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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 (CO_2) emissions, the most important greenhouse gas. 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 CO_2 emissions. Results show that population aging reduces long-term 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. These results are derived under standard

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assumptions and functional forms that are used in economic growth models. The model also assumes a closed economy, substitution elasticities that are fixed, and identical across age groups, and patterns of labor supply that vary by age group, but are fixed over time.

JEL classification: D91; J11; O41; Q43

Keywords: Economic growth; Carbon emissions; Climate change; Overlapping generations; Population aging

1. Introduction

Population growth and technical change are among the most important factors to consider in projections of future carbon dioxide (CO_2) 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 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 (O'Neill et al., 2001). 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 carbon dioxide (CO_2) 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 CO_2 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.

1.1. 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, which is the typical approach in models that compare costs and benefits of alternative emissions abatement strategies (Manne, 1999; Cline, 1992; Peck and Teisberg, 1992; Nordhaus, 1994; Manne et al., 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 ILA 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. Models with fixed savings rules often compensate for this simplification with detailed energy sectors, and other important 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 rational expectations, which coincides with perfect foresight for the deterministic case, 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 may be substantially different from models based on fixed savings rules. While the assumption of perfect foresight may not be realistic, it does incorporate information about the future into current decisions, and from the point of view of economic theory, is an improvement over fixed savings rules. Perfect foresight is also interpreted as a first-order approximation to rational expectations in the case of uncertainty (Fair and Taylor, 1983). Some economic growth models mix different types of savings behavior by assuming a fraction of the population solves a dynamic optimization problem, while others follow a fixed savings rule (McKibbin and Vines, 2000).

1.2. 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 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 (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 that lack qualitatively important demographic features. He concludes that Nordhaus' (1994) model, in particular, is sensitive to changes in the intergenerational weights used in the social welfare function. Gerlagh and van der Zwaan (2000, 2001) reach even stronger conclusions, and question whether ILA models are appropriate for analysis of climate change policies. They attribute differences between their results, and those that find OLG and ILA models produce similar outcomes, to an explicit representation of longer life expectancy and population aging in their three-period OLG model.

1.3. Multiple dynasty approach

We introduce population aging into the Population–Environment–Technology (PET) model, an energy–economic growth model, by developing a "multiple dynasty" structure that shares features of ILA and OLG approaches. The original PET model has an ILA structure with perfect foresight. Any disaggregation of the population into separate age groups therefore must account for the fact that households will make savings and consumption decisions based on forward looking behavior over their life cycle, and the life cycle of their children. Thus we disaggregate the population not by age groups *per se*, but by dynasties; i.e., groups that contain households of a given age today and that track those households, and the households of their children, as they age over time.

We use the results of new household projections for the U.S. 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, today's 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, descendents 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 of aging 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 CO_2 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, where long run emissions are only reduced by around 15%. We also find that effects of aging on emissions can be as large, or larger than, effects of technical change in some cases.

Energy–economic growth models are based on many assumptions, some more limiting than others, and the PET model is not exceptional in this regard. Important assumptions in the PET model include constant elasticity forms for utility and production functions; rational (i.e., maximizing) behavior of consumers and firms, additively separable utility functions with geometric discounting of intertemporal decisions, and perfect foresight for savings and investment decisions. These are standard assumptions in neoclassical growth models.

In addition to the standard assumptions of neoclassical growth models, results in this article are based on some specific assumptions about elasticity values, international trade, and changes in labor force participation. Utility functions in the PET model that describe demand by households for different consumer goods contain two important elasticity parameters. Empirical information about these parameters is limited, and results in the paper are sensitive to the choice of values for both.

We abstract from complications related to international trade, and treat the U.S. as a closed economy to focus on issues related to population aging. The economics literature on demography has a precedent for this simplifying assumption in the seminal work of Barro and Becker (1989). The PET model is fully capable of simulating trade among several countries or regions, but lacking household projections and other demographic information for these, putting trade aside is convenient for developing the population component of the U.S. model. Including trade in the model between regions, without demographic information comparable to the U.S., would presumably dilute the effects of aging, and at the same time, complicate the analysis, perhaps without additional insight.

One of the most important assumptions in the model for results in this article is that future labor force participation varies by age group but is fixed in per capita terms over time. A similar simplifying assumption is also found in Barro and Becker (1989), but in the present paper, this assumption has a direct effect on results, and is probably not realistic. A plausible consequence of population aging is increased labor force by participation by older age groups. In addition, population aging, and increased life expectancy, will increase pressure on pension systems. In response, policy-makers may increase the age of retirement, or decrease benefits. Both options have been discussed recently in the U.S. The former would certainly increase labor supply by older age groups, and the latter would likely have similar effects. Each of these assumptions is an area for future work.

Section 2 of the article describes the PET model and household economic data. The household projections are described in Section 3, and results of simulations with the PET model are presented in Section 4. We conclude with a discussion of our analysis, results, and directions for future research in Section 5.

2. 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 (CO_2) emissions. The PET model accounts for all CO_2 emissions from use of fossil fuels in the U.S. economy, including government and other non-consumer-related sources. This article uses the PET model to analyze how total CO_2 emissions from use of fossil fuels in the U.S. economy could be influenced by population aging. Household and consumption components of the PET model are presented in this section, preceded by a brief overview of the model. A technical Appendix that describes the PET model is provided at the end of this article with key features of the model's production structure, government sector, and equilibrium. A separate document, available from the authors upon request, gives further details about the model's mathematical structure, calibration procedure, and data sources (Dalton and Goulder, 2001).

A schematic diagram of the PET model is provided in Fig. 1. The production component has industries operated by many perfectly competitive firms that produce intermediate goods, including energy (E) and materials (M), and final goods. Consumption (C) and investment (I) are final goods, in addition to the final good produced by a government sector in the model. 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.

