{jt} QI_{jt}. \tag{8.52}$$

The quantity of commodity i, QC_i, is this value divided by PC_i.

8.2.3 Investment and the cost of capital

Capital input in IGEM is derived from data on investment in structures, producers' durable equipment, land, inventories, and consumers' durables. This differs from the definition of investment in the NIPAs, which excludes consumers' durables.[13] As in the NIPAs, we consider government-owned capital separately from private capital. There are two sides to the private capital account. The capital stock is rented to the producers, as described in Section 8.2.2, and the annual rental payment is the capital income of the household sector. The flow of investment is purchased annually to replace and augment the capital stock. We consider both aspects of the capital market.

8.2.3.1 Aggregate investment and cost of capital

We assume that the supply of capital is determined by past investments; however, we assume that there are no installation or adjustment costs in converting new investment goods into capital stocks or transferring assets among industries. Under these assumptions the savings decision by the household is identical to the investment decision. We analyze the savings-investment decision in order to clarify the role of the cost of capital, a key equation of IGEM. Since capital formation is the outcome of intertemporal optimization, decisions today are based on expectations of future prices and rates of return. Policies announced today that affect future prices will affect investment decisions today.

The owner of the stock of capital chooses the time path of investment by maximizing the present value of the stream of after-tax capital income, subject to a capital accumulation constraint:

$$\mathrm{Max} \sum_{t=u}^{\infty} \frac{(1 - tk)(PKD_t \psi^{\mathrm{K}} K_{t-1} - tpPK_{t-1}) - (1 - t^{\mathrm{ITC}}) PII_t I_t^a}{\prod_{s=u}^{t} 1 + r_s} \tag{8.53}$$

[13] Land is not part of Investment in GDP. The rental from land is included in gross domestic income.

$$\text{s.t. } K_t = \left(1-\delta\right)K_{t-1} + \psi^{\mathrm{I}} I_t^a. \tag{8.54}$$

After-tax capital income $(1 - tk)\left(PKD_t\psi^{\mathrm{K}}K_{t-1} - tpPK_{t-1}\right)$ is related to the YK^{net} term in household income (8.36) and the discount rate r_s is the same as that in the Euler Equation (8.4).

The stock of capital available at the end of the period is K_t. The rental price of capital services is PKD_t. We require an aggregation coefficient ψ^{K} to convert the stock measure to a flow of services. The remaining terms are *tp,* the property tax rate, *tk,* the capital income tax rate, and *PK* the price of the capital stock. Finally, I_t^a is the quantity of aggregate investment, $(1 - t^{\mathrm{ITC}})PII_t$ is its price net of the investment tax credit, and ψ_t^{I} is an aggregation coefficient that reconciles the different compositions of investment and capital stock.

The solution of the maximization problem gives the Euler equation:

$$(1+r_t)\frac{\left(1-t^{\mathrm{ITC}}\right)PII_{t-1}}{\psi_{t-1}^{\mathrm{I}}} = (1-tk)\left(PKD_t\psi_t^{\mathrm{K}} - tpPK_{t-1}\right) + (1-\delta)\frac{\left(1-t^{\mathrm{ITC}}\right)PII_t}{\psi_t^{\mathrm{I}}}. \tag{8.55}$$

There is a simple interpretation of this equation: if we were to put $(1 - t^{\mathrm{ITC}})PII_{t-1}$ dollars in a bank in period $t-1$ we would earn a gross return of $(1 + r_t)(1 - t^{\mathrm{ITC}})PII_{t-1}$ at t. On the other hand, if we used those dollars to buy one unit of investment goods $(=\psi^{\mathrm{I}}$ units of capital) we would collect a rental for one period, pay taxes, and the depreciated capital would be worth $(1 - \delta)(1 - t^{\mathrm{ITC}})PII_t$ in period t prices. In a model without uncertainty these two returns are equal.

The assumption of no installation costs implies that new investment goods are perfectly substitutable for existing capital. This means that the price of capital stock is linked linearly to the price of aggregate investment:

$$PK_t = \psi_t^{\mathrm{PK}} PII_t\left(1 - t^{\mathrm{ITC}}\right). \tag{8.56}$$

The aggregation coefficient ψ_t^{PK} plays a symmetrical role to ψ_t^{I} and is used to reconcile the different weights of the asset types.

In equilibrium, the price of one unit of capital stock (*PK*) is the present value of the discounted stream of rental payments (*PKD*). Capital rental prices, asset prices, prices of capital stock, rates of return, and interest rates for each period are related by (8.55). This incorporates the forward-looking dynamics of asset pricing into our model of intertemporal equilibrium. The asset accumulation in Equation (8.54) imparts backward-looking dynamics.

Combining (8.56) and the Euler equation, we obtain the well-known cost of capital equation (Jorgenson, 1963):

$$PKD_t = \frac{1}{(1-tk)}\left[(r_t - \pi_t) + \delta(1+\pi_t) + tp\right]PK_{t-1}, \tag{8.57}$$

where $\pi_t = (PK_t - PK_{t-1})/PK_{t-1}$ is the asset inflation rate. The rental price of aggregate capital equates the demands for capital by the 35 industries and households with the aggregate supply given by K_{t-1}.

The rental payment by industry j for capital services is PKD_jKD_j, as specified in the industry cost function. The sum of these rental payments is the gross private capital income, $PKD_t\psi_t^K K_{t-1}$, in the objective function (8.53). This private capital income, less taxes, is the dividend income in (8.38) above:

$$DIV = (1-tk)\left[\sum_j PKD_jKD_j - tpPK_tK_t\right]. \tag{8.58}$$

8.2.3.2 Investment by commodity

The quantity of total investment in period t is I_t^a when the price isPII_t. In the NIPAs this total is an aggregate of investment by detailed asset classes – structures, producer durable equipment, consumer durables and inventories. In the benchmark input-output tables, expenditures in purchasers' prices are linked to producer prices via bridge tables in a way identical to how PCE is linked to the input-output categories as described earlier in Section 8.2.1.3.[14] Using these bridge tables, we have constructed a time series of investment demands by the 35 commodity groups employed in IGEM.

We allocate investment demand I_t^a to the 35 individual commodities by means of a hierarchical tier structure of production models similar to the demand for intermediate inputs in the producer model. This is given in Table 8.9, at the top tier we express aggregate investment as a function of fixed and inventory investment:

$$\begin{aligned} I^a &= I\left(I^{\text{fixed}}, I^{\text{inventory}}\right) \\ I^{\text{fixed}} &= I^f(IF_1, IF_2, \ldots, IF_{35}). \end{aligned} \tag{8.59}$$

As in the production and consumption submodels, we use translog price functions at each of the 15 nodes of the investment tier structure. For node m this is a function of the component prices $\{PII_{m1}, \ldots, PII_{m,im}\}$ and the latent variables $f_t^{\mathrm{I}m}$. For each node m,

[14] In the 1992 Input-Output Benchmark this bridge table is Table E in the *Survey of Current Business*, November 1997.

Table 8.9 Tier structure of investment function

	Symbol	Name	Components
	A	Aggregate Investment	Fixed investment, Inventory investment $I^a = I(I^{FX}, I^{IY})$
	IY	Inventory	All 35 commodities in flat Cobb–Douglas function VII^{IY}
1	FX	Fixed	Long-lived assets, Short-lived assets $I^{FX} = I(IF^{LG}, IF^{SH})$
2	LG	Long-lived assets	Construction, FIRE $IF^{LG} = I(IF_6, IF_{33})$
3	SH	Short-lived assets	Vehicles, Machinery, Services $IF^{SH} = I(IF^{VE}, IF^{MC}, IF^{SV})$
4	VE	Vehicles	Motor vehicles, Other transportation equipment $IF^{VE} = I(IF_{24}, IF_{25})$
5	MC	Machinery	Industrial machinery, Electrical machinery, Other machinery $IF^{MC} = I(IF_{22}, IF_{23}, IF^{MO})$
6	SV	Services	Services, Other services $IF^{SV} = I(IF_{32}, IF^{SO})$
7	MO	Other machinery	Gadgets, Wood products, Non-metallic products, Other miscellaneous. $IF^{MO} = I(IF^{GD}, IF^{WD}, IF^{MN}, IF^{OO})$
8	SO	Other services	Services, Transport-communications $IF^{SO} = I(IF_{34}, IF^{TC})$
9	GD	Gadgets	Primary metals, Fabricated metals, Instruments $IF^{GD} = I(IF_{20}, IF_{21}, IF_{26})$
10	WD	Wood products	Lumber and wood, Furniture and fixtures $IF^{WD} = I(IF_{11}, IF_{12})$
11	MN	Non-metallic products	Chemicals, Rubber, Stone, clay and glass, Miscellaneous manufacturing $IF^{MN} = I(IF_{15}, IF_{17}, IF_{19}, IF_{27})$
12	OO	Other miscellaneous	Mining aggregate, Textile aggregate, Paper $IF^{OO} = I(IF^{TX}, IF_{13}, IF^{MG})$
13	TC	Transport-communications	Transportation, Communications $IF^{TC} = I(IF_{28}, IF_{29})$
14	TX	Textile aggregate	Textile, Apparel, Leather, NCIs $IF^{TX} = I(IF_9, IF_{10}, IF_{18}, IF_{NCI})$
15	MG	Mining aggregate	Metal mining, Petroleum mining $IF^{MG} = I(IF_2, IF_4)$

there are *im* inputs and the set of inputs at that node is denoted $I_{\mathrm{INV}m}$. The price function is written in vector form as:

$$\ln PII^m = \alpha^{\mathrm{I}m\prime} \ln P^{\mathrm{I}m} + \frac{1}{2}\ln P^{\mathrm{I}m\prime} B^{\mathrm{I}m} \ln P^{\mathrm{I}m} + \ln P^{\mathrm{I}m\prime} f_t^{\mathrm{I}m} + \log \lambda^I \tag{8.60}$$

$$\ln P^{\mathrm{I}m} \equiv \left(\ln PII_{m1}, \ldots, \ln PII_{mi}, \ldots, \ln PII_{m,im}\right)' \; i \in I_{\mathrm{INV}m}.$$

The latent variable $f_t^{\mathrm{I}m}$ plays a role identical to that of f_{it}^{node} in (8.48) for the producer model, that is, it accounts for changes in demand patterns that cannot be explained by price movements. This vector of latent variables is also modeled as a VAR(1). The share demands corresponding to the price function are:

$$SI^m = \begin{bmatrix} PII_{m1}IF_{m1}/PII^m IF^m \\ \dots \\ PII_{m,im}IF_{m,im}/PII^m IF^m \end{bmatrix} = \alpha^{\mathrm{I}m} + B^{\mathrm{I}m}\ln PII^{\mathrm{I}m} + f_t^{\mathrm{I}m} \quad m, i \in I_{\mathrm{INV}m}. \tag{8.61}$$

Inventory investment is a variable that fluctuates with the business cycle which we do not model and we simply specify it as an exogenous share of aggregate investment:

$$VII^{\mathrm{inventory}} = \alpha^{\mathrm{IY}} VII. \tag{8.62}$$

Total inventory demand is allocated to the 35 commodities using fixed shares from the base year.

8.2.4 Government and rest of the world

The government plays an important role in IGEM. Government spending affects household welfare directly through transfer payments and public health spending, and indirectly through tax wedges. We do not specify a model for public goods and taxation, but set tax rates exogenously and take the shares of public expenditure by commodity as exogenous. We also set the government deficit exogenously, allowing the level of real purchases to be endogenous.

The government collects revenues for the social insurance trust funds and transfers these funds to households. In the new architecture for the US national accounts discussed by Jorgenson (2009), the trust funds are treated as part of household assets. For example, social security contributions and benefits are regarded as transfers within the household sector and not accounted as government revenue and expenditures. The tax rate on labor income in IGEM thus includes federal and state and local income taxes, but not social insurance contributions.

8.2.4.1 Government revenues and expenditures

The tax codes of the federal, state and local governments are very complex with progressive rates and numerous deductions and tax credits. We simplify these codes in order to obtain a tractable representation that captures the key distortions. The taxes that are explicitly recognized are sales taxes, import tariffs, capital income taxes, labor income taxes, property taxes and wealth or estate taxes.

The tax on production, tt_j^{full}, was introduced in (8.50) as putting a wedge between the seller's and purchasers' price, and it includes sales taxes and environmental taxes. The average sales tax rate is chosen to match the revenues collected, less subsidies. The labor taxes discussed in (8.35) give the effective price of leisure as the price paid by employers less the marginal tax rate tl^m. Similarly, the labor income received is the price after the average tax rate tl^a is given in (8.7). While the income tax code includes standard deductions, progressive rate schedules, alternative minimum taxes and federal-state interactions, our two labor tax rates captures the key feature that marginal rates are higher than average rates.

The effective capital income tax tk used in (8.38) and (8.57) shows the gap between the payments by producers and receipts by the household. The average tax rate represents the combined effect of corporate tax with personal income tax. The property tax tp also appears in the cost of capital Equation (8.57); this is mostly state and local property taxes. The wealth tax tw is a deduction from household income in (8.36).[15] Tariffs tr are described later in (8.71). Non-tax receipts, denoted R_t^N, include various fees charged by governments and appear as a household expenditure in (8.39). To reiterate: the effective tax rates are chosen to replicate the actual revenues; they are close, but not identical, to the statutory rates.[16]

In addition to taxes that are currently collected we introduce new taxes as part of an energy and environmental policy. Environmental taxes may be imposed on unit values or quantities (e.g. per dollar or per gallon). The externality or environmental tax on the sales value of industry j's output is denoted by tx_j^v, while the unit tax is tx_j^u. Other, non-environmental, unit taxes are denoted by tu_j. The result is that the total tax on a dollar of industry j's output is:

$$tt_j^{\text{full}} = tt_j + tx_j^v + \frac{tu_j + tx_j^u}{PO_j}\,. \tag{8.63}$$

This is the full tax on the industry output price PO_j introduced in (8.50).

The model also allows for a consumption tax, i.e. a tax on personal consumption expenditures but not on intermediate purchases. Also, taxes on capital may be modified, for example, by changing the deductibility of household mortgage interest from income for tax purposes. These features allow for the simulation of tax reforms combined with environmental taxes. In policy simulations we often impose a new tax or subsidy, but wish to maintain revenue neutrality. To implement the scenario where the new subsidy is offset by a lump-sum tax we introduce the variable $TLUMP$, which is subtracted from household income in (8.36) and added to government revenues in (8.65).

