The Distributional Impact of Climate Policy

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Abstract

The purpose of this paper is to present a new methodology for evaluating the distributional impacts of climate policy. This methodology builds directly on the framework introduced by Jorgenson, Slesnick, and Wilcoxen (1992), but generalizes it by including leisure time, as well as goods and services, in the measure of household welfare. We provide detailed results for 244 different types of households distinguished by demographic characteristics. In addition, we evaluate the overall impact of a cap-and-trade system, as represented in the proposed Waxman-Markey Bill, and find that it would be regressive in terms of full wealth. There is a wide range of outcomes for the different demographic groups, from negative to positive welfare gains; the worst off are the one-adult households with two children living in the rural South.

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1 Introduction

In this paper we present a new approach to the evaluation of economic policies based on equivalent variations in full wealth. Full wealth is the present value of full consumption over all time periods. Full consumption includes the value of leisure, as well as goods and services, at a given point of time.[2] Our approach builds on the framework introduced by Jorgenson, Slesnick, and Wilcoxen (1992) for evaluating the introduction of a carbon tax in the U.S. economy. Their framework employs the wealth associated with the alternative policies to provide a money metric for the change in household welfare. Our principal innovation is to include leisure time, as well as goods and services, in the measure of household welfare.

Our starting point for policy evaluation is a reference policy or *base case* projection of the U.S. economy. This projection is associated with no change in policy. We then consider an *alternative case* projection with a change in policy. Each case is represented by an intertemporal general equilibrium. The equilibrium consists of supply-demand balance for all commodities and factors of production in all time periods and an associated intertemporal price system. The equivalent variation for a given household is the difference between the full wealth required for the utility level associated with the alternative case and that required for the base case. Both are evaluated at the prices of the base case.

As an illustration, we evaluate proposed legislation for introducing a cap-and-trade system to control emissions of greenhouse gases in the United States. The system is described in the American Clean Energy and Security Act of 2009 (H.R. 2454), the so-called Waxman-Markey bill, passed by the House of Representatives on June 26, 2009. We have employed the Intertemporal General Equilibrium Model (IGEM) used by Environmental Protection Agency (EPA).[3] Our analysis of the Waxman-Markey bill is reported in much greater detail by EPA.[4]

In this paper we introduce an updated and revised version of IGEM that gives similar results to the EPA version. We describe the new version of IGEM in Section 2, focusing on the household model developed by Jorgenson and Slesnick (2008).[5] This model includes present and future full consumption, as well as consumption of goods and services and leisure time. The model is implemented econometrically, using data from the Consumer Expenditure Survey

[2] The term "full consumption" is employed by Becker (1965).
[3] See http://www.epa.gov/climatechange/economics/modeling.html#intertemporal
[4] See http://www.epa.gov/climatechange/economics/economicanalyses.html#hr2454
[5] More details on modeling of consumer behavior are given by Jorgenson (1997a).

(CEX), conducted by the Bureau of Labor Statistics (BLS).[6] Jorgenson and Slesnick (2008) have employed expenditure data for 150,000 households and have augmented these data with estimates of leisure time for each household, also based on the CEX. Following Slesnick (2002) and Kokoski, Cardiff, and Moulton (1994), they employ data on prices for 1980-2006 for different regions of the United States taken from the Consumer Price Index, also constructed by the BLS.[7]

In Section 3 we summarize the approach to policy evaluation originated by Jorgenson, Slesnick, and Wilcoxen (1992). We generalize this approach to treat leisure, as well as goods and services, as components of full consumption.[8] A key idea is to consider each of 244 different types of households, distinguished by demographic characteristics, as the progenitor of a *dynasty* with an infinite lifetime. Each household faces a given level of full wealth and a time path of prices for leisure, goods, and services. The household chooses a time path for full consumption that generates the maximum level of utility. We calculate the equivalent variation in full wealth as a money metric of the change in utility associated with a change in policy.

In Section 4 we present a detailed evaluation of the Waxman-Markey bill.[9] We consider the impacts of this proposed legislation on the future time path of the U.S. economy, beginning with effects on the gross domestic product (GDP) and aggregates such as consumption, investment, government expenditures, imports, and exports. We then consider the effects on different industries, focusing on the five industries that make up the energy sector. Finally, we consider the welfare impacts of the legislation on individual households. We present effects on households with different demographic characteristics, including family size, region of residence, and the race and the gender of household head, as well as different levels of resources.

The policy raises the price of goods relative to leisure, causing households to substitute toward leisure and reduce labor supply. Output falls and lower investment cumulates into bigger reductions in future GDP. The rise in leisure partially offsets the reduction in goods consumption and the net welfare impact is modest, some households are slightly worse off and some are better

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[6] See http://www.bls.gov/cex/ The CEX is the standard source of household data on expenditures for goods and services in the United States.
[7] See http://www.bls.gov/CPI/
[8] More details on measuring economic welfare are provided by Jorgenson (1997b).
[9] Recent evaluations of policies to reduce emissions of greenhouse gases in the United States are presented by Burtraw, Sweeney, and Wells (2009), Greenstein, Parrott, and Sherman (2008), Hassett, Marthur, and Metcalf (2008), Metcalf, Holak, Jacoby, Paltsev, and Reilly (2008), and Shammin and Bullard (2009).

off. We find a small regressive effect: households with lower levels of full consumption within each demographic group experience a somewhat bigger welfare loss compared to those with higher levels of consumption. Section 5 concludes the paper.

2 Intertemporal General Equilibrium Model

The Intertemporal General Equilibrium Model (IGEM) of the U.S. economy was introduced by Jorgenson and Wilcoxen (1990). Applications of the original version of the model to the analysis of energy, environmental, tax, and trade policies are presented in detail in Jorgenson (1998). The version of the model we have employed is similar to that developed for EPA and documented on the EPA Climate Economics website. The model consists of four sub-models for the household, production, government, and rest of the world sectors of the U.S. economy. We begin with a description of the household sub-model constructed by Jorgenson and Slesnick (2008).

Household sector.

The Jorgenson-Slesnick model has three stages. In the first stage full wealth is allocated to full consumption at different points of time. In the second stage full consumption is allocated to leisure and three commodity groups – nondurables, capital services, and services. In the third stage the three commodity groups are allocated among 35 individual commodities, including the five types of energy. To capture differences in preferences between households we distinguish among demographic groups. The groups are cross-classified by size, region and characteristics of the head of household as shown in Table 1.

Table 1. 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

In the first stage, households are assumed to maximize an additively separable intertemporal utility function subject to a full wealth budget constraint. A full description of this utility function is presented in Section 3 where we discuss the method used to compute the lifetime welfare effects of climate policy. In the second stage of the model household *k* maximizes a utility function defined on three commodity groups – nondurables, capital services, services – and leisure, $U(C_{ND,k}, C_{K,k}, C_{SV,k}, C_{Rk}; A_k)$, where C_{Rk} is leisure and A_k denotes the demographic characteristics of household *k*. The composition of the commodity groups is given below.

