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Demographic Determinants of Household Energy Use in the United States

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Projections of energy demand over the coming decades are critically important to understanding and anticipating future resource requirements and environmental impacts such as acid rain, local air pollution, and climate change (e.g., Nakićenović et al. 2000). Household consumption of energy for space heating and cooling, lighting, appliances, transportation, and other energy services is a key driver of national energy demand. A number of demographic factors such as population size, age structure, and levels of urbanization have potentially important direct and indirect influences on household demand. For example, aging may have direct consequences since energy consumption tends to change over the lifespan (Yamasaki and Tominaga 1997); aging could also have indirect impacts through an associated decline in household size and consequently a loss of economies of scale in energy use at the household level. However, the treatment of population-related variables in energy projections has been essentially limited to considerations of changes in population size alone (O'Neill, MacKellar, and Lutz 2001; Gaffin 1998), even though significant changes in other factors, especially age structure, are anticipated in all regions of the world.

Improvements to the development of credible projections of energy demand through a better understanding of demographic determinants of energy use would be valuable for several reasons. First, they would clarify the outlook for the potential range of projected environmental consequences of energy-related emissions. Second, they would allow better estimates of the costs of reducing emissions, which are sensitive to baseline emissions projections. Cost estimates play a key role in the current debate over appropriate climate change policy. And third, understanding energy demand across different demographic groups can help assess the potential distributional effects of emissions-reduction efforts.

We first briefly review the principal approaches to the incorporation of demographic factors in current studies of energy use and associated greenhouse gas emissions, as well as recent work on determinants of household energy use. We then present a case study of demographic influences on household energy consumption in the United States.

Past and current approaches

Most studies to date on the influence of population-related variables on energy use and greenhouse gas emissions have fallen into one of two categories: decomposition analyses and sensitivity analyses. In nearly all of these studies, population size is the only demographic variable taken into consideration, and treatment of population size does not extend far beyond using it as a scale factor.

IPAT decompositions

A common method of evaluating the contributions of population growth or other demographic factors to energy use and CO_2 emissions has been the decomposition of emissions rates into components related to each of several "driving forces" of emissions. Decompositions have been performed on national and regional data on historical emissions, on scenarios of future emissions, and on cross-sectional data to decompose differences in emissions among countries or regions. All such decompositions begin with a multiplicative identity describing emissions as the product of two or more driving forces. These identities are all variations of the well-known "IPAT" equation as applied to CO_2 emissions. IPAT describes the environmental impact (I) of human activities as the product of three factors: population size (P), affluence (A), and technology (T). It was developed in the early 1970s during the course of a debate between Barry Commoner and Paul Ehrlich and John Holdren. Commoner argued that environmental impacts in the United States were due primarily to changes in production technology following World War II, while Ehrlich and Holdren argued that all three factors were important and emphasized in particular the role of population growth (O'Neill 2002).

Identity versus explanation

Since the early 1970s, IPAT has been employed by many researchers in the analysis of a wide range of environmental issues in all regions of the world, including automobile pollution (Commoner 1991), fertilizer use (Harrison 1993), energy (Pearce 1991), air quality (Cramer 1998), and land use (Waggoner and Ausubel 2001) to name just a few. Formulating analyses in terms of an IPAT-type identity has several benefits. Perhaps the most important is that it serves as a useful orienting perspective, simplifying the conceptualization of environmental impacts by dividing driving forces into a small number of broad categories. For example, CO_2 emissions are often expressed as resulting, broadly speaking, from four general categories in what is known in climate change literature as the Kaya identity (Kaya 1990):

$$C = P \times \frac{GDP}{P} \times \frac{E}{GDP} \times \frac{C}{E} \tag{1}$$

where C is carbon emissions per year, P is population size, GDP is gross domestic product, and E is total energy use. This identity expresses CO_2 emissions as the product of population, per capita economic production (taken to be equal to per capita income), the amount of energy produced per unit of economic production (energy intensity), and the amount of carbon emitted per unit of energy produced (carbon intensity). Each category encapsulates a subset of influences. For example, energy intensity reflects the structure of an economy (a service-oriented economy will generally be less energy intensive than an economy in the early stages of industrialization) and the efficiency of its energy system. Carbon intensity reflects the fuel mix of the energy system, in particular the share of renewables and the reliance on carbon-intensive coal or less carbon-intensive natural gas.

The IPAT formulation also illustrates an important consequence of the multiplicative relationship between driving forces: that each variable amplifies changes in any other. As a result, a given change in technology may have only a small absolute effect on emissions in a society with a small, low-income population, while the same change would have a much greater effect in a populous, affluent society. Likewise, a given increment in population would have a much greater impact in affluent societies than in low-income countries, assuming similar levels of technology.

Despite these benefits, IPAT has been strongly criticized for a number of perceived flaws. Although as an identity it is always true by definition, when it is used as an explanatory model it implicitly assumes that there are only three relevant variables (or four in the case of the Kaya identity), all related in a simple linear fashion. Critics assert that its lack of social science content, particularly the influence of policies and institutions on environmental outcomes, renders it misleading at best. Some researchers have suggested that the P, A, and T variables be thought of as proximate (direct) causes of environmental impact, which are themselves influenced by a wide range of indirect, but more fundamental, ultimate causes including income distribution, land management practices, urban–rural settlement patterns, prices, political empowerment, trade relations, and attitudes and preferences (Shaw 1989; Harrison 1994). These factors may be critical to environmental outcomes and differ widely across settings, making the equation ill suited to analysis at the micro level and casting doubt on the results of larger-scale studies. Nonetheless, the fact that data for the P, A, and T variables are generally available across a range of settings has invited widespread use of IPAT for cross-site studies and studies at large spatial and temporal scales.

Limitations of decompositions

The IPAT model was developed for the purpose of quantifying arguments seeking to apportion responsibility for environmental impacts among contributing factors, and it has been widely used for this purpose ever since. The goal in such exercises is to rank the importance of the P, A, and T variables, usually to prioritize policy recommendations for reducing impacts. However, such exercises suffer from a long list of mathematical ambiguities inherent to decomposing index numbers (such as the I in IPAT) that make results difficult, if not impossible, to compare (Wexler 1996; MacKellar et al. 1998; O'Neill, MacKellar, and Lutz 2001; Amalric 1995; Ang 1995). These ambiguities also have allowed attacks on methods of quantitative analysis to fuel larger debates without bringing them closer to resolution.

A fundamental problem is that there are a number of ways to perform the decomposition, and each method leads to a different result. In the initial Ehrlich–Holdren–Commoner exchanges, for example, the decomposition method used was a comparison of the ratios of final to initial values of each of the variables over a given time period. A problem with this approach is that the changes in the driving forces do not add up to the change in impact, confounding attempts to divide up blame for I among P, A, and T. To circumvent this problem, first Commoner (1972), and later Holdren (1991) and many subsequent researchers, converted the multiplicative IPAT relation into an additive one based on average annual growth rates over a given time period. The contribution of each factor was then expressed as the ratio of its own growth rate to the growth rate of I. This growth rate decomposition methodology has been applied to data on greenhouse gas (GHG) emissions by several researchers. Probably the most widely cited study is that of Bongaarts (1992), who concluded that 50 percent of the growth in global CO_2 emissions from fossil fuels between 1985 and 2025 was due to population growth. Over the entire simulation period (1985–2100), population growth accounted for 35 percent of growth in CO_2 emissions. Other authors (Holdren 1991; Harrison 1993; MacKellar et al. 1995) have used the same method on similar data sets, arriving at a range of conclusions on the contribution of population growth to growth in energy consumption or GHG emissions.

Yet another approach to IPAT decompositions is to judge the relative importance of variables according to their effect on impact growth over the entire period. One method, which has been applied to CO_2 emissions (Bartiaux and van Ypersele 1993) and methane (CH_4) emissions (Heilig 1994), is to freeze the variable of interest at its initial value and calculate how much the growth in total impact is reduced as a result. An alternative, which has been applied to energy demand (Howarth et al. 1991; Ang 1993) and CO_2 emissions (Moomaw and Tullis 1999), is to freeze all variables except the one of interest and calculate the resulting change in growth in impact.

Each of these methods produces different results. There is, in fact, no single correct method. Decomposing IPAT belongs to a larger class of problems related to index numbers whose results are influenced by several factors (Fisher 1922; MacKellar et al. 1998; O'Neill, MacKellar, and Lutz 2001). We review a few of the problems here; however, this list is not exhaustive.[1]

Heterogeneity. The level of aggregation at which an analysis is performed can strongly influence the results. If population growth and per capita environmental impact are negatively correlated, as is the general case with greenhouse gas emissions, then calculations at the global level will generally assign a larger proportion of the blame to population growth than will more disaggregated analyses (Lutz 1994). The global view misses the fact that population growth is generally fastest where per capita impact is lowest. On the other hand, if per capita impact is positively correlated with population growth, as for example in the case of land degradation due to fuelwood harvesting, then a large-scale analysis will underestimate the role of population.

The offset problem. Decomposition exercises become particularly difficult to interpret when not all variables move in the same direction. For example, if there are three variables on the right-hand side of the equation and one of them is shrinking over the time period in question, it will offset the contribution of one of the growing variables, and the third variable will be left apparently accounting for a very large proportion of total environmental impact. This problem often arises in decomposing CO_2 emission trends, since carbon intensity of GDP (the product of energy intensity and carbon intensity of energy supply) is projected to fall in most regions of the world while both population and income are expected to rise. Many authors (Holdren 1991; Bongaarts 1992; MacKellar et al. 1995; Raskin 1995) sidestep the problem by collapsing carbon intensity and income into a single, more slowly growing "per capita emissions" term, but this approach artificially inflates the importance of population and discards important information about the more rapid trends of consumption growth and declining resource use per unit output.

