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Population Aging and Future Carbon Emissions in the United States

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Abstract

Changes in the age composition of U.S. households over the next several decades could affect energy use and carbon dioxide emissions. This article incorporates population age structure into an energy-economic growth model with multiple dynasties of heterogeneous households. The model is used to estimate and compare effects of population aging and technical change on baseline paths of U.S. energy use and emissions. Results show that population aging reduces long-term carbon dioxide emissions, by almost 40% in a low population scenario, and effects of aging on emissions can be as large, or larger than effects of technical change in some cases.

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Introduction

Population growth and technical change are among the most important factors to consider in projections of future carbon dioxide (CO₂) emissions and other greenhouse gases (Schelling, 1992). These emissions, primarily from burning fossil fuels for energy but also other sources such as land use, contribute to the trend of global warming that could cause earth's climate to change in unpredictable and potentially dangerous ways (O'Neill and Oppenheimer, 2002; Mastrandrea and Schneider, 2004). The role of technical change has been the focus of several studies that estimate baselines for future emissions (e.g. Weyant, 2004). The treatment of population in these projections has been limited mainly to direct scale effects from changes in population size alone. However, other demographic factors may be important. Indirect scale effects can arise through compositional changes in the population due to aging, urbanization, or other determinants of economic growth (Birdsall et al., 2001). In addition, population composition can affect consumption patterns, which vary in their indirect energy requirements because of the energy embodied in different consumer goods (Schipper, 1996; Bin and Dowlatabadi, 2005). Compositional changes in population will occur over the next several decades in many parts of the world, and effects of these changes on energy demand and emissions are currently unknown.

This article estimates potential effects of population aging on energy use and CO₂ emissions for the United States (U.S.). Our approach differs in two important ways from existing energy and emissions projections: First, we use households, rather than individuals, as the demographic unit of analysis, and second, we incorporate demographic heterogeneity by introducing the age structure of households into an energy-economic growth model. The empirical energy studies literature has identified household characteristics, such as size and age structure, as key determinants of direct residential energy demand (Schipper, 1996), and has shown that changes in the composition of U.S. households could have substantial effects on national energy demand (O'Neill and Chen, 2002). A few studies have included household characteristics in projections of future energy demand, but these have been limited to short time horizons and simple household projections (Lareau and Darmstadter, 1983; Weber and Perrels, 2000). Household characteristics have not been incorporated into energy-economic growth models, which are among the most widely used tools for

making long-term CO₂ projections and analyzing climate change policies (Weyant and Hill, 1999). To frame the development of our own methodology, we give an overview of the two families of models, infinitely lived agent (ILA) and overlapping generations (OLG), which have been used for long-term emissions projections and climate change policy analysis. We focus on the treatment of savings decisions, and assumptions implicit in solution methods, two key issues for judging a model's applicability to introducing heterogeneity in households.

Infinitely lived agent models

Most energy-economic growth models used for climate change policy analysis have a dynamic structure that is based on a variant of the infinitely lived agent in Ramsey's (1928) savings model, and are the typical approach for comparing costs and benefits of alternative emissions abatement strategies (Manne, 1999; Cline, 1992; Peck and Teisberg, 1992; Nordhaus, 1994; Manne, Mendelsohn, and Richels, 1995; Nordhaus and Yang, 1996). In such models, population is treated as a single representative household that is infinitely lived. The economy is analyzed as though there were a benevolent planner acting as a trustee on behalf of both present and future generations. Schelling (1995) and others (e.g., Azar and Sterner, 1996) have criticized the strong welfare assumptions implicit in the representative agent, planner-based ILA approach. Nonetheless, ILA models have been developed with detailed production sectors for energy and other intermediate goods, have a transparent dynamic structure to describe capital accumulation, and can be calibrated to historical data. In other words, ILA models are broadly consistent with economic theory, and currently provide the most detailed empirical tools for evaluating the costs, and perhaps benefits, of controlling greenhouse gas emissions.

While these models have many similarities, they also exhibit important differences. Many models adopt a recursive, or backwards-looking, formulation of investment decisions, and are based on a variation of the Solow (1956) growth model that assumes some type of fixed savings rule, usually a constant fraction of income in each period. Fixed savings rules are usually a simplification that avoids solving a dynamic optimization problem. Nonetheless, models with fixed savings rules often compensate for this simplification with detailed energy sectors, and other realistic features such as land-use and demographic change (e.g., MacCracken, et al., 1999).

Other models in the energy economics literature adopt a forward-looking approach to capital accumulation that assumes perfect foresight about the future productivity of capital, prices, and other variables (e.g., Goulder, 1995). The properties of a dynamic competitive equilibrium with forward-looking behavior are substantially different from models based on fixed savings rules. In fact, a dynamic equilibrium with fixed savings rules is not an authentic competitive equilibrium because households are not, strictly speaking, utility maximizers. While the assumption of perfect foresight may not be realistic, it does incorporate information about the future into current decisions, and is thus an improvement over fixed savings rules from the point of view of economic theory. Moreover, perfect foresight can be interpreted as a first-order approximation to rational expectations (Fair and Taylor, 1983). Some economic growth models mix different types of savings behavior by assuming a proportion of the population solves a

dynamic optimization problem, while others follow a fixed savings rule (McKibbin and Vines, 2000).

Overlapping generations models

Overlapping generations (OLG) models provide an alternative to ILA models for dealing with sustainability and other intergenerational welfare issues (Howarth and Norgaard, 1992; Farmer and Randall, 1997). The OLG models have an explicit demographic structure to describe key life-cycle stages. Like their ILA counterparts, OLG models come with a variety of structural assumptions and solution techniques. In general, OLG models have dynamic properties that are different from ILA models (Auerbach and Kotlikoff, 1987; Geanakoplos and Polemarchakis, 1991; Kehoe, 1991). However, these differences depend critically on the assumption that savers in OLG models plan only for their own retirement, and do not care about future generations. For example if parents care about the welfare of their children, a bequest motive exists that influences savings behavior, and leads to an OLG model that is similar to ILA models in terms of discounting (Barro, 1974).

The Blanchard-Yaari-Weil model of perpetual youth provides a set of conditions under which OLG and ILA approaches are equivalent (Blanchard, 1985, Blanchard and Fischer, 1987). Marini and Scaramozzino (1995) use a version of this model to show that solving a social planner's problem with overlapping generations collapses to the representative agent framework as a special case only when there is an absence of heterogeneity among generations. In other words, the suitability of the planner-based ILA approach to environmental policy analysis reduces to an empirical issue of whether there is significant heterogeneity in the savings and consumption decisions of different generations.

Recently, several OLG models have been used to re-examine the climate change policy implications derived from the planner-based ILA models cited above. In some cases, OLG models yield results that are similar to corresponding ILA models (Stephan, et al., 1997; Manne, 1999). However, other studies find substantial differences between results with OLG and ILA models. Howarth (1996, 1998) matches a two-period OLG model to assumptions in Nordhaus (1994), and finds that modest to aggressive reductions in greenhouse gas emissions are justifiable in terms of economic efficiency. Howarth shows that, in general, ILA models can be represented as reduced-form OLG models without qualitatively important demographic features. He concludes that Nordhaus' (1994) model, in particular, is strongly sensitive to changes in the intergenerational weights used in the social welfare function. Gerlagh and van der Zwaan (2000, 2001) reach stronger conclusions, and question whether ILA models are appropriate for analysis of climate change policies. Differences in their results from other OLG models, notably Stephan et al. (1997) and Manne (1999), are attributed to an explicit representation of longer life expectancy and population aging in their three-period OLG model.

Multiple dynasty approach

We develop an energy-economic growth model that shares features of ILA and OLG approaches. We introduce demographic dynamics into the Population-Environment-Technology (PET) model, a computable general equilibrium model of the economy with detail in the energy sector, by using household projections to construct “cohorts” of households, where household age is defined by the age of the household head (Deaton, 1997). These projections, carried out with the ProFamy model (Zeng et al., 1998), represent a substantial improvement over previous household projection models, which have typically relied on simple headship rate methods that have several serious shortcomings (Jiang and O’Neill, 2004). Household cohorts from the ProFamy model are grouped into three infinitely lived dynasties in the PET model. Each dynasty contains households separated in age by the average length of a generation, taken to be thirty-years. For example, eighty-year-old, fifty-year-old, and twenty-year-old households are grouped in a single dynasty, based on the assumption that the younger households are, on average, descendants of the older households. Note that by increasing the length of a generation, the number of dynasties increases and our approach converges to the simplest OLG framework, with each dynasty represented by only one cohort, excluding any altruistic behavior. Conversely, a shorter generational length reduces the number of dynasties and is closer to a typical ILA framework. Therefore, heterogeneity in dynasties increases with generational length.

To calibrate the PET model, estimates of consumption expenditures, savings, asset accumulation, labor supply, and other variables for households in each age group were derived from the U.S. Consumer Expenditure Survey (CES). The PET model has seventeen consumer goods, including energy intensive goods like utilities and fuels, and less intensive goods such as education or health (Goulder, 1995). Households in different age groups are associated with distinct income and consumption levels, based on the CES data. Differences among age groups imply that each dynasty is associated with a specific pattern of income and consumption, based on its age distribution at each point in time. These differences have implications for energy demand, both directly and indirectly.

In our results, the most important effects are caused by differentials in labor income across age groups that create complex dynamics for consumption and savings. These dynamics, and other relationships implied by the household projections and CES data, create interacting effects that influence each dynasty’s current and future consumption and savings decisions. A dynamic general equilibrium model is required to analyze these interacting effects on behavior, including how price changes for individual consumer goods affect tradeoffs between consumption and savings at the level of individual households.

Using the PET model, we are able to decompose and analyze these general equilibrium effects. We use the model to analyze how household-level variables respond to plausible changes in the age composition of U.S. households over the next several decades. We also use the model to estimate how changes in household-level variables affect the whole economy, and whether projected changes in the age composition of U.S. households could have a substantial influence on total energy demand and CO₂ emissions. Our results show that combining ILA and OLG approaches creates complicated dynamics for the age structure of each dynasty, which cause cycles

in labor income that affect savings and consumption directly, and also have indirect effects on energy demand. We find that including heterogeneity among U.S. households reduces long-term emissions, by almost 40% in our low population scenario. Effects of heterogeneity are less extreme in other scenarios, and our results estimate that emissions are around 15% lower. We also find that effects of aging on emissions can be as large, or larger than effects of technical change in some cases.

The following section describes the PET model and household economic data. The population and household projections are described in the third section, and results of simulations with the PET model are presented afterwards. We conclude with a discussion of our analysis, results, and directions for future research.

Population-Environment-Technology Model

The PET model is a global-scale dynamic computable general equilibrium model designed to analyze economic tradeoffs associated with production and use of fossil fuels, and carbon dioxide emissions. A separate document, available from the authors, gives mathematical descriptions and data sources of the PET model (Dalton and Goulder, 2001). An overview is given here, and schematic diagram of the model is provided in Figure 1. The production component of the PET model has industries with many perfectly competitive firms that produce intermediate goods, including energy and materials, and final goods. Consumption and investment are final goods, and a government sector produces a final good. Production functions for each industry in the model have a capital-labor-energy-materials (KLEM) structure, with a nested constant elasticity of substitution form. There is a separate nest for energy inputs with oil and gas, coal, refined petroleum, and electricity. Other intermediate goods are aggregated, and produced by a single materials industry. Exogenous technical change is included in the PET model using separate productivity coefficients that change over time for each input of each production function in the model. Growth in the productivity coefficients for different inputs include patterns of labor, capital, and energy augmenting technical change.

