DISSERTATION

HOUSEHOLD CARBON DIOXIDE EMISSIONS IN THE UNITED STATES:

THE ROLE OF DEMOGRAPHIC CHANGE

Submitted by

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ABSTRACT

HOUSEHOLD CARBON DIOXIDE EMISSIONS IN THE UNITED STATES:

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This dissertation is comprised of five chapters discussing the importance of the measurement of household carbon dioxide emissions and the demographic determinants of those emissions in developing an understanding of anthropogenic climate change and the potential for future carbon dioxide emissions mitigation strategies. Chapter 1 discusses the scientific consensus regarding the impact of human activities in generating global warming and the effects of this warming on the earth's climate.

In Chapter 2, I first discuss the Consumer Expenditure Survey data compiled and the methodology used to measure household carbon intensity of expenditures and carbon dioxide emissions, combining economic input-output modeling with a life cycle assessment modeling to track industry to industry transactions and the corresponding resource use from extraction to end use disposal. Second, I show that carbon pricing policies are indeed regressive with lower income households having significantly higher carbon intensities of consumption. As suggested in the previous literature, this result stems from the allocation of household expenditures among direct and indirect uses of energy. This expenditure allocation decision is driven, not only by household income, but also by characteristics that vary over the life course, most notably household size and composition. Therefore, lastly I show that household carbon dioxide emissions and intensities follow distinct trajectories over the life cycle, independent of household income, resulting from a reallocation of expenditures necessitated by the evolving needs of households at different stages in the life cycle.

In Chapter 3, I discuss the demographic characteristics that are the drivers of the variation in emissions and intensities among heterogeneous households and how these demographic characteristics have changed, on average, over the past few decades in the United States. Of these changes, most notable are changes in mean household size, the age of household head, and the proportion of one- and two-person households. As baby boomers begin to retire and young individuals choose delay or forego household formation, expenditure allocation decisions of the average household are evolving, thereby changing the relationship between population growth and carbon dioxide emissions in the United States.

In Chapter 4, to formalize the channel through which these changing dynamics of population growth and CO_2 emissions occur, I first generate age-emissions profiles to show the importance of the age of a household member in contributing to total household emissions. I find that children contribute dramatically less than an adult and elderly contribute relatively less than an adult, but more than a child; results which are consistent with findings in the previous literature. In other words, an individual follows a distinct trajectory of emissions over their lifetime. The magnitude of this emissions curve is being attenuated over time as a result of improvements in energy efficiency, but these reductions are becoming smaller in time, consistent with the concept of diminishing returns to technology. Second, to incorporate the ability of households to experience economies of scale in their emissions through cohabitation, I construct an equivalence scale model in which I adjust for both the size and composition of households in the estimation of household CO_2 emissions. I find that the ability of the average household in the United States to experience economies of scale in emissions has decreased since 2003 resulting in a substantial increase in mean household emissions. Lastly, to quantify this effect I use counter-factual prediction to determine that mean household carbon dioxide emissions would be

over ten percent lower in 2009 if the ability of households to experience economies of scale had remained constant at 2003 levels.

Finally, in Chapter 5 I highlight the importance and policy implications of this research, most importantly regarding the consideration of the composition of the population when estimating and projecting greenhouse gas emissions. Given the differences in energy use and emissions among households of different sizes and compositions, if the proportions of these population groups change over the next century in the developing world, as they have in developed nations over the past century, then emissions projections using population growth and estimates of per capita emissions may result in misleading conclusions regarding mitigation strategies and adaptation policies in a changing global climate.

JEL Classification Codes: D12, J10, Q54.

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CHAPTER I

Anthropogenic Climate Change and Household Carbon Dioxide Emissions

Introduction

Anthropogenic climate change is caused primarily by the emissions of greenhouse gases (GHGs) such as carbon dioxide (CO_2), methane, and nitrous oxide. Recent scientific evidence indicates that the present level of ambient GHG concentration is well above the level of natural variability and is primarily driven by human behavior (IPCC, 2007a; Suh et al., 2006; Pacala et al., 2003; Karl & Trenberth, 2003). According to the 2007 Intergovernmental Panel on Climate Change Fourth Assessment Report, "global atmospheric concentrations of GHGs have increased markedly as a result of human activities since 1750 and now far exceed pre-industrial values determined from ice cores spanning many thousands of years" (IPCC, 2007a) (See Figure 1.1). Carbon dioxide is the most important of these anthropogenic greenhouse gases. The global atmospheric concentration of CO_2 has increased from a pre-industrial value of about 280 ppm to 379 ppm[1] in 2005 which greatly exceeds the natural range over the last 650,000 years of history, according to ice core samples taken from Greenland and Antarctica (IPCC, 2007a).