15 In the current NIPAs, this is a "capital transfer receipt" that affects the balance sheet but not the flow of disposable income. In IGEM we follow older conventions and account this as a reduction of household income that reduces the government's "net borrowing" account.

16 The estimated tax rates are given in Jorgenson *et al.* (2009b, table G1).

Government expenditures fall into three major categories – goods and services purchased from the private sector, transfers to the household and foreigners, and interest payments on debt to household and foreigners. These are denoted by VGG, $G^{\mathrm{TRAN}} + G^{\mathrm{tran,row}}$ and $GINT + GINT^{\mathrm{row}}$. We treat subsidies as negative sales taxes and include these in the calculation of taxes on outputs in (8.63). Transfers and interest payments are set exogenously as described in Section 8.3.2 below.

Total spending on commodities, including labor and capital services, is denoted VGG and this has to be allocated to individual commodities. Government consumption VG_i of commodity i is set to actual purchases in the sample period. For projections, these are fixed shares of total spending, using shares from the final year:

$$\begin{aligned} VG_{it} &= PS_{it} G_{it} = \alpha_i^{\mathrm{G}} VGG_t \\ PLD_{Gt} LD_{Gt} &= \alpha_L^{\mathrm{G}} VGG_t \\ VG_{GK,t} &= \alpha_K^{\mathrm{G}} VGG_t. \end{aligned} \tag{8.64}$$

The quantity of public consumption G_i is the value divided by the supply price. The government does not rent capital from the private sector but rather owns the stock of public capital. We follow the NIPAs in adding this imputation to both the expenditure side and the income side of the government accounts.

8.2.4.2 Total government accounts and deficits

The total revenue of the government is the sum of the sales tax, tariffs, property taxes, capital income taxes, labor income taxes, wealth taxes, non-tax revenues, unit output taxes, externality taxes, imputed capital consumption, income from government enterprises (industry 35) and lump-sum taxes:

$$\begin{aligned} R\_TOTAL = {} & R\_SALES + R\_TARIFF + R\_P + R\_K + R\_L + R\_W \\ & + R^{\mathrm{N}} + R\_UNIT + R\_EXT + VG_{GK} + YK^{\mathrm{gov}} + TLUMP, \end{aligned} \tag{8.65}$$

where:

$$R\_SALES = \sum_j tt_j PO_j QI_j; \; R\_TARIFF = \sum_i tr_i PM_i M_i;$$

$$R\_P = tpPK_{t-1} K_{t-1}; \; R\_K = tk\big(YK - R\_P\big) + tkGINT + tkY^{\mathrm{ROW}};$$

$$R\_L = tl^a P^{\mathrm{h}} LS/(1 - tl^m) = tl^a \sum_j PLD_j LD_j;$$

$$R\_W = tw(PK.K + BG + BF); \; R\_UNIT = \sum_j tu_j QI_j;$$

$$R\_EXT = \sum_j tx_j^{\mathrm{v}} PI_j QI_j + \sum_i tx_i^{\mathrm{rv}} PM_i M_i + \sum_j tx_j^{\mathrm{u}} QI_j + \sum_i tx_i^{\mathrm{ru}} M_i;$$

R^{N}, YK^{gov} and VG_{GK} are non-tax receipts, government enterprise surpluses and government capital consumption. Total government expenditures are the sum of purchases, transfers and interest payments to both domestic households and to the rest of the world:

$$EXPEND = VGG + G^{\mathrm{tran}} + G^{\mathrm{tran,row}} + GINT + GINT^{\mathrm{row}}. \tag{8.66}$$

Given our treatment of the social insurance funds as household assets, the government interest payments, $GINT$, include interest to the trust funds, minus payments from the funds to the government for operating expenses. These interest payments are normally set exogenously as a function of the projected government debt. IGEM allows an alternative formulation tying the payments to the endogenous rate of return.

The public deficit is total outlays less total revenues, a concept equal to the official net borrowing requirement:

$$\Delta G_t = EXPEND_t - R\_TOTAL_t. \tag{8.67}$$

These deficits add to the public debt which is separated between debt held by US residents and debt held by foreigners, $BG + BG^*$. The increase in the domestic debt is the total deficit less the portion financed by foreigners (negative government foreign investment, GFI),

$$BG_t = BG_{t-1} + \Delta G_t + GFI. \tag{8.68}$$

Historically, there are no official accounts of this equation; however, the BEA's recent "integrated macroeconomic accounts" provides this with a statistical discrepancy item that we also include.[17] The stock of debt to the rest of the world is, similarly, the accumulation of the foreign borrowing, including the statistical discrepancy:

$$BG_t^* = BG_{t-1}^* - GFI. \tag{8.69}$$

These deficit and stocks of debt are set to actual values for the sample period, and set to official projections beyond that.

To summarize: we set tax rates exogenously and set the deficit exogenously. The model generates economic activity and hence endogenous revenues. Government transfers and interest are also set exogenously. Thus, the remaining item, general government final purchases, VGG, is determined residually.

8.2.4.3 Rest of the world – imports, total supply and exports

Since IGEM is a one-country model, the supply of goods by the rest of the world, and the demand for US exports, are not modeled explicitly for each commodity. We follow the standard treatment and regard imports and domestic outputs as imperfect substitutes,

[17] See Teplin *et al.* (2006).

the Armington assumption, which is reasonable at our level of aggregation.[18] We also assume that US demand is not sufficient to change world relative prices.

The total supply of commodity i at period t is an aggregate of the domestic and imported varieties:

$$QS_{it} = QS(QC_i, M_i, t). \tag{8.70}$$

Domestic commodity supply QC_i is given earlier in (8.52), while M_i denotes the quantity of competitive imports. The price of imports is the world price multiplied by an effective exchange rate, plus tariffs tr and, possibly, new externality taxes tx:

$$PM_{it} = \left(1 + tr_{it} + tx_i^{\mathrm{rv}}\right) e_t PM_{it}^* + tx_i^{\mathrm{ru}}. \tag{8.71}$$

e_t is the world relative price; its role will be made clear after the discussion of the current account balance below.

We treat the total supply function in a similar manner to the model of producer behavior. The demands for domestic and imported varieties are derived from a translog price function for the total supply price:

$$\begin{aligned} \ln\ PS_{it} &= \alpha_{ct} \ln PC_{it} + \alpha_{mt} \ln PM_{it} + \frac{1}{2}\beta_{cc} \ln^2 PC_{it} + \frac{1}{2}\beta_{mm} \ln^2 PM_{it} \\ &\quad + \beta_{cm} \ln\ PC_{it} \ln PM_{it} + f_{ct}^{\mathrm{M}} \ln PC_{it} + f_{mt}^{\mathrm{M}} \ln\ PM_{it}. \end{aligned} \tag{8.72}$$

The demand for imports in share form derived from this cost function is:

$$\frac{PM_{it}M_{it}}{PS_{it}QS_{it}} = \alpha_{mt} + \beta_{mm} \ln \frac{PM_{it}}{PC_{it}} + f_t^{\mathrm{M}i}. \tag{8.73}$$

Again, when $\beta_{mm} = 0$ it implies that the demand has unit price elasticity, while a large positive value means an inelastic demand for imports. The total value of the supply of commodity i to the domestic market and exports is:

$$PS_{it}QS_{it} = PC_{it}QC_{it} + PM_{it}M_{it}. \tag{8.74}$$

Imports into the US have risen rapidly during our sample period, not only in absolute terms but as a share of domestic output. This change cannot be explained by price movements alone, so that we employ the state-space approach to modeling changes in the pattern of imports that are not induced by price movements. The right-hand side of (8.73) contains a latent variable, f_{it}^{M}, modeled as in the producer model (8.44). The estimated parameters are given in Jorgenson *et al.* (2009b, Table 3.9). The estimated β_{mm}s are quite elastic; many are negative, so that the substitution elasticity is greater than unity. The latent

[18] That is, while we may regard the imports of steel of a particular type as perfectly substitutable, the output of the primary metals industry is a composite of many commodities and would have an estimated substitution elasticity that is not large.

variables play particularly large roles in Leather, Apparel, and Miscellaneous manufacturing; the imports of crude oil and refined petroleum also have significant non-price effects.

We have now closed the loop in the flow of commodities. We began with the producer model purchasing intermediate inputs at price PS_i and selling output at price PO_j. The price of intermediates is the total supply price given in (8.24) as a function of domestic and imported commodities.

The inputs into the industry production functions include NCIs as listed in Table 8.6. In the zero-profit Equation (8.42), the value of such imports by industry j is $PNCI_j QP^j_{\text{NCI}}$. Like the competitive imports, the price of NCIs is the world price multiplied by the exchange rate:

$$PNCI_{jt} = \left(1 + tr_{jt}\right) e_t PNCI^*_{jt}. \tag{8.75}$$

Beyond the sample period, world prices are projected to change at the same rate as productivity growth in US industry prices. That is, PM^*_{it} is assumed to change at the same rate as the latent variable f^{P}_{it} in the domestic output price function (8.43).

For exports we also follow the standard treatment in single country models. A translog price function with a latent state variable is used to allocate supply between domestic supply and exports. Historical data on export prices received in the sample period move differently from prices of imports into the US. We simplify IGEM by using one world price for each commodity i. We thus write the allocation function in terms of the import price, PM_{it}:

$$SX^i_t = \frac{PC_{it} X_{it}}{PC_{it} QC_{it}} = \alpha_{xt} + \beta_{xx} \ln \frac{PM_{it}}{PC_{it}} + f^{\text{X}}_{it}. \tag{8.76}$$

We use a latent variable to track the historical changes that cannot be explained by price movements alone. We use the import prices instead of the actual export prices. Note that this function is derived from profit maximization by the supplier, so that the implied price function is convex, not concave as in the price function used in modeling imports. The share elasticities for the manufacturing commodities are between 0.05 and 0.31, with the biggest values in Other transportation equipment and Machinery (which includes computers). The latent variable play a smaller role in the export functions compared to the import functions in general, but is substantial for Electrical equipment and Motor vehicles.

The current account balance in dollars is the value of exports less imports, plus net interest receipts, and less private and government transfers:

$$\begin{aligned} CA_t = {} & \sum_i PC_i X_i - \sum_i e_t PM^*_i M_i - \sum_j ePNCI^*_j NCI_j + Y^{\text{row}}_t \\ & - GINT^{\text{row}} - CR_t - G^{\text{tran,row}}_t. \end{aligned} \tag{8.77}$$

The current account surplus, less the portion due to government foreign investment, adds to the stock of net private US foreign assets:

$$BF_t = BF_{t-1} + CA_t - GFI. \tag{8.78}$$

Note that the total claims on the rest of the world are the private assets less the government debt, $BF_t - BG_t^*$.

The closure of the external sector is treated in various ways in different trade models. One could set the current account exogenously and let the world relative price, e_t, adjust. Alternatively, one could set e_t exogenously and let the current account balance be endogenous. In a dynamic model the second option would require something like a portfolio choice model to determine the demand for foreign assets and hence the path of current account balances. This is beyond the scope of IGEM and we set the current account exogenously, making e_t endogenous, so that (8.77) is satisfied.

8.2.5 Emissions

IGEM is equipped with a number of externality variables that are defined to suit the needs of a particular analysis. These can include energy consumption in BTUs, emissions of carbon dioxide from combustion and sulfur dioxide emissions. For the analysis of climate change mitigation policy below, we define a single variable – total greenhouse gas emissions from all sources and gases.

The externalities in IGEM may be process-related, depending on output, or product-related, depending of the quantity of inputs such as coal. The externality coefficients for the environment are derived from the detailed historical data in the Environmental Protection Agency (2010b), *Inventory of US Greenhouse Gas Emissions and Sinks: 1990–2008*. This emissions series is sorted and aggregated to create the emissions totals corresponding to the externality variable defined above. These totals are then allocated based on the output and inputs of each industry and final demand sector.

$$EXT_{xt} = \sum_j XP_{jx} QI_{jx} + \sum_j \sum_{i \in \text{fuels}} XC_{ijx} QP_{it}^j. \tag{8.79}$$

The emission coefficients for the IGEM industries are described in more detail in Jorgenson *et al.* (2009b); we note here that there are trends in these industry-level aggregate coefficients due to changes in composition and other technical changes over time. For projections beyond the sample period, the emission coefficients either are set to the last sample point or, as appropriate, follow historical trends, but tapering to a steady state.

8.3 INTERTEMPORAL EQUILIBRIUM AND ECONOMIC GROWTH

The previous section describes all the components of supplies and demands for commodities and factor services in IGEM. This is a dynamic model with an intertemporal equilibrium, and we now characterize the equilibrium where all the supply and demand conditions are met. We present this in a manner that leads naturally to the development of the solution algorithm discussed below.

The Cass–Koopmans neoclassical model of economic growth has a saddle-path property: given the initial value of the state variable there is a unique value of the costate variable for which the model converges to a steady state that satisfies the transversality condition. In IGEM the capital stock is the state variable. The path of this stock is determined by the Euler equation derived by maximizing of the household's objective function. Full consumption is the costate variable.

Given the initial stock of capital, there is only one value of full consumption in the initial period that will be on the saddle path that satisfies the transversality condition. There are other state variables in the system, such as the government debt, claims on foreigners and the latent variables estimated by means of the Kalman filter. However, these state variables are not determined by optimizing behavior in IGEM, and are set exogenously and do not have associated costate variables.

In a disaggregated model like IGEM a well-defined steady state requires all industries to have the same rate of productivity growth in the very long run. In IGEM we focus on the intermediate term (75 years) and specify a TFP growth rate for each industry in the intermediate term that replicates the observed variety of behavior. After 75 years, we impose a zero rate of TFP growth and allow the model to converge to its steady state.

8.3.1 Market balance and intertemporal equilibrium

We first describe the equilibrium within each period, *given* the inherited capital stock and a guess of full consumption for that period. Under the assumptions of constant returns to scale and factor mobility the equilibrium prices clear all markets at zero profits for each period. We then describe the intertemporal equilibrium with the Euler equation linking full consumption across time periods.