Technical change is described in the PET model using separate productivity coefficients that change exogenously over time for each input of each production function in the model. This representation allows different patterns of labor, capital, and energy augmenting technical change including Hicks-, Solow-, and Harrod-neutral types. While changes in these productivity coefficients are exogenous, the resulting pattern of input use including energy is driven by changes in relative prices, and therefore endogenous. Thus, economic growth and the carbon intensity of production are endogenous model outputs. Time-paths for different productivity coefficients are selected so that outputs such as growth rates for per capita GDP and trends in

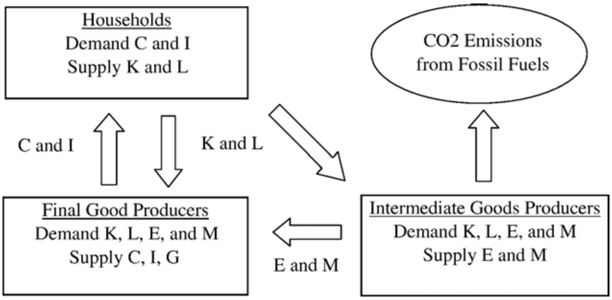

Fig. 1. Overview of the PET model. Households demand consumption and investment goods (C and I), and supply capital and labor (K and L). Final good producers supply C, I, and a government good (G). Intermediate goods producers supply energy and materials (E and M). The primary energy producers, which are coal, oil and gas industries, create CO_2 emissions.

carbon intensities are consistent with a particular scenario. An advantage of this approach is to specify the rates and patterns of technical change in terms of the PET model's structural parameters rather than using a purely exogenous mechanism such as an Autonomous Energy Efficiency Improvement (AEEI) parameter.

Each production function in the PET model has a separate nest for energy inputs with a substitution parameter 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 a substitution 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 CO_2 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. 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 CO_2 emissions. Currently, we have household economic data and projections for the U.S. only. Therefore, we are 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 in a more controlled setting. 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.

2.1. 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 individuals, 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

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

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, by way of Walras' Law, to be the numeraire 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 a representative household.

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

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

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.

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

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

We describe two steps in the solution algorithm for each household's optimization problem to aid explanation of results below. A technical description of the dynamic algorithm is given at the end of the Appendix. 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,

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

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 $\overline{p}_{it}$ 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 that

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

A solution to the Euler Eq. (5), capital law-of-motion (1), and budget constraint (2), which also satisfies a set of transversality conditions, is sufficient to maximize (3). Moreover, the solution is unique (Stokey and Lucas, 1989). The transversality conditions use the shadow value of capital for each household λ_{it}, and require that

$$\lim_{t\rightarrow\infty}\lambda_{it}k_{it} = 0 \tag{6}$$

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, as represented by the ratio of the return on capital to the price of investment goods,

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

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 Eq. (5), and a variation of the Fair–Taylor algorithm (Fair and Taylor, 1983), to compute the optimal transition from $\overline{k}_i$ to k^* for each household.

2.2. 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.

The CES data report only total household expenditures and do not distinguish between domestic and foreign produced consumer goods. As noted above, we treat the U.S. as a closed economy to simplify the analysis and isolate demographic effects in a more controlled setting. Thus, all consumer goods in the analysis are produced according to benchmark data for the U.S. economy, which biases our results to the extent that the energy intensity of foreign-produced goods is substantially different than domestic production.

The CES Interview survey has a sample size of approximately 5500 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). 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_{ijt} 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).

Table 1
Expenditure shares for different age groups (%)

Age of household head									
Good	Mean	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 services	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

Source: Consumer Expenditure Survey, 1998.

In Table 2 we summarize other age specific economic activities. 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.

3. 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, 2006), 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 in 2100, driven by differences in assumptions about fertility, mortality, and international migration (because the U.S. is one of the world's major migration destination countries, immigration assumptions play a particularly

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)

Age of household head	Mean	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	3316	1080	2253	3442	4674	5020	2299	3036	6808
Labor income	14,198	9659	14,753	15,278	21,583	14,440	4014	1324	1325
Capital income	2020	192	769	1336	2081	4115	4998	5019	3777
Capital	33,377	3076	5894	17,040	43,867	66,295	95,910	87,351	83,277
Gov. transfers	371	−440	−882	−811	−1066	1270	6098	7957	7384
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

Source: Consumer Expenditure Survey, 1998.

important role in future population outcomes). 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 Fig. 2. The procedure first sorts households into groups based on ten-year intervals so that households headed by 15–25 year-olds form one group, 26–35 year-olds form another, and so on. The oldest group is based on household heads that are aged ninety-six or older. These age groups are linked together to form dynasties based on the mean age of childbearing, which in the U.S. is about thirty. For example in the year 2000, households headed by twenty, fifty, and eighty year-olds are in the same dynasty. In 2010, these household heads have aged by ten years, and therefore, this dynasty now consists of households headed by thirty, sixty, and ninety year-olds. 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. Dynamic paths for expenditure shares, derived from the household projections, 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 share parameters within each dynasty that change over time to reflect the changing demographic composition. In addition to these demographically driven changes in

Table 3
U.S. population (millions) and shares (%) living in households of different ages in high, medium, and low population scenarios

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+
High population scenario										
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
Medium population scenario										
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
Low population scenario										
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

Source: Jiang and O'Neill (2006).

parameter values within each dynasty, real labor income and expenditures on different consumer goods are influenced in model simulations by changes in prices, capital accumulation, and in some cases, government policies.