The IPCC concludes with very high confidence[2] that the global average net effect of human activities on the climate since 1750 has been one of warming (IPCC, 2007a). This warming of the climate system is unequivocal based on the observed increases in global air and water temperatures, widespread melting of snow and ice, and rising average global sea level

[1] ppm (parts per million) is the ratio of the number of greenhouse gas molecules to the total number of molecules of dry air. For example, 300 ppm means 300 molecules of a greenhouse gas per million molecules of dry air. (IPCC, 2007a)
[2] According to the IPCC, "very high confidence", is used to express expert judgments on the correctness of the underlying science, in this case that it has a 90% chance or better of being correct (IPCC, 2007a).

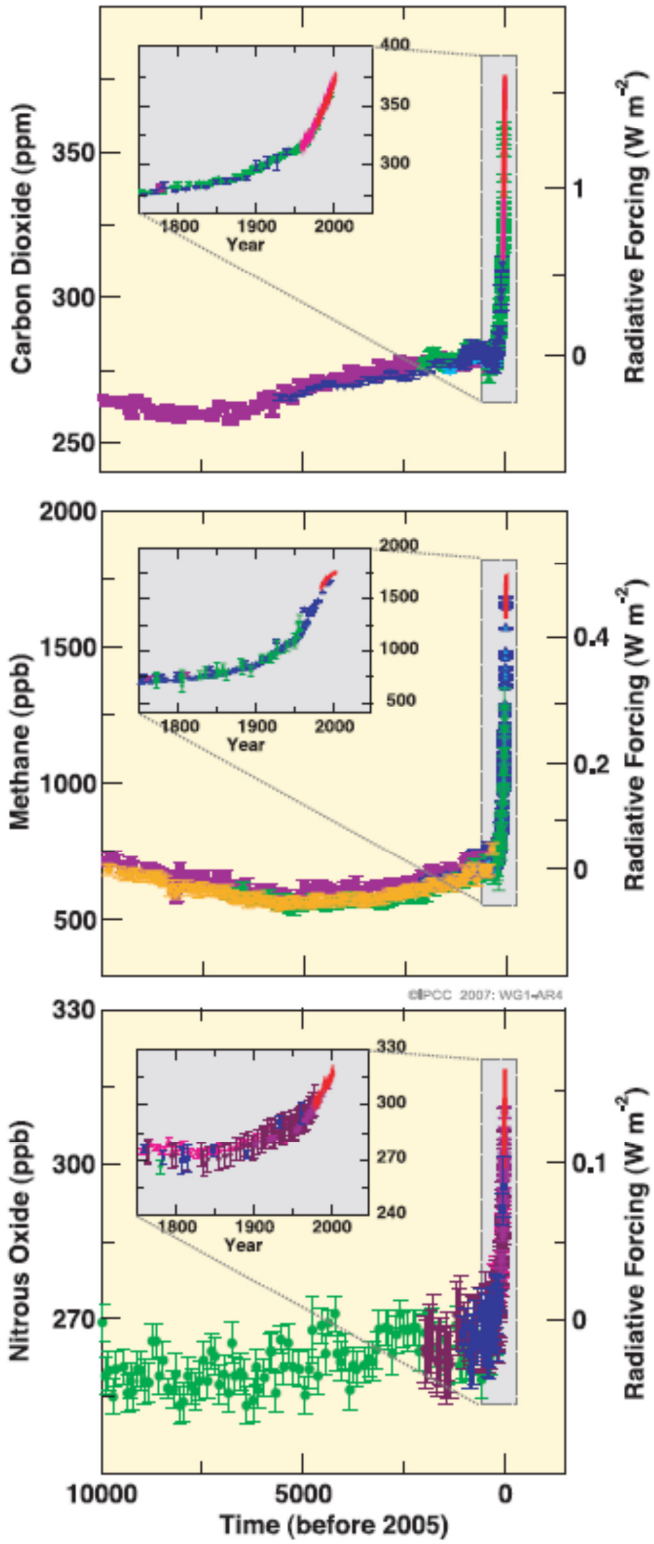


Figure 1.1. Changes in greenhouse gases from ice core samples and modern data.
(IPCC, 2007a: Summary for Policymakers. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.*)

(Refer to Figure 1.2). Eleven of the twelve years between 1995 and 2006 were the hottest on the instrumental record of global surface temperature[3] at that time, and the linear warming trend over the last 50 years is twice that of the last 100 years (IPCC, 2007a). Crowley (2000) concludes that the warming experienced by the Northern Hemisphere over the past century is unprecedented relative to the previous 1000 years of earth's history. Furthermore, he finds that the same climate model that can successfully explain a great deal of the variation in Northern Hemisphere temperature over the years 1000 – 1850 indicates that only around 25% of the twentieth century increase in temperature can be attributed to natural variability in earth's climate. Therefore, the majority of the warming over the past 100 years is consistent with that predicted from GHG increases (Crowley, 2000). This substantial warming has, and will continue to influence the global climate in ways that have significant impacts on human civilization.