In the commodity markets the demand side of the economy consists of intermediate demands by producers, household consumption, investment demand, government demand, and exports. The supply, QS_i, comes from domestic producers and imports as given in (8.74). In the equilibrium within each period, the industry output prices PO_j equate demands and supply:

$$PS_i QS_i = \sum_j PS_i QP_{ij} + PS_i(C_i + I_i + G_i) + PC_i X_i. \tag{8.80}$$

In capital market equilibrium, the demand for capital input from all industries and households is equal to the supply from the stock of inherited capital, K_{t-1}. We have been careful to stress the distinction between the stock and flow of capital and how these stock and flow measures are independently aggregated.[19] Capital income is equal to the aggregate service price multiplied by the effective service flow, which in turn is given by the capital stock multiplied by the aggregation coefficient ψ_t^{K}. The equilibrium condition in value terms is:

$$PKD_t \psi_t^{\mathrm{K}} K_{t-1} = \sum_j PKD_{jt} KD_{jt}. \tag{8.81}$$

Since we assume that capital is mobile across sectors, only one capital rental price is needed to clear this market. However, we observe different rates of return in the historical data. To reconcile this with our simplifying assumption of capital mobility, we treat the industry rental price as a constant times the economy-wide rental price:

$$PKD_{jt} = \psi_{jt}^{\mathrm{K}} PKD_t. \tag{8.82}$$

For the sample period we calculate the ψ_{jt}^{K} coefficients from the actual data on industry costs of capital, and for the projection period we set them equal to the last sample point. With these industry-specific adjustments, the economy-wide price PKD_t equates supply and demand for capital services:

$$\sum_{j=1}^{\mathrm{C}} \psi_{jt}^{\mathrm{K}} KD_{jt} = KD_t = \psi_t^{\mathrm{K}} K_{t-1}. \tag{8.83}$$

Turning to the labor market, supply (LS_t) comes from the household demand for leisure given in (8.16) and the demand is the sum over the demands from the 35 industries and government (LD_{jt}). The equilibrium condition in value terms is:

$$P_t^{\mathrm{h}} LS_t = P_t^{\mathrm{h}} \left(LH_t - \psi_{Ct}^{\mathrm{R}} N_t^{\mathrm{R}}\right) = \left(1 - tl_t^m\right) \sum_j PLD_{jt} LD_{jt}. \tag{8.84}$$

Recalling the discussion for the leisure price in (8.33), ψ_C^{R} is an aggregation coefficient linking the time endowment to aggregate leisure.

As with the price of capital input, the price of labor input differs across sectors in the historical data. To reconcile this with the simplifying assumption of labor mobility, we first set the economy-wide wage rate equal to the price of the time endowment (P^{h}), adjusted for the marginal labor tax. We then use fixed constants to scale the industry wage rates to the economy-wide wage rate:

$$PLD_j = \psi_j^{\mathrm{L}} \frac{P^{\mathrm{h}}}{(1 - tl^m)}. \tag{8.85}$$

19 The stocks are aggregated using asset price weights while the service flows are aggregated using the user cost of capital given in (8.59).

The price of aggregate time endowment, P^{h}, clears the market for labor:

$$LS_t = LH_t - \psi^{\mathrm{R}}_{Ct} N^{\mathrm{R}}_t = \sum_j \psi^{\mathrm{L}}_{jt} LD_{jt}. \tag{8.86}$$

Three additional equations must hold in equilibrium. The first is the exogenous government deficit (8.67), which is satisfied allowing government spending on goods VGG to be determined endogenously. The second is the exogenous current account surplus (8.77), which is satisfied by allowing the world relative price e_t to be endogenous. The third is the savings and investment equilibrium:

$$S_t = P^{\mathrm{I}}_t I^a_t + \Delta G_t + CA_t. \tag{8.87}$$

Household savings is first allocated to the two exogenous items – lending to the government to finance the public deficit (ΔG) and lending to the rest of the world (CA), both adjusted for government borrowing from abroad. The remainder is allocated to investment in domestic private capital. Investment and savings decisions are not separate in IGEM, so that (8.87) holds as a result of household intertemporal optimization.

8.3.1.2 Intertemporal equilibrium

The steady state of the Cass–Koopmans model is reached when the state and costate variables are stationary. The two dynamic equations – capital accumulation (8.54) and the Euler Equation (8.4) – determine the steady state (ss). By setting $K_t = K_{t-1}$ and $F_t = F_{t-1}$ we obtain the two equations that determine the steady state (in addition to the equations characterizing the intraperiod equilibrium just discussed):

$$\delta K_{\mathrm{ss}} = \psi^{\mathrm{I}}_{\mathrm{ss}} I^a_{\mathrm{ss}} \tag{8.88}$$

$$r_{\mathrm{ss}} = \rho. \tag{8.89}$$

The steady state obtains when investment exactly covers depreciation and the interest rate equals the rate of time preference.

Along the transition path, from the first period with the inherited state variables to the steady state, the following equations must hold: the capital accumulation Equation (8.54), the Euler Equation (8.4) linking full consumption between adjacent periods, the cost of capital Equation (8.57) linking the marginal product of capital with the rate of return and capital gains.

8.3.1.3 Solution algorithm

IGEM, as described so far, has some 4000 endogenous variables for each period. We approximate the steady state at $T = 120$ periods after the initial shock. We structure our algorithm to solve the model in steps that are described more fully in Jorgenson *et al.* (2009b, appendix J). Briefly, this algorithm consists of: (i) Solving for the steady state, (ii) guessing a path of full consumption, $\{F^g_t\}^T_{t=1}$, and (iii) calculating a sequence of intratemporal equilibria consistent with this guess and the initial capital stock. In the next step, (iv) the sequence of realized interest rates is used to check whether Euler Equation (8.4) holds in each period. If not, (v) the guessed vector of full consumption is revised and the process repeated. At the solution, the Euler equation holds for all t and is consistent with both the initial capital stock and the sequence of period-by-period interest rates.

For each intratemporal equilibrium, we do not solve 4000 equations simultaneously but rather triangulate the system into a series of nested loops, where each loop involves only a small number of equations and unknowns. This algorithm solves the resulting system quickly and is relatively easy to debug. Once the base-case transition path is determined, alternative policy cases usually only take seconds to compute.

8.3.2 Exogenous Projections and the Base Case

The variables determined outside the model include the time endowment, the level of technology represented by the state variables, the government and current account deficits, world prices, and the aggregation coefficients. While these exogenous variables are major determinants of the steady state and the growth rate in the base case, they play relatively modest roles in determining the effect of policy shocks. We briefly describe here how we project these exogenous variables and the behavior of the model in the base case; the details are in Jorgenson *et al.* (2009b).

The time endowment is a function of the population composition and relative wages, as given in (8.31). This is projected using the population projection by sex and age from the Bureau of the Census (2008).[20] We assume a small improvement in the level of educational attainment over the projection period as described in Jorgenson *et al.* (2009b, Chapter 2). We also assume that the relative wages of each demographic group remains unchanged at the last sample point.

In projecting hours we have to decide on the treatment of business cycles. In particular, the near term forecasts are for a slow recovery after the Great Recession of 2009, with a period of above average unemployment rates. A simulation beginning in 2010 that extrapolates average leisure hours observed in the sample period would overstate work, output and energy use. To avoid this we make a simple adjustment of the time endowment using the Congressional Budget Office projections of unemployment rates.

The government accounts include transfers, interest payments, deficits and stocks of debt which are all set exogenously. These are projected over the first 10 years using the forecasts of the federal budget from the Congressional Budget Office (Congressional Budget Office, 2010a), augmented by straightforward assumptions about state and local government accounts. Tax rates are given implicitly by the revenue forecasts. Beyond the 10-year window in Congressional Budget Office (2010a) we use the Long-Term

[20] Census Bureau projections of the US population released in 2008 are available at http://www.census.gov/population/www/projections/natproj.html.

Outlook in Congressional Budget Office (2010b) to generate the trend in tax rates out 75 years. The federal revenue from individual and corporate taxes is projected to rise from 11.4% of GDP in 2011 to 21.0% in 2060 under the "baseline scenario." Beyond 2020, the deficit is assumed to fall gradually to zero by 2060 to give a smooth transition to the steady state. The share of the deficit financed by foreigners is very high in the 2000s and we make a simple assumption that this share falls gradually back to zero in 2060.

There is less expert guidance for current account forecasts, we take the five-year forecast from IMF (2010) and then assume that it falls gradually to zero by 2060 in line with our assumptions about the government borrowing requirement. Growth in energy import prices is taken from the Energy Information Administration's *Annual Energy Outlook 2010* (Energy Information Administration, 2010). Finally, we note again that the state variables in the production, consumption, investment, import and export functions are projected using VARs like those in (8.44). These determine the non-price trends in input demands, consumption, imports and exports.

8.3.2.2 Base case

We simulate IGEM to create a base case with the setting of exogenous variables described above. The first years, 2010–2015, represent a continuation of recent trends and recovery from the Great Recession. Then, driven by demographics, vanishing budget and current account deficits, tax policy and the state variables for production, consumption, investment, exports and imports, the US economy experiences stable but slightly modulating growth as it tracks toward its steady state over the remainder of this century. From 2100 to 2110, expansion begins to slow, achieving a zero-growth steady state over the period 2110–2130.

Table 8.10 gives the average growth rates of key economic variables for the first 50 years of this expansion, 2010–2060. GDP growth averages 2.4% annually over this interval.

Table 8.10 Base case: macroeconomic outcomes (average annual growth in real quantities, 2010–2060, %)

Real GDP	2.4
Consumption	2.1
Investment	2.0
Government	1.8
Exports	4.0
Imports	2.3
Household full consumption (goods, services and leisure)	1.5
Capital stock	2.1
Labor demand (labor supply)	1.0
Leisure demand	1.1
Total factor productivity (value added)	0.8
Total greenhouse gas emissions ($GtCO_2$-e)	1.5

Consumption and investment grow more slowly as the historically rapid expansion in household and commercial capital slows. Growth in government purchases reflects the new fiscal realities of the base-case deficit and tax rate assumptions. Import growth, as expected, aligns with the overall economy while exports signal a rebalancing as a consequence of a continuing weakened dollar early on, high productivity in key export producing sectors such as agriculture and high technology manufacturing and vanishing current account deficits.

On the supply side, growth in aggregate final net output of 2.3% annually is provided by capital, labor and TFP. The growth in the capital stock leads to growth in capital services that contributes around 0.9 percentage points to output growth. The growth in labor input at 1.0% annually contributes another 0.6 percentage points annually with the balance provided by the approximately 0.8% annual growth in productivity.

As shown in growth rates of the 35 sectors in Table 8.11, there is a changing mix of energy inputs in the base case. Electricity use grows almost exactly with GDP at 2.4% annually. The inputs into power generation change with coal, gas and capital (e.g. renewables) fueling the load. Total national coal consumption grows at 2.5% annually, slightly faster than the overall economy. With petroleum and gas use growing at much slower rates, aggregate fossil fuel use tracks the overall economy but it too grows at a slower rate. Greenhouse gas emissions grow at 1.5% *per annum* (Table 8.10) and continue their decline relative to GDP, but not at the rates observed most recently. While petroleum and gas use diminish significantly in relative importance, electricity and, hence, coal use do not. In this base case simulation, it is the intensity of coal use that accounts for the slowing rate of decline in the ratio of emissions to GDP.

For the non-energy industries and commodities, the growth rates in Table 8.11 appear plausibly in line with growth overall and with expectations arising from historical observation. For example, US agriculture continues as a comparatively high productivity growth industry with corresponding benefits for US exports and food production and consumption. Productivity growth differences also are reflected in the slower growing construction and personal services sectors and the traditionally much more rapidly growing high technology non-electric and electric machinery industries. Growth in print and publishing gives way to other forms of communications and financial services continue to outpace the general economy. Finally, we see several industries (e.g. mining and metals) that clearly benefit from the aforementioned rebalancing of the US economy toward exports.

8.4 WELFARE MEASUREMENT

Our methodology for measuring the welfare effects of policy changes was introduced by Jorgenson *et al.* (1997b). The household sector is comprised of infinitely-lived households that we refer to as *dynasties*. Each household takes commodity prices, wage rates

Table 8.11 Base case: domestic industry and commodity outcomes (average annual growth in real quantities, 2010–2060, %)

		Production	Supply	Consumption
1	Agriculture	4.7	4.5	4.3
2	Metal mining	2.9	2.7	2.5
3	Coal mining	2.6	2.5	2.5
4	Petroleum and gas	0.4	0.4	0.4
5	Non-metallic mining	2.8	2.8	2.7
6	Construction	1.6	1.6	1.6
7	Food products	2.9	2.7	2.6
8	Tobacco products	0.2	0.2	0.2
9	Textile mill products	3.2	2.9	2.6
10	Apparel and textiles	2.9	2.5	2.4
11	Lumber and wood	2.6	2.4	2.4
12	Furniture and fixtures	1.7	1.6	1.5
13	Paper products	2.6	2.4	2.4
14	Printing and publishing	1.2	1.2	1.2
15	Chemical products	2.2	2.1	2.0
16	Petroleum refining	1.1	1.2	1.2
17	Rubber and plastic	2.8	2.6	2.6
18	Leather products	2.3	2.0	2.0
19	Stone, clay and glass	3.1	2.9	2.8
20	Primary metals	3.2	2.7	2.5
21	Fabricated metals	2.5	2.4	2.3
22	Industrial machinery	6.1	5.6	4.7
23	Electronic and electric equipment	6.0	5.6	4.8
24	Motor vehicles	2.8	2.3	2.0
25	Other transportation equipment	2.6	2.4	1.9
26	Instruments	2.8	2.7	2.6
27	Miscellaneous manufacturing	3.5	3.1	3.0
28	Transport and warehouse	3.2	3.1	2.9
29	Communications	3.2	3.2	3.2
30	Electric utilities	2.5	2.4	2.4
31	Gas utilities	1.7	1.9	1.9
32	Trade	2.2	2.2	2.2
33	FIRE	3.0	2.9	2.9
34	Services	1.7	1.7	1.7
35	Government enterprises	1.6	1.6	1.5

and rates of return as given. All dynasties are assumed to face the same vector of prices p_t and the same nominal rate of return r_t. The quantity of a com-modity, including leisure, consumed by dynasty d in period t is C_{ndt} and the full expenditure of dynasty d on consumption in period t is M_{dt}.

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

$$V_d = \sum_{t=0}^{\infty} \delta^t \ln V_{dt}, \tag{8.90}$$

where $\delta = 1/(1+\rho)$ and ρ is the subjective rate of time preference. The intratemporal indirect utility function is expressed in terms of *household equivalent members*, N_{dt}:

$$\ln V_{dt} = \alpha^{\mathrm{H}\prime} \ln p_t + \frac{1}{2} \ln p_t{}' B^{\mathrm{H}} \ln p_t - D(p) \ln \frac{M_{dt}}{N_{dt}}, \tag{8.91}$$

where:

$$N_{dt} = \frac{1}{D(p_t)} \ln p_t B_A A_d,$$

and A_d is a vector of attributes of the dynasty allowing for differences in preferences among households.