Interaction between variables. Even the earliest users of the IPAT equation explicitly recognized that it made the simplifying assumption that P, A, and T behaved independently. Arguments have since been made for the existence of bi-directional relationships among all of the variables. A few studies have tested the IPAT relationship as applied to CO_2 emissions against national-level data. Dietz and Rosa (1997), in a multiple regression analysis on 1989 data for 111 countries, found that the impact of population size on emissions was roughly linear, if anything becoming disproportionately large for the most populous nations. Affluence also had a roughly proportional effect on emissions up to a transition point around US$10,000 per capita, beyond which its influence stabilized or even declined. DeCanio (1992) also estimated an IPAT-type model based on cross-sectional data from the late 1980s to examine the sensitivity of emissions to alternative scenarios for per capita income. Regression analysis indicated an inverted-U relationship between per capita emissions and per capita income with a turning point at around US$17,000 per capita.

Implausible scenario comparison. All decomposition exercises aimed at producing policy-relevant results suffer from the shortcoming that they do not take into account how much change in a particular variable is plausible. Instead, they estimate the contribution of one variable to total impact by implicitly comparing a particular set of data to a hypothetical scenario in which that variable remains constant at its initial level. While they may shed light on the narrower (but still important) question of the source of absolute changes in environmental impact, decomposition results do not necessarily translate directly into priorities for intervention. From a policy point of view, it is much more relevant to ask how much a realistic scenario for one variable, relative to a baseline path, would change impact over a given period of time. Realistic alternative scenarios account for, among other things, momentum built into population age structures that make immediate population stabilization impossible, as well as momentum in technological systems and patterns of consumption.

Sensitivity analysis

An alternative approach to analyzing the role of population in energy use and CO_2 emissions has been sensitivity analysis—that is, comparing scenarios from an energy/emissions model in which various assumptions about driving forces are tested in a systematic way. Models used in such studies have ranged from simple IPAT-type formulations to more complex energy-economy models.

Although the problems associated with IPAT decompositions lead to results that are difficult to interpret and compare, the use of simple linear models in sensitivity analyses avoids many (though not all) of the problems associated with decomposition exercises and can be a useful initial approach to a complicated problem. O’Neill, MacKellar, and Lutz (2001) use a linear IPAT model to perform sensitivity analyses of the effect of population growth on GHG emission scenarios. They also modify the model to explore the potential significance of indirect, nonlinear effects, as well as the importance of alternative demographic variables such as numbers of households (detailed discussion of the role of households in energy use follows in the next section). They find that these alternative formulations substantially alter the absolute level of emissions projected for the next century. For example, a model based on numbers of households produces emissions scenarios that are 25 percent higher by 2100 than a model based on numbers of people. On the other hand, they conclude that in all cases emissions are sensitive to alternative population scenarios; that is, a more slowly growing population leads to a substantial reduction in emissions relative to a baseline scenario even when nonlinearities or household effects are incorporated.

Yang and Schneider (1998) employed the Kaya identity to analyze a prominent set of CO_2 emissions scenarios for the twenty-first century (Pepper et al. 1992). They identified energy intensity improvements and population growth in developing countries, and GDP growth and carbon intensity improvements in industrialized countries, as major contributors to emissions in these scenarios. Kolsrud and Torrey (1992) and Birdsall (1994) used similar approaches to conclude that GHG emissions are relatively insensitive to population growth. However, their conclusions resulted from the use of relatively short time frames (through 2050) and narrowly divergent population scenarios that do not reflect the full range of potential population paths. Moreover, Kolsrud and Torrey (1992) considered sensitivity to developing-country population growth only. DeCanio (1992) estimated a nonlinear IPAT-type model from historical data and used it mainly to test sensitivity to economic growth. He found that increasing affluence had a less-than-proportional impact on emissions in scenarios for the middle of the next century; for example, an increase in the global average growth rate of per capita income from 1 percent to 1.5 percent produced income levels that were 46 percent higher in 2050, while emissions increased only 29 percent.

A small but influential number of studies employing more complex energy/emissions models have also examined the sensitivity of projection results to population. In general, these models can be divided into two broad classes: projection, or scenario, models (e.g., Edmonds, Wise, and Barnes 1995; Lashof and Tirpak 1990; Alcamo 1994), which combine assumptions about population, economic growth, and various factors affecting the evolution of the energy system to produce energy/emissions scenarios; and optimization, or endogenous-policy, models (e.g., Manne and Richels 1992; Manne, Richels, and Mendelsohn 1995; OECD 1992; Fankhauser 1994; Nordhaus 1994), which solve for emissions and economic growth paths that optimize the present value of the utility of future income streams. Both classes treat population mainly as a scale factor.

Early analyses conducted by Nordhaus and Yohe (1983) and Edmonds et al. (1986) found population to be a relatively unimportant source of uncertainty in projections of CO_2 emissions. As an examination of alternative assumptions makes clear, however, the reason that population ranks low as an uncertainty factor is not because these models are insensitive to population, but because demographic momentum makes population a more certain variable relative to others that appear in the models. For example, in the Nordhaus and Yohe study, population varies by +76 percent and –44 percent around the central scenario in 2100, while the range of values for the price of non-fossil fuels varies by +293 percent and –78 percent around its central scenario in the same year. In the Edmonds et al. study, population uncertainty is only assumed to be +28 percent/–22 percent in 2100, while uncertainty in labor productivity is a staggering +2260 percent/–99 percent. Thus one should not conclude from these studies that the models are insensitive to population. As Edmonds et al. (1986) note, their model is actually relatively sensitive to marginal population perturbations; considering 1 percent perturbations of all parameters, population was found to be among the top five most sensitive variables in the model. Similarly, in a sensitivity analysis carried out by Nordhaus (1994) on the Dynamic Integrated model of Climate and the Economy, or DICE, the aggregated output of DICE was found to be more sensitive to population growth assumptions than any other variable, including exogenous productivity growth and the rate of time preference. Gaffin and O'Neill (1997) used the DICE model to investigate optimal CO_2 emission levels assuming population followed the UN high, medium, and low paths. They found that optimal emissions in 2150 differed by more than a factor of six across these three scenarios, essentially scaling up and down with population.

Household characteristics and energy use

Most work to date has focused on the influence of population size on energy use and CO_2 emissions. On balance, results indicate that population size is an important factor (although not necessarily the most important factor) in future energy demand and emissions. However, other demographic variables could be important as well, and constitute the most promising new directions for research in this area. Among them are the influence of aging, changes in lifestyles, and changes in household size and composition on energy use. Although we do not discuss it here, more explicit consideration of the influence of urbanization on energy use appears to be an underdeveloped but promising avenue of research as well.

Previous work focusing on direct energy use by households (energy consumed in the household for space heating and cooling, water heating, lighting, appliance use, transportation, and other energy services) and/or indirect use (energy used in the production and transport of other goods consumed by the household) has identified demographic factors as important to explaining cross-sectional variation in energy use. For example, energy studies literature has identified household characteristics as key determinants of direct residential energy demand (Schipper 1996; Poulsen and Forrest 1988; Schipper et al. 1989). Household size appears to have an important effect, not only on energy use per household but on a per capita basis as well, most likely because of the existence of substantial economies of scale in energy use at the household level (Ironmonger, Aitken, and Erbas 1995; Vringer and Blok 1995). The existence of household economies of scale means that as household size increases, the per capita cost of maintaining a given standard of living declines. The principal source is the sharing of public goods such as space, home furnishings, transportation, and energy. The sharing of energy services results in lower per capita energy use in larger households, all else equal. Thus as populations age and average household size declines, the loss of economies of scale can be expected to increase per capita energy use more than would otherwise be expected. Economies of scale have received considerable attention in the economic literature on household consumption, although the focus has not been on energy (e.g., Bosch–Domenech 1991; Deaton and Paxson 1998).

Research focusing specifically on transportation has found substantial differences in travel demand across households that differ in the age and gender of the householder, household size and composition, and family type (Prskawetz, Jiang, and O'Neill 2001; Pucher, Evans, and Wenger 1998; Carlsson-Kanyama and Linden 1999). The lifecycle concept has been used as a framework for capturing variation in travel demand across households that differ by some combination of family size, family type, age of the householder, and marital status (Greening and Jeng 1994; Greening et al. 1997). It has also been suggested that gender-specific cohort effects may be important, since younger generations, and women in particular, have different travel habits than previous generations (Büttner and Grübler 1995; Spain 1997).

A few studies have included demographic detail in analyzing links between total household consumption and both direct and indirect energy requirements. However, these studies have generally been limited to short time horizons and have used simple household projections. For example, Lareau and Darmstadter (1983) forecast US demand for energy through 2000 based on projected demand for 23 categories of goods and an input–output table for the economy. Household characteristics were included by disaggregating the population into five household types defined by number of children, age of householder, and geographic region. They concluded that demographic factors are not a major influence on results, but the time horizon for the demographic analysis was only 13 years (1977–1990), much too short to be affected by demographic trends. Weber and Perrels (2000) model direct and indirect energy consumption for France, Germany, and the Netherlands between 1990 and 2010, disaggregating the population into households in 11 lifecycle stages and consumption into several categories of goods. They also find demographic characteristics to have only a limited influence on results, but again the time horizon is short (20 years) and the reliability of the household projections is unclear. Several studies have embraced the total energy demand approach without applying it to forecasting. For example, Lenzen (1998) uses consumer expenditure survey data, input–output tables, and greenhouse gas intensity factors to demonstrate substantial differences in greenhouse gas emissions implicit in consumption across household types in Australia. Similarly, Biesiot and Noorman (1999) summarize a comprehensive Dutch project that calculated the energy and greenhouse gas emissions requirements of household consumption based on analysis of expenditure patterns, input–output matrices for production, and process analysis. While the project included some focus on variations in consumption across household types (Vringer and Blok 1995), its main goal was to determine the scope for reducing energy use through changes in consumption patterns.