The world's oceans are warming, based on observations since 1961; the temperature of the global ocean has increased to depths of nearly two miles, and the ocean has been absorbing 80% of the heat added to the climate system. This warming of the seawater causes it to expand contributing to the rise in sea level. Mountain glaciers and snow cover have declined on average in both the northern and southern hemispheres, contributing to sea level rise, as well as reductions in the size of the Greenland and Antarctic ice sheets (IPCC, 2007a). On the continental, regional, and ocean basin scales, numerous long-term changes in climate have been observed, including changes in "arctic temperatures and ice, widespread changes in precipitation amounts, ocean salinity, wind patterns and aspects of extreme weather including droughts, heavy precipitation, heat waves and the intensity of tropical cyclones (including hurricanes and typhoons)" (IPCC, 2007a). Observational evidence from around the world shows that many

[3] Measured as the average of near-surface air temperature over land and sea surface temperature. (IPCC, 2007)

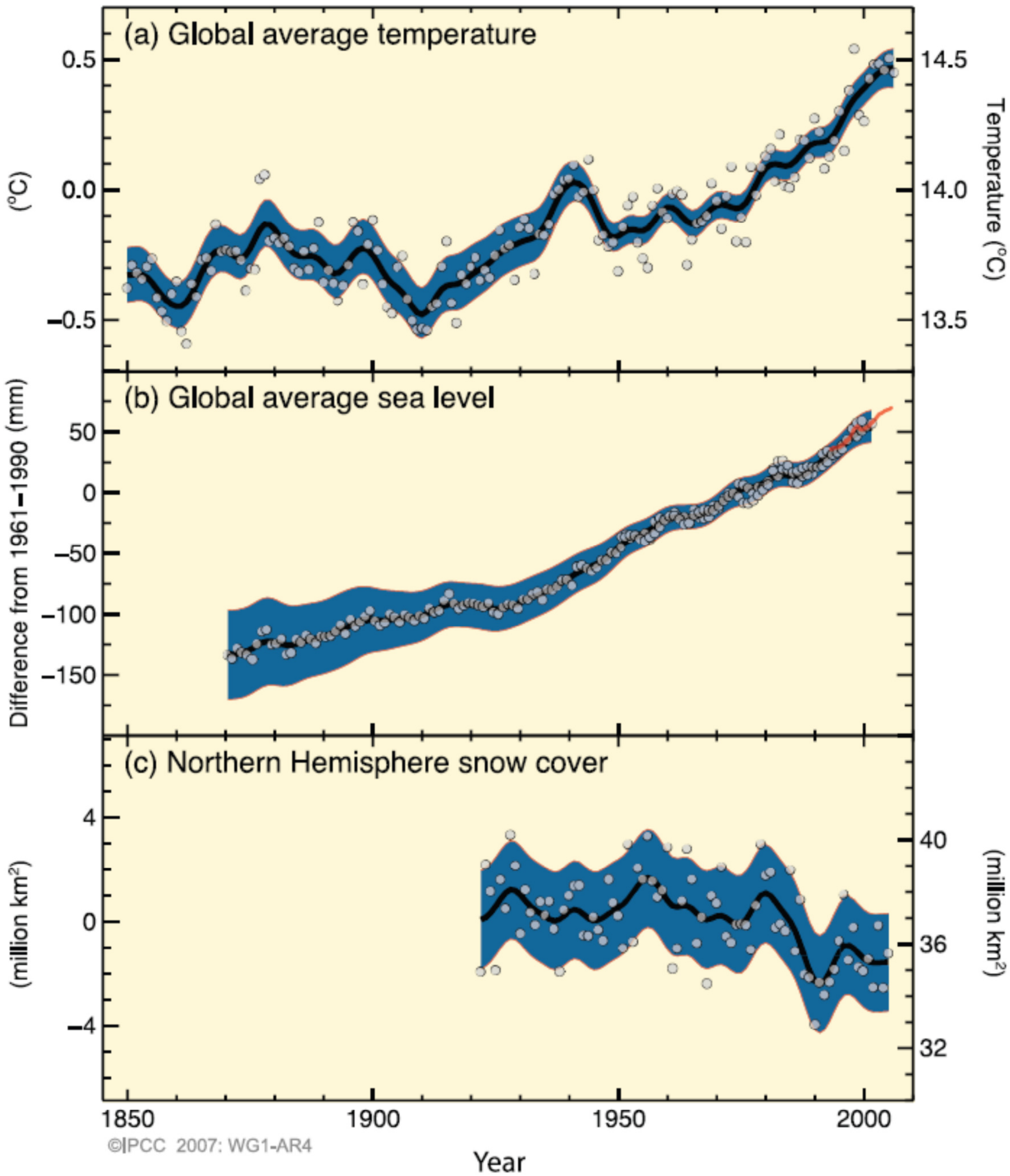


Figure 1.2. Changes in Temperature, Sea Level, and Northern Hemisphere Snow Cover[4]
(IPCC, 2007a: Summary for Policymakers. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.*)

[4] Observed changes in (a) global surface temperature, (b) global sea level from tide gauge and satellite data and (c) Northern Hemisphere snow cover for March-April. All changes are relative to corresponding averages for the period 1961 – 1990. Smoothed curves represent decadal average values while circles show yearly values. The shaded areas are the uncertainty intervals estimated from a comprehensive analysis of known certainties (a and b) and from the time series (c). (IPCC, 2007a)

natural systems are being affected by these changes in climate, particularly temperature increases.