Each production function in the PET model has a substitution parameter for energy inputs that is assumed to be greater than the substitution parameter for KLEM inputs, implying that energy inputs are more substitutable in production with one another, than energy is with other inputs. Estimating or assigning appropriate values for substitution parameters is an important topic in applied general equilibrium analysis, and has been the subject of past work with the PET model. We assign values here based on a standard configuration of the model, with the substitution elasticity for energy inputs set equal to 2.0 for all industries, implying modest substitutability of energy inputs, and an elasticity for KLEM inputs of 0.4, so that demand for these inputs is relatively inelastic. Different assumptions regarding the structure of production functions and substitution elasticities appear in the energy and climate change literature (e.g. Weyant and Hill, 1999). The substitution elasticities given above are consistent with this literature. Because oil and gas, and coal industries produce primary energy from fossil fuels, outputs of these industries account for CO₂ emissions in the model.

The consumption component of the PET model is based on a population with many households that take prices as given. Each consumer good in the model is produced by a different industry, and one industry produces investment goods.

Households demand consumer goods, and receive income by supplying capital and labor to producers. Households save by purchasing investment goods, and in the model, savings behavior is determined by solving an infinite horizon dynamic optimization problem for the dynasty to which the household belongs. Consumption and savings are described in more detail below.

The following sections present parts of the PET model related to household consumption and savings, and the data used to calibrate the household component of the model. These parts of the model are central to our general equilibrium analysis of demographic factors that affect energy use and CO₂ emissions. The PET model includes international trade, and can analyze different countries and world regions, but currently we have household economic data and projections for the U.S. only. Therefore, we are primarily interested in interactions between household consumption and factor supply within the U.S. economy. We have omitted trade from work in this article to simplify the model, and isolate effects of demographic factors. We recognize that results are likely to be affected by this omission, but an initial assessment without effects of trade provides a useful benchmark against which further work can be compared, and still allows an informative comparison of results with demographic heterogeneity.

Household consumption and savings

Using age of the household head, we classify individual households in the population into three separate dynasties, indexed by i . Each dynasty consists of a large number of identical households, extending a standard assumption in neoclassical growth models that the population consists of a large number of identical households. Our extension to multiple dynasties is consistent with neoclassical growth theory, and from the point of view of general equilibrium analysis, is more natural and interesting than assuming all households are the same.

Let n_{it} denote the total number of people living in each household type at time $t \geq 0$. Each household is endowed with labor l_{it} , and an initial stock of assets \bar{k}_i , which are expressed in average per capita terms. Likewise, other variables are expressed in per capita terms, except where noted. Capital owned by different households is homogeneous, and perfectly substitutable in production. Households save by purchasing investment goods x_{it} , at price q_t . Investment is added to a stock of household assets, or capital k_{it} , which depreciates at rate $\delta > 0$ that is the same for all households, according to the law-of-motion

$$k_{it+1} = (1 - \delta)k_{it} + x_{it}. \quad (1)$$

Household capital income is determined by the rental rate of capital, r_t , which is the same for all households. Labor's wage rate, w_t , is also assumed to be equal across households, so that differences in labor income are from variations in per capita labor supply or productivity. Labor is assumed, without loss of generality, to be the numeraire good in our analysis, and $w_t = 1$ for all t .

The PET model has 17 consumer goods, indexed by j . Per capita consumption for households of type i , of good j , at date t is denoted by c_{ijt} . The price of each consumer good is denoted by p_{jt} . Households have a common discount factor $0 < \beta < 1$, and intertemporal substitution parameter $-\infty < \rho < 1$. Preferences for different consumer goods are characterized by a substitution parameter $-\infty < \sigma < 1$ that is also assumed to be the same for all households. The expenditure share parameters μ_{ijt} are differentiated for households, and can vary over time.

This article evaluates the importance of demographic factors during a transition period of one hundred years, and does not address possible effects on the long run equilibrium. Therefore, we assume that households are identical in the long run. The rationale for this assumption is to establish consistency for comparing results in cases with and without demographic heterogeneity. In cases with demographic heterogeneity, values for per capita labor supply, l_{it} , and expenditure shares, μ_{ijt} , tend over time to equal values for all i . These long run conditions imply the terminal or long run balanced growth path equilibrium with demographic heterogeneity is the same as the reference case with representative households.

Simulations with the PET model start at 2000. The transition period in the model is one hundred years, the time span of the demographic projections described below. Simulations continue for another hundred years, during which we assume that demographic heterogeneity gradually disappears so that all households are identical at 2200. Even without these long run restrictions on l_{it} and μ_{ijt} , if capital income tax rates ϕ_{it} are the same for each i , then other assumptions in the model, described below, imply that asset stocks of each dynasty, k_{it} , expressed in per capita terms, converge endogenously to equal values. In other words, per capita asset holdings are the same across dynasties in the long run, even if labor income or consumption patterns are different. This result depends on the tax rates for capital income being the same for each dynasty, but is not directly affected by the tax rate on labor income θ_{it} .

In the model, households receive per capita lump-sum transfers from the government, g_{it} , which is a net value so that negative values represent net payments by households. Private transfers, among households, are represented in the model, but are not distinguished here to save notation. The budget constraint for a household in dynasty i at date t is

$$\sum_{j=1}^{17} p_{jt} c_{ijt} + q_t x_{it} = (1 - \theta_{it}) w_t l_{it} + (1 - \phi_{it}) r_t k_{it} + g_{it}. \quad (2)$$

Demand for consumption goods is influenced by tradeoffs across goods at each t , and by dynamic factors related to savings and investment. Households take prices as given, are rational with forward-looking behavior, and in particular have perfect foresight of future values for all variables that affect their investment decisions. These variables include relevant prices, such as q_t and r_t , and future asset holdings by other households. Forward-looking behavior implies that equilibrium conditions in the model are dynamically consistent. Although the assumption of perfect foresight is restrictive in terms of the information structure of the model, this approach is preferable to an even

more restrictive information structure, such as ignoring the value of future information altogether, which is true of models that use fixed savings rules to drive investment. Perfect foresight may be justified either by appealing to some type of certainty equivalence, or as the first step in an algorithm that converges to a rational expectations equilibrium (Fair and Taylor, 1983).

Tradeoffs across goods are described with a constant elasticity of substitution expenditure function, and over time by a constant elasticity of substitution intertemporal utility function. The PET model does not include leisure in household utility functions. Therefore, labor supply is inelastic, and given by each household's labor endowment, l_{it} , which is determined by the CES data described below.

Given prices, and subject to constraints (1) and (2), each household of type i chooses sequences of consumption $\{c_{ijt}^*\}$, for all j , and investment $\{x_{it}^*\}$, to maximize

$$\frac{1}{\rho} \sum_{t=1}^{\infty} \beta^t n_{it} \left(\sum_{j=1}^{17} \mu_{ijt} c_{ijt}^{\sigma} \right)^{\frac{\rho}{\sigma}}. \quad (3)$$

We describe two steps in the solution algorithm for each household's optimization problem to aid explanation of results below. Other parts of the dynamic algorithm are described in detail in the PET model's technical document (Dalton and Goulder, 2001). In the first step, demand for each consumer good is determined from prevailing prices by minimizing total expenditures, subject to a given level of utility, at each date t . A dual price index is used to calculate the marginal cost of consumption for each household, which varies across households because of heterogeneity in expenditure shares. The price index dual to the expenditure function in (3) has a closed-form expression for each household type,

$$\bar{p}_{it} = \left(\sum_{j=1}^{17} \mu_{ijt}^{\frac{1}{1-\sigma}} p_{jt}^{\frac{\sigma}{\sigma-1}} \right)^{\frac{\sigma-1}{\sigma}}. \quad (4)$$

Each price index includes a weighted sum that depends on expenditure shares for each household, and the prices of consumer goods faced by all households. In the general equilibrium PET model, prices of consumer goods are influenced in complex ways by changes in factor supply, including effects on labor of an aging population. The dual price index (4) summarizes price changes across goods to indicate overall effects on the marginal cost of consumption for each household. The marginal cost of consumption \bar{p}_{it} is compared to the price of investment goods q_t to determine optimizing tradeoffs for households between consumption and savings at each t .

The second step in each household's problem is solving for paths of consumption expenditures and investment, for all t , that maximize (3). While price changes for consumer goods have static effects on the pattern of consumption, the tradeoff between consumption and savings affects model dynamics. The model's solution algorithm uses the Euler equations that are first-order conditions from maximizing (3), subject to (1) and (2), which after manipulation imply

$$\frac{q_t}{\bar{p}_{it}} \left(\sum_{j=1}^{17} \mu_{ijt} c_{ijt}^\sigma \right)^{\frac{\sigma-1}{\sigma}} = \beta \left(\frac{r_{t+1} + (1-\delta)q_{t+1}}{\bar{p}_{it+1}} \right) \left(\sum_{j=1}^{17} \mu_{ijt+1} c_{ijt+1}^\sigma \right)^{\frac{\sigma-1}{\sigma}}. \quad (5)$$

The Euler equations (5), capital law-of-motion (1), budget constraint (2), and transversality conditions

$$\lim_{t \rightarrow \infty} \lambda_t k_t = 0 \quad (6)$$

are necessary and sufficient for maximizing (3). Moreover, a solution to (3) is unique (Stokey and Lucas, 1989). The transversality conditions ensure that each household's sequence of capital stocks is bounded. We use this fact to compute a steady state level of the capital stock that is the same for all households, k^* , which satisfies conditions assumed above.

The PET model allows labor augmenting and other types of technical change. Let γ denote the long run rate of labor augmenting technical change. The long run condition used to compute the steady state level of the capital stock is given by the steady state, or balanced growth path, ratio of the return on capital to the price of investment goods

$$(1 - \phi_{it}) \frac{r_t}{q_t} = \frac{1}{\beta} (1 + \gamma)^{1-\rho} - (1 - \delta). \quad (7)$$

By assumptions above, parameters on the right-hand side of (7) do not depend on time, and are the same across household types. Because households face the same prices on capital and investment, if capital income tax rates are the same across households, then per capita asset accumulation is equal in the long run, which was mentioned above in the description of long run conditions. The PET model uses the Euler equations (5), and a variation of the Fair-Taylor algorithm (Fair and Taylor, 1983), to compute the dynamic transition from \bar{k}_i to k^* for each household.

Production, consumption, and income data

The pattern of expenditure shares on energy and other inputs varies across industries. Brenkert et al. (2004) describes the benchmark input-output data that are used in the PET model. These data are used to calibrate the PET model's production functions, and are derived from the U.S. National Income and Product Accounts (NIPA), and other sources. To calibrate the model's household demand system, we use data from the U.S. Consumer Expenditure Survey (CES). The CES is a nationally representative survey composed of two parts: An Interview survey, and a Diary survey. In some cases, CES survey results are different from NIPA data. To resolve differences in the consumption and production data, we use CES data to determine aggregate expenditure shares of each consumer good at the economy-wide level, and apply these economy-wide shares to total consumption expenditures in order to determine the output of each consumer good industry. Conditional on the CES-determined output levels, demands for energy and other inputs of each industry are determined using input-output ratios derived from NIPA data. Additional details on the calibration procedure are described in Dalton and Goulder (2001).