The utility function V_d is maximized subject to the lifetime budget constraint:

$$\sum_{t=0}^{\infty} \gamma_t M_{dt}(p_t, V_{dt}, A_d) = \Omega_d \tag{8.92}$$

where:

$$\gamma_t = \prod_{s=0}^{t} \frac{1}{1+r_s},$$

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

$$\ln M_{dt}(p_t, V_{dt}, A_d) = \frac{1}{D(p_t)} \left[\alpha^{\mathrm{H}\prime} \ln p_t + \frac{1}{2} \ln p_t{}' B^{\mathrm{H}} \ln p_t - \ln V_{dt} \right] + \ln N_{dt}. \tag{8.93}$$

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

$$\ln V_{dt} = \frac{D_t}{D_{t-1}} \ln V_{dt-1} + D_t \ln \left(\frac{D_{t-1} \gamma_t N_{dt} P_t}{\delta D_t \gamma_{t-1} N_{dt-1} P_{t-1}} \right), \tag{8.94}$$

where we have used D_t to denote $D(p_t)$ and the aggregate price term:

$$P_t = \exp \left(\frac{\alpha^{\mathrm{H}\prime} \ln p_t + \frac{1}{2} \ln p_t{}' B^{\mathrm{H}} \ln p_t}{D_t} \right). \tag{8.95}$$

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

$$\ln\ V_{dt} = \frac{D_t}{D_0} \ln\ V_{d0} + D_t \ln\left(\frac{D_0 \gamma_t N_{dt} P_t}{\delta^t D_t N_{d0} P_0}\right), \tag{8.96}$$

We can represent dynastic utility as a function of full wealth and initial and future prices and interest rates. We begin by rewriting the intertemporal budget constraint as:

$$\sum_{t=0}^{\infty} \gamma_t N_{dt} P_t V_{dt}^{-1/D_t} = \Omega_d, \tag{8.97}$$

Substituting (8.96) into (8.97) and simplifying yields the following:

$$\ln V_{d0} = -D_0 \ln\left(\frac{\Omega_d}{N_{d0} R}\right), \tag{8.98}$$

where:

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

Equation (8.98) enables us to evaluate dynastic utility in terms of full wealth:

$$\begin{aligned} V_d &= \sum_{t=0}^{\infty} \delta^t \ln\ V_{dt} \\ &= \sum_{t=0}^{\infty} \delta^t \left[\frac{D_t}{D_0}\ \ln\ V_{d0} + D_t \ln\left(\frac{D_0 \gamma_t N_{dt} P_t}{\delta^t D_t N_{d0} P_0}\right)\right] \\ &= \sum_{t=0}^{\infty} \delta^t \left[- D_t \ln \frac{\Omega_d}{R} + D_t \ln\left(\frac{D_0 \gamma_t N_{dt} P_t}{\delta^t D_t P_0}\right)\right], \\ &= S \ln R - S \ln \Omega_d + \sum_{t=0}^{\infty} \delta^t D_t \ln\left(\frac{D_0 \gamma_t N_{dt} P_t}{\delta^t D_t P_0}\right) \end{aligned} \tag{8.99}$$

where:

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

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

$$\ln \Omega_d(\{p_t\}, \{\gamma_t\}, V_d) = \frac{1}{s}\left[S \ln R + \sum_{t=0}^{\infty} \delta^t D_t \ln\left(\frac{D_0 \gamma_t N_{dt} P_t}{\delta^t D_t P_0}\right) - V_d\right], \quad (8.100)$$

where $\{p_t\}$ is the time profile of prices and $\{\gamma_t\}$ is the profile of discount factors.

We employ the intertemporal expenditure function (8.100) in measuring the monetary equivalent of the effect on welfare of a change in policy. We let $\{p_t^0\}$ and $\{\gamma_t^0\}$ represent the time profiles of prices and discount factors for the base-case and V_d^0 the resulting level of welfare. Denoting the welfare of the dynasty after the imposition of the new policy by V_d^1, the equivalent variation in full wealth is:

$$\Delta W_d = \Omega_d(\{p_t^0\}, \{\gamma_t^0\}, V_d^1) - \Omega_d(\{p_t^0\}, \{\gamma_t^0\}, V_d^0). \quad (8.101)$$

The equivalent variation in full wealth (8.101) is the wealth required to attain the welfare associated with the new policy at prices of the base case, less the wealth required to attain base-case welfare at these prices. If the equivalent variation is positive, the policy produces a gain in welfare; otherwise, the policy change results in a welfare loss. Equivalent variations in full wealth enable us to rank the base-case policy and any number of alternative policies in terms of a money metric of dynastic welfare.

8.5 EVALUATION OF CLIMATE POLICY

We next consider the evaluation of three cap-and-trade policies to control greenhouse gas emissions in the US. The caps refer to economy-wide emissions of six greenhouse gases — carbon dioxide, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons and sulfur hexafluoride. The least extreme of these policies freezes total annual greenhouse gas emissions at the 2005 level of 7.2 metric gigatonnes of carbon dioxide equivalent ($GtCO_2$-e) through 2050. The most extreme policy imposes a "cap" or cumulative emissions limit on greenhouse gas of 205.4 GtCO2-e over the period 2012—2050. The requisite trend reduction in emissions ultimately targets an emissions level in 2050 of 3.6 GtCO2-e. This is 50% of the 7.2 GtCO2-e of greenhouse gas observed in 2005 and more than 40% below the 6.1 GtCO2-e of 1990. This policy is a primary US policy scenario for the Energy Modeling Forum 24 (EMF 24). It also is very close to the central case described by Goettle and Fawcett (2009) in their contribution to EMF 22 and to the policy outcomes for total greenhouse gases arising from the US House and Senate legislative initiatives, 2007—2010.[21] Our central policy case, and

[21] See: http://www.epa.gov/climatechange/economics/economicanalyses.html.

the focus of much of our subsequent discussion, lies halfway between these extremes. Specifically, cumulative emissions, 2012–2050, are capped at 241.4 GtCO2-e with annual emissions tracking to 5.4 GtCO2-e by 2050.

After 2050 we opt for price rather than emissions certainty. Specifically, we hold constant the allowance prices that are necessary to achieve the 2050 emissions target. In each case, the 2050 price is fixed indefinitely in terms of constant GDP purchasing power. Were emissions to remain at 2050 levels, cumulative emissions, 2051–2060, would total 72.0, 54.0 and 36.0 $GtCO_2$-e under the progressively restrictive targets. By freezing the 2050 allowance prices, these amounts rise to 78.9, 59.1 and 39.7 $GtCO_2$-e, respectively.

In these simulations, we assume the US government auctions emissions allowances or permits and, therefore, controls all revenue collection and redistribution. Through 2050 IGEM endogenously determines the time path of allowance prices that achieves the necessary annual abatement. Figures 8.1 and 8.2 show the emissions levels and allowance prices corresponding to these three scenarios which are denoted by "2005 Level," "25% Target" and "50% Target." Figure 8.1 also shows the baseline greenhouse gas emissions path, thus providing a sense of the magnitude of required abatement.

In our central case, allowance prices begin at just under $1 (2005 dollar) per tonne in 2012 and rise exponentially to $109 per tonne by 2050. With a flat level of emissions

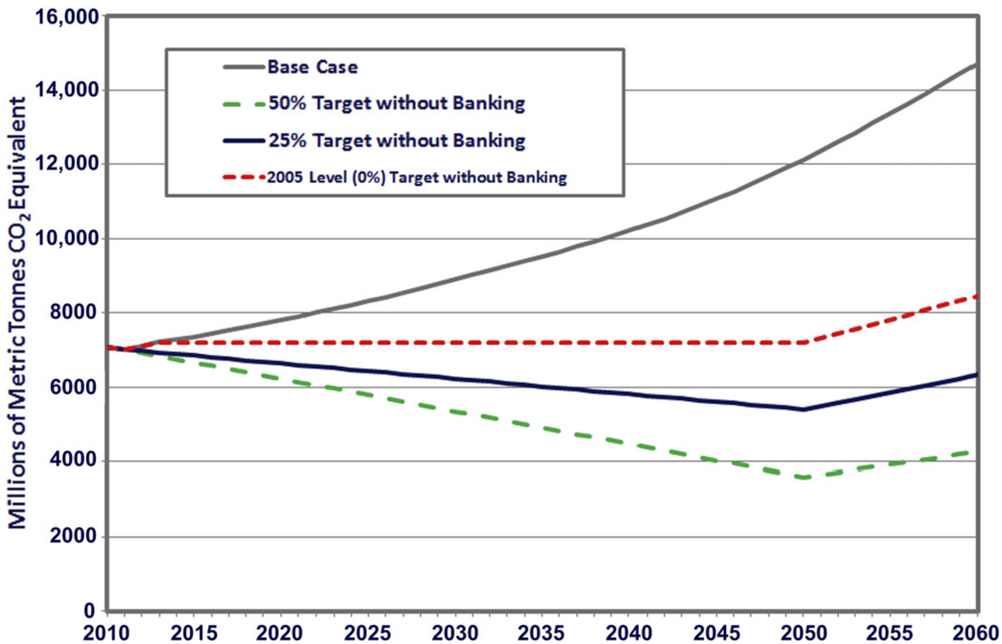

Figure 8.1 Total greenhouse gas emission.

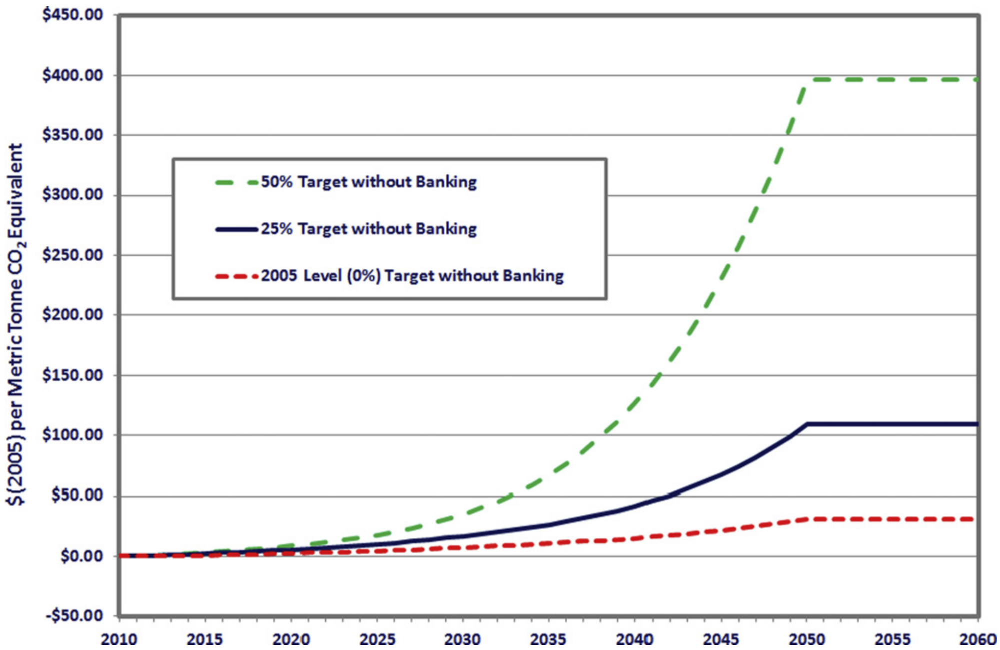

Figure 8.2 Allowance prices.

under the least restrictive policy, the constraint is not binding until 2013, the price rising moderately from 7 cents in 2013 to $31 per tonne in 2050. As evidence that more aggressive abatement becomes increasingly more expensive, under the 50% target allowance prices again begin at under $1 per tonne in 2012 but rise to $396 per tonne by 2050. The differences in these time patterns clearly demonstrate IGEM's structure and econometric foundations exhibit anything but constant-elasticity behavior. See Figure 8.2.

Emissions abatement occurs through three mechanisms — output reductions, input substitutions and price-induced technical change. The demand functions in IGEM capture the first two effects and endogenous technical change incorporates the third. To illustrate these effects in their purest form, the simulations do not include the opportunities related to non-CO_2 abatement, such as bio-electricity generation, carbon capture and storage technologies, domestic sequestration and other offsets and international permit trading that characterize our earlier policy analyses. The allowance prices and economic costs are thus higher here than in the analyses that include these options.[22]

[22] To see the power of these external abatement opportunities in reducing allowance prices and the economic costs of mitigation policy refer to Jorgenson *et al.* (2009a) and Environmental Protection Agency (2012a).

For the same reason, our simulations of the outcomes of cap-and-trade policies are compared to a base case that is produced by the model, rather than calibrated to a particular time pattern of energy consumption (coal, oil, gas and electricity) and economic growth, as is typical of policy assessments. For example, the Environmental Protection Agency instructions to their analysts include GDP and energy forecasts from the Department of Energy. These calibrations require adjustments to the industry cost functions. Our intent in this exercise is to measure the econometrically determined impacts of climate policy in a transparent manner and thus avoid these adjustments.

IGEM's model closure and steady-state condition requires vanishing government and current account deficits, and most policy scenarios require twin deficit neutrality. By design, these closures imply that variations in US saving fully account for the variations in US investment and capital formation; there can be no crowding-out or crowding-in of private investment from these two sources. With allowance revenues as a new source of government income, a key assumption in setting the policy simulation is the treatment of the government budget.

With an endogenous tax (or transfer), either we keep nominal revenues and expenditures equal to the base case, thus preserving deficit *and* revenue neutrality, or we keep real expenditures on goods equal to the base case and preserve only deficit neutrality. Although there is no price inflation in IGEM, there are large changes in relative prices due to the policy; a dollar buys a different basket of goods in year *t* in the policy case compared to the base case. To keep welfare comparisons simple we keep an index of real aggregate government expenditures under the cap-and-trade policy equal to that of the base case.

8.5.1 Impact on economic growth and industry

The consequences for the economy are examined by considering the average adjustments over the period 2010–2060 as these generally are representative of what happens in any given year. As shown in Table 8.12 and Figure 8.3, the emissions constraints and resulting allowance prices adversely affect each aspect of aggregate GDP – consumption, investment, government purchases, exports and imports.