To characterize substitutability among leisure and the three commodity groups, we represent the maximum level of utility as a function of prices and full consumption by means of the translog indirect utility function $V(p_k, m_k; A_k)$, where:

$$(1) \quad -\ln V_k = \alpha_0 + \alpha^H \ln \frac{p_k}{m_k} + \tfrac{1}{2} \ln \frac{p_k}{m_k}' B^H \ln \frac{p_k}{m_k} + \ln \frac{p_k}{m_k}' B_A A_k$$

where $p_k = (P^C_{ND}, P^C_K, P^C_{SV}, P^C_R)'$ is a vector of prices faced by household k, α^H is a vector of parameters and B^H and B_A are matrices of parameters that describe price, total expenditure, and demographic effects and A_k is a vector of variables that describe the demographic characteristics of household *k*. The value of full expenditure is:

$$(2) \qquad m_k = P^C_{ND} C_{NDk} + P^C_K C_{Kk} + P^C_{SV} C_{SVk} + P^C_R C_{Rk}.$$

An hour of leisure has a different opportunity cost for each member of each household. We assume that the quantity of leisure R^m_k for person *m* is non-work hours multiplied by labor quality given by the after-tax wage rate, relative to the base wage $q^m_k = p^m_R / p^0_R$. We assume a time endowment of $\bar{H} = 14$ hours a day for each adult. The annual quantity of effective leisure for an individual is the time endowment less hours worked *LS* weighted by labor quality, $R^m_k = q^m_k(\bar{H}^m_k - LS^m_k)$.

The quantity of leisure for household *k* is the sum over all adult members, $C_{Rk} = \sum_m R^m_k$, and the value is the nominal wage multiplied by leisure hours:

(3) $$P_R^C C_{Rk} = p_R^0 \sum_m R_k^m = \sum_m p_R^m (\bar{H}_k^m - LS_k^m) .$$

The demand functions for commodities and leisure are derived from the indirect utility function (1) by applying Roy's Identity:

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

where $D(p_k) = -1 + \iota ' B^H \ln p_k$, w_k is the vector of shares of full consumption, and ι is a vector of ones.

We require that the indirect utility function obeys the restrictions implied the theory of individual consumer behavior and the requirements for exact aggregation discussed below:

(5) $$B^H = B^H ' ; \qquad \iota ' B^H \iota = 0 , \qquad \iota ' B_A = 0 , \qquad \iota ' \alpha^H = -1,$$

where B^H are the share elasticities, $\iota ' B^H$ represents the full expenditure effect, and the kth column of B_A determines how the demands of demographic group *k* differs from the base group. These restrictions and their incorporation into the estimation process are described in detail by Jorgenson and Slesnick (2008).

Let n_k be the number of households of type k. Then the vector of aggregate demand shares for the U.S. economy is obtained by aggregating over all types of households:

(6) $$w = \frac{\sum_k n_k m_k \mathbf{w}_k}{\sum_k n_k m_k}$$

$$= \frac{1}{D(p)} \left[\alpha^H + B^H \ln p - \mathbf{\iota} B^H \xi^d + B_A \xi^L \right]$$

where *M* is the national level of full expenditures and the distribution terms are:

(7) $$\xi^d = \sum_k n_k m_k \ln m_k / M ; \qquad M = \sum_k n_k m_k$$

$$\xi^L = \sum_k n_k m_k A_k / M$$

By constructing a model of aggregate 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 include demographic information through the distribution terms in (7). For the sample period we observe the values of these terms. For the period beyond the sample we extrapolate them, using projections of the U.S. population by sex and race. That is, 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.

The estimated price and income elasticities are reported in Table 2; a full set of results is given by Jorgenson and Slesnick (2008). 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 nondurables, 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. Nondurables and capital services are necessities with full consumption elasticities less than one, while services are a luxury.

Table 2. Price and Income Elasticities

	Uncompensated Price Elasticity	Compensated Price Elasticity	Expenditure Elasticity
Nondurables	-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

Table 3 gives the fitted shares of the four commodity groups at different levels of full consumption for the reference household. The share allocated to nondurables falls rapidly as expenditures rise while the share allocated to capital services falls. Leisure value is hours multiplied by wage rates and the share rises with rising wage rates of the higher income households.

Table 3. Full expenditures and household budget shares

Full Expenditures ($)	Nondurables	Capital	Services	Leisure
7500	0.208	0.151	0.055	0.586
25000	0.164	0.137	0.06	0.626
75000	0.123	0.124	0.065	0.693
150000	0.098	0.116	0.068	0.713
275000	0.075	0.108	0.071	0.718
350000	0.066	0.106	0.072	0.716

In the third stage of the household model quantities of nondurables, capital services, and other services – N^{ND}, N^{K} and N^{CS} – are allocated among 35 individual commodities and capital services. We do not employ demographic information for this part of the model and use a nested tier structure of homothetic indirect utility functions. This structure is given in Table 4. For example in the energy node, total energy consumption is allocated among gasoline, fuel oil and coal, electricity, and gas. The model tracks changes in the composition of consumption due to non-price effects using latent variables in the same way as in the production model (9) given below.

The share demand functions at each node *m* of the tier structure are:

(8) $$SN_t^m = \alpha^{Hm} + B^{Hm} \ln PN_t^{Hm} + f_t^{Hm} \quad ,$$

where PN^{Hm} is the vector of prices at node *m* and f^{Hm} is the vector of latent variables. When B^{Hm} =0 the demand function reduces to linear logarithmic form.

A full set of estimates of unknown parameters of the household model for all 16 nodes is given by Goettle, *et al.* (2009). Most of the estimated share elasticities (β_{ii}^{Hm}) are between -0.1 and 0.1. About half are negative, that is, the price elasticity is greater than one. The latent variables f_t^{Hm} 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 since has flattened.

Table 4. Tier structure of the household model, 2005 (bil $)

Tier 1		Tier 2		Tier 3		Tier 4		Tier 5	
Full consumption	23423	Nondurables	2715	Energy	503	gasoline & 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		
				Cons. Goods	942	Clothing-shoe	342	shoes	55
								clothing	287
						Hhld articles	181	toilet art.; cleaning	138
								furnishings	43
						drugs	265		
						Misc goods	154	toys	66
								stationery	20
								imports	7
								reading materials	61
		Capital svc	1972						
		Cons. svc	4303	Housing	536	rental housing	334		
						owner maintenace	202		
				HH operation	281	water	64		
						communications	133		
						domestic service	20		
						other household	64		
				Transportation	324	own transportation	263		
						transportation svc	62		
				Medical	1491	medical services	1350		
						health insurance	141		
				Misc svcs	1670	personal svcs	116		
						Business Svcs	646	financial svcs	499
								other bus. svcs	147
						Recreation	458	recreation	358
								foreign travel	100
						educ & welfare	451		
		Leisure	14432						

Production sector

A total of 35 industries are identified in IGEM, including five related to energy production. Jin and Jorgenson (2009) have modeled substitution among inputs in these 35 producing industries by a nested series of translog price functions.[10] The top tier determines the price of output as a function of the prices of capital, labor, energy and non-energy inputs (K, L, E, M):

(9) $$\ln PO_t = \alpha_0 + \sum_i \alpha_i \ln p_{it} + \tfrac{1}{2}\sum_{i,k} \beta_{ik} \ln p_{it} \ln p_{kt} + \sum_i \ln p_{it} f_{it}^p + f_t^p$$

$$p_i,\ p_k = \{P_K, P_L, P_E, P_M\}$$

Jin and Jorgenson (2009) represent technical change by latent variables in a Kalman filter.[11] The latent variables $f_{Kt}^p, f_{Lt}^p, f_{Et}^p, f_{Mt}^p, f_t^p$ are generated by a vector autoregression. This allows non-price determinants of changes in technology to be extrapolated into the projection period. For example, rapid price declines due to productivity growth in electrical machinery are maintained in our base case and alternative case projections. The wide range of past behavior for individual industries is summarized in Table 5.