The CES Interview survey has a sample size of approximately 5,500 households and is based on recall of expenditures over the past three months and income over the past year. It is aimed at capturing relatively large expenditures and those that occur on a regular basis. The Interview survey has a rotating panel design: Each panel is interviewed for five consecutive calendar quarters and then dropped from the survey. A new panel is then introduced. Therefore, about 20% of the addresses are new to the survey each quarter. The Diary survey is based on a written account of expenditures over the past two weeks, and is aimed at better capturing small, frequent purchases.

The CES data are used for economic analyses of consumption (e.g., Paulin, 2000; Schmitt, 2004). Details of our work with the CES data are described in a separate document (O’Neill, 2005). In brief, data are integrated by choosing for each consumption category whether the Interview or Diary data are more reliable according to the Bureau of Labor Statistics. The CES categories are then aggregated into the 17 consumer good categories used in the PET model (Goulder, 1995). Mean annual per capita expenditures for these goods are calculated by household type. Household types are defined by characteristics of the “reference person” in the household, defined in the CES data as the first member mentioned by the respondent when asked to “Start with the name of the person or one of the persons who owns or rents the home.” We use the reference person as our “householder” or “household head”.

Values in Table 1 show how consumption of the 17 consumer goods varies across age groups using expenditure shares, or fraction of total expenditures, for each good. We use these expenditure shares as benchmark data for the PET model, which are converted to share parameters μ_{ij} that calibrate the model’s household demand system. To summarize key differences in expenditure patterns, we distinguish between younger versus older households. As discussed below, the household projections show that future compositional changes are driven by shares of the population at opposite ends of the age range in Table 1. As seen in the table, older households spend a substantially larger share of income than younger households on utilities, services, and health care, and a substantially smaller share on clothing, motor vehicles, and education.

Since the most energy intensive goods are utilities and fuels, expenditure patterns in Table 1 imply that aggregated consumption in older households is more energy intensive than consumption in younger households. The utilities category is about two-thirds electricity, with the remaining third split between natural gas, and payments for water and sewer services. Electricity demand is driven principally by appliance use, and natural gas consumption by space conditioning (EIA, 2004). Although older households spend a larger fraction of income on utilities, absolute levels of expenditures on utilities are roughly the same across the younger and older households when income differences are taken into account, which is consistent with previous work on patterns in residential energy use (Bin and Dowlatabadi, 2005). The fuels category is 80-90% gasoline, and is therefore influenced mainly by car use. The remainder is split primarily between fuel oil and natural gas. While old households spend a larger share of per capita income on fuels than young households, income differences imply the absolute level of fuel use is substantially smaller, which is consistent with other work (O’Neill and Chen, 2002).

Government transfers in Table 2 include social security, workers compensation, unemployment benefits, and other kinds of public assistance, and these favor older

households in per capita terms by a wide margin. Savings includes retirement contributions, down payments on purchases of property, mortgage payments, capital improvements, and investments in own businesses or farms. Assets include the value of financial accounts and securities plus the equity share of property.

Household Projections and Dynasties

In Table 3, we present population and household projections from the ProFamy model for three scenarios. The ProFamy projections run from 2000 to 2100. For simplicity, population is assumed to stay constant after 2100 in our analysis. Values in the table give total population in each year of the projection, followed by percentage shares of the population living in households of different ages, in order to more clearly distinguish differences in both scale and composition across scenarios. Work with the ProFamy model, which jointly projects population and households, and methods for developing the U.S. household projections, are described in a separate paper (Jiang and O'Neill, 2005), and an overview is given here.

The scenarios we use are based on a set of plausible demographic assumptions for fertility, mortality, migration, and union formation and dissolution rates that span a wide range of outcomes in terms of population size, age structure, and household size. Assumptions for demographic rates, and how to combine them in each scenario, were chosen in order to produce one scenario with relatively small, old households (our low scenario), one scenario with relatively large, young households (our high scenario), and one scenario with moderate outcomes (our medium scenario). Population size varies among the three scenarios by more than a factor of four at 2100. An important property of the projections is that the age composition of households in the low scenario is markedly different from the pattern in high and medium scenarios, with people living in older households making up a much greater percentage of the population under conditions of low fertility and mortality.

We use the population distribution by household age to construct dynasties that consist of a series of cohorts of households of different ages at each point in time. The procedure for constructing cohorts and dynasties from the ProFamy projections is outlined in Figure 2. This procedure implies that each dynasty has a specific household age distribution at each point in time, based on the population size of each cohort.

We use benchmark data from the CES for households of different ages to derive weighted-mean per capita labor supply and expenditure shares for consumer goods for each dynasty over time. Per capita labor supply for each age group is derived from the CES data, and multiplied by the population living in households of different ages. The sum of these products determines total labor supply of each dynasty. Then for each dynasty, the ratio of total labor supply over the dynasty's total population size determines the mean per capita labor supply. Expenditure shares are translated into share parameters for the PET model's demand system during model calibration. In this way, the ProFamy projections are used to determine the changing composition of the population across household types within each dynasty. The CES data are used to calculate average per capita labor supply, and household expenditure shares within each dynasty that change over time to reflect the changing demographic composition.

Results

We conducted two sets of simulations with the PET model to analyze the effects on emissions of population aging in the United States over the next hundred years. To isolate effects of demographic factors, the first set does not include technical change. The second set includes technical change, and is organized in the same way as the first set of simulations, which is divided into three groups. The first group uses a configuration of the PET model with a single representative household and no aging. This group is considered the starting point for our analysis, and is similar to the typical approach used currently for many models in the climate change literature. The second group uses a configuration of the model with heterogeneous households that includes three dynasties with age-specific demographic heterogeneity in consumption patterns, initial capital, and labor supply. A comparison of results from the second group of simulations with those in the first group provides the basis for our main conclusions on whether the introduction of demographic heterogeneity can substantially affect emissions.

The third group of simulations also uses a representative household configuration of the PET model with a single dynasty, but aggregate labor supply changes over time to be consistent with a changing age structure. This “representative households with aging” configuration has the same total labor supply as the heterogeneous household configuration, and this comparison tests whether results obtained with heterogeneous households can be approximated using a simpler model, with a single dynasty. Each of the three groups consists of 12 simulations, based on the low, medium, and high household projections described above, and stratified by four combinations of household substitution parameters for sensitivity analysis. We use low, medium, and high household projections to test the effects of aging under alternative, but plausible, population scenarios of future demographic changes.

Heterogeneous versus representative households

The model configuration with heterogeneous households has three dynasties that follow the dynamics in Figure 2. For each dynasty, age-specific weights for consumption expenditures are derived from values in Table 1. Initial capital and weights for labor supply are derived from Table 2. The model configuration for representative households without aging has per capita expenditure shares that are equal to the mean values in Table 1. Labor supply, consumption expenditures, and other variables are equal in per capita terms, and are derived from mean values in Table 2. Benchmark values for transfers and income tax rates are set to zero to simplify the interpretation of results.

The multiple dynasty structure of the model configuration with heterogeneous households has interesting implications for the dynamics of labor income and capital. Graphs in Figure 3 show these dynamics. The top graph in Figure 3 shows per capita labor income for the three dynasties. Population aging causes the downward trends in per capita labor income for the dynasties, and the effects of aging are strongest in the low population scenario. In contrast, per capita labor income for a representative household is a flat line at \$20,000 per year. The dynasties can be identified from their supply of labor in 2000. For example in 2000, dynasty 1 has a cohort in the 45-55

group, which has the largest per capita labor income. Thus, dynasty 1 has the largest labor income in 2000.

Labor income directly affects the dynamics of savings and capital, which are presented in the bottom graph of Figure 3. Capital for a representative household is illustrated with a flat line at about \$70,000 per person. In Figure 3, the variation across dynasties in each year exceeds the variation across population scenarios within each dynasty until about 2050, after which variation across scenarios is larger. An implication is that age structure is important in the short run, but because of population momentum, effects of aging in the short run are similar across population scenarios. However in the long run, aging and the population scenario have differential effects.

The graphs in Figure 4 compare results for total CO₂ emissions, and per capita CO₂ emissions, over time for heterogeneous and representative households. Total emissions with heterogeneous households are driven by changes in age composition of the population. Results show that total emissions with heterogeneous households range from 0.9 to 5.1 billion metric tons per year at 2100. For representative households, changes in emissions over time are due to changes in the size of the population, and emissions range from 1.4 to 5.9 billion metric tons per year by 2100 in the three population scenarios.

The top graph in Figure 4 shows that heterogeneity leads to lower emissions in each population scenario. Differences between emissions in simulations with heterogeneous and representative households are a combination of direct effects from changes in labor supply due to aging, and indirect or general equilibrium effects from changes in capital accumulation, prices, or other factors. Aging implies fewer young workers, whose per capita labor contribution tends to be greater than the population mean. Hence, aging implies a reduction in aggregate labor supply for a given population size.

The bottom graph in Figure 4 shows per capita emissions for heterogeneous and representative households in each population scenario with no technical change. Because total population within each scenario is the same, differences in per capita emissions are caused exclusively by changes in total emissions. Per capita growth in output, measured by gross domestic product (GDP) per person, is essentially zero with representative households, and changes in carbon intensity, represented by CO₂ emissions per dollar of GDP, are also minor. Consequently, per capita emissions with representative households are essentially constant over time and across population scenarios, around 5.3 tons per person.

The bottom graph in Figure 4 shows that demographic heterogeneity in the low population scenario reduces per capita emissions by about two metric tons per person by 2100. Per capita labor supply, which is a weighted average over different age groups, is similar in medium and high population scenarios, which is why per capita emissions are relatively close. The scarcity of young workers drives results in the low population scenario, which has substantial effects on per capita emissions. The range of per capita emissions between low and high population scenarios is about one ton per person by 2100, but because of population momentum, these effects are not apparent until after 2050.

Population aging and representative households

A model configuration with identical households is used to evaluate whether the main effects of population aging can be incorporated into the model simply by scaling the labor supply of representative households. This representative household configuration with aging has the same level of aggregate labor as the model with heterogeneous households. In comparison to the model with representative households and no aging, the long-term emissions reductions for representative households with aging are about 85% of those associated with heterogeneous households for our reference values of the household substitution parameters. Thus, much of the effect of population aging in our reference case can be captured in a representative household model with dynamic labor supply. However, whether a representative household model is adequate in other cases is unclear. For example in simulations with alternative values of the household substitution parameters, described next, the direction of these effects changes.

Sensitivity analysis of household substitution parameters

The substitution parameters ρ and σ in each household's utility function from (3) directly affect results. Our reference value for households' intertemporal substitution parameter is $\rho = 0.5$, or an elasticity of $1/(1-\rho) = 2.0$. This value is taken from Goulder (1995), who reports it is in the range of estimates obtained by Hall (1988), and Lawrance (1991). Our reference value for the substitution elasticity of consumer goods is also 2.0, or $\sigma = 0.5$. We conduct a sensitivity analysis to examine how results with inelastic values for ρ and σ differ.

Values for the intertemporal substitution elasticity are important in macroeconomic models (Guisar, 2003), and obtaining reliable and consistent estimates has been a problem. Beudry and van Wincoop (1996) use panel data for U.S. states, and report estimates close to a value of one, and significantly different from zero. Note that an elasticity of one implies a ρ of zero, which is equivalent in the limit to the natural log utility function. An elasticity of zero implies $\rho \rightarrow -\infty$, which is the Leontief case of perfect complements. A recent study, using a new econometric approach, estimates intertemporal substitution elasticities less than one, but not significantly different from zero (Yogo, 2004). Therefore, negative values for ρ seem plausible. Inelastic values for σ are also plausible. To represent inelastic demand for different consumption goods, we use an alternative value for the consumption substitution parameter of $\sigma = -3.0$, or an elasticity of 0.25. To represent inelastic consumption over time, we use an alternative value for the intertemporal substitution parameter of $\rho = -3.0$. The reference and alternative values for these parameters are intended to span a plausible range that includes both substitutes and complements in consumption.