Changes in snow cover, ice, and other frozen ground, including permafrost, have been determined with high confidence[5] to cause "enlargement and increased numbers of glacial lakes, increasing ground instability in permafrost regions, and rock avalanches in mountain regions, and changes in some Arctic and Antarctic ecosystems, including those in sea-ice biomes, and also predators high in the food chain" (IPCC, 2007b). There is high confidence that hydrological systems are being affected as follows: "increased runoff and earlier spring peak discharge in many glacier- and snow-fed rivers and warming of lakes and rivers in many regions, with effects on thermal structure and water quality" (IPCC, 2007b). Based on evidence from a wide range of species, there is very high confidence that recent warming is significantly affecting terrestrial biological systems, including such changes as: "earlier timing of spring events, such as leaf-unfolding, bird migration, and egg-laying, and poleward and upward shifts in ranges in plant and animal species" (IPCC, 2007b). There is high confidence that there has been a trend in many regions since the 1980s, based on satellite observations, toward an earlier 'greening'[6] of vegetation in the spring linked to longer growing seasons due to recent warming (IPCC, 2007b). Substantial new evidence is showing with high confidence that rising water temperatures is associated with observed changes in marine and freshwater biological systems, such as "shifts in ranges and changes in algal, plankton and fish abundance in high-altitude oceans, increases in algal and zooplankton abundance in high-latitude and high-altitude lakes, and range changes and earlier migrations of fish in rivers (IPCC, 2007b). The consistency between observed and

[5] According to the IPCC, "high confidence", is used to express expert judgments on the correctness of the underlying science, in this case that it has about an 80% chance of being correct. (IPCC, 2007)
[6] Measured by the Normalized Difference Vegetation Index, which is a relative measure of the amount of green vegetation in an area based on satellite images. (IPCC, 2007b)

modeled changes in several studies and the spatial agreement between significant regional warming and consistent impacts at the global scale is sufficient for the IPCC to conclude with high confidence[7] that "anthropogenic warming over the last three decades has had a discernible influence on many physical and biological systems" (IPCC, 2007b). Continuing to emit greenhouse gases at current rates would likely cause further warming and induce additional changes in the climate that would very likely be of greater magnitude than those already observed. The risks to human civilization of this increased GHG emissions and warming are many and varied, but are certain to impose costs; psychological, social, and economic.

In general, the costs and benefits of climate change for industry, settlement, and society will vary by location and scale; but in the aggregate, net effects will tend to be more largely negative the more dramatic the changes in climate (IPCC, 2007b). The most vulnerable of industries and societies are "generally those in both coastal and river flood plains, those whose economies are linked with climate-sensitive resources, and those in areas prone to extreme weather events, especially where rapid urbanization is occurring" (IPCC, 2007b). Poor communities can be particularly vulnerable to climate change as they tend to have limited adaptive capabilities and tend to be more reliant on resources that are very sensitive to changes in climate, such as local food and water. The intensification of extreme weather events will cause the economic and social costs of those events to increase substantially (IPCC, 2007b). One of the most serious costs of climate change may be the impact on the health status of millions of people all over the world, particularly those with low adaptive capacity. "Increases in malnutrition and consequent disorders, with implications for child growth and development; increased deaths, disease and injury due to heat waves, floods, storms, fires, and droughts; the

[7] See note 5.

increased burden of diarrheal disease; the increased frequency of cardio-respiratory diseases due to higher concentrations of ground-level ozone related to climate change; and, the altered spatial distribution of some infectious disease vectors" are all possible implications of increased anthropogenic GHG emissions (IPCC, 2007b). While it is possible that climate change may bring some benefits, such as fewer deaths from cold exposure, the negative health effects will far exceed any potential benefits. How different societies respond and adapt to the health impacts of climate change will depend critically on the factors that directly influence the health of the population, such as education, health care, public health initiatives, and infrastructure and economic development (IPCC, 2007b). It is evident that anthropogenic GHG emissions have led to a warming of earth's climate resulting in significant changes in climate patterns. Given the slow response time of the world's oceans, much of the damage from past and present GHG emissions has been done. For the next two decades a warming of about 0.2°C per decade is projected for a range of emissions scenarios; and even if emissions were held constant at year 2000 levels, a further warming of about 0.1°C per decade would be expected (IPCC, 2007b). However, in an effort to minimize the potential costs placed on future generations, it is in the best interest of the human civilization to reduce the growth of GHG emissions thereby reducing the rate of anthropogenic warming and the risk of catastrophic climate change.