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[10] More detail about econometric modeling of producer behavior is provided by Jorgenson (2000).
[11] Jin and Jorgenson (2009) can be downloaded from http://www.economics.harvard.edu/faculty/jorgenson/files/EconometricModelingTechChangehuijin_draft081308.pdf

Table 5. Industry output, energy use in 2005 and historical growth.

	Output	Energy share	Output growth 1960-05	TFP growth 1960-05
	(bil $)	(% output)	(% p.a.)	(% p.a.)
1 Agriculture	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 Petroleum and Gas	260	7.6	0.40	-0.58
5 Nonmetallic 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 Textiles	36	1.4	-0.28	0.97
11 Lumber and Wood	130	2.9	2.03	0.15
12 Furniture and Fixtures	101	1.9	3.27	0.69
13 Paper Products	168	4.4	2.04	0.47
14 Printing and Publishing	230	1.1	1.83	-0.15
15 Chemical Products	521	4.9	2.81	0.55
16 Petroleum Refining	419	51.3	1.63	0.08
17 Rubber and Plastic	188	2.5	4.21	0.87
18 Leather Products	6	2.7	-2.36	0.33
19 Stone, Clay, and Glass	129	5.9	1.90	0.54
20 Primary Metals	251	5.1	0.84	0.32
21 Fabricated Metals	296	2.2	1.94	0.51
22 Industrial Machinery	424	1.3	5.92	2.65
23 Electronic & Electric Equip	331	1.4	6.50	3.81
24 Motor Vehicles	442	0.9	3.22	0.27
25 Other Transportation Equip	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 Transport and Warehouse	668	13.1	3.01	0.99
29 Communications	528	0.8	5.65	1.16
30 Electric Utilities	373	14.2	2.94	0.30
31 Gas Utilities	77	55.0	-0.45	-0.86
32 Trade	2488	3.2	3.72	0.84
33 FIRE	2752	1.2	4.19	0.77
34 Services	4354	1.7	3.93	-0.27
35 Goverment Enterprises	328	7.8	2.43	0.19

"Energy share" includes feedstocks

The remaining sectors of IGEM are the government and rest-of-the-world sectors. The solution of this forward-looking model generates a cost-of-capital equation that links asset prices between two consecutive periods with the marginal product of capital and the rate of return. This solution also incorporates an Euler equation characterizing intertemporal choice. Translog price functions similar to (9) are used to represent the commodity demands by the government sector, as well as exports and imports. Latent variables are used to capture the non-price effects of changes in technology and preferences.

In the rest-of-the-world sector of IGEM imported commodities are imperfect substitutes with the domestic varieties. The current account deficit is specified exogenously and this constraint is met by adjusting the world relative price. The tax system is represented by exogenous tax rates on capital, labor, output, imports and property. The government budget deficit is set exogenously, transfers and interest payments are set exogenously, and government purchases of goods are the endogenous variables that satisfy the budget constraint.

In IGEM emissions of carbon dioxide (CO2) are generated from fossil fuel consumption. In addition, the model includes four sets of variables representing other greenhouse gas (GHG) emissions –emissions of non-CO2 GHG gases, CO2 emissions from sources other than fossil fuel use, GHG emissions from sources covered by a particular policy, and emissions not covered by the policy. The externality coefficients for the environment are derived from the detailed historical data in the EPA's *2009 U.S. Greenhouse Gas Inventory Report.*

Mitigation strategies, other than those associated with fossil fuel consumption, are not represented within the household and production sub-models, but are included in IGEM through marginal abatement cost (MAC) schedules. These include abatement opportunities related to residential and commercial mitigation strategies, non-CO_2 greenhouse gases, international permit trading, and domestic carbon sequestration. Marginal abatement cost curves for these strategies are derived from studies conducted for EPA and can be downloaded from EPA's Climate Economics website.

Base case projection

To allow for a direct comparison of our estimates of policy impacts with estimates from other models we calibrate the growth of gross domestic product (GDP) in IGEM to the real GDP growth in the *Annual Energy Outlook 2009* (AEO 2009) from the Energy Information

Administration of the U.S. Department of Energy. For the period covered in AEO 2009, 2007-2030, we also calibrate the base case projection of IGEM to the AEO 2009's energy utilization – the use of coal, oil, gas and electricity.

The level of GDP is targeted by applying an economy-wide adjustment to total factor productivity growth. The consumption of energy is targeted by adjusting productivity growth in the domestic energy production sectors. Import prices are set equal to those in AEO 2009. For comparison with the simulations done for EPA, we calibrate the GDP in the period 2030-2050 to the projections of the ADAGE model of RTI International.

The most important exogenous variables in IGEM are those related to the population, government finances and international financial flows. The population projection is taken from the U.S. Bureau of the Census[12], the quality of aggregate labor is projected assuming a modest improvement in educational attainment, and the federal government deficits, expenditures and implied tax rates are taken from the Congressional Budget Office (2009). We project a gradually declining path for the U.S. current account deficit.

3. Welfare measurement

Our methodology for measuring the welfare effects of policy changes was introduced by Jorgenson, Slesnick, and Wilcoxen (1992). As presented in section 2 above, the household sector is comprised of infinitely-lived households that we refer to as dynasties. Each household takes commodity prices, wage rates, and rates of return as given. All dynasties are assumed to face the same vector of prices p_t at time t and the same nominal rate of return r_t. The quantity of a commodity, 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} as given in (2) above.

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

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

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

where $\delta = 1/(1+\rho)$ and ρ is the subjective rate of time preference. The intratemporal indirect utility function (4) is expressed in terms of *household equivalent members*:

(11) $$\ln V_{dt} = \alpha^H{}' \ln p_t + \tfrac{1}{2} \ln p_t{}' B^H \ln p_t - D(p) \ln \frac{M_{dt}}{N_{dt}}$$

where $N_{dt} = \dfrac{1}{D(p_t)} \ln p_t B_A A_d$ 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:

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

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

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:

(13) $$\ln M_{dt}(p_t, V_{dt}, A_d) = \frac{1}{D(p_t)} [\alpha^H{}' \ln p_t + \tfrac{1}{2} \ln p_t{}' B^H \ln p_t - \ln V_{dt}] + \ln N_{dt}$$

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

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

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

(15) $$P_t = \exp \left(\frac{\alpha^H{}' \ln p_t + \tfrac{1}{2} \ln p_t{}' B^H \ln p_t}{D_t} \right)$$

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

$$\ln V_{dt} = \frac{D_t}{D_0} \ln V_{d0} + D_t \ln\left(\frac{D_0 \gamma_t N_{dt} P_t}{\delta^t D_t N_{d0} P_0} \right) \tag{16}$$