Values in Table 4 summarize comparisons among the model configurations, substitution parameters, and population scenarios. Our primary comparison is between the two model configurations that consider population aging. Values in the table for the reference case with $\rho = 0.5$ and $\sigma = 0.5$ are taken from the simulations shown in Figure 4. In this case, for the low population scenario, emissions are about 37% less in 2100 with heterogeneous households relative to the representative household configuration without aging. Most of this difference is due directly to scale effects from

changes in labor supply associated with population aging because emissions at 2100 for the representative household configuration with aging are about 31% less than for representative households without aging. The remaining difference occurs through capital dynamics and general equilibrium effects. The effects of population aging on emissions are smaller for medium and high population scenarios, about 18% and 13% respectively, because the effects of population aging are not as strong.

For each population scenario, values in Table 4 for the representative household configuration with aging do not vary much for different substitution parameters. The reason is that variation in exogenous labor supply alone has neutral scale effects on the PET model, which is a standard property of neoclassical growth models. Therefore, baseline emissions for the single dynasty cases are scaled by the size of the labor force, but are not sensitive to the choice of household substitution parameters. Results in Table 4 for heterogeneous households are also insensitive to the consumption substitution parameter σ for cases with the reference value of $\rho = 0.5$ for the intertemporal substitution parameter.

However, most energy-economic growth models include only a single consumer good, and this type of aggregation is equivalent to assuming perfect complements, $\sigma \rightarrow -\infty$, for different consumer goods. In Table 4, reductions in baseline emissions with the inelastic value of $\rho = -3.0$ are smaller than for the reference case. In this case, compared to representative households with no aging, reductions in baseline emissions for heterogeneous households are smaller than representative households with aging in corresponding population scenarios. As noted above, the implication is that simply scaling the labor supply of a single, representative dynasty to account for future aging gives ambiguous results that either underestimates or overestimates, depending on true values of household substitution parameters, the emissions reductions associated with an aging population.

According to Table 4, emissions reductions for heterogeneous and representative households with aging are similar for cases with the inelastic value of $\sigma = -3.0$ for the consumption substitution parameter. However, substitutability of different consumer goods seems plausible in a developed country like the U.S. With $\sigma = 0.5$ and $\rho = -3.0$, differences in emissions reductions between heterogeneous and representative households with aging are substantial in early years of the simulations, for each population scenario, and differences remain large, throughout the simulation horizon, for the low scenario.

Demography and technical change

Technical change is expected to be an important factor in future CO₂ emissions, and is a prominent feature of current energy-economic growth models (Weyant, 2004). The flexible production structure of the PET model can simulate different patterns of technical change. For comparison, the SRES scenarios provide a logical framework for organizing alternative assumptions about future technical change (IPCC, 2000). Our second set of simulations uses the SRES A1 scenario to compare emissions with representative and heterogeneous households in the presence of a plausible pattern of future technical change according to the SRES methodology. The simulations with technical change are based on the representative household configuration of the PET

model, with our medium population projection to be consistent with the A1 scenario, and our reference values of 0.5 for both household substitution parameters. Productivity growth rates for labor and energy were selected so that variables related to GDP and CO₂ emissions in the PET model match averages for different models used in the SRES A1 scenario for the OECD region, as seen in Figure 5.

The SRES A1 scenario uses medium population projections for the OECD countries, but on average, these differ in growth rates by about 0.5% per year from our medium projection for the U.S. Therefore, we match the PET model to average growth rates for per capita GDP from SRES. To match these growth rates in the PET model, labor productivity measured in efficiency units is assumed to grow at 1.6% per year through 2160, and then gradually falls to zero at 2200. Growth in labor productivity increases the scale or size of the economy, but does not affect the carbon intensity of output, which is measured by the ratio of CO₂ emissions over GDP. To match average rates of decline in carbon intensity for OECD countries in A1, we assume productivity growth rates of 2.9% per year through 2160 in the use of refined petroleum and electricity by the energy and materials producing industries in the PET model. After 2160, we assume these growth rates gradually fall to zero at 2200, and the economy reaches a steady state. The top graph in Figure 5 shows the relative growth rate over time of per capita U.S. GDP from the PET model under these assumptions, compared to the SRES models for this scenario in the OECD region. The bottom graph in Figure 5 shows the relative annual rate of change over time in carbon intensity. Note the PET model resembles the AIM model in both graphs, which is the “marker” for the A1 emissions scenario.

The graphs in Figure 6 compare results for U.S. GDP and CO₂ emissions with and without technical change for representative and heterogeneous households. The top graph shows the effects of population aging on U.S. GDP as the difference between curves for representative and heterogeneous households. The upward trend in the pair of curves without technical change is attributed to population growth in our medium household projection. For the upper pair of curves, the scale of the economy grows with technical change, and the absolute difference in GDP with representative and heterogeneous households is close to \$20 trillion by 2100, expressed in year 2000 dollars, compared to about \$4 trillion without technical change. However, the relative difference in GDP is about the same in both cases, around 16% less with heterogeneous households.

The bottom graph in Figure 6 shows the effects of demographic heterogeneity and technical change on CO₂ emissions. The results of these comparisons are interesting. As also seen in Figure 4, CO₂ emissions exhibit a roughly linear increase over time with the medium household projection and representative households. Changes in the composition of the population with heterogeneous households affect emissions relatively soon in the simulation horizon, reducing emissions almost 10% by 2030, compared to the corresponding case with representative households. In contrast, differences in emissions between representative households with and without technical change are relatively minor before 2060, and the effects of technical change on emissions do not catch up to the effects of population aging until 2086. The explanation for this result derives from the fact that both population growth and economic growth have scale and composition effects.

In the medium household projection, the composition effect from population aging is relatively strong compared to the scale effect from population growth. The scale effect for technical change is due primarily to increases in labor productivity. The composition effect for technical change comes from productivity improvements in the use of refined fuels and electricity, relative to the use of more carbon intensive energy sources such as oil and coal. The process of fuel switching induced by this type of technical change causes a steady decline over time in the carbon intensity of output. Other things being equal, the decline in carbon intensity would reduce emissions. However in Figure 6, emissions reductions induced by the composition effect of declining carbon intensities are neutralized for several decades by the contemporaneous increase in emissions caused by the scale effects of labor augmenting technical change.

While the comparison of effects on emissions from technical versus demographic change is interesting, Figure 6 shows the combined effects are also important, and close to additive in the long run for this particular group of simulations. The population composition effect in the absence of technical change reduces emissions by about 18% by 2100. Effects of energy and labor augmenting technical change reduce emissions by another 24%, relative to emissions with heterogeneous households and no technical change. In comparison, effects of both aging and technical change in the bottom curve on the graph reduce emissions by 38% relative to the top curve with representative households and no technical change.

Results in Figure 6 are derived from a single group of simulations, and are not conclusive. Simulations using the SRES A1 scenario are intended to illustrate the interesting possibilities of combining effects of demography and technical change in the PET model. The results of sensitivity testing in Table 4 imply the relative strengths of scale and composition effects depend on the parameter values, population scenario, and model configuration used for analysis. For example in other groups of simulations with our low household projection and reference values for the household substitution parameters, the effects of technical change in A1 do not catch up to the effects of aging on emissions before 2100. This case is interesting because the average population growth rate for OECD countries in the A1 scenario, 0.2%, is in fact closer to the average population growth rate in our low projection, -0.1%, than to the average growth rate in our medium projection, 0.7%. On the other hand, emissions are much closer with our inelastic value for the consumption substitution parameter, and effects of technical change on emissions surpass the effects of aging at 2045, instead of 2086 with the reference value for this parameter. Of course, these results will vary across SRES scenarios, which is a topic for future research.

Discussion

Demographic factors are usually treated implicitly in energy-economic growth models. This article describes a modeling framework, household projections, and economic data to estimate the effects of population aging on U.S. energy use and CO₂ emissions. Our framework is based on the Population-Environment-Technology (PET) model, a standard neoclassical growth model with detail in energy inputs and consumer goods that is extended to incorporate population age structure and other demographic features. The PET model is decentralized, there is no social planner, and the dynamic competitive

equilibrium in each simulation is solved directly from market clearing conditions, and the maximizing behavior of households and firms.

For the model to be consistent with the interpretation of decentralized forward-looking households over an infinite planning horizon, we assume intergenerational altruism in the form of parents caring about the welfare of their children. While this form of altruism is implicit in the dynastic structure of neoclassical growth models, we developed an explicit procedure for linking cohorts into three heterogeneous infinitely lived dynasties. Each dynasty contains households separated in age by the average length of a generation, which is about thirty-years, so that on average, younger households are descendants of the older households. Taken together, the three dynasties combine features of existing infinitely lived agent (ILA) and overlapping generations (OLG) models, and this approach offers several advantages.

To populate the three dynasties, we use household projections from the ProFamy model, which is a major improvement over previous household projection methods. We develop low, medium, and high population scenarios with the ProFamy model. The influence of population aging is strongest in our low scenario, which exhibits large compositional changes in the age structure of the population over time. Compositional changes due to aging are present in the medium and high scenarios, too, but to a lesser degree. We developed age profiles of expenditure patterns, labor income, asset holdings, and other economic variables for each dynasty from the U.S. Consumer Expenditure Survey (CES). These age profiles have measurable differences across age groups both in the levels and composition of labor and capital income, and expenditure shares for the seventeen consumer goods in the PET model. Age-specific heterogeneity in factor incomes, consumption patterns, and population composition create interacting effects that flow back and forward through the economy. A decentralized general equilibrium framework, such as the PET model, is needed to decompose and analyze these interacting micro and macroeconomic effects. Scarcity of labor and capital at a point in time, as well as expected future changes in these factors, are signaled by market prices that are observed by households. These price signals are incorporated directly into consumption and savings decisions of households in the PET model.

The OLG structure of household cohorts in the PET model implies that per capita labor income and capital accumulation within each dynasty are cyclical, with a general downward trend from the effects of aging on per capita labor supply. Labor income for each dynasty follows the same thirty-year pattern, increasing for ten-years after a young cohort enters the workforce, followed by a steady twenty-year decline that is caused by other cohorts aging. Capital accumulation of each dynasty is influenced by labor income, but the general pattern is qualitatively different. Capital is accumulated by each dynasty for the ten-year period that labor income rises, but then is relatively stable for a decade, followed by a ten-year decline. This general pattern implies that dynasties save during periods of high labor income when there are many young or middle-age households, and spend down their capital stocks when households are older and labor income is lower. This general pattern is consistent with the life-cycle savings behavior found in OLG models.

We use the PET model to estimate effects of population aging by comparing emissions baselines from simulations with age-specific heterogeneity to baselines without aging and representative households. To isolate demographic effects, the first

set of simulations does not include technical change. Our results compare two types of heterogeneous households to representative households. The first type has heterogeneity only in expenditure shares for different consumer goods that depends on age of the household head. The second type has heterogeneity in expenditure shares, and also in sources of household income, including capital and labor.