4. 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

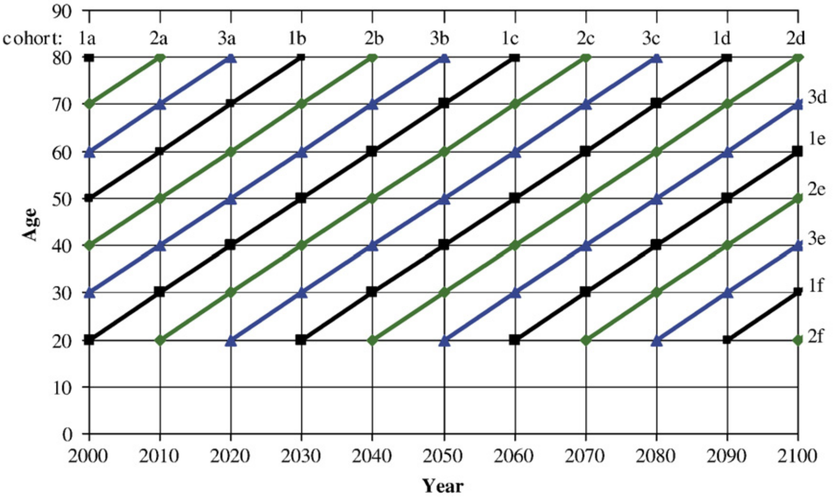

Fig. 2. Cohort structure of dynasties in the PET model. Dynasty 1 consists of cohorts 1a–f (boxes). Dynasty 2, consists of cohorts 2a–f (circles). Dynasty 3, consists of cohorts 3a–e (triangles).

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 by 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 household with aging" configuration has the same total labor supply as the heterogeneous households configuration, but is neutral with respect to other demographic factors, 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.

4.1. Heterogeneous versus representative households

The model configuration with heterogeneous households has three dynasties that follow the dynamics in Fig. 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 a representative household 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. The OLG structure of households within dynasties 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.

The top graph in Fig. 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 for each dynasty follows a thirty-year cycle, 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 presented in the bottom graph of Fig. 3, which is influenced by labor income, but the general pattern is qualitatively different from labor income. 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. In contrast, capital for a representative household is illustrated with a flat line at about $70,000 per person.

In Fig. 3, the variation across dynasties in each year within a given population scenario exceeds the variation across 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 Fig. 4 compare results for total CO_2 emissions, and per capita CO_2 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 ton/year in 2100. For a representative household, 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 ton/year by 2100 in the three population scenarios.

The top graph in Fig. 4 shows that effects of heterogeneity lead 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 prices or capital accumulation. 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 Fig. 4 shows per capita emissions for heterogeneous and representative households in each population scenario with no technical change. Because total population within

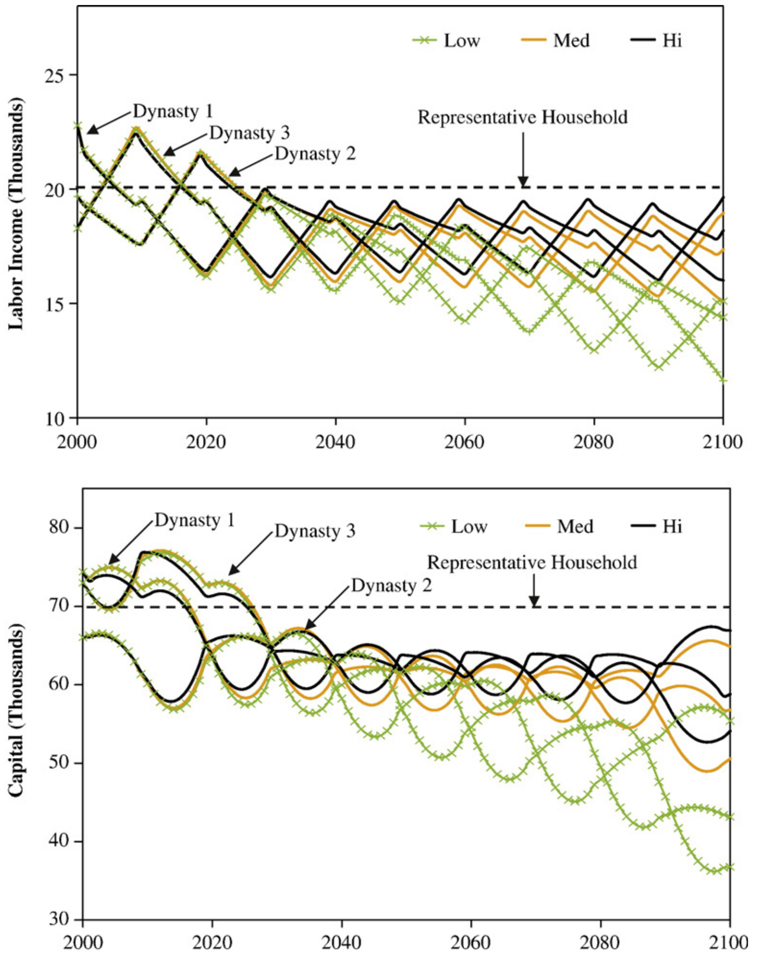

Fig. 3. Per capita dynamics for labor income (top) and capital stock (bottom) in thousands of year 2000 dollars for the 3 dynasties in the low (hatched), medium (light solid), and high (dark solid) population scenarios.

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 a representative household, and changes in carbon intensity, represented by CO_2 emissions per dollar of GDP, are also minor. Consequently, per capita emissions with a representative household are essentially constant over time and across population scenarios, around 5.3 t/person.

The bottom graph in Fig. 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.

4.2. Population aging with a representative household

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 a representative household. 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 a representative household and no aging, the long-term emissions reductions for a representative household 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.