Equation (16) enables us to 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:

$$\sum_{t=0}^{\infty} \gamma_t N_{dt} P_t V_{dt}^{-1/D_t} = \Omega_d \tag{17}$$

Substituting (16) into (17) and simplifying yields the following:

$$\ln V_{d0} = -D_0 \ln\left(\frac{\Omega_d}{N_{d0} R} \right) \tag{18}$$

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

Equation (18) enables us to evaluate dynastic utility in terms of full wealth:

$$\begin{aligned} V_d &= \sum_{t=0}^{\infty} \delta^t \ln V_{dt} \\ &= \sum_{t=0}^{\infty} \delta^t \left[\frac{D_t}{D_0} \ln V_{d0} + D_t \ln\left(\frac{D_0 \gamma_t N_{dt} P_t}{\delta^t D_t N_{d0} P_0} \right) \right] \\ &= \sum_{t=0}^{\infty} \delta^t \left[-D_t \ln \frac{\Omega_d}{R} + D_t \ln\left(\frac{D_0 \gamma_t N_{dt} P_t}{\delta^t D_t P_0} \right) \right] \\ &= S \ln R - S \ln \Omega_d + \sum_{t=0}^{\infty} \delta^t D_t \ln\left(\frac{D_0 \gamma_t N_{dt} P_t}{\delta^t D_t P_0} \right) \end{aligned} \tag{19}$$

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:

$$(20) \qquad \ln \Omega_d(\{p_t\},\{\gamma_t\},V_d) = \frac{1}{s}\left[S\ln R + \sum_{t=0}^{\infty} \delta^t D_t \ln\left(\frac{D_0\gamma_t N_{dt} P_t}{\delta^t D_t P_0}\right) - V_d \right],$$

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

We employ the expenditure function (20) 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:

$$(21) \qquad \Delta W_d = \Omega_d(\{p_t^0\},\{\gamma_t^0\},V_d^1) - \Omega_d(\{p_t^0\},\{\gamma_t^0\},V_d^0)$$

The equivalent variation in full wealth (21) 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.

Table 2 gives a total of 384 household types. However, the number of types with a positive number of households is only 244. In Section 4 below we report the equivalent variations of full wealth resulting from introduction of a cap-and-trade policy for all 244 types. We calculate the equivalent variations at mean wealth, half the mean wealth and twice mean wealth.

4. Evaluation of Climate Policy

We next consider the evaluation of a cap-and-trade policy to control greenhouse gas emissions in the United States. This policy is described in the American Clean Energy and Security Act of 2009 (H.R. 2454). The core scenario has an allowance price beginning in 2012 at \$9.65 in \$(2000) per metric ton carbon dioxide equivalent ($MTCO_2Eq$). With optimal banking, this price rises at a rate of five percent annually through 2050. The core scenario includes the resource costs for non-CO_2 abatement, bio-electricity, carbon capture and storage, and domestic and international offsets. The Act provides allocations of permits to compensate various sectors: to households for the higher costs of electricity, natural gas and home heating oil, to refiners, to the automobile industry, to the construction sector and to a selection of industries highly exposed to international trade.

A key assumption in setting the policy simulation is the treatment of the government budget. We could keep nominal revenues and expenditures equal to the base case or keep real expenditures on goods equal to the base case with an endogenous tax (or transfer). Although there is no price inflation in IGEM there are large changes in relative prices due to the policy, that is, a dollar buys a different basket of goods in year *t* in the policy case compared to the base case. Our procedure is to keep nominal government expenditures under the cap-and-trade policy equal to those of the base case.

Macroeconomic effects

Table 6 summarizes the macroeconomic impacts of the cap-and-trade policy. Real GDP falls modestly in the initial periods but by 2050 it is 1.7% smaller than the base case. There is a reallocation of activities, so that consumption falls by less than GDP while exports fall substantially more and investment falls by roughly the same percentage. Since nominal government expenditures are held equal to the base case, the higher goods prices, relative to the labor price numeraire, reduce real government consumption. However, like private consumption, real government consumption falls less than GDP[13].

[13] We have analyzed this policy for the EPA using an earlier version of IGEM. The results are similar with the largest difference in the impact on investment. The reduction in investment and capital stock in the current version is less due to a smaller impact on the price of investment goods and a smaller reduction in capital income.

Table 6. Macroeconomic Impacts of HR 2454
(% change from base case)

	2012	2030	2050
Real GDP	-0.43	-0.96	-1.70
Consumption	-0.08	-0.42	-0.91
Investment	-0.51	-0.88	-1.57
Government	-0.14	-0.31	-0.58
Exports	-1.32	-2.53	-4.16
Imports	0.31	0.24	-0.20
Prices GDP	0.35	0.86	1.56
Consumption	0.16	0.56	1.08
Investment	-0.05	0.11	0.37
Household Real Full Consumption of Goods, Services and Leisure	0.07	0.02	-0.06
Capital Stock	-0.18	-0.70	-1.29
Labor Demand (Labor Supply)	-0.37	-0.66	-1.10
Leisure Demand	0.16	0.28	0.42
Exchange Rate ($/Foreign Currency)	-0.95	-1.50	-2.04

The higher goods prices lower the relative price of leisure, so that leisure demand rises. The stock of capital is changed very little in the initial periods and so the price of labor input also rises relative to the price of capital input. These shifts in labor supply and demand result in a fall in hours of work and a rise in leisure consumption. Keep in mind that full consumption is an aggregate of consumption of goods and services and leisure. In the initial periods, when the carbon prices are low, the increase in leisure dominates and full consumption is higher in the policy case. As the carbon prices rise over time the reduction in goods consumption becomes more substantial and full consumption becomes lower than in the base case.

Table 7 gives the effects for industry prices and output in 2030, that is, 18 years after the introduction of the cap-and-trade policy. The policy raises coal prices the most (61%), and reduces coal output the most (42%). The next largest impact is on refined petroleum products where the price rises by 7.5% and the output falls by 8.2%; this is followed by gas utilities and

Table 7. Industry effects of HR2454 in 2030. (% change from base case).

		Price	Output
1	Agriculture, forestry, fisheries	0.68	-1.16
2	Metal mining	1.06	-1.99
3	Coal mining	61.26	-42.49
4	Crude oil and gas extraction	-2.94	-1.69
5	Non-metallic mineral mining	1.31	-2.72
6	Construction	0.39	-0.80
7	Food products	0.49	-1.00
8	Tobacco products	0.32	-0.72
9	Textile mill products	0.64	-1.65
10	Apparel & other textile products	0.36	-0.76
11	Lumber and wood products	0.46	-1.16
12	Furniture and fixtures	0.41	-1.17
13	Paper and allied products	0.63	-1.64
14	Printing and publishing	0.21	-0.69
15	Chemicals	0.96	-2.22
16	Petroleum refining	7.52	-8.21
17	Rubber and plastic products	1.11	-2.54
18	Leather and leather products	-0.01	-0.18
19	Stone, clay and glass products	1.01	-1.75
20	Primary metals	1.31	-3.50
21	Fabricated metal products	0.55	-1.71
22	Industrial machinery	0.17	-2.01
23	Electrical machinery	0.02	-1.04
24	Motor vehicles	0.16	-0.34
25	Other transportation equipment	0.21	-1.40
26	Instruments	0.15	-1.29
27	Miscellaneous manufacturing	0.27	-0.73
28	Transportation and warehousing	0.94	-1.91
29	Communications	0.13	-0.54
30	Electric utilities (services)	5.34	-3.69
31	Gas utilities (services)	6.38	-7.35
32	Wholesale and retail trade	0.39	-1.01
33	Finance, insurance and real estate	0.29	-0.81
34	Personal and business services	0.29	-0.72
35	Government enterprises	0.60	-1.15

electric utilities, where the output falls by 7.4% and 3.7%, respectively. Given the fall in GDP due to a smaller capital stock in 2030, output of all sectors is lower than in the base case; the smallest reductions are in the non-energy intensive industries such as Services and Finance.