The effects on the economy are best understood by first considering the changes in industry prices. These changes include the direct effects of emissions pricing as well as their indirect general equilibrium consequences and are presented in Table 8.13 and Figure 8.4. Clearly, energy prices – coal, oil, gas and electricity – are most affected, with coal more so than any other commodity. This is not surprising in that almost 80% of all greenhouse gas emissions in the US are related to fossil fuel combustion. In addition, coal is high in carbon content in relation to the other fossil fuels and is used extensively along with gas and some oil in the manufacture of electricity.

Table 8.12 Macroeconomic impacts

	2005 Level	25% Target	50% Target
Emissions ($GtCO_2$-e)			
Cumulative emissions target, 2012–2050	280.9	241.4	205.4
Cumulative emissions outcome, 2051–2060	78.9	59.1	39.7
Allowance price ($(2005)/tonne CO_2 equivalent)			
2012	0	1	1
2050	31	109	396
2051 and beyond	31	109	396
Average % change from base case, 2010–2060			
Real GDP	−0.6	−1.4	−3.4
Consumption	−0.4	−0.9	−2.2
Investment	−0.9	−2.1	−5.0
Government	0.0	0.0	0.0
Exports	−1.1	−2.9	−7.0
Imports	−1.1	−2.6	−6.1
GDP prices	0.5	1.4	3.4
Consumption	0.4	1.1	2.6
Investment	0.3	0.8	1.9
Government	0.2	0.6	1.3
Exports	0.6	1.6	3.8
Imports	0.5	1.1	2.2
Household full consumption (goods, services and leisure)	−0.1	−0.1	−0.3
Capital stock	−0.5	−1.2	−2.7
Labor demand and supply	−0.3	−0.7	−1.7
Leisure demand	0.1	0.3	0.7
Exchange rate ($/foreign currency)	0.5	1.1	2.3

Domestic crude oil and gas extraction prices decline under the condition in IGEM that approximates an upward-sloping supply curve.[23] Here, the lower domestic production that follows from reduced demand is obtained at a lower cost. This is the only price (cost) reduction that occurs. All non-energy prices increase relative to the labor price numéraire. Some prices – Agriculture, Chemicals, Plastics, Stone, clay and glass, Primary metals, Electrical machinery (semiconductors), and Services (waste management) – are affected both directly and indirectly as their emissions are "covered" by

[23] An exception to the treatment in equations (8.81)–(8.83) is the crude oil and gas extraction industry, industry 4. Its capital stock measure, K_{4t}, includes land and its resource base. Given the non-reproducible nature of this base, we allow two possible closures of its market for capital services, KD_{4t}: one is to treat it symmetrically with all other industries, and two is to assume that the stock of capital in this sector is fixed (no investment and no depreciation). In the second option, we have an endogenous rental price of this fixed stock of capital, PKD_{4t} such that the demand for capital input is equal to the fixed supply: $KD_{4t} = KD_4$. This second option introduces behavior associated with an upward sloping supply curve.

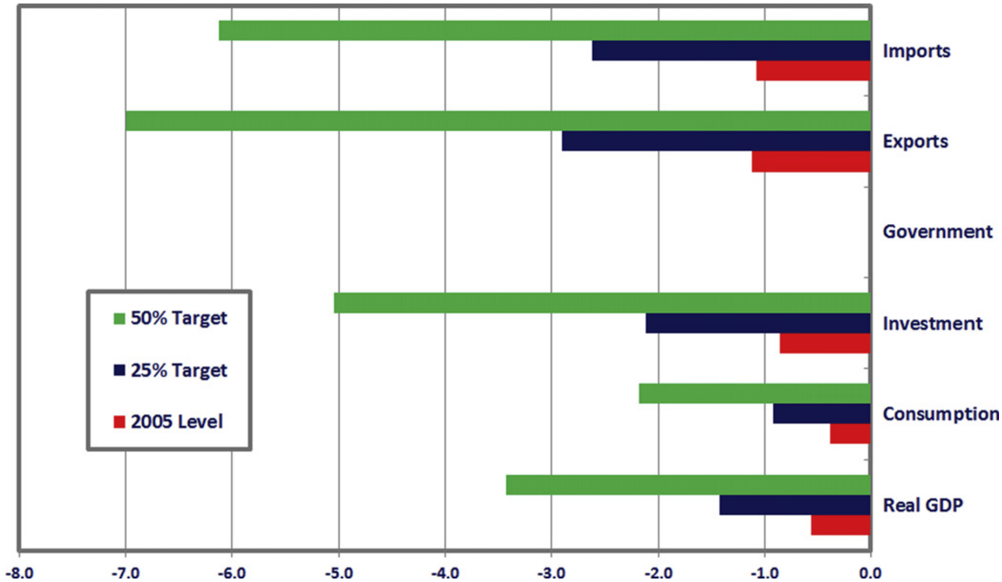

Figure 8.3 Impacts on real final demand (average percent change from base, 2010–2060).

policy. Others like Food, Lumber and wood, Paper, Motor Vehicles, Communications, Trade, Finance, and Services are affected only indirectly.

The overall impacts on the economy are dominated by the decisions of households. Their first decision concerns the intertemporal allocation of full consumption — the expenditure on good, services *and* leisure. Households know that the price increases from abatement policy will be larger "tomorrow" than they are "today" as the emissions from a growing economy make stabilization at the target emission levels more difficult over time. Households view this as a progressive erosion of real incomes and purchasing power and redistribute full consumption toward the present.

Households next decide on the allocation of full consumption between non-durable goods, household capital services and consumer services, on the one hand, and leisure, on the other.[24] The pass-through of allowance prices makes all consumer goods and services more expensive and, so, the overall price of consumption relative to labor is higher. This prompts households to substitute leisure for consumption. Within the overall increase in near-term full consumption arising from the intertemporal effect, comparatively more is spent on leisure than is spent on goods and services.

In addition to the comparatively small consumption-related impact on aggregate demand, this second decision by households has important implications for the supply

[24] The importance of and sensitivity to the consumption-leisure tradeoff is examined in detail in Volume 1, Chapter 7 of Jorgenson *et al.* (2009b).

Table 8.13 Industry effect (average % change from base case, 2010–2060)

		2005 Level		25% Target		50% Target	
		Price	Output	Price	Output	Price	Output
1	Agriculture	2.5	−3.1	7.5	−8.5	24.0	−20.2
2	Metal mining	0.9	−0.4	2.0	−2.5	4.5	−8.4
3	Coal mining	114.1	−44.4	358.3	−61.9	1191.0	−72.0
4	Petroleum and gas	−0.5	−0.2	−2.1	−0.6	−6.1	−1.7
5	Non-metallic mining	1.0	−1.6	2.3	−4.2	5.0	−10.3
6	Construction	0.3	−0.6	0.8	−1.5	2.2	−3.8
7	Food products	1.0	−1.2	2.6	−3.0	7.1	−7.2
8	Tobacco products	0.4	−0.6	1.2	−1.7	3.1	−4.3
9	Textile mill products	0.6	−1.0	1.6	−2.6	4.2	−6.4
10	Apparel and textiles	0.4	−0.5	0.9	−1.1	2.2	−2.2
11	Lumber and wood	0.5	−0.9	1.3	−2.2	3.5	−5.4
12	Furniture and fixtures	0.4	−0.7	0.9	−1.6	2.2	−3.7
13	Paper products	0.8	−1.2	1.8	−2.8	3.9	−6.0
14	Printing and publishing	0.3	−0.4	0.6	−1.0	1.4	−2.4
15	Chemical products	1.2	−2.0	3.5	−5.4	10.5	−13.3
16	Petroleum refining	1.9	−2.5	5.1	−6.4	14.0	−14.7
17	Rubber and plastic	0.7	−1.6	1.9	−3.5	5.5	−7.8
18	Leather products	0.5	−0.8	1.2	−1.9	2.8	−4.2
19	Stone, clay and glass	−0.5	0.1	0.8	−2.0	7.1	−9.0
20	Primary metals	1.9	−2.3	3.8	−5.2	8.0	−11.5
21	Fabricated metals	0.7	−1.3	1.4	−3.1	3.1	−6.7
22	Industrial machinery	0.3	−0.8	0.8	−2.0	1.8	−4.5
23	Electronic and electric equipment	0.3	−0.7	0.8	−1.8	2.1	−4.4
24	Motor vehicles	0.5	−1.2	1.1	−2.8	2.6	−6.2
25	Other transportation equipment	0.3	−0.3	0.7	−0.7	1.5	−1.7
26	Instruments	0.2	−0.5	0.4	−1.2	1.0	−3.0
27	Miscellaneous manufacturing	0.4	−0.6	1.0	−1.6	2.3	−4.2
28	Transport and warehouse	0.5	−1.1	1.2	−2.7	3.1	−6.7
29	Communications	0.2	−0.6	0.6	−1.4	1.3	−3.2
30	Electric utilities	3.3	−2.6	6.5	−4.8	11.2	−7.9
31	Gas utilities	4.6	−4.0	13.9	−11.4	43.7	−25.6
32	Trade	0.3	−0.6	0.8	−1.6	1.8	−3.7
33	FIRE	0.3	−0.6	0.7	−1.5	1.6	−3.6
34	Services	0.3	−0.5	0.6	−1.3	1.5	−3.2
35	Government enterprises	0.4	−0.7	0.9	−1.7	2.2	−4.0

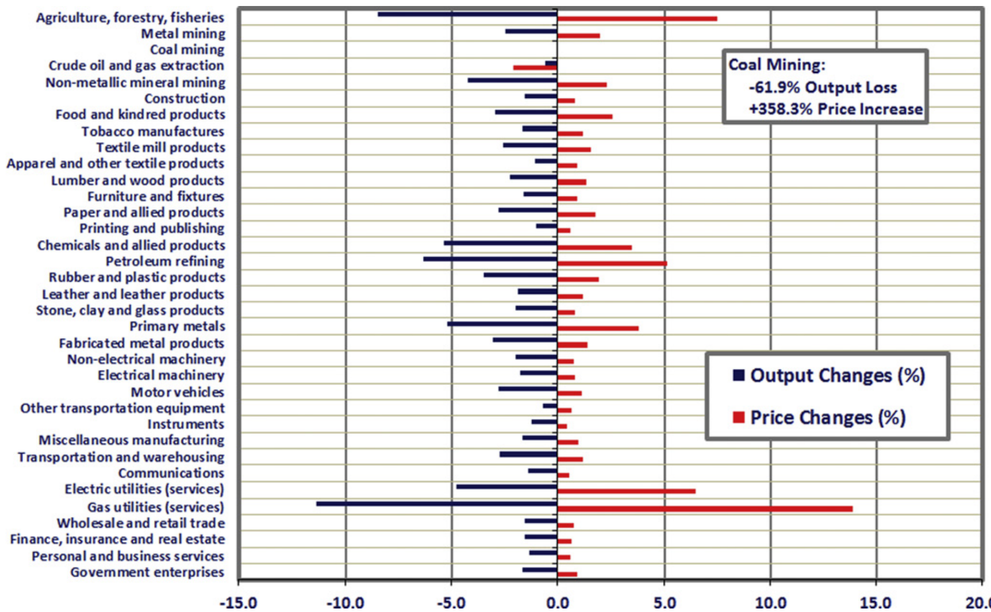

Figure 8.4 Output and price changes from base (average 2010–2060, 25% target without banking).

side of the economy. The increase in leisure demand is a reduction in household labor supply; the magnitudes of the changes are shown in Figure 8.5. While increasing leisure is welfare improving for households, their reductions in labor supply, at prevailing wages, reduce labor and, hence, national income.

The third decision by households concerns the allocation of purchases among the variety of consumer goods and services, but within the overall level of reduced total real spending. There is a redirection of expenditure away from those goods and services incurring the larger price increases and toward those experiencing the smaller price increases. As household spending is such a large fraction of overall spending, the actions taken here strongly influence the structure of real GDP and the domestic production that supports it.

Given the reduction in real incomes, and labor and capital input, the output of all industries fall, especially those related to energy (Table 8.13 and Figure 8.4). Producers minimize the cost impact by substituting away from more costly inputs and toward relatively cheaper materials, labor and capital. Ultimately, there is still a unit cost increase that is passed through as higher prices to consumers, reducing real incomes and demand, on one hand, and reducing factor supplies on the other.

There is, however, a small net benefit on the production side that helps mitigate the economic costs of abatement policy. Beyond factor substitutions, there is also price-induced technical change (ITC) at work in each industry. Price induced patterns of innovation are discussed in Section 8.2.2 above and Chapter 17. Policy changes alter the

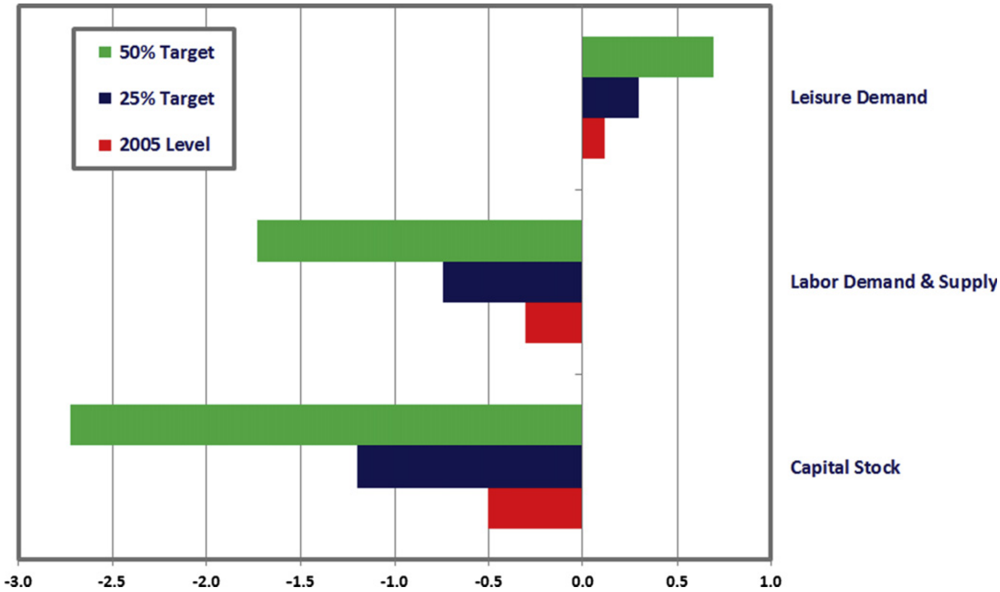

Figure 8.5 Impacts on real value added (average percent change from base, 2010–2060).

future pattern of relative prices, and so "induces" changes in productivity through the innovation term (f_{it}^p in Equation 8.43).