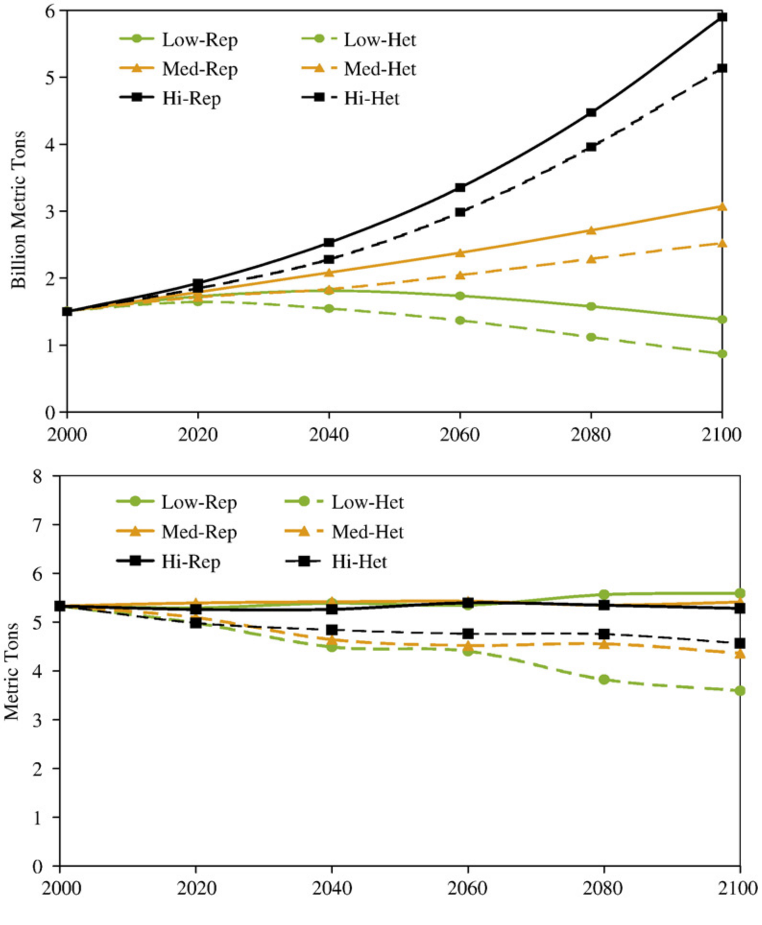

Fig. 4. Range of CO_2 emissions and per capita CO_2 emissions for heterogeneous (Het) and representative (Rep) households in low, medium, and high population scenarios.

4.3. 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 (Guvenen, 2003), and obtaining reliable and consistent estimates has been a problem. Beaudry 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 $\rho\to-\infty$, 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 Fig. 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. As discussed above, 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 a representative household 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, $\sigma\to-\infty$, 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 a representative household with no aging, reductions in baseline emissions for heterogeneous households are smaller than a representative household 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, depending on true values of household substitution parameters, either underestimates or overestimates 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.

4.4. Demography and technical change

Technical change is expected to be an important factor in future CO_2 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, and consumer goods in the model offer some interesting and realistic possibilities for interpreting effects of technical change. For example according to the expenditure shares in Table 1, population aging implies greater demand (per unit of expenditures) for utilities, an energy intensive good. In this case, ignoring the beneficial effects of technical change on the energy intensity of production could overestimate an increase in the energy intensity of consumption due to aging. On the other hand demand for health care, a non-energy intensive good, will also increase in relative terms with aging, and therefore, ignoring the effects of technical change in this case may overestimate the energy savings associated with higher health care expenditures. The reason is that an increase in health expenditures means a reduction in spending on some other

Table 4
Percentage differences in U.S. CO_2 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

goods that are more energy intensive than health care, but become less energy intensive with 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 CO_2 emissions in the PET model match averages for different models used in the SRES A1 scenario for the OECD region, as seen in Fig. 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 in general have a large effect on the carbon intensity of output, which is measured by the ratio of CO_2 emissions divided by 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 Fig. 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 Fig. 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 Fig. 6 compare results for U.S. GDP and CO_2 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 Fig. 6 shows the effects of demographic heterogeneity and technical change on CO_2 emissions. The results of these comparisons are interesting. As also seen in Fig. 4, CO_2 emissions exhibit a roughly linear increase over time with the medium household projection and a representative household. 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 a representative household. In contrast, differences in emissions between a representative household 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 about 2085. 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 Fig. 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, Fig. 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

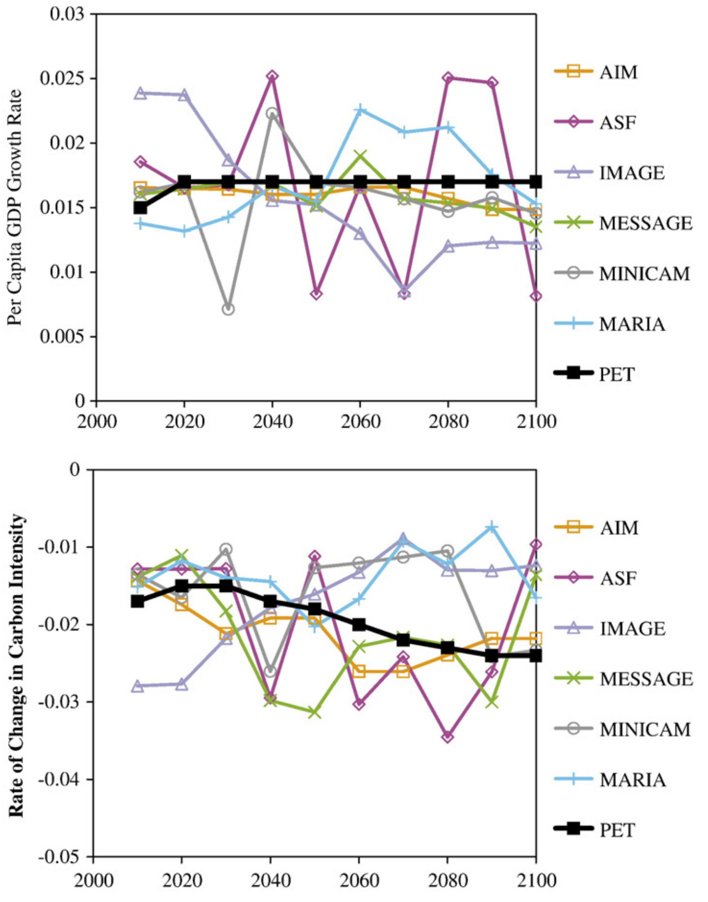

Fig. 5. Rates of change for models in SRES A1 scenario for OECD countries compared to the PET model for per capita GDP (top) and carbon intensity of GDP (bottom).