The impacts of the cap-and-trade system on the outputs of the various energy commodities depend on carbon intensity and the degree of substitutability for other inputs. The share elasticities given by the β_{ik} coefficients in (9) reveal relatively easy substitution for coal, especially in comparison to the parameter estimates in previous versions of IGEM. The share elasticities are the main determinant of the costs of abating carbon emissions.

To summarize the properties of IGEM we plot the marginal abatement cost (MAC) schedules for CO2 emissions in Figure 1. The curves are convex, so that it is increasingly more difficult to reduce these emissions. The MAC schedules shift upwards with time, so that there is a smaller reduction of emissions in future years for a given increase in the carbon price. This is driven in part by the substantial energy savings over time in the base case specified by AEO 2009. Given the more elastic substitution possibilities, these MACs are lower than those estimated in previous versions of IGEM.

Household welfare effects

We next report the impacts of a cap-and-trade policy on household welfare given by the equivalent variation in full wealth. Recall that the equivalent variation is the full wealth required to attain the welfare associated with the new policy at prices in the base case, less the wealth required to attain the welfare of the base case at the same prices. This money metric enables us to rank the base case policy and any number of alternative policies in terms of the impacts on dynastic welfare. If the equivalent variation is positive, the policy produces a gain in welfare. We present equivalent variations for each of the 244 household types, cross-classified by the demographic categories, presented in Table 1.

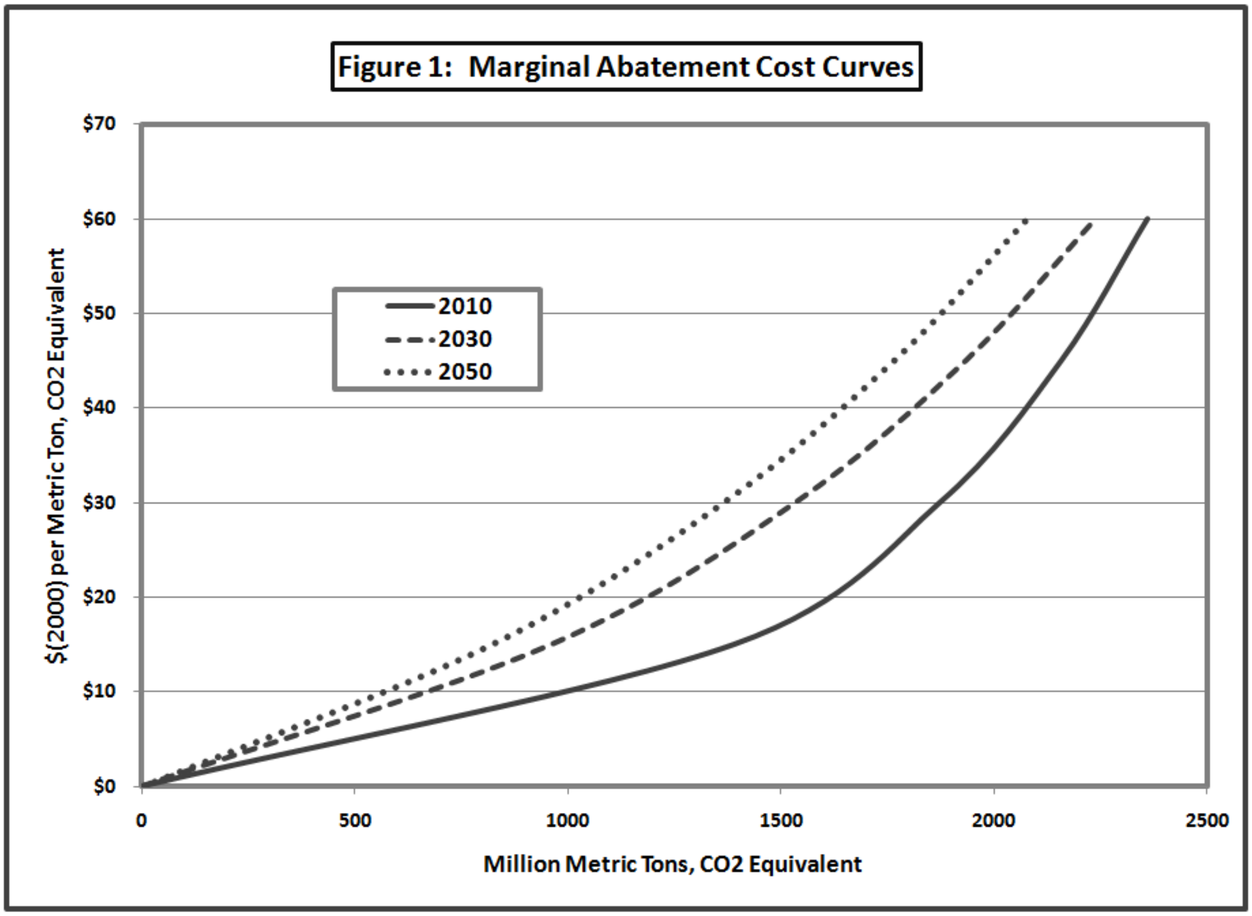

Figure 2 shows the welfare effects for the 244 household types, arranged from the most adversely to the most favorably affected. The principal curve is the solid line labeled "At mean wealth" which shows the welfare impact on households with the mean wealth among those with the same demographic characteristics. Just over one fifth of the households experience a small welfare loss while the remaining households gain slightly. As will be discussed below, the gains stem from our assumption about the government budget, which causes the real tax burden on households to drop slightly. The most negatively affected households consist of two children, with one adult living in the rural South and headed by non-white females. The most positively affected are large urban households in the West: three or more children with three or more adults headed by a nonwhite male.