The effect of price-induced technical change in these simulations leads to permit prices that are marginally higher than they would be in its absence. To see the impact, we show in Figure 8.6 the size of the induced technical change for each industry and, in the top bar, the economy-wide output-weighted sum of the industry effects. The impacts are shown for 2030 and 2050. While the ITC effect of the carbon price ranges from −0.09% to +0.12% at the industry level, the overall economy-wide effect on productivity is positive. As the economy is marginally larger, greenhouse gas emissions are marginally higher and permit prices need to be higher to achieve the required abatement.

The ITC effects also have structural implications for the economy and, so too, for energy use and greenhouse gas emissions. This is best seen by focusing on four sectors in Figure 8.6 – electric utilities, petroleum refining, gas utilities and services. ITC in the electric utilities sector plays the dominant role in the overall ITC effect observed for this policy – electricity prices are lower, and demand is higher, than would be otherwise. This is due to the estimated bias as reported in Chapter 17; technical change is "energy saving" in electric utilities. In short, the estimated relationship in this sector works somewhat against the goals of this policy. Since induced technical change helps to lower electricity prices, unconstrained energy use and emissions are higher which means that permit prices also have to be higher to achieve a given emissions reduction.

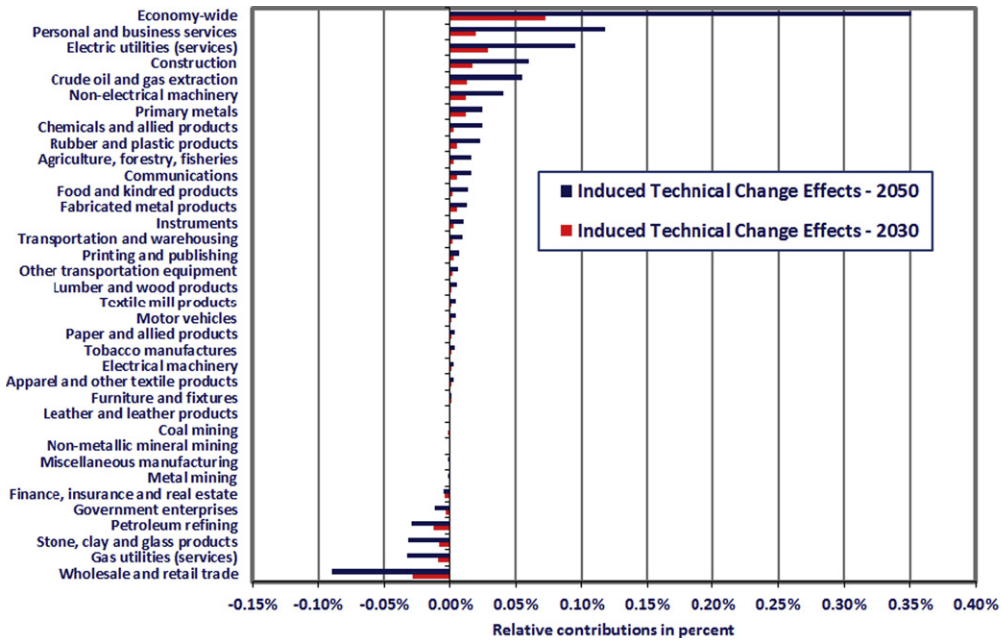

Figure 8.6 Price-induced technical change.

On the other hand, the ITC effects in petroleum refining and gas utilities counter the effects in electricity. Here, technical change works to raise prices further leading to larger reductions in their demands and greater emissions abatement. The ITC in services has an interesting effect. It raises productivity and lowers prices, which leads to higher demand and output. However, this sector is not energy- or emissions-intensive so that this change in the composition of output yields an economy that is less energy- and emissions-intensive. Hence, the permit prices are marginally lower.

The reduction in labor income arising from the reduced labor supply, combined with lower capital income from businesses, yields a lower national income. However, in terms of the labor price numéraire, nominal personal consumption increases due to the intertemporal effect of shifting spending from the future to the present. In addition, overall real consumption gives the appearance of being price inelastic as its annual decline is less than proportional to the increase in its aggregate price (Table 8.12). With falling income and rising consumption, private saving falls unambiguously. The reduction in saving leads to a corresponding reduction in nominal private investment. With higher prices for investment goods, this lower saving leads to lower real investment and hence a lower capital stock (Table 8.12 and Figures 8.3 and 8.5). The lower supplies of capital and labor limit the economy's domestic supply possibilities following the introduction of this policy.

IGEM's saving–investment balance summarizes the net flow of funds available for investment. These funds arise from three sources. The first source, discussed above, is the domestic saving of households and businesses. The second source reflects the behavior of the government and the magnitude of its deficit. The third source is due to the interactions with the rest of the world and whether the annual current account balance is in deficit or surplus.

To eliminate government's direct effects on real investment spending through the saving–investment balance, these simulations assume deficit neutrality and unchanged real government purchases. Accordingly, as the prices rise, there occurs a proportional increase in nominal government spending. Lump-sum redistributions of allowance revenues are set so as to preserve deficit and real spending levels while accommodating all other general equilibrium effects. While there are numerous potential reactions concerning the fiscal policies of governments, the above assumptions give rise to transparent outcomes that are uncomplicated by speculations as to what governments might do to soften any adverse policy impacts.

The impacts on real exports and imports appear in Table 8.12 and Figure 8.4. The prices of US exports rise relative to goods and services from the rest of the world. As exports supplies are estimated to be price-elastic, export volumes fall by proportionally more than export prices rise. The reductions in exports occur in all sectors and contribute to a direct and indirect reduction in the global greenhouse gas emissions arising from US export activities.

Real and nominal imports also decline in all sectors except for electric utilities. Import reductions occur from the overall reductions in spending associated with a smaller economy. Import reductions also occur in those commodities directly affected by abatement policy. The cap on emissions and the corresponding emissions permits fall on all commodities that contribute to US greenhouse gases, whether they are produced domestically or imported. Thus, within total imports, there are disproportionate reductions in oil, gas and other policy-sensitive commodities as their prices rise along with those of their domestic counterparts.

Since import reductions occur in all sectors except electricity, the contributions to global greenhouse gas emissions arising from US import activities also decline. Even if the small increase in electricity imports is based entirely on fossil fuel inputs, these policies do not contribute to an increase in worldwide emissions through leakage, either on average or in a given policy year.[25] For example, in 2050, the decline in emissions associated with US export reductions is 502 million tonnes CO_2-e and that associated with US import reductions is 94 million tonnes.

25 Since IGEM is a national model, we are unable to make inferences on emissions rising in other countries in reaction to US policy.

To neutralize the impact of lower exports and somewhat smaller reduction in imports on investment, the dollar weakens to maintain the current account balance at its pre-policy level. By affecting the terms of trade, this partially dampens the policy's export effect and dampens the loss of competitiveness in the carbon intensive goods. As illustrated in Figure 8.2, allowance prices increase more than proportionately to the size of the emission reduction. Not surprisingly, the economic costs of increasingly severe abatement requirements also rise disproportionately.

Figure 8.7 shows the impact on GDP for each of the three scenarios. Holding greenhouse gas emissions constant at their 2005 levels leads to an economy that is 1% smaller by 2050. In our central case, the impacts by 2050 are almost three times greater. This corresponds to an average reduction in annual real growth that is under 0.1%. In the most extreme policy, the losses in GDP again rise disproportionately. Achieving the 50% target results in an economy that is 8% smaller by 2050, incurring eight times the losses from holding annual emissions constant. As the 2050 allowance prices are held constant in real terms, the proportionate losses in real GDP in 2051 and beyond are virtually identical to those in 2050.

To put a dollar figure on the losses, we express them in terms of dollars per household. In 2020, with emissions held constant the loss per household is $298 (0.18%) in 2005 dollars. In the central case, this loss increases to $577 (0.35%) per household and

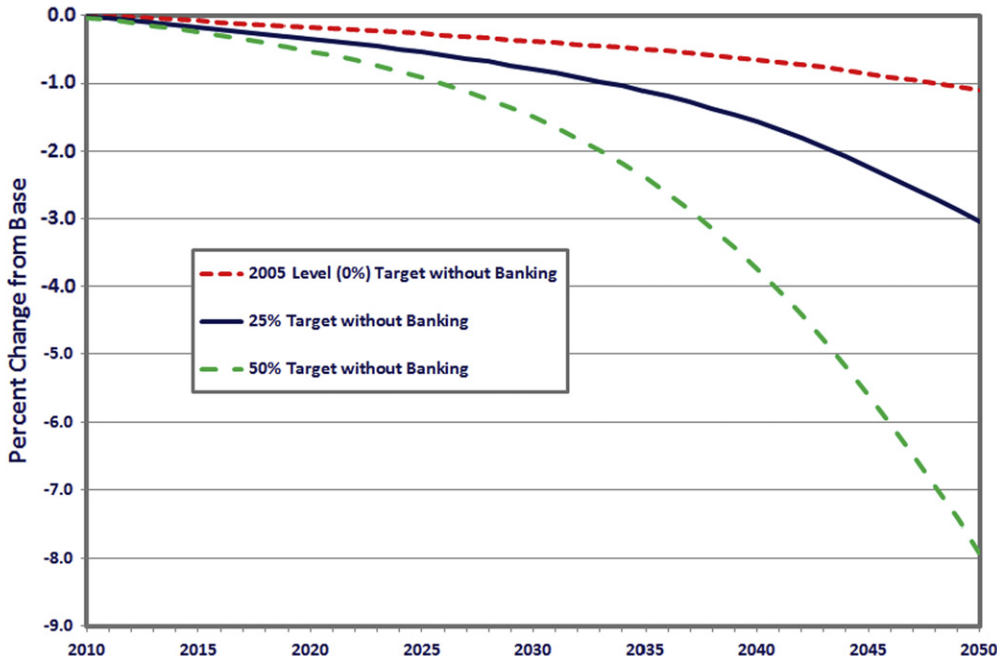

Figure 8.7 Impacts on real GDP.

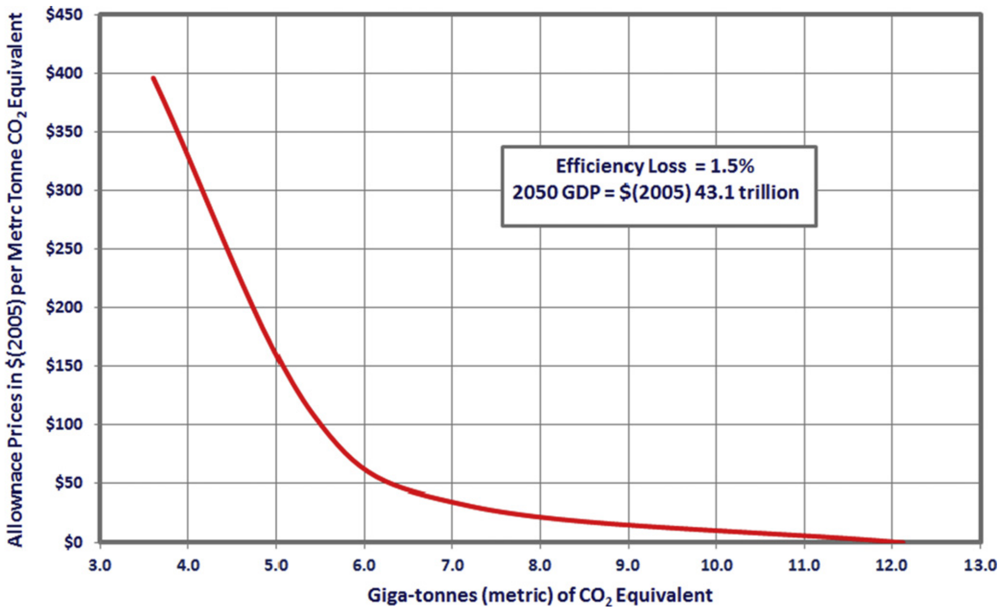

Figure 8.8 Emission demand, 2050.

rises to \$883 (0.53%) in our most extreme case. By 2050, these per household losses increase to \$2,800 (1.10%), \$7,718 (3.04%) and \$20,158 (7.94%), respectively.

Figure 8.8 plots the 2050 allowance prices against the corresponding emissions levels for each of our three cases and the base case. This loss function has the appearance of a conventional demand curve. The first 4.9 $GtCO_2$-e of greenhouse gas abatement costs \$31 in 2005 dollars, the next 1.8 $GtCO_2$-e costs \$78 and the final 1.8 $GtCO_2$-e costs \$287. This implies an efficiency loss of 1.5% of the \$43.1 trillion GDP in 2050. Figures 8.7 and 8.8 provide clear evidence that, in IGEM, emission reductions become increasingly less elastic as targets are tightened.

8.5.2 Distributional impact

We next report the impacts of the cap-and-trade policies on household welfare, as given by the equivalent variation in full wealth in Equation (8.101). Recall that the equivalent variation in full wealth is the wealth required to attain the welfare associated with a new policy at base-case prices, less the wealth required to attain the base-case welfare at these same prices. We consider equivalent variations for each of the 244 household types, cross-classified by the demographic categories presented in Table 8.3.[26]

[26] Table 8.3 gives a total of 384 possible household types. However, in the most recent Survey underlying IGEM, the number of types with a positive number of households is only 244.

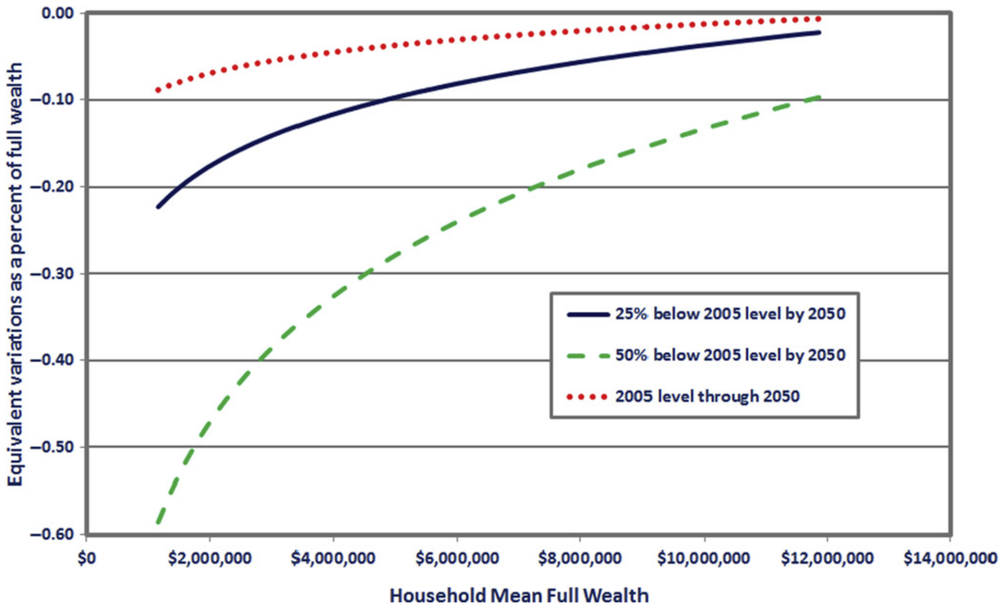

Figure 8.9 Household welfare effects and full wealth (at mean wealth without banking, 244 household types).