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 a representative household and no technical change.

Results in Fig. 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

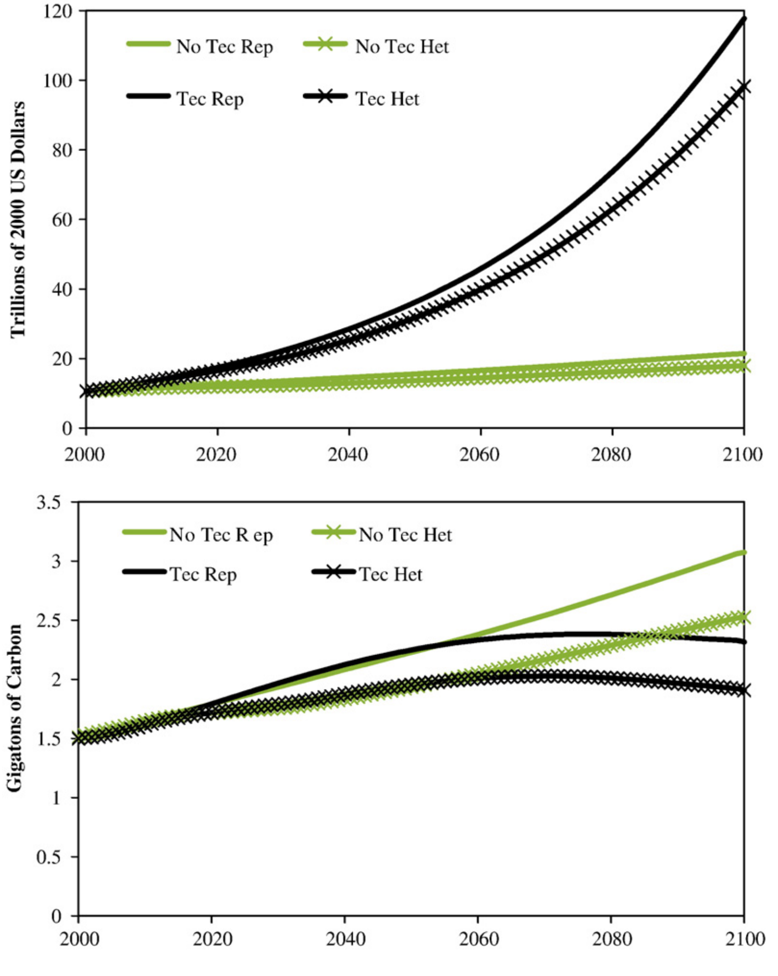

Fig. 6. GDP and CO_2 emissions under technical change assumptions consistent with the SRES A1 emissions scenario (Tec) compared to no technical change (No Tec) for representative (Rep) and heterogeneous (Het) households.

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.

5. Discussion

Demographic factors are usually treated implicitly in energy–economic growth models. This article describes a framework for modeling heterogeneity in household structure, new household projections for the U.S., and economic data for U.S. households to estimate the effects of population aging on U.S. energy use and CO_2 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 descendents 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 developed low, medium, and high population scenarios for the ProFamy model, which are driven by a range of assumptions about future fertility, mortality, immigration, and household formation and dissolution rates. 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, due mainly to higher assumed fertility, and lower assumed life expectancy, but also to higher assumed migration. While immigration can partially offset the effects on age structure of low fertility, it cannot completely offset it (UN, 2000).

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.

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 a representative household. To isolate demographic effects, the first set of simulations does not include technical change. Our results compare two types of heterogeneous households to a representative household. 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 CO_2 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 a representative household 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. The main trade-off in this result is the amount of aging in the household projections, on the one hand, and the nature of the technical change on the other.

Technical change consists of a scale effect, driven mainly by improvements in labor productivity that increase the overall size of the economy, but generally have neutral effects on energy intensity, and a technique effect from efficiency improvements or fuel switching in the energy sector that reduces the amount of CO_2 emitted per unit of production. The SRES A1 scenario assumes relatively high economic growth and modest decreases in carbon intensity. We used our medium household projection to be consistent with other assumptions in SRES A1, and therefore, using our low household projection would strengthen the effects of aging on emissions reduction, while using SRES B1, a clean scenario, in our analysis would strengthen the effects of technical change.

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, changes in the spatial distribution of households, or other demographic factors are may also be 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 compares 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) are available to estimate substitution elasticities for consumer goods, and test hypotheses about whether these vary among age groups and other demographic categories. We are in the process of developing econometric estimates for the elasticity of demand among consumer goods in the U.S. for households of different age groups, and size 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. We are currently constructing demographic information for China and India that will be incorporated into the PET model, and effects of trade with these countries will be considered in future work.

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 CO_2 emissions, relative to an autarky situation without trade. However, population aging is a global event (O'Neill et al., 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.

Appendix A. Structure of the population–environment–technology model

The mathematical structure of the PET model's production functions, dual cost functions, perfect foresight competitive equilibrium, and computational procedure are presented in this appendix to complement description of the model in Section 2. For ease of exposition, prices and tax rates that appear in Section 2 are redefined in some cases to be consistent with notation used below.

A.1. Production functions for intermediate and final goods industries

The production component of the PET model has perfectly competitive industries with many identical firms that take prices as given. These firms produce intermediate goods, including energy and materials, and final goods related to consumption and investment. Capital and labor are referred to below as factors of production. The production function for each firm has a nested constant elasticity of substitution (CES) capital–labor–energy–materials (KLEM) structure, with a separate nest only for energy inputs. In particular, these production functions exhibit constant returns to scale (CRS), and firms are aggregated without loss of generality to the industry-wide level. The version of the PET model used in this article has 23 industries: 4 energy, 1 materials, 17 consumer goods, and 1 investment good. Subscripts for industries and years are suppressed in the following equations to simplify notation.