The first type of heterogeneity affects only the composition of demand, but our results show these effects are negligible. In contrast, age-specific heterogeneity in labor income reduces CO₂ emissions by 11%, 18%, and 37% per year by 2100 in the high, medium, and low population scenarios, respectively. In our reference case, a labor scale effect accounts for about 85% of these reductions, and the other 15% is from capital dynamics and general equilibrium effects. However, sensitivity analysis indicates that simply scaling labor supply of a single representative dynasty to account for population aging has ambiguous effects that either underestimate or overestimate emissions reductions from population aging, depending on values of household substitution parameters, about which we are uncertain.

A second set of simulations compares emissions baselines with population aging to representative households in the presence of technical change. Assumptions about technical change are based on the SRES A1 Scenario for OECD countries. For our reference values of household substitution elasticities, effects on emissions from aging and decreases in carbon intensity from technical change are additive in the long run. The most interesting result is that effects of aging on emissions are as large, or larger, than effects of technology in some cases.

Results in this article support further consideration of demographic factors in emissions projections, and suggest these factors may be critical to the development of new emissions scenarios, particularly those based on low population projections for the U.S., because effects of aging are most important in this scenario. However, our model and current approach are based on several simplifying assumptions that ignore feedbacks, which could dampen, or deepen, economic effects of an aging population. For example, this article considers population age structure, but changes in household size, the proportion of immigrant households, or other demographic factors are probably also important. In addition, labor participation by older households has been increasing over the past decade, and this trend seems likely to continue, particularly if wages rise in response to changes in aggregate labor supply. We have ignored these effects by treating labor supply as an exogenous variable.

Resolving these issues is beyond the scope of this article, the aim of which is to present a new method for isolating effects of population heterogeneity for age, the most widely recognized demographic factor, in a dynamic general equilibrium setting, and establish an initial set of empirical bounds on these effects. This initial assessment provides an informative comparison of results with and without demographic heterogeneity, in the absence of some potentially confounding factors such as international trade, and thus provides a useful benchmark against which further work can be compared. Results in this article suggest that demographic factors have the potential to substantially affect long-term emissions for the U.S., and motivate further study of relationships between demographic change, economic growth, and energy use.

Future work could address some limitations of the work described in this article. First, our analysis of technical change could be extended to other SRES scenarios.

Second, household size and nativity could be included as additional demographic factors. Third, empirical estimates are needed for the household substitution elasticities used in this article. These values are associated with the substitutability of consumption over time, and across different goods, including energy intensive goods like utilities and fuels, and less intensive goods such as education or health. Some results in this article are sensitive to these values. Data from the U.S. Consumer Expenditure Survey (CES) could be used to estimate substitution elasticities for consumer goods, and test hypotheses about whether these vary among age groups and other demographic categories.

An important limitation of our current approach is that labor supply is inelastic, and does not respond to changes in real wages or other variables. Clearly, increasing labor supply is a plausible response by older age groups to changes in real wages, policy, life expectancy, or other factors that provide an incentive to delay retirement, or otherwise continue working. A thorough analysis of household economic data should be done to infer a reasonable range of alternatives for age profiles of labor supply, and to develop a set of scenarios for future labor force participation by different demographic groups.

Another important restriction is that results in this article are for the U.S. only, under assumptions of a closed economy. Several models, including the PET model, have the structure to include multiple countries or regions, and international trade, but demographic projections for other countries to support the type of analysis in this article do not currently exist. The data required for future work on these countries are extensive, including household projections, household survey data, and production data for different consumer good industries. Results with international trade are difficult to predict *a priori*, and will depend on the countries being compared. Countries that differ in age distribution will gain from trade, since labor intensive goods can be exported by the country with the younger population. International trade might be expected to diminish the effects of aging on energy use and CO₂ emissions, relative to an autarky situation without trade. However, population aging is a global event (O'Neill, MacKellar, and Lutz, 2001). Extrapolating results in this article suggests there may be a general upward bias in current global emissions projections, which should provide additional motivation for research in this area.

References

- Auerbach, A., and L. Kotlikoff, 1987, *Dynamic fiscal policy* (Cambridge University Press, Cambridge, MA).
- Azar, C., and T. Sterner, 1996, Discounting and distributional considerations in the context of global warming, *Ecological Economics* 19, 169-184.
- Barro, R., 1974, Are government bonds net wealth? *Journal of Political Economy* 82, 1095-1117.
- Beaudry, P., and E. van Wincoop, 1996, The intertemporal elasticity of substitution: an exploration using a U.S. panel of state data, *Economica*, New Series 63, 495-512.
- Bin, S., and H. Dowlatabadi, 2005, Consumer lifestyle approach to US energy use and the related CO₂ emissions, *Energy Policy* 33, 197-208.

- Birdsall, N., A. Kelley, and S. Sinding, 2001, *Population matters: demographic change, economic growth, and poverty in the developing world* (Oxford University Press, Oxford, UK).
- Blanchard, O., 1985, Debt, deficits, and finite horizons, *Journal of Political Economy* 93, 223-247.
- Blanchard, O., and S. Fischer, 1987, *Lectures on macroeconomics* (MIT Press, Cambridge MA).
- BLS (Bureau of Labor Statistics), U.S. Department of Labor, 1998, *Consumer Expenditure Survey*. <http://www.bls.gov/cex/home.htm>.
- Brenkert, A., R. Sands, S. Kim, and H. Pitcher, 2004, *Model documentation for the SGM*, Pacific Northwest National Laboratory, PNNL-14256.
- Cline, W., 1992, *Global warming: the economic stakes* (Institute for International Economics, Washington D.C.).
- Dalton, M., and L. Goulder, 2001, *An intertemporal general equilibrium model for analyzing global interactions between population, the environment and technology: PET model structure and data*. Unpublished document, California State University Monterey Bay.
- Deaton, A., 1997, *The Analysis of Household Surveys* (The World Bank, Washington, D.C.).
- EIA, 2004, *Annual energy review 2003* (Energy Information Administration, U.S. Department of Energy, Washington, D.C.).
- Fair, R., and J. Taylor, 1983, Solution and maximum likelihood estimation of dynamic nonlinear rational expectations models, *Econometrica* 51, 1169-1185.
- Farmer, M., A. Randall. 1997. Policies for sustainability: Lessons from an overlapping generations model, *Land Economics* 73, 608-622.
- Geanakoplos, J., and H. Polemarchakis, 1991, Overlapping generations, Ch. 35 in: W. Hildenbrand and H. Sonnenschein, eds., *Handbook of Mathematical Economics IV* (North-Holland, Amsterdam).
- Gerlagh, R., and B. van der Zwaan, 2000, Overlapping generations versus infinitely-lived agent the case of global warming, in: R. Howarth and D. Hall, eds., *The Long-Term Economics of Climate Change*, Vol. 3 (JAI Press, Stamford CT) 301-327
- Gerlagh, R., and B. van der Zwaan, 2001, The effects of ageing and an environmental trust fund in an overlapping generations model on carbon emissions reduction, *Ecological Economics* 36, 311-326.
- Goulder, L., 1995, Effects of carbon taxes in an economy with prior tax distortions: an intertemporal general equilibrium analysis, *Journal of Environmental Economics and Management* 29, 271-297.
- Guvonen, F., 2003, *Reconciling conflicting evidence on the elasticity of intertemporal substitution: a macroeconomic perspective*. RCER Working Paper No. 491, University of Rochester, January.

- Hall, R., 1988, Intertemporal substitution in consumption, *Journal of Political Economy* 96, 339-357.
- Howarth, R., 1996, Climate change and overlapping generations, *Contemporary Economic Policy* 14, 100-111.
- Howarth, R., 1998, An overlapping generations model of climate-economy interactions, *Scandinavian Journal of Economics* 100, 575-591.
- Howarth, R., and R. Norgaard, 1992, Environmental valuation under sustainable development, *American Economic Review* 82, 473-477.
- Intergovernmental Panel on Climate Change (IPCC), 2000, Special report on emissions scenarios (Cambridge University Press, Cambridge UK).
<http://www.grida.no/climate/ipcc/emission/>
- Jiang, L., and B.C. O'Neill, 2004, Towards a new model for probabilistic household forecasts, *International Statistical Review* 74, 51-64.
- Jiang, L., and B.C. O'Neill, 2005, Impact of demographic events on household formation and dissolution in the United States, Working Paper, Brown University.
- Kehoe, T., 1991, Computation and multiplicity of equilibria, Ch. 38 in: W. Hildenbrand and H. Sonnenschein, eds., *Handbook of Mathematical Economics IV* (North-Holland, Amsterdam).
- Lareau, T., and J. Darmstadter, 1983, Energy and household expenditure patterns, (Resources for the Future, Washington, D.C.).
- Lawrance, E., 1991, Poverty and the rate of time preference: evidence from panel data, *Journal of Political Economy* 99, 54-77.
- MacCracken, C., J. Edmonds, S. Kim, and R. Sands, 1999, The economics of the Kyoto Protocol, *Energy Journal*, Kyoto Special Issue, vii-xiv.
- Manne, A., 1999, Equity, efficiency, and discounting, Ch. 12 in: P. Portney and J. Weyant, eds., *Discounting and Intergenerational Equity* (Resources for the Future, Washington D.C.).
- Manne, A., R. Mendelsohn, and R. Richels, 1995, MERGE: A model for evaluating regional and global effects of GHG reduction policies, *Energy Policy* 23, 17-34.
- Marini, G., and P. Scaramozzino, 1995, Overlapping generations and environmental control, *Journal of Environmental Economics and Management* 29, 64-77.
- Mastrandrea, M., and S. Schneider, 2004, Probabilistic integrated assessment of "dangerous" climate change, *Science* 304, 571-575.
- McKibbin, R., and D. Vines, 2000, Modelling reality: the need for both inter-temporal optimization and stickiness in models for policy-making, *Oxford Review of Economic Policy* 16, 106-137.
- Nordhaus, W., 1994, *Managing the global commons: the economics of climate change* (MIT Press, Cambridge MA).
- Nordhaus, W., and Z. Yang, 1996, A regional dynamic general equilibrium model of alternative climate change strategies, *American Economic Review* 86, 741-765.

- O'Neill, B.C., 2005, Household expenditure patterns by demographic characteristics based on the 1998 U.S. Consumer Expenditure Survey data, Working Paper, Brown University.
- O'Neill, B.C., and B. Chen, 2002, Demographic determinants of household energy use in the United States, in: *Methods of Population-Environment Analysis*, Supplement to *Population and Development Review* 28, 53-88.
- O'Neill, B.C., and M. Oppenheimer, 2002, Dangerous climate impacts and the Kyoto Protocol, *Science* 296, June 14, 1971-1972.
- O'Neill, B.C., L. MacKellar, and W. Lutz, 2001, *Population and climate change* (Cambridge University Press, Cambridge, UK).
- Paulin, G., 2000, Expenditure patterns of older Americans, 1984-1997, *Monthly Labor Review*, May, 3-28.
- Peck, S., and T. Teisberg, 1992, CETA: A model for carbon emissions trajectory assessment, *Energy Journal* 13, 55-77.
- Ramsey, F., 1928, A mathematical theory of saving, *Economic Journal* 38, 543-559.
- Schelling, T., 1992, Some economics of global warming, *American Economic Review* 82, 1-14.
- Schelling, T., 1995, Intergenerational discounting, *Energy Policy* 23, 395-401.
- Schipper, L., 1996, Lifestyles and the environment: the case of energy, *Daedalus* 125, 113-138.
- Schmitt, J., 2004, Estimating household consumption expenditures in the United States using the Interview and Diary portions of the 1980, 1990, and 1997 Consumer Expenditure Surveys, *DEMPATEM Working Paper No. I*, available at <http://www.uva-aiaa.net/lower.asp?id=186>.
- Solow, R., 1956, A contribution to the theory of economic growth, *Quarterly Journal of Economics* 70, 65-94.
- Stephan, G., G. Muller-Furstenberger, and P. Previdoli, 1997, Overlapping generations or infinitely-lived agents, *Environmental and Resource Economics* 10, 27-40.
- Stokey, N., and R. Lucas, 1989, *Recursive methods in economic dynamics* (Harvard University Press, Cambridge MA).
- Weber, C., and A. Perrels, 2000, Modelling lifestyle effects on energy demand and related emission, *Energy Policy* 28, 549-566.
- Weyant, J., 2004, Introduction and overview, EMF 19 alternative technology strategies for climate change policy, *Energy Economics* 26, 501-515.
- Weyant, J., and J. Hill, 1999, Introduction and overview, costs of the Kyoto Protocol: a multimodel evaluation, *Energy Journal*, Kyoto Special Issue, vii-xiv.
- Yogo, M., 2004, Estimating the elasticity of intertemporal substitution when instruments are weak, *Review of Economics and Statistics* 86, 797-810.
- Zeng, Y., J. Vaupel, and W. Zhenglian, 1998, Household projection using conventional demographic data, in: W. Lutz, J. Vaupel, and D. Ahlburg, eds., *Frontiers of*

Population Forecasting, supplement to Population and Development Review 24,
59-87.