Thus a considerable gap remains between energy studies literature, which has found demographic characteristics to be important determinants of total household energy requirements, and energy projection models, which have yet to take these factors into account. An important reason for this gap is the lack of a convincing demonstration that these factors matter not only in cross-sectional analysis, but in long-term projections as well. MacKellar et al. (1995) performed an illustrative study of the potential impact of changes in household size on energy-related greenhouse gas emissions, finding that aging-related declines in household size through the year 2100 could increase global emissions by 25 percent or more relative to what they otherwise would be. However, this study was limited by considering only household size, by reliance on simple household projections, and by not drawing on household-level data to define the relationship between household size and energy demand.

A case study of US household energy use

We further explore the role that changes in distributions of households by demographic characteristics might play in aggregate household energy use by examining the case of US residential and transportation energy demand. Direct household energy use—which we divide into residential (associated with services in and around the home) and transportation (associated with personal vehicles) components—accounts for a little more than one-third of total energy use in the United States (16 percent for transportation and 21 percent for residential energy use) (EIA 2000a) and produces 38 percent of total US emissions of CO_2 (19 percent each for transportation and residential uses) (EPA 2001). Indirect energy use accounts for as much as an additional third of total energy use (Lareau and Darmstadter 1983). Thus households potentially encompass more than two-thirds of all national energy use.[2] Here we focus exclusively on direct energy use, but it is important to keep in mind that demographic influences on direct energy use likely extend to indirect energy use as well.

We first use cross-sectional data on residential and transportation energy use for 1993–94 to investigate the relationship between per capita energy use and several demographic characteristics of households, exploring in particular the relationship between energy use and household size. We then estimate the relative importance to past and future energy use of changes in distributions of households by size, age of the householder, and the presence or absence of children by drawing on historical data and demographic projections for the United States.

Data description

Data used in the analysis are drawn from the Residential Energy Consumption Survey (RECS) administered by the US Energy Information Administration (EIA 2000b), and a companion survey, the Residential Transportation Energy Consumption Survey (RTECS) (EIA 2000c). These are national surveys that collect energy-related data for occupied primary housing units. A total of ten RECS have been conducted between 1978 and 1997, and an eleventh is in progress. RTECS were conducted in 1983 and every three years between 1985 and 1994, before being discontinued. In each case they drew on a subset of households in the most recent RECS; an earlier RTECS was conducted on a monthly basis from 1979 to 1981 drawing from two additional surveys. The EIA currently makes available RECS data beginning in 1987, and RTECS data beginning in 1988. Sample size varies between survey years but generally includes several thousand households. As an example, the 1993 RECS surveyed 7,041 households, and the 1994 RTECS surveyed a subsample of 3,002 households. RECS data include energy consumption and expenditures by fuel type (natural gas, electricity, fuel oil, liquefied petroleum gas [LPG], and kerosene); physical characteristics of housing units such as square footage and appliance types, including space heating and cooling equipment; demographic and economic characteristics of households; and other information such as geographic and climatic characteristics. RTECS data describe vehicle types, vehicle-miles traveled, fuel consumption and expenditures for personal vehicles, and data on household characteristics.

A household is defined in this dataset as a housing unit that is the primary residence of the occupants. Samples are statistically selected to represent the total number of units in the United States.[3] RECS and RTECS data are collected through household interviews, rental agent interviews (for housing units that have any of their energy use included in their rent), and energy supplier questionnaires to obtain actual energy consumption amounts and expenditures for housing units surveyed.

Energy consumption is recorded in the surveys and expressed here in terms of British thermal units (Btu). Residential energy use is reported in terms of site energy: that is, the energy consumed at the site of the home (energy content of natural gas burned, electrical energy consumed in the home, and the like). We convert site energy to primary energy, which is defined as the energy content of the primary fuel for each energy source. Since electricity is derived from primary fuels such as coal, oil, and natural gas, the difference between site and primary energy is the energy lost in the production and transmission of electricity from power plants to the household site.

Household energy use: Cross-sectional analysis

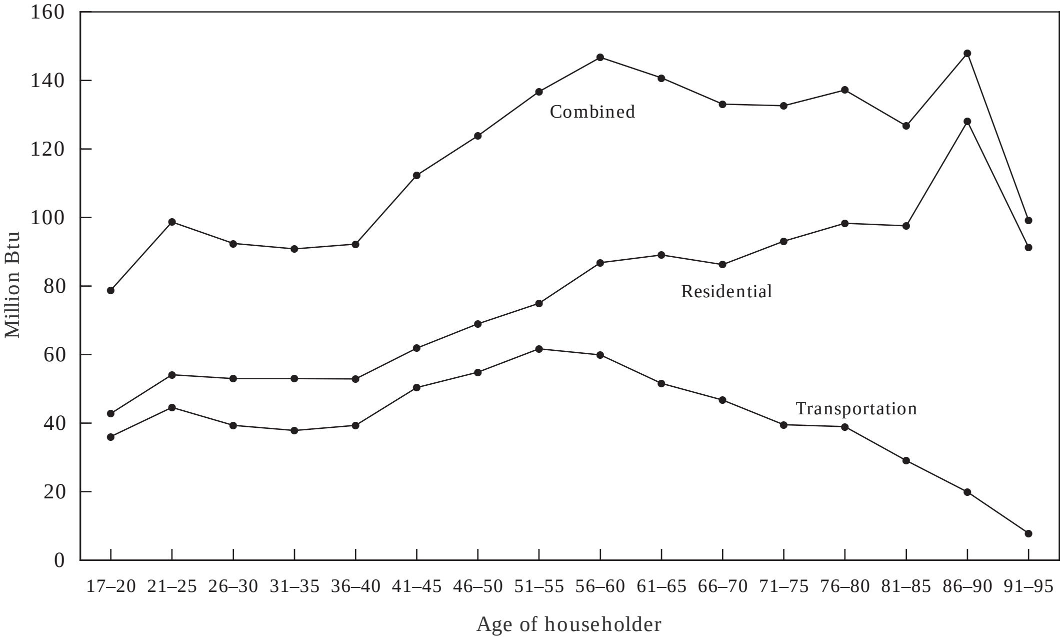
Cross-sectional data from 1993–94 (the most recent period with both RECS and RTECS data available) show that mean per capita energy consumption varies with several demographic characteristics of households. Our choice of per capita rather than per household energy consumption as the dependent variable requires explanation since, when taking the household as the unit of analysis, energy use per household would seem the more natural choice. However, our goal is more specific than explaining variation in household energy use in general. Ultimately we aim to estimate the effect on aggregate energy consumption of alternative distributions of households (in the past or the future) by various characteristics, *holding population size constant*. Changes in household distributions will affect aggregate energy consumption in this case only if they affect overall per capita energy use. If per capita consumption varies substantially across households categorized by a particular variable, then changes in the distribution of population across households within these categories will lead to a change in overall per capita consumption. The same conclusion could not be drawn if the variation across categories were in per household consumption, so we chose to express all consumption in per capita terms.

We present relationships between per capita consumption and householder age, several measures of household composition, and household size, before using a set of these characteristics in examining demographic influences on past and future energy use.

Householder age

Per capita energy use shows a clear pattern with householder age, as shown in Figure 1 for residential, transportation, and combined energy use. Residential energy use rises consistently with age, while transportation energy

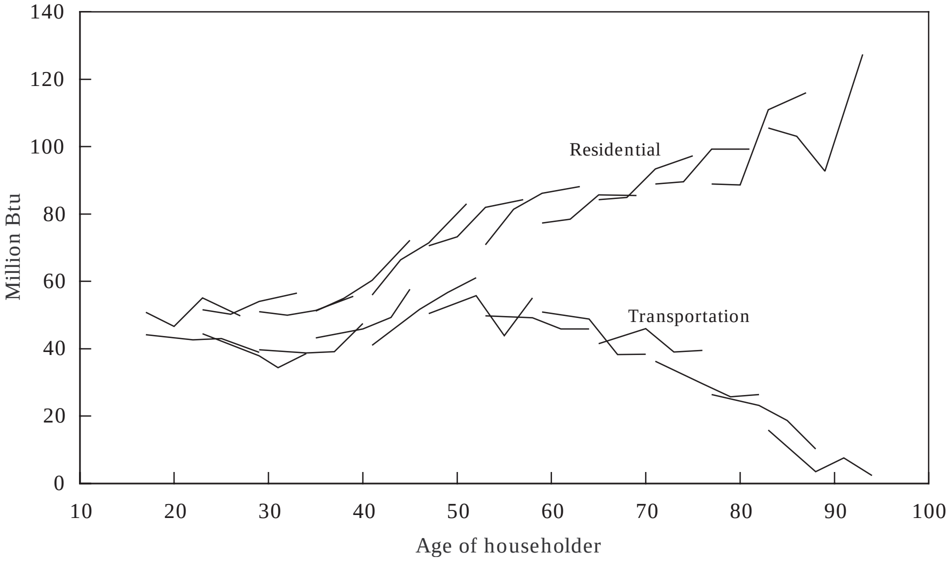
FIGURE 1 Mean per capita energy consumption by age of householder 1993–94



use rises to a peak at age 51–55 and then falls off to very low levels at the oldest ages. Several factors likely contribute to this relationship, including income, labor force status, and household size and composition.