The output of each industry X is determined by inputs of capital K, labor L, energy composite $\bar{E}$, and materials M according to a CES function,

$$X = \gamma_X(\alpha_K(G_K K)^{\rho_X} + \alpha_L(G_L L)^{\rho_X} + \alpha_{\overline{E}}(G_{\overline{E}}\overline{E})^{\rho_X} + \alpha_M(G_M M)^{\rho_X})^{\frac{1}{\rho_X}}. \tag{A1}$$

In (A1), γ_X is a scale parameter that normalizes α_K, α_L, $\alpha_{\overline{E}}$, and α_M to sum to unity. The substitution parameter $-\infty<\rho_X\leq 1$ translates into an elasticity of substitution, $\sigma_X=1/(1-\rho_X)$. As $\rho_X\to-\infty$, σ_X tends to zero. In this case, inputs are perfect complements, the corresponding production function is Leontief, and the input–output (IO) coefficients are fixed. As $\rho_X\to 1$, σ_X approaches infinity, and inputs are perfect substitutes. The coefficients G_x, with z an index over KLEM inputs, in each nest are productivity factors that can change over time. Time variation in these productivity factors is exogenous, and allows mixes of Hicks-, Solow- and Harrod-neutral types of technical change among industries in the PET model.

A separate CES nest for energy has four types of inputs: Oil and Gas E_1, Coal E_2, Electricity E_3, and Refined Petroleum E_4. These form an energy composite according to

$$\overline{E} = \gamma_E\left(\sum_{i=1}^{4}\alpha_{E_i}(G_{E_i}E_i)^{\rho_E}\right)^{\frac{1}{\rho_E}}. \tag{A2}$$

The production functions in (A1) and (A2) are used to derive dual cost functions and input demand functions for each industry. These functions form a mathematical foundation for computing market equilibrium.

A.2. Cost functions and input demand for intermediate and final goods industries

Since CRS implies that profits are equal to zero in equilibrium, the price of output in each industry is equal to its after-tax marginal cost. Let P_{E_i} denote the pre-tax price of energy type E_i, which is the same for all industries. Let τ_{E_i} represent an ad-valorem tax on the use of E_i in an industry. The cost function dual to the production function in (A2) gives the average and marginal cost of $\overline{E}$,

$$P_{\overline{E}} = \frac{1}{\gamma_E}\left(\sum_{i=1}^{4}\alpha_{E_i}^{\frac{1}{1-\rho_E}}\left(\frac{P_{E_i}(1+\tau_{E_i})}{G_{E_i}}\right)^{\frac{\rho_E}{\rho_E-1}}\right)^{\frac{\rho_E-1}{\rho_E}} \tag{A3}$$

For each type of energy, the cost-minimizing ratio $E_i/\bar{E}$ is derived from (A3) using Shephard's Lemma,

$$A_{E_i} = \left(\frac{1}{\alpha_{E_1}(\gamma_E G_{E_i})^{\rho_E}} \frac{P_{E_i(1+\tau_{E_i})}}{P_{\bar{E}}}\right)^{\frac{1}{\rho E^{-1}}}. \tag{A4}$$

Let P_K represent the price of capital, P_L the price of labor, and τ_M denote an ad-valorem tax on use of M in an industry. The cost function dual to the production function in (A1) gives the average and marginal cost of producing X,

$$P_X = \frac{1}{\gamma_X}\left(\alpha_K^{\frac{1}{1-\rho X}}\left(\frac{P_K}{G_K}\right)^{\frac{\rho X}{\rho X^{-1}}} + \alpha_L^{\frac{1}{1-\rho X}}\left(\frac{P_L}{G_L}\right)^{\frac{\rho X}{\rho X^{-1}}} + \alpha_{\bar{E}}^{\frac{1}{1-\rho X}}\left(\frac{P_{\bar{E}}}{G_E}\right)^{\frac{\rho X}{\rho X^{-1}}} + \alpha_M^{\frac{1}{1-\rho X}}\left(\frac{P_M}{G_M}\right)^{\frac{\rho X}{\rho X^{-1}}}\right)^{\frac{\rho X^{-1}}{\rho X}}. \tag{A5}$$

Let τ_X be the specific (per unit) tax on output of an industry. Since CRS implies zero profits in equilibrium, the after (gross of) tax price of X is $P_X + \tau_X$. Cost minimizing IO coefficients are derived for KLEM inputs from (A5) using Shephard's Lemma. The cost-minimizing ratio of K/X is

$$A_K = \left(\frac{1}{\alpha_K(\gamma_X G_K)^{\rho_X}} \frac{P_K}{P_X + \tau_X}\right)^{\frac{1}{\rho X^{-1}}}. \tag{A6}$$

The cost-minimizing ratio L/X is

$$A_L = \left(\frac{1}{\alpha_L(\gamma_X G_L)^{\rho_X}} \frac{P_L}{P_X + \tau_X}\right)^{\frac{1}{\rho X^{-1}}}. \tag{A7}$$

The cost-minimizing ratio $\overline{E}/X$ depends on P_E from (A3), which includes tax rates τ_E on the four energy types,

$$A_{\bar{E}} = \left(\frac{1}{\alpha_E(\gamma_X G_E)^{\rho_X}} \frac{P_{\bar{E}}}{P_X + \tau_X}\right)^{\frac{1}{\rho X^{-1}}}. \tag{A8}$$

The cost-minimizing ratio M/X is

$$A_M = \left(\frac{1}{\alpha_M(\gamma_X G_M)^{\rho_X}} \frac{P_M + \tau_M}{P_X + \tau_X}\right)^{\frac{1}{\rho X^{-1}}}. \tag{A9}$$

These cost-minimizing IO coefficients are used below to calculate input demands for intermediate goods and factors of production.

A.3. Government sector

Let $\overline{\mathrm{GT}}$ denote the benchmark level of government purchases. Let $P_{\overline{C}}$ represent a consumer price index in some arbitrary year that is an average of values for each dynasty in Eq. (4) of Section 2. Baseline government purchases are assumed to be neutral in the sense these are equal to the benchmark value in real terms, $\mathrm{GP} = P_{\overline{C}}\,\overline{\mathrm{GT}}$.