Figure 1: Overview of the PET model. Households demand consumption and investment goods (C and I), and supply capital and labor (K and L). Final good producers supply C, I, and a government good (G). Intermediate goods producers supply energy and materials (E and M). The primary energy producers, which are coal, oil and gas industries, create CO₂ emissions.

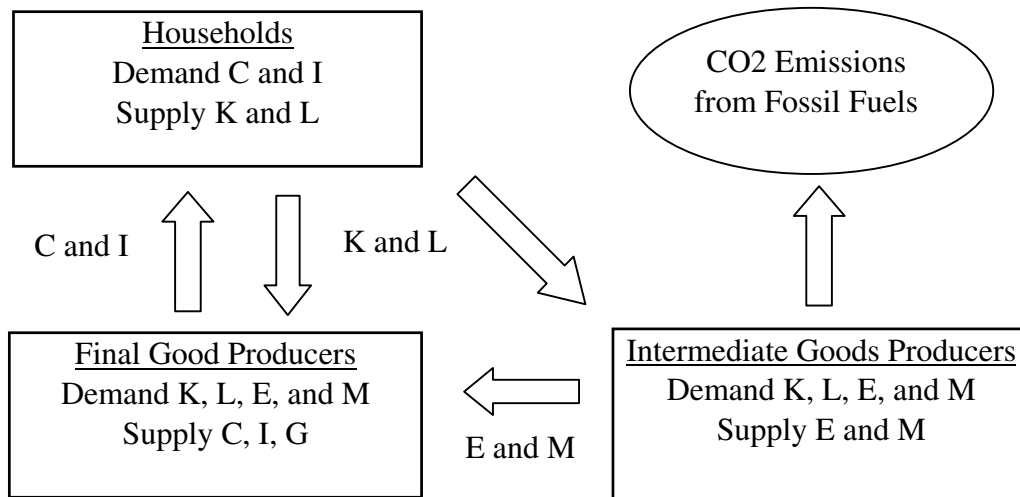


Figure 2: Cohort structure of dynasties in the PET model. Dynasty 1 consists of cohorts 1a-f (boxes). Dynasty 2 consists of cohorts 2a-f (circles). Dynasty 3 consists of cohorts 3a-e (triangles).

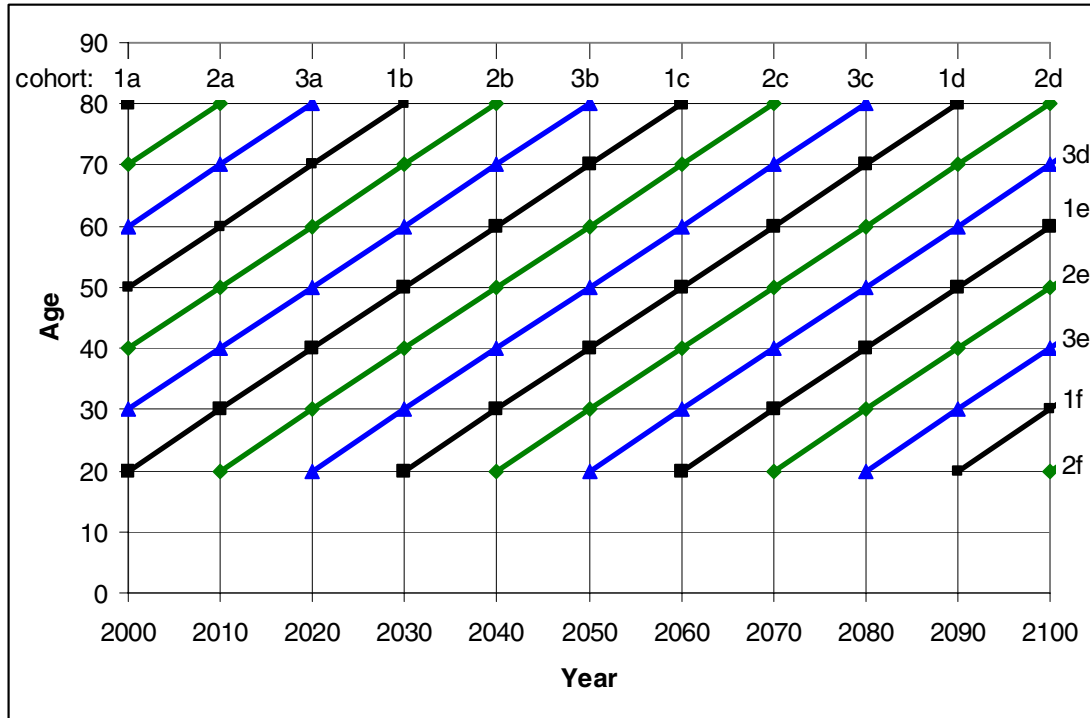


Fig. 3: Per capita dynamics for labor income (top) and capital stock (bottom) in thousands of year 2000 dollars for the 3 dynasties in the low (hatched), medium (light solid), and high (dark solid) population scenarios.

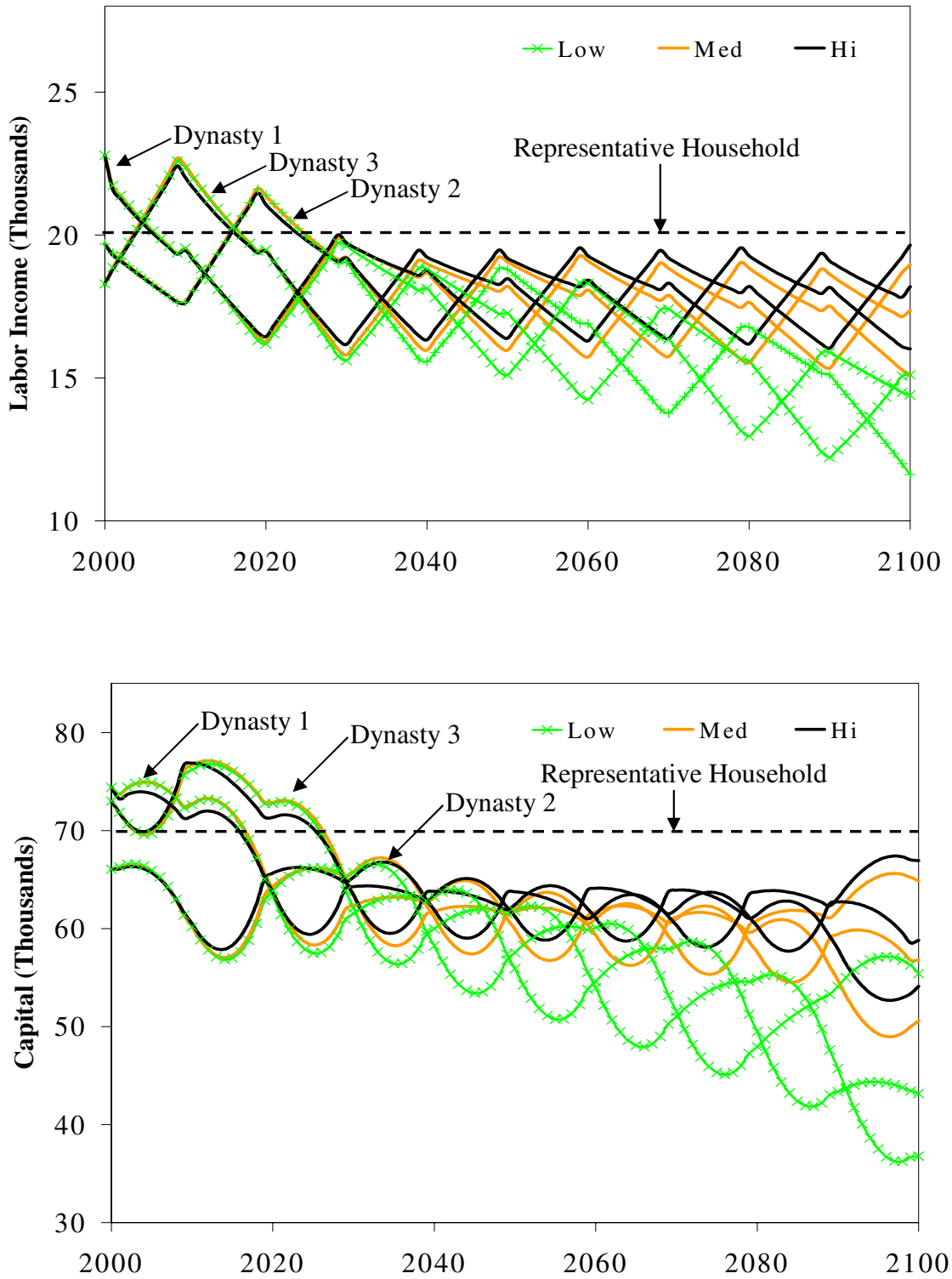


Figure 4: Range of CO₂ emissions and per capita CO₂ emissions for heterogeneous (Het) and representative (Rep) households in low, medium, and high population Scenarios.