A complicating factor in interpreting age profiles of consumption is the possible presence of cohort effects (Deaton 1997). Cohort effects in transportation behavior related to increases in licensing rates of women have been identified as an important driver of aggregate travel demand over the past several decades (Spain 1997). Although the lack of a complete set of survey results since 1978 precludes a meaningful quantitative cohort analysis, some insight can be gained by graphical analysis of available data. Figure 2 shows mean per capita residential and transportation energy consumption as a function of householder age over the period 1983–94 (transportation) and 1987–97 (residential). The lines connect consumption values along "cohorts" of households, defined as those with householders born in the same time period. Although conclusions based on just a few surveys must be preliminary, the figure suggests the existence of period and cohort effects. A period effect during the recession of the early 1990s is reflected by the relatively low consumption levels at this time across most cohorts. Cohort effects are difficult to ascertain in the residential energy use data; at older age groups where increases in energy use appear especially rapid, consumption means are less reliable because of small sample size. Also, while cohorts aged 40–50 in 1990 display somewhat more rapid consumption increases relative to cross-sectional relationships, the signifi-

FIGURE 2 US per capita energy use 1987–97 (residential) and 1983–94 (transportation), by cohort



cance of this effect is not clear. Effects are clearer in transportation energy use, where cohorts aged 35–45 in 1983 show relatively rapid increases in consumption. These cohorts were in their 20s during the 1960s and 1970s, an observation which supports the hypothesis that increases in women's licensing rates and labor force participation rates during this time contributed to an increase in travel demand.

Household composition

Several measures of household composition are possible, including number of children, number of adults, ratios of children to adults, sex of household members, and more detailed indicators of age composition such as the number of generations. The simplest measures distinguish between adults and children, and we focus on those here. For example, households with children use 35 percent less energy per capita for transportation than do adult-only households, and 44 percent less residential energy. One might take this as an indication that the number of adults is a more important determinant of per capita energy use than household size per se, but as shown in Figure 3b, per capita transportation energy use is relatively constant across households defined by numbers of adults (see curve labeled All HH). However, a more nuanced description of energy use patterns can be obtained by examining how energy use varies by number of adults within households of a particular size. Figure 3b also demonstrates that there are

FIGURE 3a Mean per capita residential energy use by number of adults and household size 1993

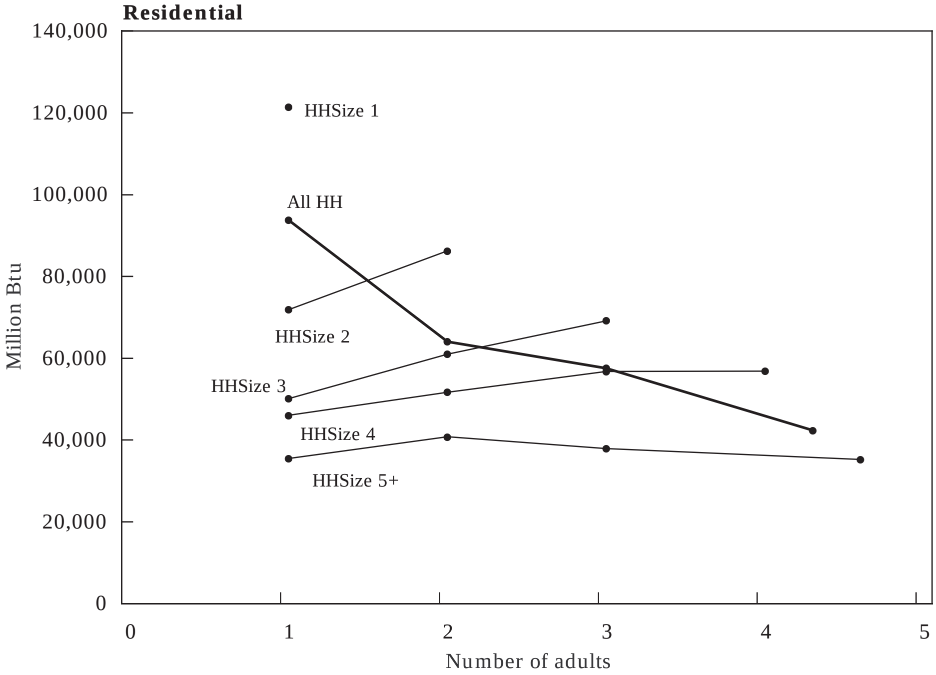
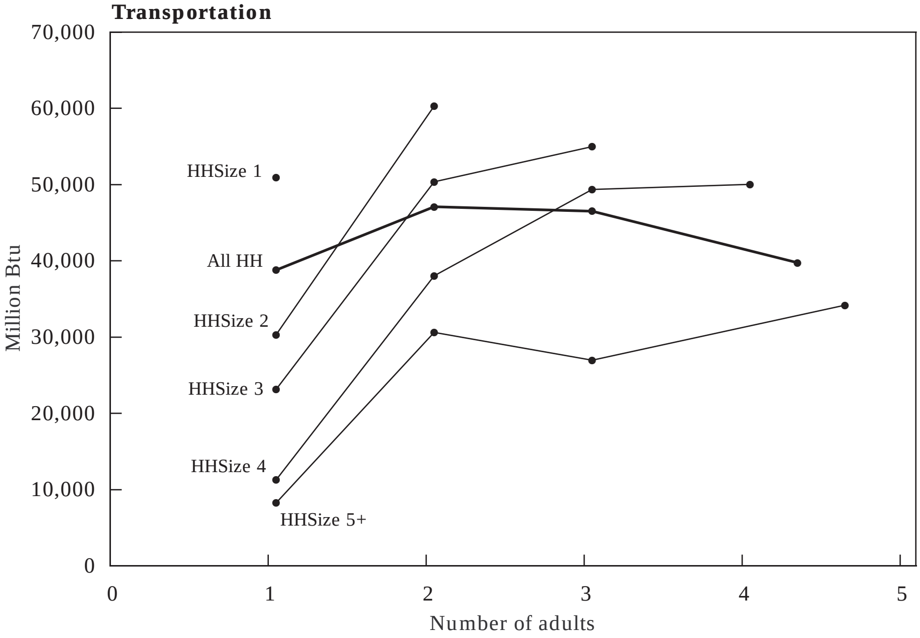


FIGURE 3b Mean per capita transportation energy use by number of adults and household size 1994

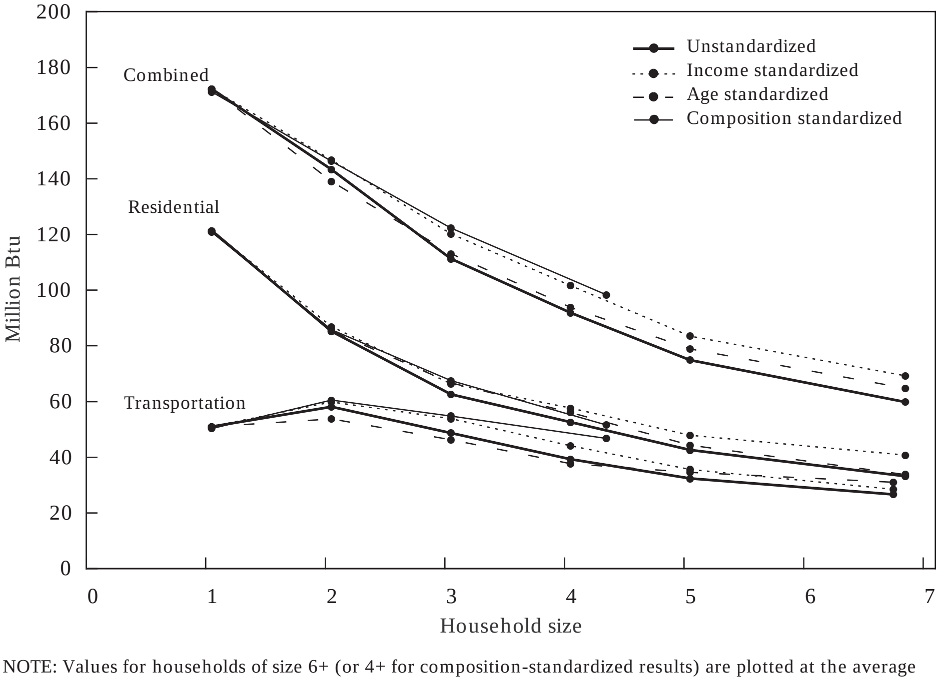


large differences in per capita energy consumption between single and multiple adult households within household size categories (although the effect is not pronounced for residential energy use; see Figure 3a). This indicates that for at least one measure (number of adults), composition *alone* does not appear to matter, but considered within a household of a particular size, the number of adults as opposed to number of children can have a substantial influence on energy use.