The technology for government output is represented by a Cobb–Douglas production function with KLEM inputs. Baseline GP divides into purchases of specific inputs according to fixed expenditure shares. Government use of capital is $K^G = \alpha_K^G \mathrm{GP}/P_K$, and the corresponding IO coefficient is $A_K^G = \alpha_K^G/P_K$. Government use of labor is $L^G = \alpha_L^G \mathrm{GP}/P_L$, and the corresponding IO coefficient is $A_L^G = \alpha_L^G/P_L$. Government use of energy inputs is $E_i^G = \alpha_{E_i}^G \mathrm{GP}/P_{E_i}$, and the corresponding IO coefficients are $A_{E_i}^G = \alpha_{E_i}^G/P_{E_i}$. Government use of materials is $M^G = \alpha_M^G \mathrm{GP}/P_M$, and the corresponding IO coefficient is $A_M^G = \alpha_M^G/P_M$.

Let $\overline{\mathrm{GT}}$ denote the benchmark value of government transfers. Like purchases, baseline government transfers are constant in real terms $\mathrm{GT} = P_{\overline{C}}\overline{\mathrm{GT}}$. In addition to baseline transfers, households receive a transfer, or lump-sum adjustment LSA, to balance the government's budget constraint. Government expenditures GEXP are the sum of purchases and transfers. Government revenues GREV include capital and labor income taxes on households from (2) in Section 2, and specific taxes on output plus ad-valorem taxes on energy use and materials for each industry,

$$\left(\tau_X + \sum_{i=1}^{4} \tau_{E_i} P_{E_i} A_{E_i} A_{\overline{E}} + \tau_M A_M\right) X.$$

A.4. Aggregate demand and supply of inputs

Aggregate supplies of labor L^{AS} and capital K^{AS} at each point in time are determined by summing over levels supplied by each dynasty. Let j be an index over all 23 industries in the model: $j=1,\ldots,4$ refers to the four types of energy, $j=5$ refers to materials, $j=6,\ldots,22$ refers to the 17 consumer goods, and $j=23$ refers to the investment good. Aggregate demand for capital is

$$K^{\mathrm{AD}} = \sum_{j=1}^{23} A_K^j X_j + A_K^G \mathrm{GP}. \tag{A10}$$

Aggregate demand for labor is

$$L^{\mathrm{AD}} = \sum_{j=1}^{23} A_L^j X_j + A_L^G \mathrm{GP}. \tag{A11}$$

Total demand for intermediate goods is the sum of demands to produce other intermediate goods, and those to produce final goods. Total demand for intermediate input $i=1,\ldots,5$ by final goods producers and government is equal to $Y_i = \sum_{j=6}^{23} A_i^j X_j + A_i^G \mathrm{GP}$. Aggregate demand for input i is

$$X_i^{AD} = \sum_{j=1}^{5} A_i^j X_j + Y_i. \tag{A12}$$

Aggregate demands for intermediate goods lead to market clearing conditions.

A.5. Conditional market equilibrium

Computing equilibrium in the PET model is a two-stage procedure. The first stage is essentially static, and computes market clearing prices conditional on a sequence of guesses for variables dated $t+1$ in the system of dynamic Eqs. (1), (2), (5) in Section 2. The second stage updates these guesses, and is described below.

A conditional equilibrium requires that supplies of intermediate goods $i=1,\ldots,5$ satisfy $X_i=X_i^{\mathrm{AD}}$. Since technologies are CRS, equilibrium implies supplies of intermediate goods may be solved directly from demand conditions. Let x be the column vector $(X_1,\ldots,X_5)'$, y is the column vector of final demands $(Y_1,\ldots,Y_5)'$, and A denotes a 5×5 matrix of IO coefficients A_i^j for use of intermediate goods $i=1,\ldots,5$ by intermediate goods industries $j=1,\ldots,5$.

Substitute X_i for X_i^{AD} in (A12) to obtain a system of equations that can be written compactly in matrix notation, $x=Ax+y$. Let I be the 5×5 identity matrix. A solution to the system is given by $x=(I-A)^{-1}y$, which determines outputs of the intermediate goods industries x in terms of final goods production y. Therefore, the entire production system in the PET model at a point in time may be expressed in terms of factor prices P_K and P_L, and the lump-sum adjustment LSA. A conditional competitive equilibrium in each year of a model run is defined by i) markets clearing for capital and labor, and ii) a balanced government budget:

$$\begin{aligned} &K^{\mathrm{AD}}=K^{\mathrm{AS}},\\ &L^{\mathrm{AD}}=L^{\mathrm{AS}},\\ &\mathrm{GREV}=\mathrm{GEXP}. \end{aligned} \tag{A13}$$

By Walras' Law, one of the conditions in (A13) is redundant, and without loss of generality, the wage rate of labor is normalized to unity, $P_L=1$. The numerical procedure used in the PET model solves for values of P_K and LSA to simultaneously solve the market clearing condition for capital and balance the government's budget constraint. The market clearing condition for labor is checked at each guess of P_K and LSA to ensure that Walras' Law is satisfied, at every guess, even when the model is out of equilibrium.

A.6. Perfect foresight competitive equilibrium

Dynamic equations in the PET model are solved using a perfect foresight competitive equilibrium. A perfect foresight competitive equilibrium has two overarching conditions: first, households and firms take prices as given and behave optimally conditional on these prices, and second, prices are such that all markets clear, or in other words, supply is equal to demand. Market clearing is a feature of the conditional market equilibrium defined above. Optimizing behavior in the PET model means that firms maximize profits, or equivalently minimize costs, as described above, and households maximize the intertemporal utility function in Section 2 based on perfect foresight expectations and subject to their budget and other constraints. Important components of the dynamic algorithm are described in Section 2, including the Euler Eq. in (5) from households' maximization problem, the transversality conditions in (6) that imply a stationary long run capital stock, and the steady-state Eq. (7) that describes long run conditions on the capital stock.