In Chapter 17 we describe the wide range of full expenditure values for each demographic category. Figure 8.9 shows the welfare effects for the three policy scenarios at the mean full wealth for each of the 244 household types. The percentage losses are smaller than those for GDP because households respond to the changing prices by changing their consumption patterns. The welfare losses also are smaller because of the offsetting increases in leisure demand and the lump-sum transfers of allowance revenues.

The households with lower full wealth suffer a larger percentage loss in welfare. Smaller households and others with lower full wealth consume less leisure and have larger budget shares of consumer goods. Hence, they are more adversely affected by the direct and indirect effects of mitigation policy. Moreover, as emissions targets are tightened, the welfare losses increase at an increasing rate as mean household wealth decreases. Lower expenditure households are harmed more and, the more aggressive the abatement policy, the more they are harmed.

Figures 8.10 and 8.11 show the welfare effects associated with only the 25% target. In Figure 8.10, the 244 household types are arranged from the lowest to the highest levels of mean full wealth. In Figure 8.11, the 244 household types are arranged from the most to the least adversely affected. The principal curve is the solid line in each graph labeled "At mean wealth." This shows the welfare impact on households with the mean wealth among those with the same demographic characteristics. For mean wealth, all households experience a welfare loss ranging from −0.02 to −0.22% of full wealth are

Figure 8.10 Household welfare effects and full wealth (25% target without banking, 244 household types).

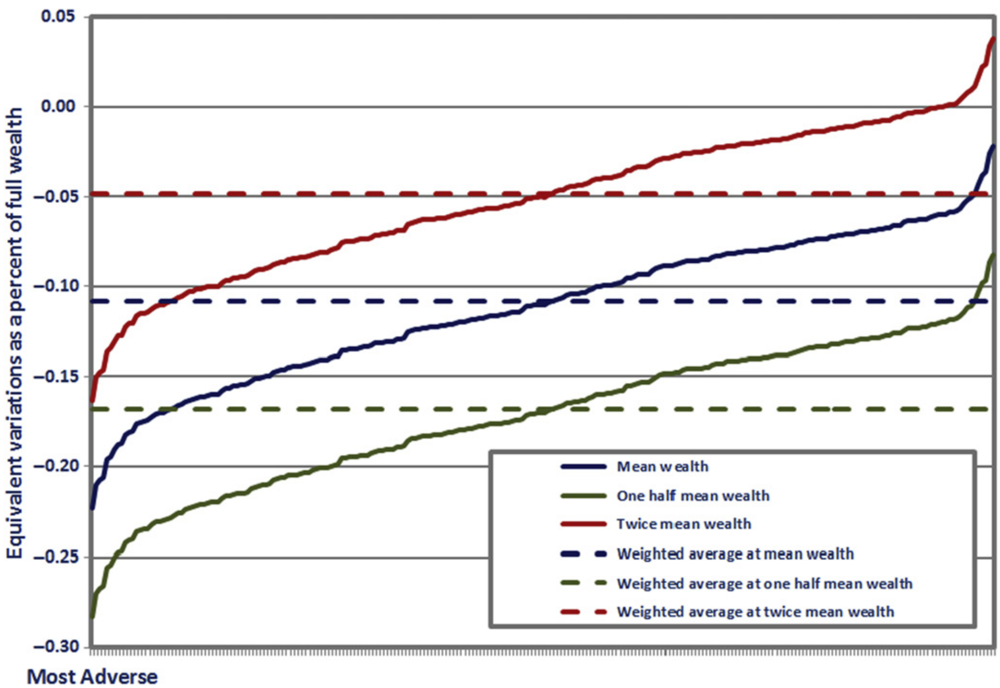

Figure 8.11 Household welfare effects (25% target without banking, 244 household types).

included. The most negatively affected households consist of one child with one adult living in the rural South and headed by non-white females. The least negatively affected are large urban households in the West, households with three or more children and three or more adults headed by non-white males.

To illustrate how the policy affects households with different levels of full wealth, the effects in Figure 8.10 and 8.11 also are shown for half and twice mean wealth. The population-weighted average welfare effects are −0.17, −0.11 and −0.05% of lifetime expenditure at the half mean, mean, and twice mean levels, respectively, as represented by the horizontal lines in Figure 8.11. It must be emphasized that these are the average household effects. Figures 8.10 and 8.11 show that the effects of the policy change are regressive; the equivalent variations become more negative as full wealth decreases both across and within demographic groups. However, it should be noted that in all cases the welfare losses are relatively small, the worst case being under 0.3% of full wealth.

Figure 8.12 decomposes the welfare effect by isolating the impact of price changes alone. The solid line in Figure 8.12 shows the solid curves from Figures 8.9 and 8.10 for mean wealth. The dashed line below it shows the welfare effects due solely to price changes, holding household full expenditure at its base case value. In the absence of changes in expenditure, households experience net welfare losses in the range of 0.23−0.43% of their full wealth. However, the lump-sum redistributions required to

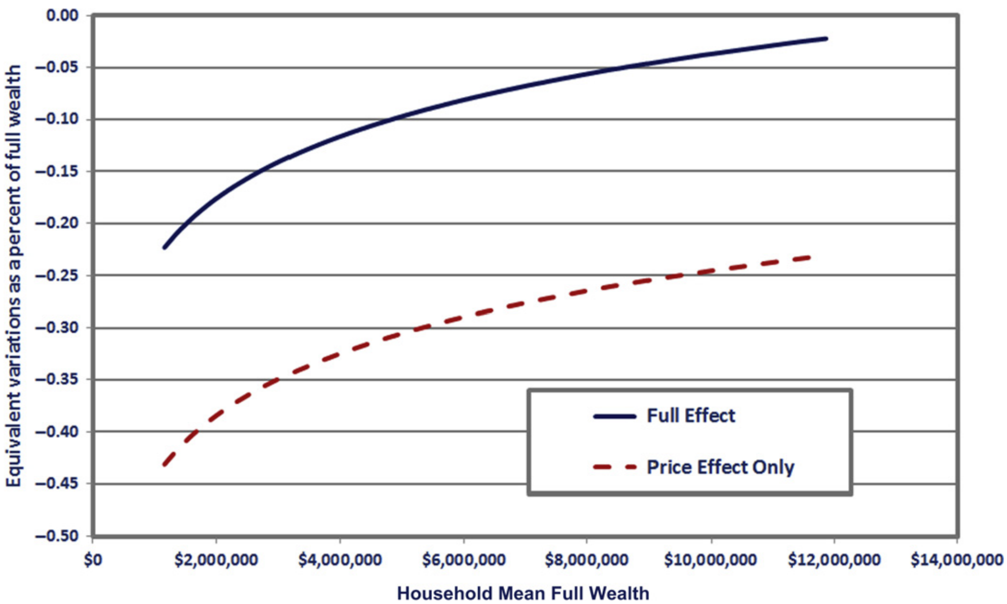

Figure 8.12 Decomposition of household welfare effects (25% target without banking, at mean full wealth).

hold real government spending at its base-case levels partially compensate the price effects.

With leisure such a large share of household budgets, there is a natural concern as to the influence of family size on the findings summarized above. Accordingly, we examine the two most populous segments of the household sample — households with two adults and no children (28.8% of all households), and households with one adult and no children (29.5%). The dominance of leisure in full wealth is evident here. In Figures 8.9, 8.10 and 8.12, single-person adult households are concentrated at the lower end of the spectrum for lifetime expenditure while two-person adult households are concentrated in its middle range. However, what matters most here are the robust findings of regressivity when controlling for leisure this manner. For both groups, climate policy results in larger welfare losses at lower levels of full wealth and, in both cases, this pattern is invariant to scale.

Table 8.14 decomposes the welfare losses across the demographic details of the 244 household types. These are summarized by the population-weighted averages within each group. Clearly, households containing three or more adults are generally better off than those with two adults, which in turn are better off than single-adult households. This is not surprising in that larger households generally are wealthier in terms of their lifetime spending on goods, services *and* leisure. Within these groups, the presence of children is of equal interest. Households with three or more adults are better off with three or more or no children and are worse off with one or two children. Households with two adults fare progressively worse the fewer children they have whereas the opposite occurs in households with only one adult. Among single-adult households and within each grouping based on the number of children, rural households headed by females fare worst.

In the sample, 18.9% of the household population resides in the Northeast, with 23.0, 36.5 and 21.6% residing in the Midwest, South and West, respectively. Most of the households with large welfare losses are located in the South or Midwest and the largest losses occur in the South. The households with the smallest proportional losses are in the West and, on average, this region fares the best followed by the Northeast, South and Midwest.

Households headed by non-white females comprise 7.4% of the sample population. Households headed by white females comprise 22.5% of the sample. Households headed by non-white and white males, comprise 10.3 and 59.8% of the sample, respectively. The household types with largest welfare losses are headed by females though, on average, there is not much difference between those headed by whites or non-whites. Male-headed households fare much better, owing to their greater wealth. Here, again, the average difference between the races is not large. Overall, the welfare gap across the sexes is much more significant than that across the races. The households with the largest losses are concentrated in rural areas. The larger

Table 8.14 Household welfare effects, 25% target (population weighted-average equivalent variations as a % of full wealth)

	Full wealth		
	Half mean	**Mean**	**Twice mean**
Children, adults per household			
3+, 3+	−0.124	−0.064	−0.004
2, 3+	−0.127	−0.067	−0.007
1, 3+	−0.125	−0.065	−0.005
0, 3+	−0.124	−0.064	−0.004
3+, 2	−0.144	−0.084	−0.023
2, 2	−0.146	−0.086	−0.026
1, 2	−0.149	−0.089	−0.029
0, 2	−0.152	−0.092	−0.032
3+, 1	−0.222	−0.162	−0.102
2, 1	−0.216	−0.156	−0.096
1, 1	−0.213	−0.153	−0.093
0, 1	−0.213	−0.153	−0.093
Region of household			
Northeast	−0.165	−0.105	−0.045
Midwest	−0.176	−0.116	−0.056
South	−0.173	−0.113	−0.053
West	−0.156	−0.096	−0.036
Race and gender of household head			
Non-white female	−0.202	−0.142	−0.082
White female	−0.201	−0.141	−0.081
Non-white male	−0.160	−0.100	−0.040
White male	−0.154	−0.094	−0.033
Location of household			
Urban	−0.166	−0.106	−0.046
Rural	−0.193	−0.133	−0.073
Overall	−0.168	−0.108	−0.048

(92.1%), wealthier urban population fares better than the smaller (7.9%), poorer rural segment.

8.5.3 Effects of banking emissions allowances

A common provision in climate policy is the intertemporal transfer of emissions allowances through *borrowing* allowances for repayment in the future and *banking* allowances for future use. Significant borrowing requires an excess supply of allowances and relatively low in-kind interest rates governing their repayment. In US policy initiatives to date, these conditions are not met, generally because of the high borrowing costs in proposed legislation. Accordingly, we do not permit borrowing.

Banking of allowances is a common feature of proposals for climate policy (Environmental Protection Agency, 2012a). However, the rules governing the time horizon are often unclear. There appear to be three possibilities. (i) Banking is allowed to continue beyond the terminal policy date. In this case, policy assessment requires assumptions about the annual supply of allowances beyond the terminal date in order to determine the initial allowance price and the final year of banking drawdown. (ii) Banking expires at the terminal target date of the policy. Any remaining banked allowances would then be worthless and allowance prices would rise sharply to clear the market. (iii) Banking expires in the terminal date of the proposal. After expiration of banking, the allowance prices are set to avoid a sharp price spike. This is another form of so-called safety-valve pricing. Under these conditions, the climate proposal secures emissions certainty through its terminal date and price certainty thereafter.

For the purposes of this exercise, we adopt two of these approaches as alternatives to our central case involving the emissions target 25% below 2005 levels by 2050. First, banking is permitted, 2012–2050, but the covenant expires beginning in 2051. Under the conditions of optimal banking, allowance prices through 2050 grow annually by 5%, a rate common to many such assessments, from a starting price that ensures the same cumulative emissions, 2012–2050, as occur without banking. In 2051 and beyond, allowances prices then either revert to the non-banking price in 2050 or are held fixed in terms of GDP purchasing power at the 2050 banking price. We denote the first of these as banking with no safety valve and the second as banking with a safety valve.

Under banking, the effective allowance prices, shown in Figure 8.13, begin at just over $7 (2005 dollars) in 2012 and rise 5% annually to just under $48 by 2050. This time path of prices yields the same cumulative emissions of 241.4 $GtCO_2$-e as would occur without banking. As we will show, this is less harmful to the overall economy and household welfare. In 2051, banking is no longer permitted and the allowance price reverts to $109 per tonne (no safety valve) or remains at $48 per tonne indefinitely (safety valve). The transition to a yet another price-oriented policy from a quantity-focused one leads to still higher emissions than occur without banking; over the period 2051–2060, the cumulative emissions are 71.8 $GtCO_2$-e here versus 59.1 $GtCO_2$-e in our central case without banking (and versus the 54.0 $GtCO_2$-e that would occur were emissions held constant).