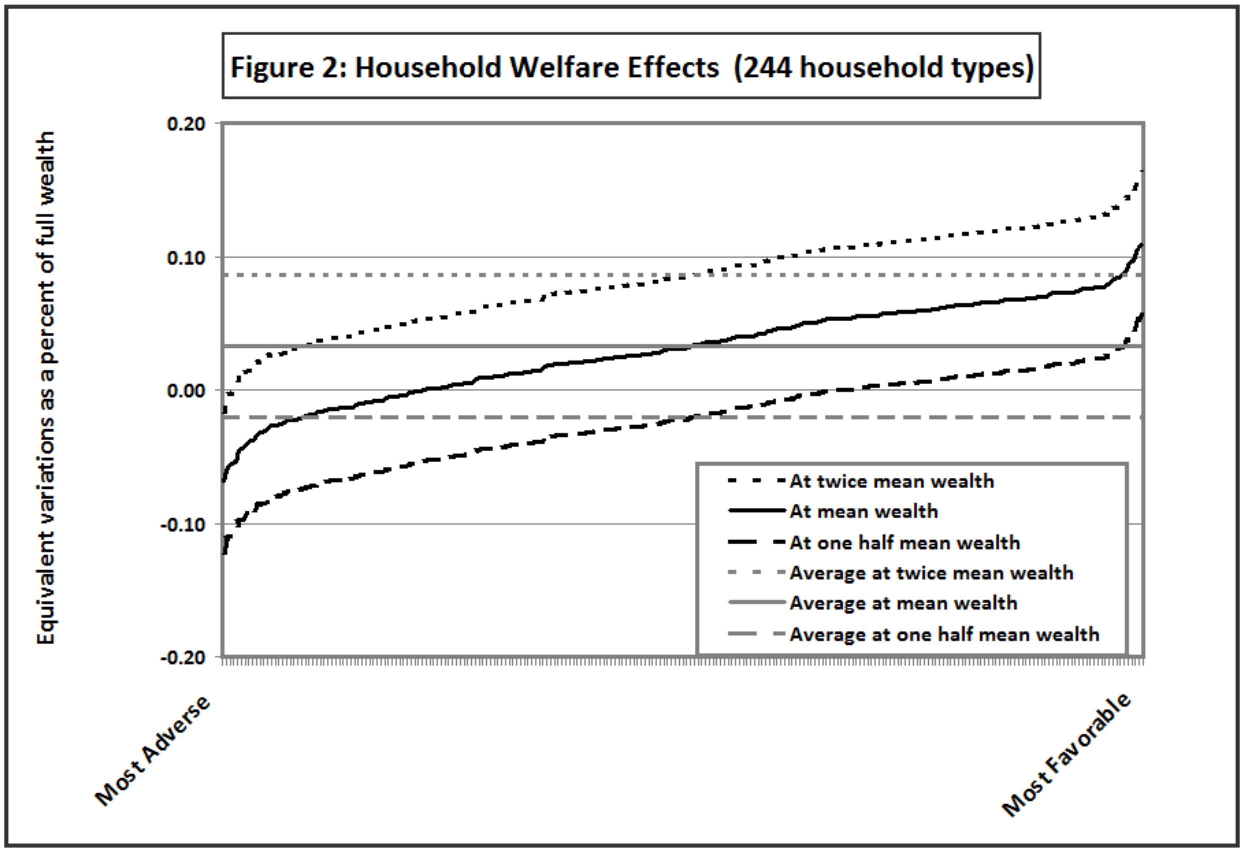

Figure 2: Household Welfare Effects (244 household types)

To illustrate how the policy affects households with different levels of full consumption, the effects in Figure 2 also are shown for one half and twice mean wealth. The population-weighted average welfare effects are -0.02, 0.03 and 0.08 percent of lifetime full wealth at the one half mean, mean, and twice mean levels, respectively, as represented by the horizontal lines in Figure 2. It should be emphasized that these are effects on individual households, not measures of social welfare. Figure 2 shows that the effects of the policy change are regressive: the equivalent variations become less negative (or more positive) as full wealth increases. However, it should be noted that in all cases the welfare effects are small: substantially less than one percent of wealth.

Figure 3 decomposes the welfare effect by isolating the impact of price changes alone. The solid line in Figure 3 shows the curve from Figure 2 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, all households would experience a net welfare loss, with values ranging from -0.34 to -0.17 percent of full wealth. However, lump sum tax rebates required to hold nominal government spending at its base case level cause expenditure to rise. Moreover, since as shown in Table 6, the real value of government spending falls slightly, the real tax burden also falls slightly, and the consequent increase in real household expenditure leads to the generally positive character of the results. An alternative budget rule that kept real government spending constant would cause less revenue to flow back to households and would cause a downward shift in the set of equivalent variations.

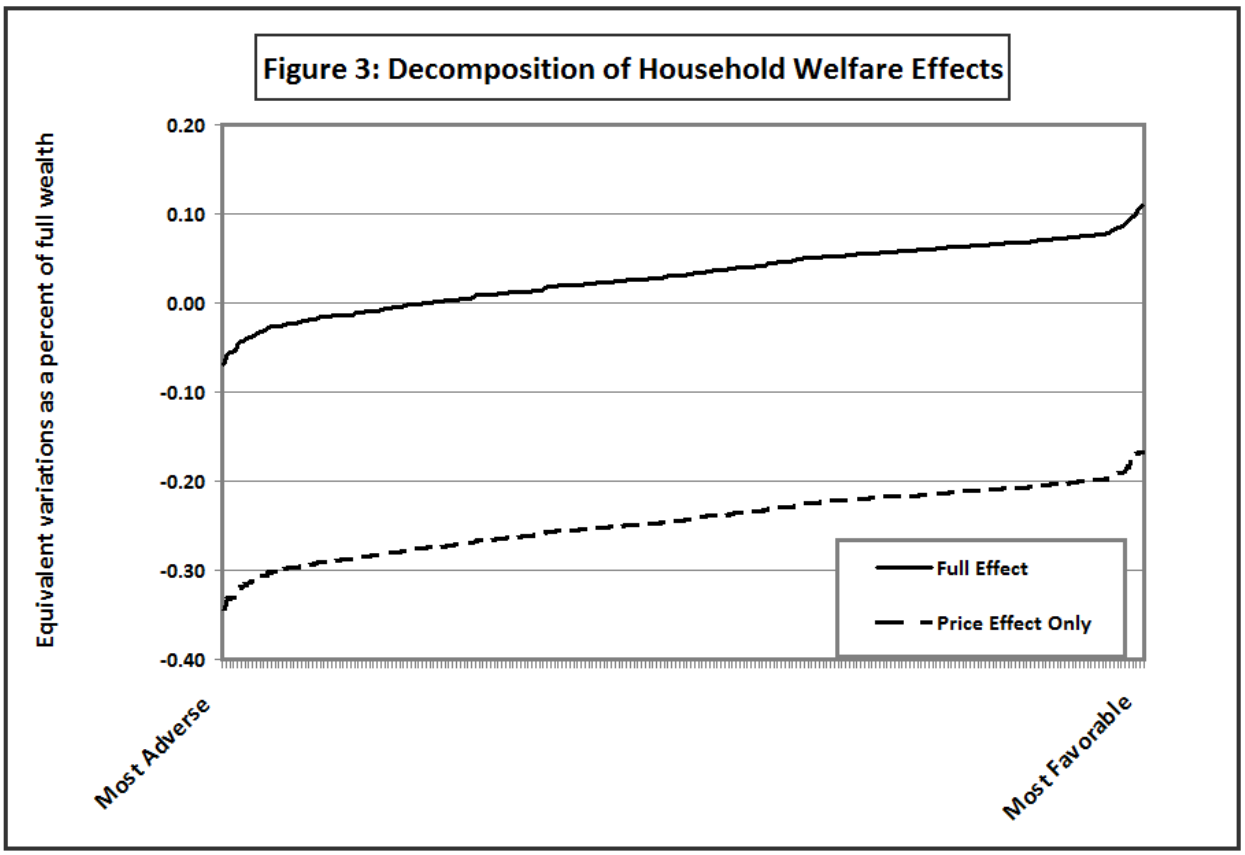

Figure 4 orders the welfare losses first by the number of adults, second by the number of children from most to least, and finally from the most adversely to most favorably affected. The first 55 bars correspond to 3+ adult households, the second 91 bars to 2-adult households, and the last 78 bars to 1-adult households. 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. Among the single adult households, within each grouping based on the number of children, rural households headed by females fare worst.