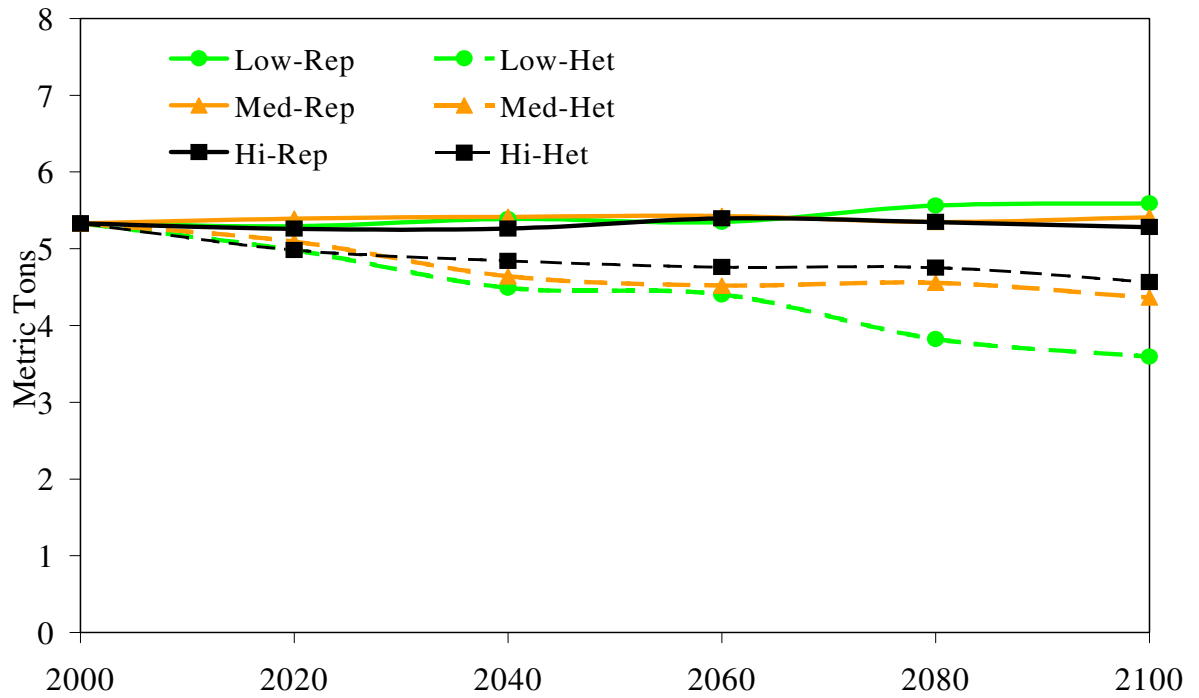
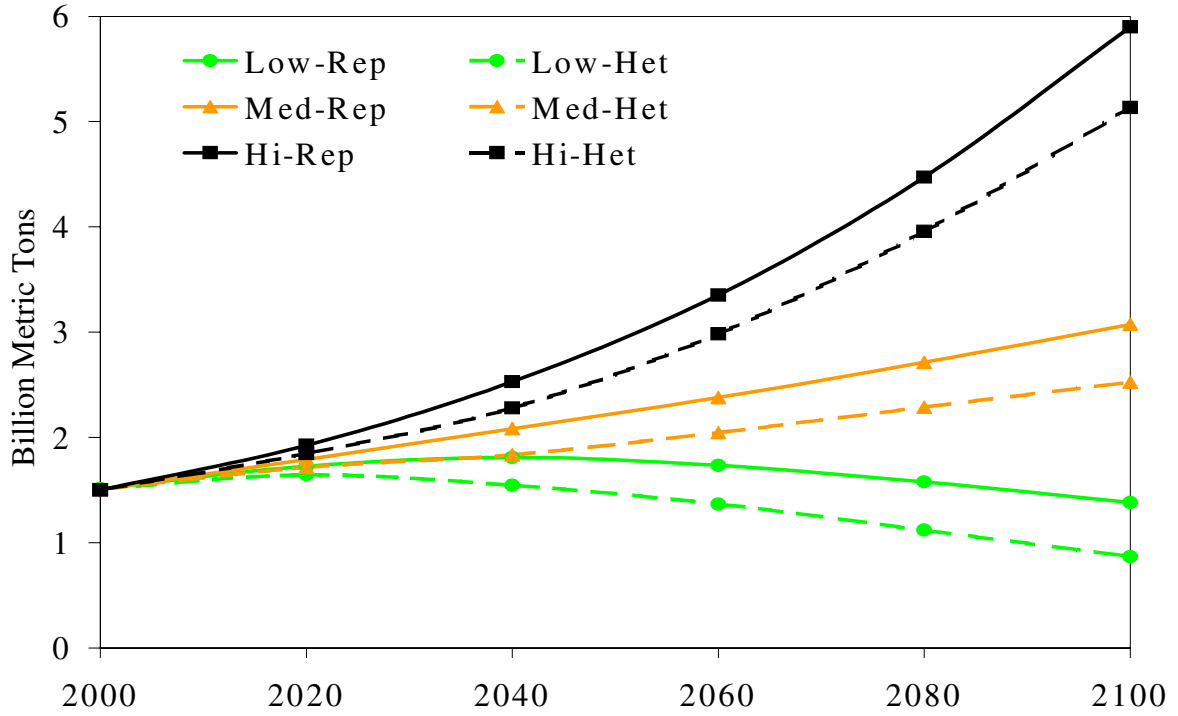


Figure 5: Rates of change for models in SRES A1 scenario for OECD countries compared to the PET model for per capita GDP (top) and carbon intensity of GDP (bottom).

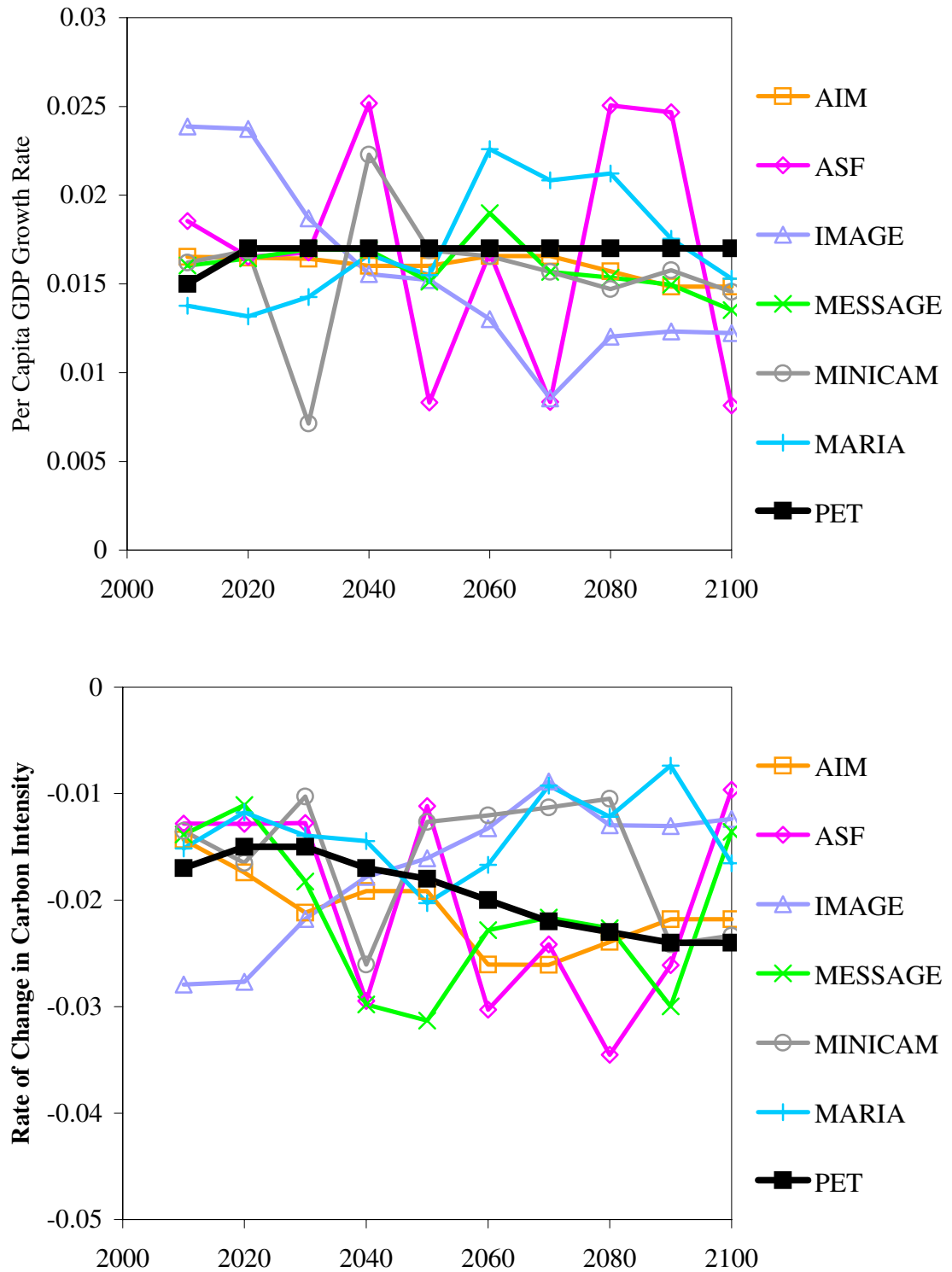


Figure 6: GDP and CO₂ emissions under technical change assumptions consistent with the SRES A1 emissions scenario (Tec) compared to no technical change (No Tec) for representative (Rep) and heterogeneous (Het) households.

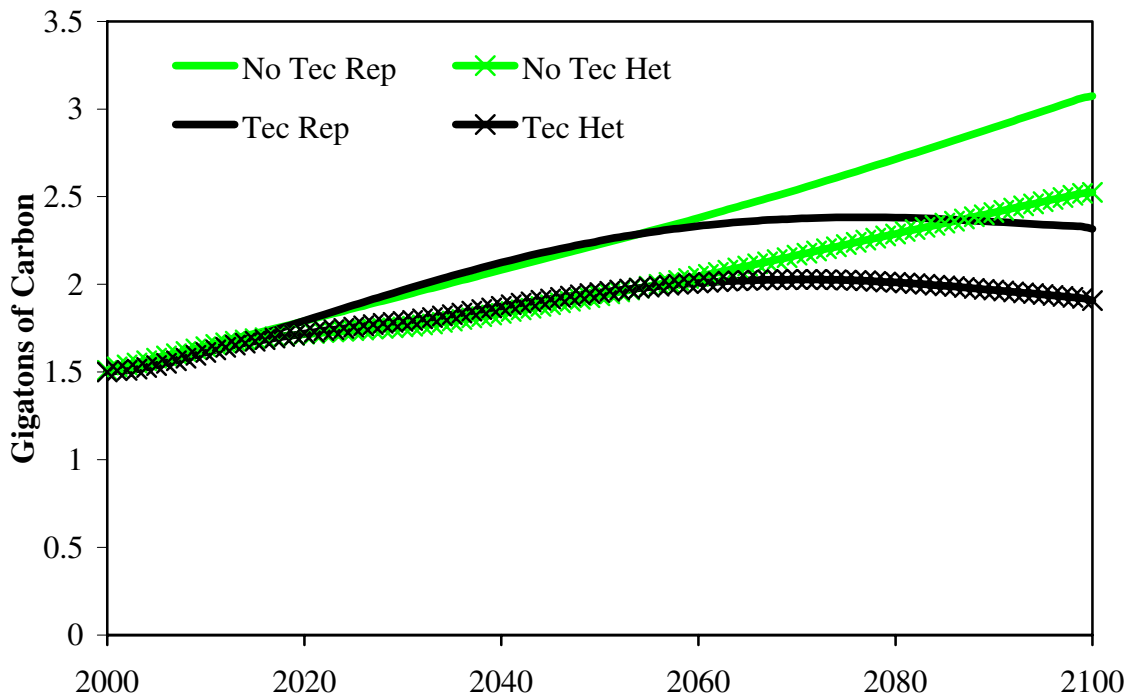
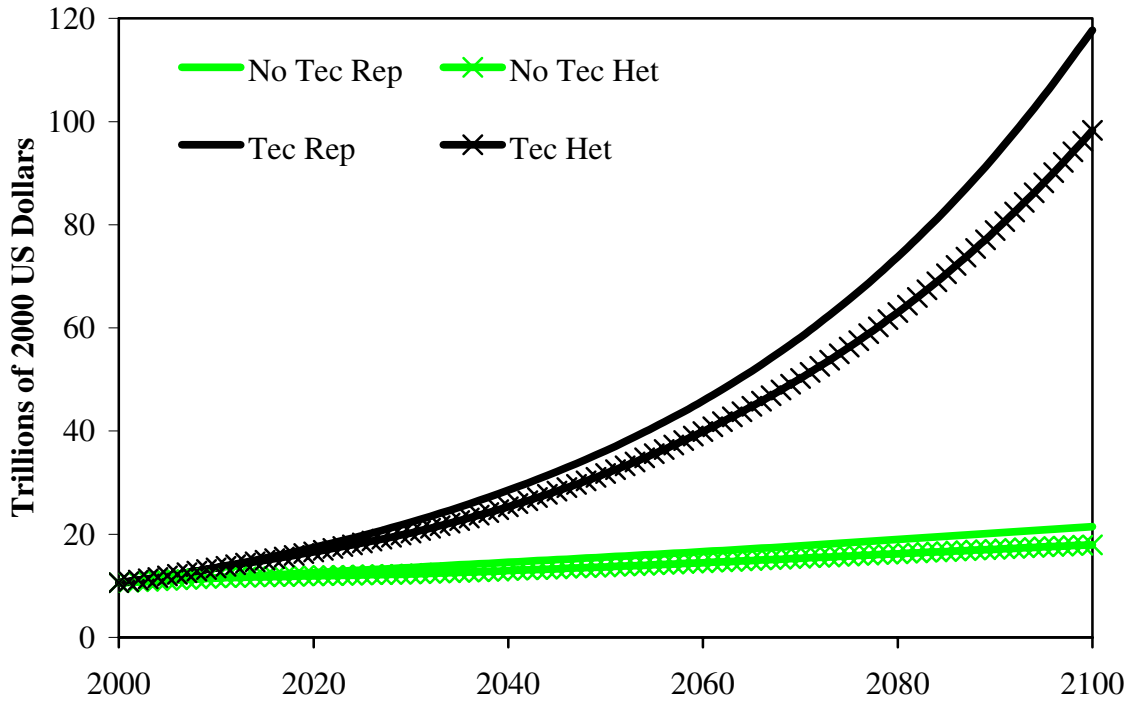