All countries, both developed and developing, will eventually have to reduce their GHG emissions. Leadership by industrialized countries will be necessary in order to initiate a movement toward climate protection. The reason for this is twofold: developed countries have the means and resources required to engage in dramatic shifts in energy consumption and production and are responsible for the majority of the increased GHG emissions over the past century; and are therefore most responsible for the warming experienced over that time.

Developed countries, home to 20% of the world's population, are responsible for about 63% of net CO_2 emissions from the burning of fossil fuels and land use changes[8] from 1900-1999, with North America alone responsible for 25% (Baumert & Kete, 2002). The top five emitters of CO_2 from fossil fuels over this time period are the United States (30.3%), the European Union (22.1%), Russia (8.9%), China (7.0%), and Japan (3.7%) (Baumert & Kete, 2002). It is clear that the United States and Europe have an obligation to command leadership in the movement toward a future of reduced GHG emissions.

The current state of the United States political system is making it increasingly difficult to enact any carbon abatement policies; however, economists have long agreed that market-based solutions such as carbon taxation or cap-and-trade permit systems are the most efficient tool in reducing GHG emissions (Baumol & Oates, 1988). These policies are designed in a manner that forces firms to internalize the costs of their polluting behavior by making the cost of a unit of carbon emissions to be some non-zero value. A carbon tax does this by directly taxing the carbon content of fuels while a cap-and-trade permit system does this by requiring firms to surrender valuable permits in proportion to the carbon content of fossil fuels. These policies amend the incentive structure of the economy by adjusting the price signals accordingly. Carbon intensive products will become more expensive relative to less carbon intensive products encouraging firms to change input ratios towards "greener" technologies and resources. The result of this will be increased prices of final goods for household consumption with products entailing more energy intensive production processes becoming relatively more expensive than others.

[8] Such as harvesting of forest products, clearing for agriculture, and vegetation regrowth.

The major concern in implementing these types of policies to reduce to GHG emissions is how the cost burden will be distributed across the population. The seemingly most obvious problem is that the burden of costs arising from these policies would fall disproportionately on lower income households, in other words, these policies are regressive[9]. The reason for this, as explained by the existing literature, is that lower income households spend a larger proportion of their expenditures on direct energy requirements such as electricity, home heating, and transportation (Hasset et al, 2007; Shammin & Bullard, 2009; Cornwell & Creedy, 1996: Poterba, 1991). Empirically, this result can be shown by an examination of the carbon intensity of household consumption across different income groups. This carbon intensity is measured as the carbon emissions generated both directly and indirectly via household consumption; specifically, as the metric tons of CO_2 per dollar of expenditures. High income households have significantly lower carbon intensities due to the lower proportion of direct energy requirements in their expenditures. (Shammin & Bullard, 2009) Therefore, lower income households would see a larger increase in the average price of their consumption bundle than would higher income households.

In Chapter 2, I first discuss the Consumer Expenditure Survey data compiled and the methodology used to measure household carbon intensity of expenditures and carbon dioxide emissions, combining economic input-output modeling with a life cycle assessment modeling to track industry to industry transactions and the corresponding resource use from extraction to end use disposal. Second, I show that while at first glance carbon pricing policies are indeed regressive with lower income households having significantly higher carbon intensities of consumption. As suggested in the previous literature, this result stems from the allocation of

[9] The burden of the policy decreases as household income increases.

household expenditures among direct uses of energy and indirect uses of energy. This expenditure allocation decision is driven, not only by household income, but also by characteristics that vary of the life course, most notably household size and composition. Therefore, lastly I show that household carbon dioxide emissions and intensities follow distinct trajectories over the life cycle, independent of household income, resulting from a reallocation of expenditures necessitated by the evolving needs of households at different stages in the life cycle.

In Chapter 3, I discuss the demographic characteristics that are the drivers of the variation in emissions and intensities among heterogeneous households and how these demographic characteristics have changed, on average, over the past few decades in the United States. Of these changes, most notable are changes in mean household size, the age of household head, and the proportion of one- and two-person households. As baby boomers begin to retire and young individuals choose delay or forego household formation, expenditure allocation decisions of the average household are evolving, thereby changing the relationship between population growth and carbon dioxide emissions in the United States.