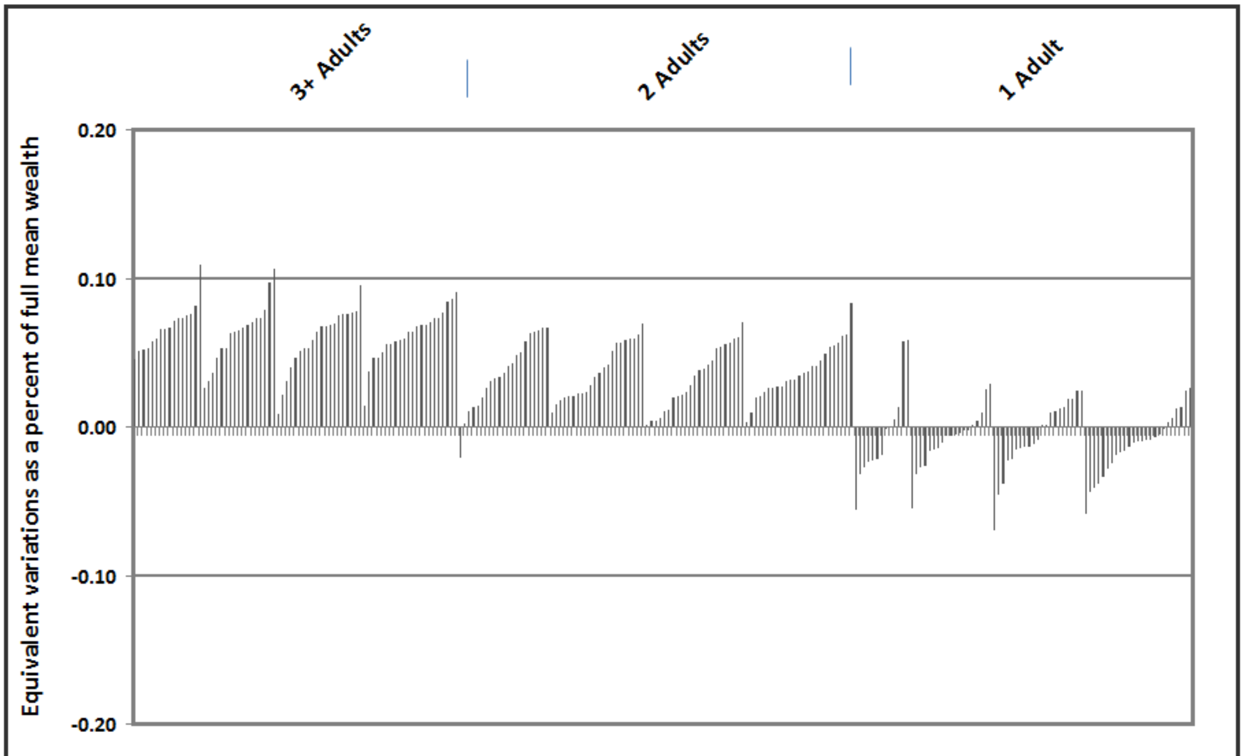

Figure 4: Household Welfare Effects by Family Size

Figure 5 shows the welfare losses by region of residence (the first 56 bars are for the households in the Northeast, ordered by the size of the welfare change). In the sample underlying these results, 18.9% of the 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 welfare losses are located in the South or Midwest, and the largest losses occur in the South. The households with the largest gains are in the West.

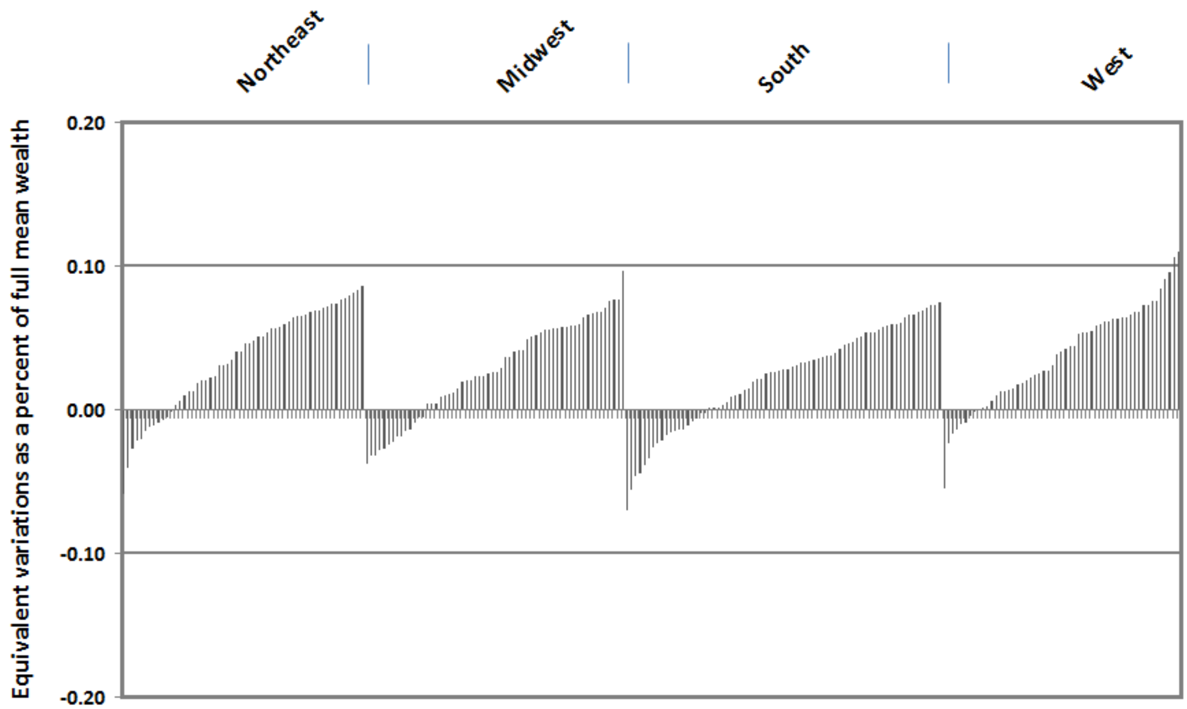

Figure 5: Household Welfare Effects by Region

Figure 6 sorts the welfare changes first by gender and then by race of head. 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. Most household types with welfare losses are headed by females, especially white females. The largest gains occur in households with three or more adults headed by non-white males in the West. Finally, Figure 7 orders the welfare losses by type of residence, urban and rural. The households with the largest losses are concentrated in rural areas. Households in urban areas generally gain.