The mechanisms of adjustment described above apply equally to the no-banking and banking scenarios. However, it is clear from Tables 8.15 and 8.16 that banking reduces the economic costs of compliance. It is true that banking leads to larger economic losses from 2012 through 2030 but these are comparatively small. Banking leads to substantially smaller economic losses over the remainder of its existence. With the new safety valve, by 2050, the reduction in real GDP under banking is around half of that which occurs in its absence, 1.6 versus 3.0%. With no safety valve, the 2050 comparison is 1.8 versus 3.0% which is still substantial. Obviously, the longer term

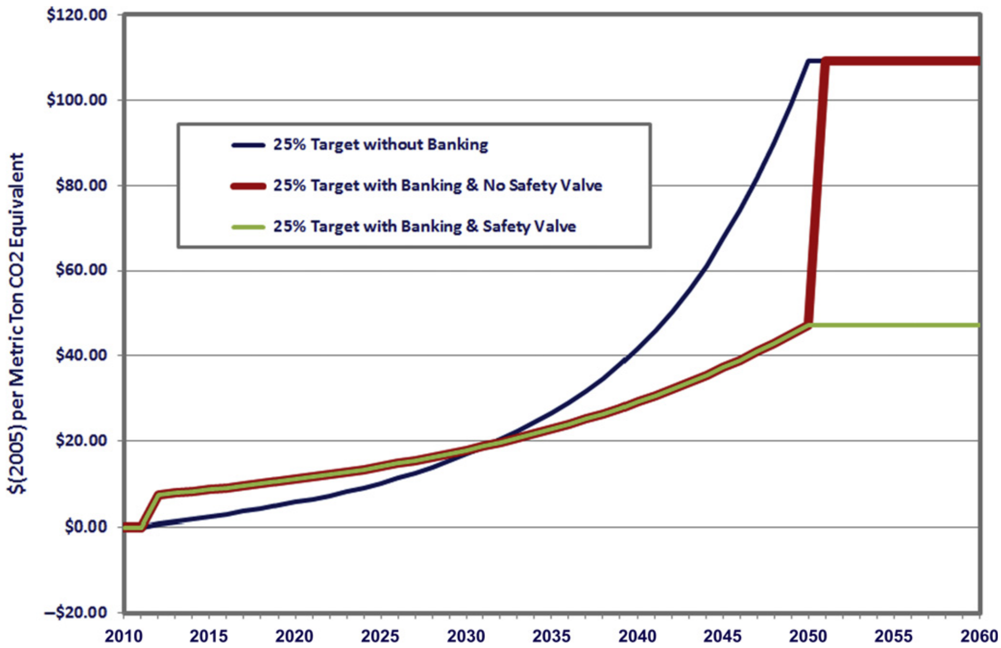

Figure 8.13 Allowance prices.

benefits of banking depend on what happens post-2050. With price reversion, the 2060 loss in GDP is 2.9% whether or not banking was allowed, 2012–2050. The continuation of the 2050 banking price, 2051 and beyond, reduces this loss to 1.8%. Clearly, long-run policy specifications matter.

There is an interesting finding relating to the mix of abatement with and without banking. Over the period 2012–2050, both policies achieve the same level of cumulative emissions reductions. However, under banking, more of the abatement comes from reductions in coal use and less from petroleum, natural gas and other sources (Table 8.16). With banking, coal prices are higher from the beginning, leading to larger percentage reductions in coal use early on. By taking advantage of the arbitrage opportunity offered by banking, allowance prices then rise by 5% annually. This controls the increases in coal prices and comparatively large percentage reductions in coal use continue to occur, although less elastically.

Without banking, the increases in coal prices start small, leading to smaller reductions in coal use. Subsequently, coal price increases become much, much larger and further reductions in coal use are harder to achieve. This requires more abatement from reductions in the uses of oil and gas and from other emissions-generating activities. By the time the allowance price reaches $109 (2005 dollars) per tonne CO_2-e (as compared to $48 with banking), coal demand has fallen by over 90% and has become significantly inelastic, further shifting the burden of abatement to other sources.

Table 8.15 Macroeconomic impacts (25% target)

	No Banking	Banking Safety valve	No safety valve
Emissions ($GtCO_2$-e)			
Cumulative emissions target, 2012–2050	241.4	241.4	241.4
Cumulative emissions outcome, 2051–2060	59.1	71.8	59.1
Allowance prices (\$(2005)/tonne CO_2 equivalent)			
2012	1	7	7
2050	109	48	48
2051 and beyond	109	48	109
Average % change from base case, 2010–2060			
Real GDP	−1.4	−1.0	−1.3
Consumption	−0.9	−0.7	−0.8
Investment	−2.1	−1.4	−1.9
Government	0.0	0.0	0.0
Exports	−2.9	−2.1	−2.7
Imports	−2.6	−1.8	−2.4
GDP prices	1.4	1.0	1.2
Consumption	1.1	0.8	1.0
Investment	0.8	0.6	0.7
Government	0.6	0.4	0.5
Exports	1.6	1.2	1.4
Imports	1.1	0.8	1.0
Household full consumption (goods, services and leisure)	−0.1	−0.1	−0.1
Capital stock	−1.2	−0.9	−1.1
Labor demand and supply	−0.7	−0.5	−0.7
Leisure demand	0.3	0.2	0.3
Exchange rate (\$/foreign currency)	1.1	0.8	1.0

Allowance banking gives rise to somewhat larger economic costs in the initial years following enactment. Subsequently, banking with or without safety-valve pricing secures more substantial cost savings. There is strong evidence that banking is preferred to non-banking as a policy covenant. This most certainly is true over the 2010–2060 period reported above. However, it is also true in terms of dynastic welfare over an infinite time horizon as is shown in Figure 8.14. On average, with no safety valve and at mean full wealth, climate policy under banking incurs a marginally smaller net welfare loss, −0.10% versus −0.11%. At half mean full wealth, the comparative figures are −0.16

Table 8.16 Industry effects (25% target; average % change from base case, 2010—2060)

		No banking		Banking			
				With safety valve		No safety valve	
		Price	Output	Price	Output	Price	Output
1	Agriculture	7.5	−8.5	4.6	−5.6	6.4	−7.5
2	Metal mining	2.0	−2.5	1.5	−1.2	1.8	−2.0
3	Coal mining	358.3	−61.9	208.0	−63.3	309.5	−65.2
4	Petroleum and gas	−2.1	−0.6	−1.2	−0.4	−1.8	−0.5
5	Non-metallic mining	2.3	−4.2	1.8	−3.0	2.2	−3.9
6	Construction	0.8	−1.5	0.6	−1.0	0.7	−1.4
7	Food products	2.6	−3.0	1.7	−2.0	2.3	−2.6
8	Tobacco products	1.2	−1.7	0.8	−1.2	1.0	−1.5
9	Textile mill products	1.6	−2.6	1.1	−1.8	1.4	−2.4
10	Apparel and textiles	0.9	−1.1	0.7	−0.8	0.8	−1.0
11	Lumber and wood	1.3	−2.2	0.9	−1.5	1.2	−2.0
12	Furniture and fixtures	0.9	−1.6	0.7	−1.1	0.9	−1.5
13	Paper products	1.8	−2.8	1.4	−2.1	1.6	−2.6
14	Printing and publishing	0.6	−1.0	0.5	−0.7	0.6	−0.9
15	Chemical products	3.5	−5.4	2.2	−3.6	3.1	−4.8
16	Petroleum refining	5.1	−6.4	3.7	−4.7	4.7	−5.9
17	Rubber and plastic	1.9	−3.5	1.3	−2.6	1.7	−3.2
18	Leather products	1.2	−1.9	0.9	−1.4	1.1	−1.7
19	Stone, clay and glass	0.8	−2.0	−0.1	−0.6	0.5	−1.5
20	Primary metals	3.8	−5.2	3.2	−4.1	3.7	−5.0
21	Fabricated metals	1.4	−3.1	1.1	−2.3	1.3	−2.9
22	Industrial machinery	0.8	−2.0	0.6	−1.4	0.7	−1.8
23	Electronic and electric equipment	0.8	−1.8	0.6	−1.2	0.7	−1.6
24	Motor vehicles	1.1	−2.8	0.9	−2.0	1.0	−2.6
25	Other transportation equipment	0.7	−0.7	0.5	−0.5	0.6	−0.7
26	Instruments	0.4	−1.2	0.4	−0.8	0.4	−1.1
27	Miscellaneous manufacturing	1.0	−1.6	0.7	−1.0	0.9	−1.5
28	Transport and warehouse	1.2	−2.7	0.9	−2.0	1.1	−2.5
29	Communications	0.6	−1.4	0.4	−1.0	0.5	−1.2
30	Electric utilities	6.5	−4.8	5.5	−4.1	6.3	−4.7
31	Gas utilities	13.9	−11.4	8.9	−7.7	12.3	−10.2
32	Trade	0.8	−1.6	0.6	−1.1	0.7	−1.4
33	FIRE	0.7	−1.5	0.5	−1.1	0.6	−1.4
34	Services	0.6	−1.3	0.5	−0.9	0.6	−1.2
35	Government enterprises	0.9	−1.7	0.7	−1.2	0.8	−1.5

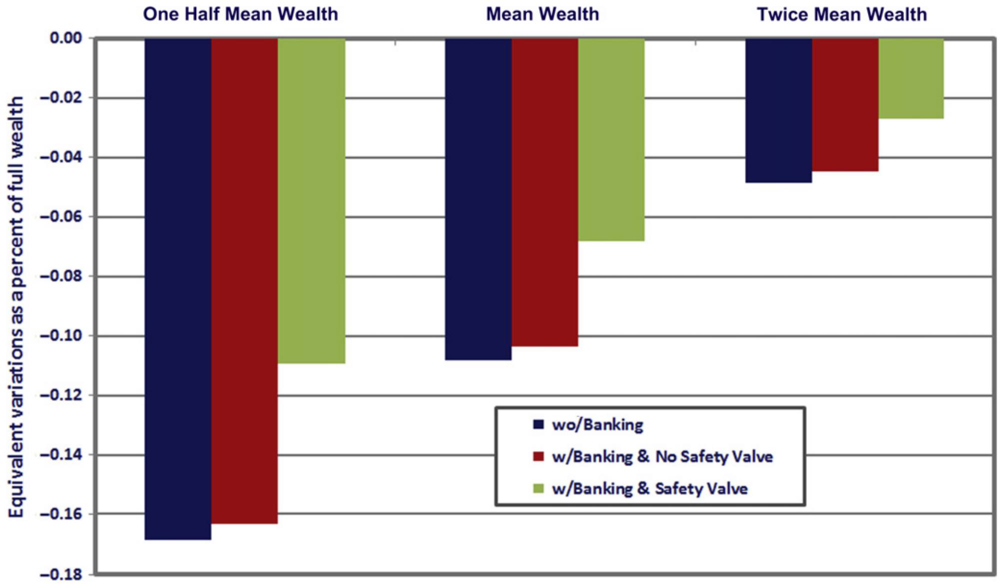

Figure 8.14 Household welfare effects (population weighed average, 25% target).

versus −0.17% and, at twice mean full wealth, the welfare losses under banking are −0.04% of lifetime expenditure compared to −0.05% without it. With safety valve pricing post-2050, the improvements in welfare losses become more substantial. At mean full wealth, it is −0.07 versus −0.11%, at one half mean full wealth, it is −0.11 versus −0.17% and, at twice mean full wealth, it is −0.03 versus −0.05%.

Banking with or without safety valve pricing introduces a measure of progressivity in an otherwise regressive policy. In Figure 8.14, we observe the spread increasing with falling wealth (i.e. moving right to left) indicating that the benefits of banking increase as full wealth decreases across household types. We note, however, that the percentage welfare improvements from banking favor wealthier households. The absolute benefits of banking also increase as full wealth decreases within a household type. That is, the spread increases with falling wealth − twice mean to mean and then mean to half mean − for a given reference household. These findings certainly add merit to the inclusion of banking as a matter of policy.

8.6 CONCLUSIONS

Econometric general equilibrium modeling is a very important addition to economic methodologies for evaluating energy and environmental policies. The traditional approach originated by Johansen is based on calibration of the models of household and producer behavior to a single data point. This useful simplification is a severe limitation in the application of these models to the analysis of energy and environmental policies.

The estimates of the costs of these policies are dramatically increased by ignoring the possibilities for substitution among inputs and induced changes in technology in responding to policy changes.

Econometric general equilibrium models retain long-established principles of microeconomic theory in modeling producer and consumer behavior. Exact aggregation over models for individual households makes it possible to incorporate demographic characteristics that reflect the enormous heterogeneity of household behavior. The intertemporal price system embodied in IGEM since its introduction by Jorgenson and Wilcoxen (1998) is essential to overcome the Lucas (1976) critique of macroeconometric models, which applies equally to CGE models.

The progress of econometric general equilibrium modeling has been impeded by the lack of appropriate national accounting data, except for the US. With the completion of the EU KLEMS project in 2008 and the establishment of the World KLEMS Initiative in 2010 (http://www.worldklems.net), this obstacle has been substantially reduced. These data are now available in the official statistics for many countries and are updated regularly for countries included in the EU KLEMS project.

The industry-level production accounts employed by Jorgenson *et al.* (2005) and employed in IGEM are consistent with the *2008 System of National Accounts* (United Nations *et al.*, 2009) and the new architecture for the US national accounts proposed by Jorgenson *et al.* (2006). Using the econometric methodology presented in this chapter, it is possible to develop econometric general equilibrium models for the major advanced countries of the world. Data will soon be available to extend this approach to 40 or more economies, including the leading emerging economies like China and India.

The new version of IGEM for evaluation of alternative climate policies employed by the US Environmental Protection Agency (2000, 2010) incorporates a new model of household behavior developed by Jorgenson and Slesnick (2008). This model successfully incorporates labor—leisure choices, as well as choices among goods and services, into the evaluation of climate policy. The model also incorporates demographic characteristics of individual households that reflect the heterogeneity of the US population.

Like the models of household behavior used in previous versions of IGEM, the Jorgenson—Slesnick model encompasses all the restrictions implied by the theory of consumer behavior. The new model also satisfies the conditions required for exact aggregation, so that we construct a model of aggregate consumer behavior for IGEM by aggregating over individual households. We then recover money measures of the impact on household welfare of changes in climate policy.

We provide results for 244 different types of households distinguished by demographic characteristics. We confirm the findings of previous studies of climate policy, including the study of a carbon tax by Jorgenson *et al.* (1997b), that the impact of climate policy would be regressive and negative, but is a relatively small effect. Overall, our findings imply that incorporating labor—leisure choice into the evaluation of alternative climate policies is a very worthwhile addition to policy analysis. This can be done while preserving the well-established framework for policy evaluation introduced by Jorgenson *et al.* (1997b).

An important goal for future research on econometric general equilibrium modeling is the development of econometric methods for inferences about the outcomes of CGE models. These would include confidence intervals and tests of hypotheses based on measures of production, like GDP and levels of industrial output, and measures of individual and social welfare. Jorgenson *et al.* in Chapter 17 of this Handbook describe how this can be done and apply the results to outcomes from the IGEM model presented in this chapter.

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