In Chapter 4, to formalize the channel through which these changing dynamics of population growth and CO_2 emissions occur, I first generate age-emissions profiles to show the importance of the age of a household member in contributing to total household emissions. I find that children contribute dramatically less than an adult and elderly contribute relatively less than an adult, but more than a child; results which are consistent with findings in the previous literature. In other words, an individual follows a distinct trajectory of emissions over their lifetime. The magnitude of this emissions curve is being attenuated over time as a result of improvements in energy efficiency, but these reductions are becoming smaller in time, consistent with the concept of diminishing returns to technology.   Second, to incorporate the ability of households to experience economies of scale in their emissions through cohabitation, I construct an equivalence scale model in which I adjust for both the size and composition of households in the estimation of household CO_2 emissions. I find that the ability of the average household in the United States to experience economies of scale in emissions has decreased since 2003 resulting in a substantial increase in mean household emissions. Lastly, to quantify this effect I use counter-factual prediction to determine that mean household carbon dioxide emissions would be over ten percent lower in 2009 if the ability of households to experience economies of scale had remained constant at 2003 levels.

Finally, in Chapter 5 I highlight the importance and policy implications of this research, most importantly regarding the consideration of the composition of the population when estimating and projecting greenhouse gas emissions. Given the differences in energy use and emissions among households of different sizes and compositions, if the proportions of these population groups change over the next century in the developing world, as they have in developed nations over the past century, then emissions projections using population growth and estimates of per capita emissions may be grossly inaccurate and result in misleading conclusions regarding mitigation strategies and adaptation policies in a changing global climate.

CHAPTER II

Measurement of Household CO_2 Emissions and the Incidence of Climate Policy

2.1 Introduction

There are multiple ways in which to measure household carbon dioxide emissions. In fact, there is currently no established system of calculating and reporting total household carbon dioxide emissions that households are responsible for generating, both directly and indirectly, at least not in any comprehensive way. The US Environmental Protection Agency (EPA) and Energy Information Agency (EIA) publish annual reports on United States greenhouse gas (GHG) emissions. However, these reports are organized around the major sectors of the United States economy: residential, commercial, industrial, and transportation. The EIA estimates that in 2009 the United States generated 6,575.5 million metric tons of carbon dioxide equivalent emissions[10] with the residential sector accounting for approximately 18 percent of this total (EIA, 2011). However, residential emissions, as defined by the EIA, originate primarily from direct fuel consumption (principally, natural gas) for heating and cooking and electricity for cooling (and heating), appliances, lighting, televisions, computers, and other household electronic devices (EIA, 2011). While technically sound this approach does not provide a complete picture of household emissions or suggest ways in which these emissions could be reduced. Furthermore, households are also responsible for a portion of transportation related emissions, primarily resulting from gasoline expenditures. Therefore, this approach fails to provide both individuals and policymakers with information regarding the environmental consequences of household expenditure decisions. While this approach is fairly accurate in estimating carbon dioxide

[10] "the amount of CO_2 emissions that would cause the same time-integrated radiative forcing, over a given time horizon, as an emitted amounted of a long-lived GHG or a mixture of GHGs" (IPCC, 2007c, p. 36).

emissions for the economy as a whole by adding up the components and is consistent with government planning and budgeting it fails to illuminate the micro level foundations that generate these macro level outcomes. Ultimately, the reason why is that it does not focus on people or their households; in other words, it does not focus on their behavior.

In contrast to this approach, the EIA also routinely conducts the Residential Energy Consumption Survey (RECS) collecting energy usage characteristics on the housing unit, usage patterns, and demographic characteristics. In this approach, the various energy end uses in households are documented and the resulting carbon dioxide emissions estimated. This includes energy used for heating and cooling systems, cooking, water heating, appliances, lighting, and other electronic devices. While this approach provides information regarding the composition of household energy use, it still only analyzes this direct portion of household energy use. While this is necessary and useful information in the determination of opportunities for advances in energy conservation and efficiency it does not shed any additional light on the interactions of households with other sectors of the economy.

Over the past several decades the use of input-output analysis, using methods developed by Wassily Leontief (1970), has made it possible to carry out more complex and comprehensive assessments of household energy consumption and carbon dioxide emissions. The foundation for this approach, which I will describe in this chapter, rests in two related concepts: 1) life-cycle analysis, a method of estimating the impact of any resource use over a product's life cycle – from raw material extraction to end use consumer disposal; and 2) embodied energy (or embodied emissions), energy use and carbon dioxide emissions that occur at various stages in the life cycle of goods and services that individuals eventually consume. Section 2 will discuss the use of life-cycle analysis and input-output modeling in compiling the dataset used in this analysis. Section

3 will highlight the differences in energy use and carbon dioxide emissions of households of different income levels and the importance of the consumer life cycle in the determination of climate policy incidence. Finally, Section 4 will draw some conclusions.

2.2. The Data

Households in the United States maintain their lifestyles through the purchase of goods and services. By consuming these goods and services households generate GHG emissions, both directly and indirectly. Electricity use, home heating, and driving automobiles give rise to GHG emissions directly. While the consumption of other products, such as food, clothing, and many services, generate GHG emissions indirectly via the emissions embodied in their production processes.