Household size

Figure 4 shows that per capita energy use generally declines with household size (heavy solid lines in Figure 4). Two-person households use about 17 percent less energy (residential + transportation) per person than do single-person households, and three-person households use more than a third less energy per person than do people living alone. Transportation energy use in single-person households appears to be an exception to the general decline in per capita use with household size. Separate analysis

FIGURE 4 Mean per capita energy use by household sizes 1–6+, actual and standardized for income, age, and composition 1993–94



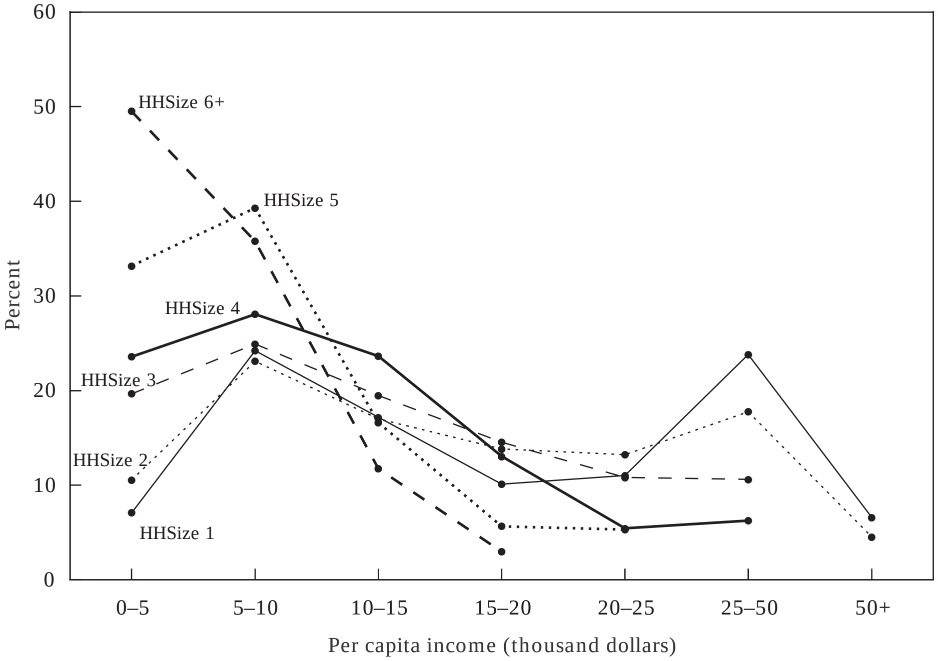
NOTE: Values for households of size 6+ (or 4+ for composition-standardized results) are plotted at the average household size for the category. Composition-standardized results use 4+ as the top size category because of small sample sizes for larger adult-only households.

shows that this occurs because a substantial fraction (28 percent) of single-person households do not own a car, and that this fraction consists primarily of older households (above age 60). If households without cars are excluded from the analysis, the more typical monotonic decline in energy consumption with household size reasserts itself.

These results confirm the basic findings of other studies on the influence of household size on energy use (Vringer and Blok 1995; Ironmonger, Aitken, and Erbas 1995). This pattern might be due to economies of scale, or it might be due to covariation of other household characteristics such as income, age, or composition. Understanding the source of the consumption–size relationship is important because, among other reasons, it would help inform judgments about its stability. Energy projections incorporating household size might be considered more robust if the relationship is generated more by the public goods aspect of energy consumption than by differences in the mixes of household types within size categories. Insight into the source of the relationship can be obtained by examining how much it changes while controlling for other factors. We examine three potential sources. First, per capita income falls with household size, and since income is correlated with energy use, it could be a contributing factor to the basic result. Second, larger households tend to consist of children to a greater extent. Since children can be expected to consume less energy than adults, this compositional effect is a potential source of the decline in per capita energy use with household size. And finally, energy consumption typically changes with the age of the householder, which could be thought of as a marker for family life cycle stage. Thus if the distribution of households by age (which hereafter we use to indicate age of householder) varies across household size, it could contribute to the observed pattern.

Income. Per capita transportation and residential energy use rises with per capita income for nearly all household sizes (the exceptions are households of size 4 or more, for which transportation energy use flattens out at higher income levels). Figure 5 shows that the distribution of households by per capita income levels varies significantly across household size. One-person households tend to have more people at the highest income levels, and larger households are concentrated at increasingly low levels of per capita income. This pattern, combined with the variation in energy use with income, implies that part of the reason that energy use falls with rising household size is an income effect: larger households tend to have lower per capita incomes and therefore lower rates of energy consumption per household member.[4] To quantify the effect of income on energy consumption across household size, the size distribution of mean per capita energy use was standardized for per capita income. Standardization is a means of separating the influence of compositional variables and specific rates on an overall rate (Kitagawa 1964) and has been used extensively in both de-

FIGURE 5 Distribution of population by per capita income as percent of population living in each household size 1 to 6+, 1993–94



NOTE: For each household size, the highest income category plotted here represents an open-ended category. For example, the point plotted in the $15,000–$20,000 category for households of size 6+ includes all households with incomes of $15,000+; likewise the $20,000–$25,000 category for five-person households includes incomes of $20,000+.

mography (e.g., Retherford and Ogawa 1978; Zeng et al. 1991) and energy studies (Ang and Choi 1997; Ang 1995). While there are many permutations of the basic methodology (DasGupta 1994), in essence it estimates what the overall rate would be if a population had the composition of a standard population, facilitating comparisons that “control for” differences in composition.

The standardization is performed by expressing per capita energy use for households of size *h* as

$$e_h = \sum_i \frac{N_{h,i}}{N_h} e_{h,i} \tag{2}$$

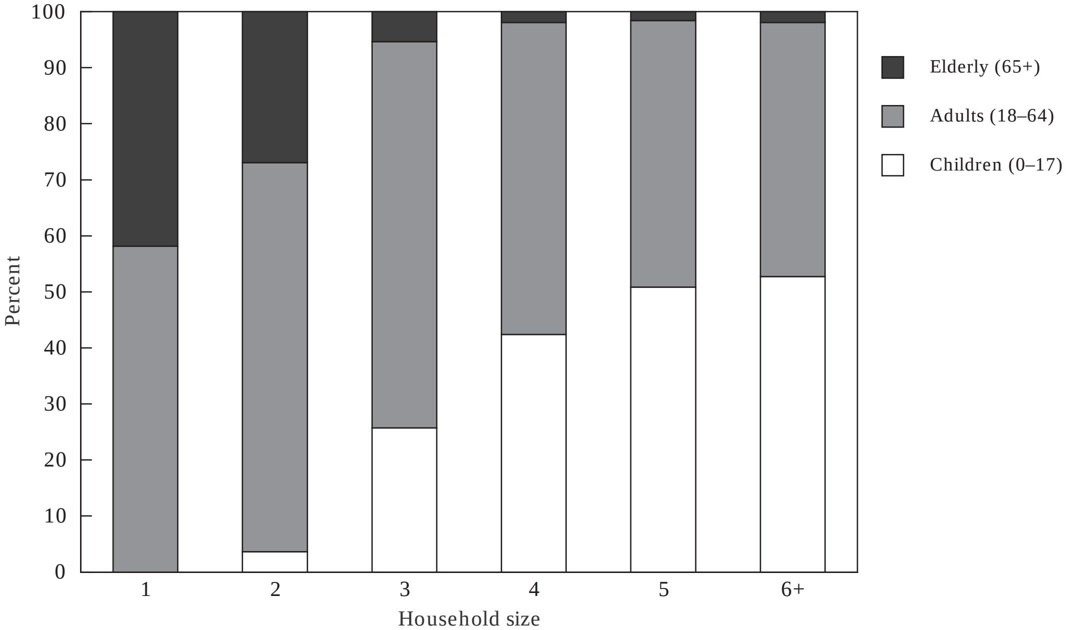
where *e* is per capita energy use, *N* is numbers of people, and *i* indexes the per capita income category. Equation 2 expresses the mean per capita energy use in households of size *h* as the population-weighted average of per capita energy use in each income category. Energy use is standardized by applying the weights for one-person households to all household size groups.

The dotted lines in Figure 4 show the results for income-standardized residential, transportation, and combined energy use. Income-standardized per capita energy use is slightly higher than the unstandardized rates, because the one-person households used for standardization fall more frequently into higher per capita income categories in which per capita consumption rates are higher. However, income-standardized per capita energy use still falls substantially with increasing household size. This suggests that the decline in per capita energy use with household size is unlikely to be mainly an income effect.

Household composition. We limit our analysis of the effect of covariation of composition and size to the most obvious aspect of age composition: the presence of children (defined as under age 18). Figure 6 shows the percent distribution of household members by broad age group for each household size category. As would be expected, larger households contain more children and fewer elderly (as a fraction of the population within each household size category) than do smaller households; the fraction of household members that are children rises from 0 to 0.47 as household size increases from 1 to 5.

To quantify this compositional effect, we standardize per capita energy use by household size for age composition by calculating means for adult-only households (i.e., the composition of one-person households).

FIGURE 6 Distribution of household members by broad age groups for various household sizes 1993



The thin solid lines in Figure 4 show the results: composition-standardized consumption is higher than unstandardized rates, especially in the case of transportation energy use. Composition-standardized transportation energy use falls off only slightly with household size as size increases beyond two. Thus much of the decline in unstandardized per capita transportation energy use with household size appears to be due to the presence of children, most of whom are not drivers and therefore contribute proportionately less to demand than do adults.[5] The composition effect on residential energy use is much weaker, suggesting that children's contribution to demand for space heating, water heating, and the like is more nearly equal to an adult's demand than is the case for demand for transportation.