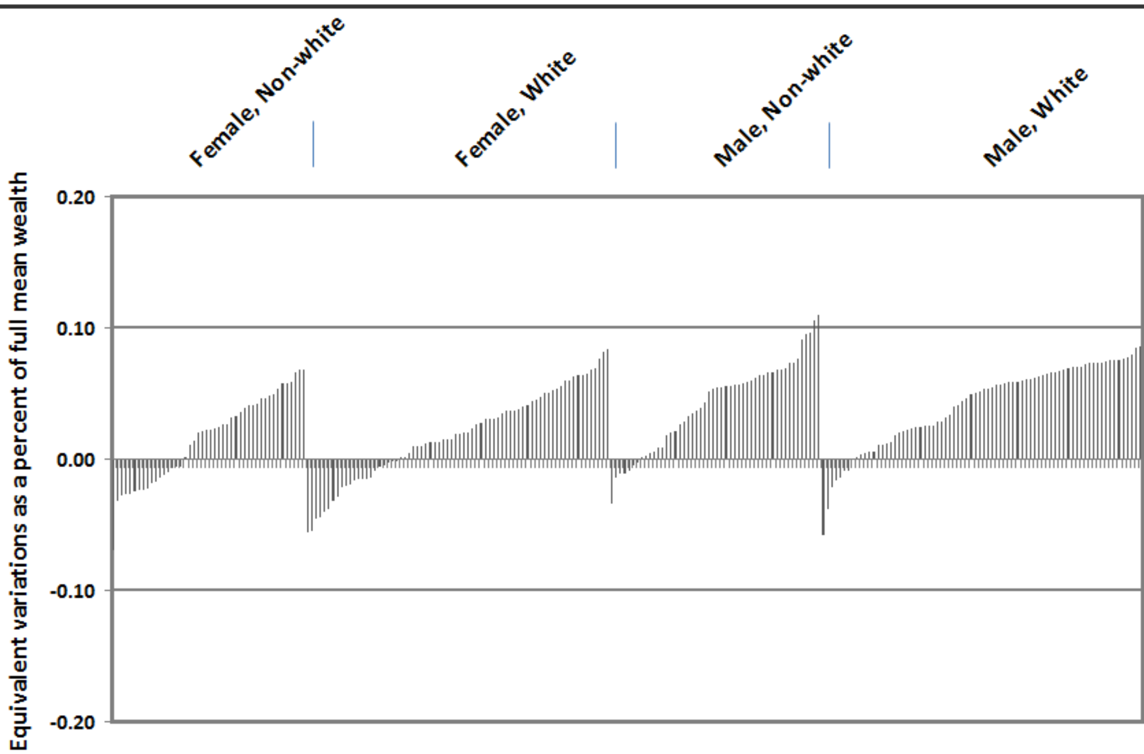

Figure 6: Household Welfare Effects by Gender and Race of Head

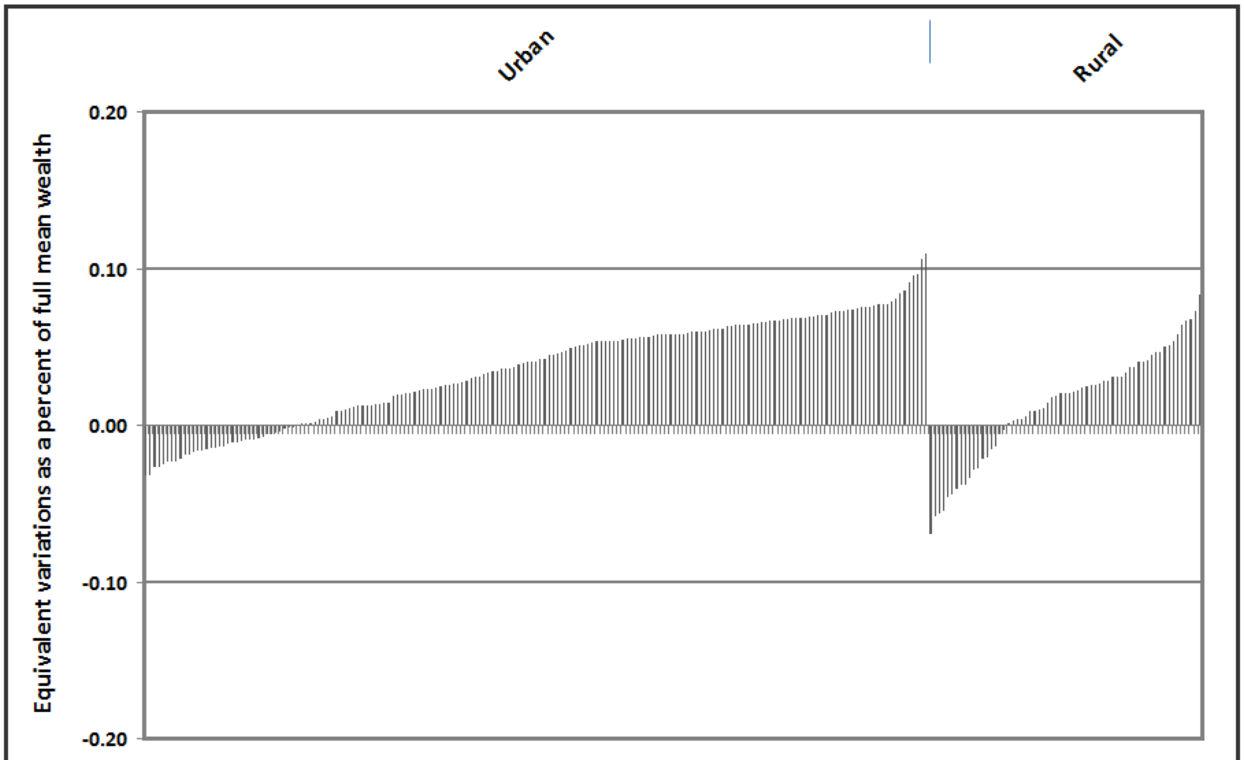

Figure 7: Household Welfare Effects by Type of Residence

5. Conclusion

In this paper we have successfully incorporated labor-leisure choices, as well as choices among goods and services, into the evaluation of climate policy. This has required the construction of a new version of the Intertemporal General Equilibrium Model (IGEM), employed for evaluation of climate policy by the Environmental Protection Agency. This incorporates a new model of household behavior developed by Jorgenson and Slesnick (2008) that includes labor supply.

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 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, Slesnick, and Wilcoxen (1992), that the impact of climate policy would be regressive.[14] In addition, we show that the overall welfare impacts of climate policy are sensitive to assumptions about the link between climate policy and government expenditures. Overall, our findings imply that incorporating labor-leisure choice into the evaluation of alternative climate policies can be done while preserving the well-established framework for policy evaluation introduced by Jorgenson, Slesnick, and Wilcoxen (1992). This earlier framework, however, must be augmented by a model of household behavior with the features introduced by Jorgenson and Slesnick (2008).

[14] These include the studies listed on footnote 9.

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