2.2.1. Consumer Expenditure Survey

In order to measure the GHG emissions resulting from household consumption, household expenditure microdata was obtained from the Consumer Expenditure Survey (CEX) by the Bureau of Labor Statistics (BLS) for the years 1996 – 2009 which reports consumer expenditures on a variety of goods and services, as well as a plethora of demographic information. The CEX consists of two separate components: the Interview Survey and the Diary Survey each with its own questionnaire and independent sample. The quarterly Interview Survey is designed to collect detailed data on major expenditure items covering 60-70% of total household expenditures. In addition, global estimates are obtained for food and other selected items which account for an additional 20-25% of total expenditures. Therefore, up to 95% of total household expenditures are covered by the Interview Survey. Each quarter of data is processed independently by the BLS, thus estimates are not dependent on any one consumer unit (CU) participating in the survey for five consecutive quarters. The initial interview collects demographic and family characteristics data including age, sex, race, marital status, education, and family size. This information is updated at each subsequent interview. The second through fifth interviews use uniform questionnaires to collect expenditure information from the previous three months. Income information, such as salary, wage, unemployment compensation, child support, and alimony is only collected in the second and fifth interviews. Each quarter 20 percent of the sample are new households introduced for the first time; replacing one-fifth of the sample that completed its fifth interview in the previous quarter. This rotating design is designed to provide more efficient data collection and estimation.

Upon receipt of the data by the BLS from the Bureau of the Census, the data undergoes a series of edits that correct any inconsistencies and irregularities and CU weights are derived using BLS specifications. Each CU included in the CEX represents a given number of CUs in the United States population. The weighting procedure is the four step process described below[11]:

> 1) The basic weight is assigned to an address and is the inverse of the probability of selection of the housing unit.
>
> 2) A weight control factor is applied to each interview if sub-sampling is performed in the field.
>
> 3) A non-interview adjustment is made for units where data could not be collected from occupied housing units. The adjustment is performed as a function of region, housing tenure, family size and race.
>
> 4) A final adjustment is performed to adjust the sample estimates to national population controls derived from the Current Population Survey. The adjustments are made based on both the CU's member composition and the CU as a whole. The weight for the CU is adjusted for individuals within the CU to meet the controls for 14 age/race categories, 4 regions, and 4 region/urban categories. The CU weight is also adjusted to meet the control for total number of CUs and total number of CUs who own their living quarters. The weighting procedure uses an

[11] As described by the BLS, in the 2009 Consumer Expenditure Interview Survey Public Use Microdata, User's Documentation, released October 5, 2010, pg. 137.

iterative process to ensure that the sample estimates meet all the population controls.

Therefore, samples for the CEX are national probability samples of households designed to be representative of the total U.S. civilian non-institutional population.

In order to augment the data collected in the Interview Survey, the Diary Survey collects expenditure data on items purchased every day for two one-week periods. This survey is designed to track expenses on small frequently purchased items such as food, beverages, food consumed away from home, gasoline, housekeeping supplies, nonprescription drugs and medical supplies, and personal care products and services. At the beginning of the two week period the interviewer records demographic and household characteristics information from the consumer unit (CU) and a diary to record expenditures for the following week is left with them. At the completion of the first week, the interviewer picks up the diary, reviews the entries, clarifies any questions, and leaves a second diary for the following week. At the end of the second week, the diary is picked up and reviewed. These data can then be used as a supplement to the global estimates of these expenditures in the Interview Survey for certain demographic subgroups. In this manner, subtle differences in expenditure habits can be observed among a variety of household subgroups. For the purposes of this paper, this is extremely useful, as it provides a way to distinguish between food consumption decisions among heterogeneous households. For example, a household that consists of devoted vegetarians will have a vastly different carbon intensity of food consumption than one that consumes large amounts of beef, pork, and poultry. Furthermore, as consumer preferences for meat or preferences for fresh versus processed fruits and vegetables change over time it is important to incorporate these changes in the determination of carbon emissions resulting from food consumption.

However, before the CO_2 emissions resulting from the consumption of goods and services can be calculated a large amount of data work must be completed in order to pool the quarterly cross-sections in the CEX from 1996 to 2009. There are two hurdles to overcome before these data could be used as a consistent pooled cross-section: income imputation and time inconsistencies. The CEX is designed in such a way as to provide nationally representative data within each year of the survey, not to provide a time series of expenditure patterns. However, this is precisely what is needed in the current context.

2.2.2. Income Imputation

Starting with the publication of the 2004 CEX data the surveys include some data that have been produced using a multiple imputation technique. The purpose of this procedure is to fill in blanks due to nonresponse (i.e. the respondent does not know or is not willing to provide a value for a source of income received by the consumer unit). The process preserves the mean of each income source and yields variance estimates that take into account the fact that some of the values are imputed rather than reported.