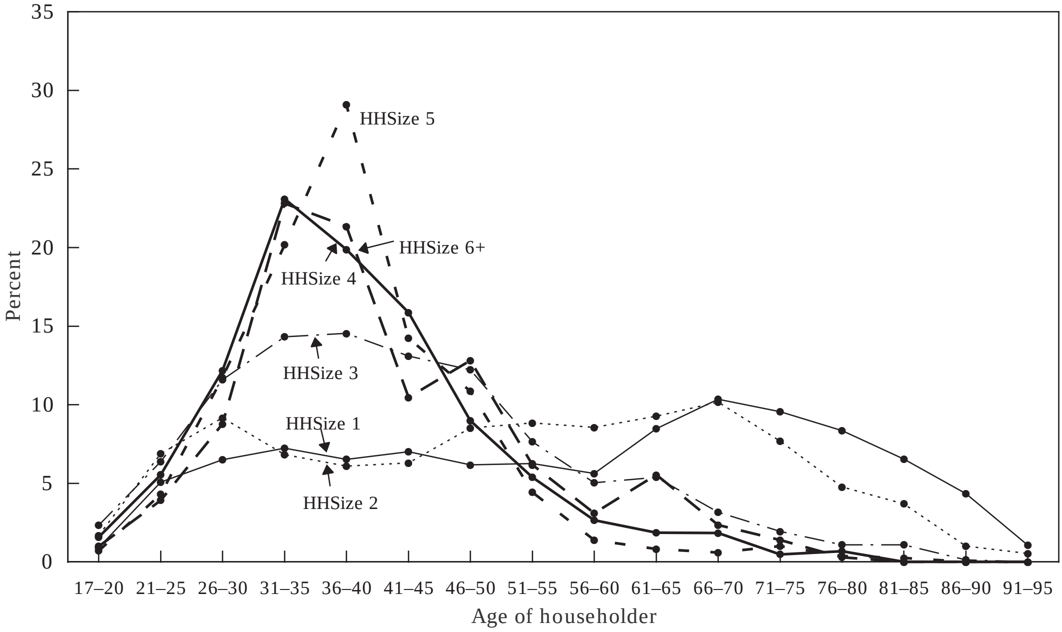
When residential and transportation energy results are combined, the effect of composition on total household energy demand is modest, although slightly stronger than the effect of income. (In fact, the income effect is itself probably strongly influenced by composition, since the decline in per capita income with household size is most likely substantially driven by the increase in the fraction of children.) Thus, while composition appears to play a role, especially in the case of transportation energy, adult-only results still indicate a substantial decline in energy use with household size, suggesting economies of scale may still be at work.

Householder age. The distribution of population by age of householder varies substantially across household size (Figure 7). One- and two-person households have a bimodal distribution of young and elderly householders, while larger households display peaks at increasingly narrow younger age groups: from 26–50 for three-person households to 31–40 for 5 and 6+ person households. Thus some of the difference in energy consumption across household size is likely due to variations in age.

The dashed lines in Figure 4 show mean per capita energy use by household size standardized for age. Age-standardized residential energy use is higher than unstandardized rates, since one-person households have an older age distribution with higher per capita consumption rates (Figures 1 and 6). The results for transportation energy use are more complicated. Since per capita transportation energy use is low at young ages, peaks, and then falls at older ages to levels lower than those for the youngest households, the result of substituting an older distribution of households for a younger one is not obvious. As shown in Figure 4, age-standardized transportation energy use turns out to be lower than unstandardized rates for households of size four or less, but slightly higher for households of size five or more. When results are combined, the net effect of age standardization is generally to increase consumption rates, since residential energy use is greater than transportation energy use; however, the magnitude of this effect is small.

Cross-sectional analysis therefore shows that energy consumption varies strongly with age, some aspects of composition (particularly the number of adults within specific size categories), and household size. While income, age,

FIGURE 7 Distribution of population by age of adult householder as percent of population living in each household size 1 to 6+, 1993–94



and composition all contribute to the consumption–size relationship, a substantial residual effect remains that could be attributed to economies of scale.

Demographic determinants of historical energy use

To gain insight into the quantitative significance of household characteristics to changes in aggregate energy consumption over time, we standardize the mean per capita rate of household energy consumption to the composition of the US population several decades ago. This approach is similar to analyses in the energy studies literature that have decomposed trends in residential energy use into components attributable to changes in energy intensity, fuel mixes, total population size, and other factors (Schipper, Haas, and Sheinbaum 1996). Here we add a new element by considering changes in the composition of the population by household characteristics.

In order to examine the most recent data available for both residential and transportation energy use, we again use the 1993 RECS and 1994 RTECS data. In this case, however, we standardize to the composition of the US population in 1960. The question under consideration can be usefully framed as: if a projection were made in 1960 of per capita household energy use in 1993, how great would the error be if changes in demographic composition variables were ignored while all other factors (income, prices, technology, and the like) were accurately projected?

Standardization is performed for household size, age, and composition separately, and then for size and age together and size and composition together, and for residential, transportation, and combined energy use. Results are shown in Table 1.

The standardization for household size alone uses the following expression for mean per capita energy use (e) in 1993:

$$e = \sum_h \frac{N_h}{N} e_h \qquad (3)$$

The household size-standardized rate simply replaces the 1993 distribution of population by household size (N_h/N) with the 1960 distribution, while retaining the 1993 size-specific consumption rates (e_h). The result is that standardized per capita household energy consumption in 1993 is about 96 million Btu (MBtu), 14 percent lower than the actual rate of 111 MBtu. The effect is stronger for residential energy (15 percent lower) than for transportation energy (11 percent lower). The reason for these reductions is that the distribution of the US population by household size has undergone a marked shift away from large households and toward smaller ones over the period 1960–93, driving a decline in average household size from about 3.3 to about 2.6 over this period. In 1960, only 4 percent of the US population lived in one-person households, while 25 percent lived in households of six or more people. By 1993, the proportion living in one-person households had climbed to 10 percent, while the proportion living in households of six or more had fallen to about 10 percent.

Another way to interpret the standardization result is that if a projection of future energy demand were made in 1960 that was accurate in all other respects but ignored the influence of changes in household size, en-

TABLE 1 Per capita energy consumption (million Btu) in 1993–94 in the United States, unstandardized and standardized to the composition of the 1960 population; also shown is the percent difference from unstandardized consumption rate

	Residential		Transportation		Combined	
	Per capita consumption	Percent difference	Per capita consumption	Percent difference	Per capita consumption	Percent difference
Unstandardized	66.0	0	45.1	0	111.2	0
Standardized for:						
Size	55.7	–15.3	40.0	–11.0	95.8	–13.6
Age	65.4	–0.9	46.4	2.8	111.8	0.6
Composition	57.7	–12.6	39.2	–13.0	97.0	–12.8
Size–Age	56.9	–13.6	41.0	–9.0	97.8	–11.7
Size–Composition	54.2	–17.5	38.8	–13.6	93.0	–16.0

ergy demand in 1993 would have been underestimated by 14 percent. This is a sizable effect over 33 years. For comparison, per capita residential energy use increased by 35 percent between 1960 and 1993 (EIA 2000a), so that more than two-fifths (15 percent/35 percent) could be attributed to changes in demographic composition. Transportation data are available only for the sector as a whole rather than for personal vehicles; the data indicate an increase in per capita terms of 51 percent. If energy use for personal vehicles increased by approximately the same amount, then compositional change might have accounted for about one fifth (11/51) of the increase. These effects are especially significant given that most of the change in household size occurred before 1980, and the household size distribution has been relatively stable since then.

To standardize for householder age, a similar calculation was performed (using Equation 3 but summing over age categories rather than size categories). The result is an age-standardized per capita household energy consumption of 112 MBtu, nearly identical with the unstandardized value. This net effect is the result of small offsetting impacts of age standardization on transportation energy use (a slight increase over the unstandardized rate) and residential energy use (a slight decrease). The reason for such a minimal effect is that distributions of population by householder age differ little between 1960 and 1993. In 1960, only a slightly smaller fraction of the population lived in households aged 65 or older, and a slightly greater fraction in households aged 25–35 and 45–65. Since per capita consumption of residential energy rises with householder age (Figure 1), the age-standardized rate is slightly lower than the current one. In contrast, the rate of transportation energy use falls at older ages, so the age-standardized rate for transportation is slightly higher. However, overall the effect is small.

To standardize for composition, we are constrained by data limitations. Because data are collected at the level of the household, and households contain both adults and children, we cannot calculate adult- and child-specific rates of energy consumption to use in a standardization equation analogous to Equation 3. As an alternative, we make bounding assumptions. If adults and children consumed at identical rates, standardization would have no effect. A maximum effect would be achieved if children were assumed not to consume energy at all, and all consumption were assigned to adults. In this case, we could express per capita energy use as

$$e = \sum_{A} \frac{N_A}{N} e_A \tag{4}$$

where the subscript A represents adults, e_A is the per adult consumption rate, and N_A/N is the fraction of the population consisting of adults. Standardization is performed by applying the 1960 adult fraction of the population to the 1993 per adult energy consumption rate. Results show that the composition-standardized household energy consumption rate is about 13 percent lower than the actual rate (results are nearly identical for residential and transportation energy considered separately). The reduction occurs because the (younger) 1960 population had a smaller fraction of adults than the 1993 population. While this effect is nearly as large as the effect of changes in household size, it must be kept in mind that it is a maximum estimate, based on the assumption that children do not contribute at all to energy consumption. If children's adult-equivalent consumption rate were 0.5, for example, the magnitude of the effect would be halved.