Table 1: Expenditure shares for different age groups (%). Source: BLS 1998.

Good	Mean	Age of Household Head							
		15-25	25-35	35-45	45-55	55-65	65-75	75-85	85-95
1. Food	15.29	15.41	14.71	15.55	15.29	15.31	15.55	16.43	12.43
2. Alcohol	1.02	1.69	1.22	0.96	0.84	1.02	0.87	0.99	0.24
3. Tobacco	0.85	0.93	0.83	0.89	0.86	0.98	0.76	0.43	0.37
4. Utilities	4.22	2.90	3.74	4.01	3.98	4.69	5.53	6.71	6.07
5. Housing Services	20.50	21.54	23.80	21.69	18.82	17.80	16.19	17.63	33.63
6. Furnishings	4.48	3.76	4.29	4.35	4.84	5.07	4.66	4.16	1.21
7. Appliances	1.35	1.65	1.25	1.41	1.33	1.49	1.21	1.19	0.87
8. Clothing	4.93	5.35	5.31	5.28	5.40	4.07	4.00	2.85	1.59
9. Transportation	8.25	7.71	8.33	7.99	8.68	8.90	8.25	6.78	4.70
10. Motor Vehicles	12.01	14.47	13.06	12.65	12.57	11.20	9.42	5.08	5.12
11. Services	7.22	5.48	6.25	6.53	7.31	8.35	9.53	10.04	9.19
12. Financial Service	2.99	1.93	2.95	3.20	2.80	3.55	2.88	3.26	1.58
13. Recreation	3.75	3.38	3.67	3.65	4.02	3.70	3.99	3.88	2.07
14. Nondurables	1.98	2.12	2.16	2.09	2.07	1.76	1.74	1.06	0.70
15. Fuels	3.40	3.50	3.29	3.40	3.50	3.59	3.42	3.02	2.25
16. Education	1.76	5.50	1.29	1.75	2.41	1.14	0.50	0.19	0.37
17. Health	5.99	2.69	3.84	4.60	5.28	7.39	11.51	16.30	17.62

Table 2: Total consumption expenditures, savings, income, government (Gov.) and household (HH) transfers, and income tax rates for different age groups (per capita values in 1998 dollars). Source: BLS 1998.

	Mean	Age of Household Head							
		15-25	25-35	35-45	45-55	55-65	65-75	75-85	85-95
Consumption	13,214	11,355	11,824	12,175	15,987	15,336	14,156	12,555	12,084
Savings	3,316	1,080	2,253	3,442	4,674	5,020	2,299	3,036	6,808
Labor income	14,198	9,659	14,753	15,278	21,583	14,440	4,014	1,324	1,325
Capital income	2,020	192	769	1,336	2,081	4,115	4,998	5,019	3,777
Capital	33,377	3,076	5,894	17,040	43,867	66,295	95,910	87,351	83,277
Gov. transfers	371	-440	-882	-811	-1,066	1,270	6,098	7,957	7,384
HH transfers	48	342	210	32	7	65	-244	-364	-474
Capital tax rate	0.23	0.39	0.34	0.31	0.30	0.17	0.16	0.15	0.17
Labor tax rate	0.09	0.06	0.08	0.08	0.10	0.10	0.18	0.26	0.18

Table 3: U.S. population (millions) and shares (%) living in households of different ages in high, medium, and low population scenarios. Source: Jiang and O’Neill (2005).

		Population Shares (%) by Age of Household Head								
Year	Population	15-25	25-35	35-45	45-55	55-65	65-75	75-85	85-95	95+
<i>High Population Scenario</i>										
2000	281.4	6.5	23.0	30.5	19.7	9.4	6.5	3.6	0.9	0.1
2010	316.6	7.3	21.7	25.0	20.7	13.6	7.0	3.6	1.0	0.1
2020	361.2	6.2	21.8	24.5	17.5	14.6	10.1	4.2	1.0	0.1
2030	414.3	6.4	19.9	24.9	17.4	12.5	11.2	6.3	1.3	0.2
2040	475.0	6.7	20.5	23.3	17.7	12.4	9.6	7.3	2.3	0.2
2050	546.3	6.9	20.8	23.9	16.5	12.5	9.5	6.5	3.0	0.4
2060	630.2	6.9	20.6	24.0	16.9	11.7	9.6	6.6	3.0	0.6
2070	728.3	7.0	20.5	23.7	17.0	12.0	9.1	6.7	3.3	0.7
2080	841.5	6.9	20.4	23.5	16.8	12.1	9.3	6.5	3.6	0.9
2090	970.4	6.9	20.2	23.3	16.7	12.0	9.4	6.8	3.6	1.1
2100	1117.0	6.8	20.1	23.1	16.6	11.9	9.4	7.0	3.8	1.2
<i>Medium Population Scenario</i>										
2000	281.4	6.5	23.0	30.5	19.7	9.4	6.5	3.6	0.9	0.1
2010	307.8	6.7	21.0	25.2	21.3	13.9	7.1	3.6	1.1	0.1
2020	333.8	5.8	20.6	23.9	18.0	15.4	10.6	4.4	1.1	0.2
2030	360.6	5.8	18.9	23.9	17.4	13.2	12.2	6.9	1.4	0.2
2040	387.8	5.6	19.2	22.5	17.7	12.9	10.7	8.5	2.6	0.3
2050	414.5	5.4	19.0	22.9	16.8	13.2	10.7	7.8	3.7	0.5
2060	442.3	5.3	18.6	22.7	17.2	12.6	11.1	7.9	3.9	0.7
2070	472.3	5.2	18.4	22.2	17.0	13.0	10.7	8.4	4.3	0.8
2080	504.9	5.0	18.1	22.1	16.8	12.9	11.0	8.2	4.8	1.1
2090	538.3	4.9	17.7	21.8	16.8	12.8	11.1	8.7	5.0	1.4
2100	573.0	4.7	17.4	21.5	16.6	12.8	11.1	8.9	5.4	1.7
<i>Low Population Scenario</i>										
2000	281.4	6.5	23.0	30.5	19.7	9.4	6.5	3.6	0.9	0.1
2010	303.7	6.8	21.0	24.9	21.1	14.0	7.2	3.7	1.1	0.1
2020	321.2	5.3	20.3	23.6	17.9	15.7	11.1	4.7	1.2	0.2
2030	331.4	4.5	17.6	23.6	17.5	13.7	13.1	7.8	1.8	0.3
2040	334.1	3.9	16.4	21.8	18.0	13.8	12.0	10.0	3.7	0.4
2050	328.5	3.3	14.9	21.0	17.2	14.8	12.6	9.7	5.6	0.9
2060	317.9	2.9	13.4	19.8	17.0	14.6	14.1	10.7	6.0	1.6
2070	305.0	2.5	12.0	18.4	16.5	15.0	14.2	12.3	7.0	2.0
2080	287.7	2.3	10.7	16.9	15.7	15.0	15.1	12.9	8.5	2.9
2090	269.9	2.1	10.1	15.5	14.8	14.7	15.5	14.0	9.4	3.9
2100	250.5	2.0	9.5	14.9	13.7	14.1	15.5	14.8	10.7	4.8

Table 4: Percentage differences in U.S. CO₂ emissions with population aging compared to the first representative household configuration in low (L), medium (M), and high (H) population scenarios, and for alternative values of the intertemporal (ρ) and consumption (σ) substitution parameters.

Year	Rep. W/Aging			Heterogeneous			Rep. W/Aging			Heterogeneous		
	L	M	H	L	M	H	L	M	H	L	M	H
$\rho = 0.5, \sigma = 0.5$						$\rho = 0.5, \sigma = -3.0$						
2000	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.1	0.1
2020	-4.9	-4.4	-4.1	-4.8	-4.2	-4.1	-4.9	-4.4	-4.1	-5.1	-4.5	-4.3
2040	-12.7	-10.1	-8.3	-14.6	-11.9	-9.8	-12.7	-10.2	-8.3	-14.8	-12.0	-9.9
2060	-18.3	-11.8	-9.2	-21.2	-14.0	-11.0	-18.2	-11.8	-9.2	-21.4	-14.0	-11.0
2080	-25.0	-13.2	-9.7	-29.0	-15.7	-11.5	-24.9	-13.2	-9.7	-29.3	-15.7	-11.5
2100	-31.5	-14.9	-10.8	-37.2	-17.9	-13.0	-31.6	-14.9	-10.8	-37.4	-17.9	-13.0
$\rho = -3.0, \sigma = 0.5$						$\rho = -3.0, \sigma = -3.0$						
2000	0.2	0.2	0.2	-0.1	0.1	0.0	0.3	0.2	0.2	0.1	0.1	0.1
2020	-5.5	-4.8	-4.3	-1.0	-0.8	-1.0	-5.3	-4.7	-4.3	-2.6	-2.2	-2.2
2040	-12.6	-9.8	-8.1	-8.6	-7.3	-6.3	-12.6	-9.9	-8.1	-10.5	-8.7	-7.3
2060	-18.4	-11.7	-9.1	-13.7	-10.0	-8.0	-18.3	-11.7	-9.1	-16.2	-11.2	-8.9
2080	-25.1	-13.3	-9.8	-19.0	-11.3	-8.4	-25.1	-13.2	-9.7	-22.3	-12.6	-9.3
2100	-31.1	-14.8	-10.7	-25.3	-13.0	-9.5	-31.3	-14.8	-10.8	-29.0	-14.4	-10.5