Computing a perfect foresight equilibrium is a two-point boundary problem that is solved using a variation of the Gauss–Seidel relaxation algorithm (Press et al., 1996). The two boundary conditions are initial capital stocks for each household type, and the steady-state capital stock, which is assumed to be the same for all households. The dynamic algorithm for computing a perfect foresight competitive equilibrium uses the dual concepts of prices and quantities, based on the fact that a set of market prices implies a sequence of capital stocks, and conversely, a sequence of capital stocks implies a set of market prices. A guess of capital stocks and derived prices form a conditional market equilibrium, which is described above. The sequence of derived prices is used to define households' expectations, and these expectations imply an updated guess of capital stocks. This procedure is iterated until the sequence of capital stocks and derived prices are consistent with the definition of a perfect foresight competitive equilibrium.

Recalling notation from Section 2, q_t is the price of investment goods for households, r_t is the rental rate of capital received by households, w_t is the wage rate received by households (normalized to unity above), ϕ_{it} is tax rate on capital income, and $\overline{p}_{it}$ is the composite price of consumption from (4) in Section 2 for households of type i at date t. Define composite consumption by

$$\overline{c}_{it} = \left(\sum_{j=1}^{17} \mu_{ijt} c_{ijt}^{\sigma}\right)^{\frac{1}{\sigma}}. \tag{A14}$$

An optimal transition to the stationary capital stock level is computed by defining a dynamic variable for each household type equal to the right hand side of (5) in Section 2 in terms of composite consumption,

$$z_{it+1} = \beta \overline{c}_{it+1}^{\rho-1} \frac{(1-\phi_{it})r_{t+1} + (1-\delta)q_{t+1}}{\overline{p}_{it+1}}. \tag{A15}$$

Guessing a sequence of capital stocks over a simulation horizon of T years, $\hat{k}_{it}^{1} t=1,\ldots, T$ implies a corresponding guess for the dynamic variables $\hat{z}_{it}^{1}$. A requirement for the guess of capital stocks is that the path starts at the initial level for each household type $\overline{k}\, i$ and finish at date T with the steady state level, common to all household types. Thereafter, k_{it} follows the balanced growth path for all household types associated with constant rates of population growth and labor-augmenting technical change.

Using $\hat{z}_{it}^{1}$ as a starting guess, the model is solved forward for $t=1,\ldots, T$ based on these dynamic variables. After solving for the conditional equilibrium prices at $t=1$ based on the current guess of capital at $t=2$, which in general differ from steady-state prices due to a relative scarcity or abundance of capital, a *derived* value of the capital stock is defined for $t=2,\ldots, T-1$ from the first round guess to be

$$\hat{k}_{t+1}^{d(1)} = \frac{((1-\varphi_{it})r_t + (1-\delta)q_t)k_t^1 + (1-\theta_{it})w_t l_t + g_t - \overline{p}_t^{\frac{\rho}{\rho-1}}\left(\frac{\hat{z}_t^1}{q_t}\right)^{\frac{1}{\rho-1}}}{q_t}. \tag{A16}$$

Next, the dynamic variables are *updated* using the definition of z_{it+1} in (A15). Let ξ_t denote the growth in labor productivity, and π_t the population growth rate, at year t relative to levels in $t-1$. Define a total growth factor $\Gamma_t=(1+\xi_t)(1+\pi t)$, and levels of composite consumption for $t=1,\ldots,$ T are calculated from the first-round guess of capital using each household's budget constraint,

$$\overline{c}_{it} = \frac{(1-\phi_{it})r_t\hat{k}_{it}^{1} + (1-\theta_{it})w_t l_t - q_t(\Gamma_t\hat{k}_{it+1}^{1} - (1-\delta)\hat{k}_{it}^{1}) + g_{it}}{\overline{p}_{it}}. \tag{A17}$$

Then, the *derived* value of the dynamic variable from the first round guess is

$$\hat{z}_{it}^{d(1)} = \beta\overline{c}_{it}^{\rho-1}\frac{(1-\phi_{it})r_t + (1-\delta)q_t}{\overline{p}_{it}}. \tag{A18}$$

The second round of guesses for the capital stocks and dynamic variables are defined as a weighted average of the first round guesses and the derived values. Let $0<\psi_k,\psi_z<1$ be the weights for the capital stocks and dynamic variables, respectively. Then, for $t=1,\ldots, T$, define

$$\hat{k}_{it}^{2}=\psi_k\hat{k}_{it}^{d(1)}+(1-\psi_k)\hat{k}_{it}^{1}, \tag{A19}$$

$$\hat{z}_{it}^{2}=\psi_k\hat{k}_{it}^{d(1)}+(1-\psi_z)\hat{z}_{it}^{1}, \tag{A20}$$

The dynamic algorithm proceeds by repeating the derivation and updating these steps until the maximum relative distance between two consecutive guesses of capital stocks and dynamic variables is less than some small positive value $\varepsilon>0$. Let $\hat{K}_i^j$denote the sequence of guesses $\hat{K}_{it}^{j}$, $j=1,\ldots T$ for each household type, and define $\hat{Z}_i^j$ as the sequence of guesses for the dynamic variables. The relative distance operator between successive guesses of the capital stock for each household type is defined by

$$||\hat{K}_i^j-\hat{K}_i^{j-1}||=\sum_{t=1}^{T}|\frac{\hat{k}_{it}^{j}-\hat{k}_{it}^{j-1}|}{\hat{k}_{it}^{1}} \tag{A21}$$

The distance operator for dynamic variables is defined in the same way. The dynamic algorithm iterates until, for all household types i,

$$\max\{||\hat{K}_i^j-\hat{K}_i^{j-1}||,||\hat{Z}_i^j-\hat{Z}_i^{j-1}||\}<\varepsilon. \tag{A22}$$

The test condition in (A22) ensures the Cauchy criterion for convergence is satisfied.

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