We next examine how these demographic factors act together. Standardizing for household size and age together (using Equation 3 but summing over age categories within size categories, and then over size categories) by applying the 1960 household size and age composition of the population to the 1993 category-specific consumption rates, we calculate a size- and age-standardized per capita household energy consumption of 98 MBtu, 12 percent less than the unstandardized rate, and slightly higher than the rate standardized for size alone. Examining the results of standardizations for residential and transportation energy use separately shows that the effect of householder age is complicated after controlling for size. For example, standardizing residential energy use for age alone slightly decreases per capita energy use. But standardizing for age after size *increases* energy use above the rate standardized for size alone. The source of this reversal of the influence of age is the difference between changes in the distribution of population by householder age alone, and changes in the distribution by householder age within each household size category. The distribution of the 1960 population within nearly all household size categories is actually older than the 1993 distribution; adults under 45 were less likely to head these smaller households then than they are now. The younger overall distribution by age alone occurs because of shifts in population between, rather than within, size categories (the 1960 population was more concentrated in larger, and younger, household sizes). Therefore age standardization increases per capita consumption within smaller household sizes, and the subsequent size standardization produces a correspondingly higher overall per capita consumption rate than would have been the case without standardizing for age first.

The effect of the standardization for age after size on transportation energy use acts in the opposite sense: it decreases energy use below the rate standardized for size alone. While the same demographic dynamics apply to both standardizations, the fact that transportation energy use falls off at older ages causes the age standardization within household size categories to decrease, rather than increase, size-specific consumption rates.

Standardizing for composition along with size yields consumption rates that are lower than standardizing for size alone. For example, while size standardization reduced household energy consumption by 14 percent, and composition standardization reduced it by 13 percent, standardizing for both factors reduced consumption by 16 percent. Thus the effects of size and composition reinforce each other, but not additively. In this case, standardizing for composition alone likely captures size effects. When standardizing for composition within household size, however, composition has little additional effect over size because the fraction of members of households of a particular size consisting of children has not changed much.

The analysis of demographic influences on historical energy consumption shows that changes in the distribution of population by household size have substantially influenced household energy use over the past several decades. Household size changes that occurred primarily over just two decades were responsible for about 14 percent of household energy use in 1993. The effect of changes in household age were found to be minimal. Changes in household composition have also likely played a modest role, although data constraints make possible only an estimate of their maximum effect.

Methodological considerations

A number of methodological considerations must be kept in mind when interpreting these results. First, as discussed in the previous section, variations in energy use by household size arise from a number of sources. Size per se, through an economy of scale effect, appears to play an important role, but income, age composition of the household, and age of the householder all were shown to have an effect as well. Thus the size-standardized rate calculated here includes all of these effects. That is, by applying the 1960 household size distribution to the current distribution of per capita energy use rates, the shift toward larger household size also implies a shift toward lower per capita income (since income falls with household size), a younger household composition (since larger households have proportionately more children), and younger heads of households.

Second, standardization essentially assumes that compositional variables are independent of specific rates. That is, in our case it is implicitly assumed that a change in the distribution of population by household size would not in itself lead to a change in the size-specific energy use rates (the analogous assumption for other standardizations holds as well). This is not of course true at the population level—the point of the exercise is precisely to see how much the overall mean energy consumption rate changes when composition is altered—but it is an implicit assumption at the level of specific categories that must be kept in mind.

Third, standardization techniques generally leave an unexplained residual, or interaction effect. In our case, this means that standardizing to the 1960 population composition and separately to the 1960 specific rates will not give results that add to the full change in energy consumption over the period analyzed. Some fraction of the change will be left unaccounted for. It results from the fact that both composition and specific rates are changing over the time period considered, and so standardizing to their values at the beginning of the period does not capture the effect of these changes. There are a number of ways to handle this (DasGupta 1994) if an important goal of the analysis is to account in some sense for the full change in the overall rate over the period considered. Here, however, we do not seek to decompose the full change in energy use over the last several decades, but rather to estimate the error that would have been incurred had changes in certain demographic factors been overlooked. This question lends itself more naturally to standardization than does a complete decomposition exercise.

Fourth, given our criticism of decomposition exercises applied to IPAT-type analyses, it is worth pointing out similarities and differences between those analyses and this one. After all, many IPAT decompositions are essentially standardizations.[6] Many of the same potential pitfalls apply here. For example, although we disaggregate by household size, age, and composition, further disaggregation by additional variables could yield different results. Some of the pitfalls do not apply given the purpose of our analysis—the aim here is not to proportion responsibility for the total change in energy consumption over a given period to various driving forces, but to quantify the effect of demographic factors over this period irrespective of the contribution of other variables. Thus the exercise is not as deeply affected by the "choice of variables" issue; for example, although disaggregating specific rates into additional variables can complicate the interpretation of IPAT decompositions, it does not affect the calculation of how much lower energy use would be with a different demographic composition. In addition, although we argue that comparing plausible alternative scenarios is more appropriate for policy analyses than measuring the importance of a variable by explicitly or implicitly holding it constant, in this case we are analyzing the potential error in disregarding particular factors in projection outcomes and *not* the potential for policy to change outcomes. In this case, holding variables constant is a natural choice.

Contribution of future changes in household size and age distributions

Energy forecasts are subject to large uncertainties due to uncertainty in future economic growth and technological progress. Before concluding that it is worthwhile to add demographic detail to such projections, it is important to investigate what the magnitude of the influence of changing demographic characteristics of households might be. To do this, we perform a set of simplified projections in which demographic effects are assumed to be functions of summary statistics such as average household size and fractions of the population living in households of different ages. These functions are calibrated to historical data. This approach, while approximate, allows future effects to be estimated based on simplified household projections. More sophisticated projections are not yet available. The U.S. Census Bureau performs projections only to the year 2010, and includes only households by age and race of householder and five family types. Zeng (1999) has produced detailed projections to 2050, but results were still preliminary at the time of this writing.

We first examine the effect of changes in household size on per capita energy consumption by assuming that it can be represented as a function of the proportional change in average household size and a constant elasticity,

$$e(\bar{h},t)=e_s(t)\left(\frac{\bar{h}}{\bar{h}_o}\right)^{\varepsilon} \tag{5}$$

where the subscript o indicates the time associated with the reference distribution by household size, $\bar{h}$ is average household size (total population divided by total number of households), and ε is a constant elasticity of mean per capita energy use with respect to changes in average household size. Here $e_s(t)$ is mean per capita energy use standardized for household size; that is, the energy use that would be realized if changes in household size relative to its value at time t_o were not taken into account. The variable $e(\bar{h},t)$ is unstandardized mean energy use; that is, the per capita consumption realized when accounting for household change.

We estimate ε separately for residential and transportation energy use, using all RECS and RTECS surveys, and standardizing consumption in each survey year to reference population distributions in each year between 1960 and the year of the survey. This takes maximum advantage of the available range of energy use patterns and population distributions. We find ε = –0.70 for residential energy use (adj. R^2 = 0.99, t = –294.2), and ε = –0.51 for transportation energy use (adj. R^2 = 0.99, t = –108.4).[7] That is, for every 1 percent decrease in average household size, average per capita residential energy use by the population increases by 0.70 percent, and per capita transportation energy use increases by 0.51 percent.

Under the assumption that this relationship will continue to hold in the future, the influence of future changes in household size can be calculated from projections of future changes in average household size. To develop a plausible range of such changes, we project the number of US households by applying current age-specific household headship rates to the projected future age distribution of the population in 2050 and 2100 for three scenarios (USCB 2000). Table 2 shows that average household size actually changes very little: it drops from a 2000 value of 2.63 persons per household to 2.46 in the middle scenario and 2.21 in the low scenario by

TABLE 2 Projected long-term changes in average household size and associated effects on per capita residential and transportation energy use

Scenario[a]	Average household size			Size-driven percent changes in residential energy consumption		Size-driven percent changes in transportation energy consumption	
	2000	2050	2100	2000–2050	2000–2100	2000–2050	2000–2100
USCB low	2.63	2.36	2.21	+8	+13	+6	+9
USCB middle	2.63	2.51	2.46	+3	+5	+2	+4
USCB high	2.63	2.66	2.69	–1	–2	–1	–1
Zeng (1999), Scenario D	2.63	2.00		+21		+15	

[a]"USCB" scenarios are USCB population projections combined with constant age-specific household headship rates.

2100. In the high scenario, it actually increases to 2.69 over this period. As a result, the impact of these changes on per capita energy use is very small in the middle and high scenarios—a few percent increase or decrease—and climbs to more than 10 percent only in the low scenario. The reason for this moderate change is the nature of the age profile of headship rates. Although these rates are higher at older than at younger ages, they are relatively flat over most age groups. Thus even the sizable changes in age structure projected by the USCB (especially in the low scenario) do not have a large impact on household size, and therefore on energy consumption. However, it is possible that age-specific headship rates could change over the projection period, rather than remaining constant as assumed here, and if so then average household size could change more than calculated. Preliminary results from detailed projections using the ProFamy model (Zeng 1999) suggest that household size could fall as low as 2.0 by 2050 assuming high marriage/union dissolution rates combined with low fertility (TFR = 1.90 by 2020) and low mortality (life expectancy = 86 for males and 92 for females by 2050). In this case, the effect on residential energy consumption could be more than 20 percent over the next 50 years. Thus household size changes appear to have the potential to substantially influence energy use, but the changes in living arrangements that would bring this about can only be anticipated with the use of detailed demographic projections.

Next we examine the effect of changes in the distribution of the population by householder age on per capita energy consumption by assuming that it can be represented as a function of the proportional change in the fraction of the population living in households within particular age groups:

$$e(a_{<45}, a_{65+}, t) = e_s(t)\left(\frac{a_{<45}}{a_{<45,o}}\right)^{\beta_1}\left(\frac{a_{65+}}{a_{65+,o}}\right)^{\beta_2} \tag{6}$$

where $a_{<45}$ is the fraction of the population living in households with heads less than age 45, a_{65+} is the fraction living in households with heads age 65 and older, β_1 and β_2 are elasticities, and $e_s(t)$ is per capita energy use standardized for age. This particular functional form was chosen by considering the age profile of energy consumption (Figure 1), changes in the distribution of population by household age over time, and trial and error. It divides the population into those living in younger households with relatively low per capita consumption levels, older households with either high (for residential) or low (for transportation) per capita consumption, and, implicitly, middle-aged households with intermediate (for residential) or high (for transportation) per capita consumption.

Estimating β_1 and β_2 separately for residential and transportation energy use, using all RECS and RTECS surveys, and standardizing consumption in each survey year to reference population distributions in 1960, 1970, 1980, and 1990, we find $\beta_1 = -0.17$ ($t = -11.4$) and $\beta_2 = 0.03$ ($t = 10.3$) for residential energy use (adj. $R^2 = 0.94$), and $\beta_1 = -0.17$ ($t = -8.8$) and $\beta_2 = -0.06$ ($t = -10.4$) for transportation energy use (adj. $R^2 = 0.98$). That is, a one percent increase in the fraction of the population living with householders age <45 causes a 0.17 percent decrease in both residential and transportation energy use. A one percent increase in the fraction of the population living with householders age 65 or older causes a 0.03 percent increase in residential energy use, and a 0.06 percent decrease in transportation energy use.

To estimate the impact these relationships would have on future consumption requires projecting future distributions of population by householder age for three householder age groups (0–44, 45–64, and 65+). The simplest such projection can be performed by assuming that the proportion of the population within each population age group that is a member of each householder age group remains constant over time. To take an example, currently about 3 percent of the population age 25–34 are members of households age <25, about 73 percent are members of households age 25–34, and about 10 percent are members of households age 35–44 (and so on for older households). If these proportions remain constant over time, then the change in the fractions of the population in each age category are simply related to the changes in the population living in households in each age category.[8] These assumptions of constant age-specific household membership rates (where the membership rates are themselves specific to householder age groups) are analogous to the constant age-specific headship rate assumption used in the projection of average household size. Constant membership rate projections can reflect changes in the population distribution by householder age driven by changes in the population age structure. However, they cannot reflect behavioral changes such as changes in age at leaving home, the mean age of childbearing, or the propensity of the elderly to live with their children; these changes affect the likelihood that a person in a particular age group will be a member of a household of a particular age. Separate analysis shows that membership rates within broad age groups have remained relatively stable, but this does not rule out substantial changes in the future.

Table 3 shows the results using the same three population projections and 1998 age-specific household membership rates. As the population ages, the fraction living in households age <45 drops from a current value of 0.53 to between 0.44 and 0.51 by 2050, depending on the scenario, and falls as low as 0.39 in the low scenario by 2100. The fraction living in households age 65+ rises from a current value of 0.15 to between 0.19 and 0.24 by 2050, and doubles to 0.30 by 2100 in the low scenario. However, the estimated impact of these changes in energy consumption is small, generally a few percent, and rises at most to an 8 percent increase in residential energy use in 2100 in the low scenario. The effect on transportation energy use is especially small since the shift in population away from younger households and toward older households has offsetting effects, since both are relatively low-consuming groups in per capita terms.

In summary, it does not appear that changes in household distribution by either size or age, as projected with simple constant headship and membership rate methods, would have a substantial influence on future energy consumption in the United States. One important qualification to this conclusion is that the demographic projections may not fully capture the true range of plausible future household size and age distributions. Indeed preliminary results from a detailed projection suggest that at least for household size, substantially larger changes (and larger effects on energy use) are possible. A second qualification is that our method of capturing demographic influences on energy use is simple and may miss important

TABLE 3 Projected changes in proportions of population living in households with householders age <45 and 65+, and associated effects on per capita residential and transportation energy use

	Proportion living with householder age <45			**Proportion living with householder age 65+**			**Age-driven percent changes in residential energy consumption**		**Age-driven percent changes in transportation energy consumption**	
Scenario[a]	**2000**	**2050**	**2100**	**2000**	**2050**	**2100**	**2000–2050**	**2000–2100**	**2000–2050**	**2000–2100**
USCB low	0.53	0.44	0.39	0.15	0.24	0.30	+5	+8	0	+1
USCB middle	0.53	0.47	0.46	0.15	0.22	0.24	+3	+4	0	0
USCB high	0.53	0.51	0.51	0.15	0.19	0.20	+2	+2	–1	–1

[a] "USCB" scenarios are USCB population projections combined with constant age-specific household membership rates.

effects. We have limited our analysis to size and age, using aggregate measures to represent more complex distributions, and also have investigated potential effects separately. In reality, the size and age effects are linked, and preliminary work in other industrialized-country contexts shows that in the future the two may sometimes reinforce and sometimes oppose each other (Prskawetz, Jiang, and O'Neill 2001). In addition, demographic variables may interact with economic influences. For example, income or price elasticities of energy demand that depend on demographic characteristics of households would provide a different means by which demographic change could affect future energy use. Effects will depend importantly on the extent and pattern of future changes in the composition of the population by household characteristics. A better understanding of the potential for such changes can only be obtained by undertaking more detailed household projections.

Conclusions

In most studies of past and future energy demand and associated greenhouse gas emissions, the treatment of demographic influences has essentially been limited to considerations of the role of changes in population size. There appears to be room for improvement that could contribute to more flexible, credible, and self-consistent scenarios of future energy use, and a more complete understanding of historical patterns of energy consumption. Considerations of the influence of changes in age structure, lifestyles, household size, and (although not discussed in this chapter) urbanization appear to be promising avenues of research, and several studies have made strides in these areas. Our illustrative case study of residential and transportation energy use in the United States reveals a substantial influence of some demographic factors, particularly household size, on historical energy use. Projections of future effects driven by simple household projections do not anticipate strong effects, but if demographic changes are larger than in the benchmark scenarios we develop here, influences on energy use could be much greater. Further work that explores the potential for changes in household size, age, and composition in more detail is required to draw more definitive conclusions.

In addition, household characteristics are likely to change substantially in many other countries. In developing countries household size averages around five and signs of decline, driven in particular by lower fertility, are becoming apparent (Bongaarts 2001). Aging, behavioral changes favoring nuclear over extended families, later ages at marriage, higher divorce rates, and increased propensities to live alone are expected to contribute to further shifts in size and structure. These larger demographic changes could have more substantial effects on energy use than would be expected in industrialized countries.

Notes

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1 Additional issues are the choice of variables, approximation methods, and alternative normalizations. For a full discussion see MacKellar et al. (1998) and O'Neill, MacKellar, and Lutz (2001).

2 This fraction is substantially higher if the fact that much of production for export is aimed at foreign households is taken into account.

3 The RECS used a multistage area sample design. Sample weights include adjustments for nonresponse bias and ratio adjustments to ensure that the weights add up to an independent U.S. Census Bureau estimate of the number of households (EIA 2000b).

4 The figures also reveal a limitation of the data: the RECS and RTECS report annual income as a categorical variable in per household terms. The top income category was $100,000+ per household. Since it is per capita income that is of interest here, categories were converted to per capita terms by dividing by household size. Since for each household size the categories are divided by a different number of household members, this created six different sets of per capita income categories, with an increasingly restrictive maximum category as shown in the figure. For example, the highest income category for people in households with six or more people is $16,667+, while for one-person households it is $100,000+. To account for the differences in category boundaries between household sizes, households were reclassified according to a revised set of income categories for the purposes of comparison in Figures 5 and 6. Despite these limitations, the general sense of rising consumption with rising per capita income across household size remains.

5 In some ways it makes more sense to analyze the composition effect on transportation energy demand in terms of drivers and non-drivers, rather than adults and children. Separate results not reported here show that conclusions are qualitatively similar: driver-only households exhibit a flatter but still declining trend in per capita consumption with household size.

6 For example, we could just as well substitute the 1960 US population for the 1997 population in an expression for total energy consumption written in IPAT style as E = P e, where E is total energy consumption, P is total population, and e is per capita energy consumption. This would constitute a standardization for population size.

7 Separate analysis shows that these elasticity estimates are not very sensitive to the base year used for the standardization. The elasticity for residential energy use is also not sensitive to the particular RECS survey used. The elasticity for transportation energy use shows more sensitivity to the survey year, with values ranging from –0.47 to –0.57 across the four surveys used here.

8 Let a denote the age of household members and "α" denote the age of the householder (or equivalently, as in the text, the age of the household). Then P_a, P_α, and $P_{a,\alpha}$ are the population of age a, the population living in households of age α, and the population of age a living in households of age α, respectively. Let the age-specific household membership rate (ASHMR) be the likelihood that a person of age a is living in a household of age α, or

$$ASHMR(a,\alpha) = \frac{P_{a,\alpha}}{P_a}$$

Given a set of assumed age-specific household membership rates, the distribution of population by household age (P_α) can be derived from an age-specific population projection by

$$P_\alpha = \sum_a ASHMR(a,\alpha) P_a$$

We calculate membership rates for population age groups <12, 12–17, 18–24, 25–34, 35–44, 45–64, and 65+, and household age groups <20, 20–24, 25–29, 30–34, 35–39, 40–44, 45–54, 55–64, 65–74, and 75+. Data are from USCB (1998), Table 18. Note that this method of household projections can be combined with constant age-specific headship rate assumptions to create projections of average household size by age of householder as well.

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