The method used for multiple imputations is regression-based. Basically, a regression is run to provide the coefficients for use in estimating values for the missing data points.[12] These coefficients are shocked by adding random noise to each and missing values are estimated using the shocked coefficients. These estimates are then shocked again to ensure that consumer units with identical demographic characteristics are not assigned identical income estimates. The resulting values are then used to fill in the missing values, while reported values are preserved. This process is repeated an additional four times, resulting in a total of five different imputed values for each missing data point. Additionally, the imputed data includes one additional

[12] For a detailed theoretical understanding of the multiple imputation process, see Rubin (1987).

estimate representing the mean of all five estimates. When using income variables as control variables in regression analysis or when estimating means, the mean imputation can be used with no resulting loss in efficiency. However, if income variances or regression parameters are to be estimated, using only the mean imputation values will result in statistical bias. Using any one imputation estimate or the mean estimate to draw inferences leads to bias by inadequately capturing the uncertainty built into the data resulting from the fact that some of the data are imputed rather than reported. Therefore, the CEX data obtained herein contain only reported values for income variables from 1996 through 2003, and both reported and imputed values from 2004 through 2009. In practice, this enables the preservation of more observations in the latter half of the data. I will return to this discussion at the end of Section 2.

2.2.3. Time Inconsistences

While many time inconsistences are present in the CEX, there is also a surprising amount of consistency from one year to the next. Most importantly, variable names are preserved over time, while many variables are added and dropped; a core set of expenditure and demographic variables are present in the data from 1996 to 2009. While labor intensive, this allows for the construction of a pooled cross-section with a consistent set of variables over time. Once this set is established the task becomes the confirmation of measurement and coding consistencies over time. In practice, this was achieved by starting with the 1996 first quarter CEX Interview survey data and appending the additional 55 quarters of data one at a time. At each step in this process the core set of variables established by the 1996 data are matched and all coding and measurement consistencies are examined and adjusted as necessary. Once complete this process produces a nationally representative pooled cross-section of expenditure, demographic, household characteristics, income, and geographical data of the United States from the first quarter of 1996 through the fourth quarter of 2009.

2.2.4. Measuring the Carbon Intensity of Household Expenditures

The energy and emissions requirements of household consumption have been the subject of continuing environmental and economic research since the early 1970s (Leontief, 1970; Bullard & Herendeen, 1975; Hannon, 1975; Herendeen & Tanaka, 1976). It remains to be the subject of continued research due to the changing consumption, emissions, and demographic patterns in the United States, as well as continuing refinements and variations in household consumption and emissions measurement techniques (Hertwich, 2005; Kok et al., 2006; Tukker & Jansen, 2006; Kerkhof et al., 2009). The most prevalent and widely used techniques include economic input-output (EIO) models, life-cycle assessment (LCA) analysis, and hybrid models incorporating elements of these two techniques (EIO-LCA). This section will describe each in turn and elaborate on the model used for the purposes of this research.

2.2.5. Life-Cycle Assessment (LCA) Models

Life-cycle assessment is a tool used to determine the environmental impact of product systems and services, including resource uses and emissions during production, distribution, use, and disposal of the product; often referred to as a "cradle to crave" technique for tracking environmental impacts, emphasizing the accounting of impacts from primary resource extraction to end-use disposal. It is important to point out that while LCA has many similarities to EIO analysis; its foundations are quite different. LCA models are engineering-based and present the flow of physical products among different production, distribution, and disposal processes.

Hertwich (2005) reviews a variety of life-cycle approaches to sustainable consumption taking a broad definition of life-cycle analysis. LCA consists of three distinct analytical steps: process determination, impact determination, and the assessment and aggregation of these environmental impacts. In other words, LCA asks these questions: what processes are involved in the life cycle of a product, what and how many resources are used and what level of emissions are generated throughout these processes, and how can we measure, track, and record these impacts? Figure 2.2.1 summarizes the general components of a life-cycle model.

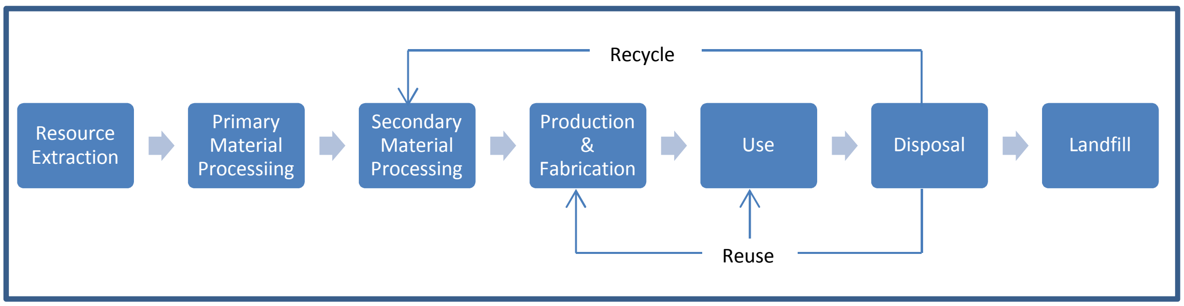


Figure 2.2.1 Example Process Chain Life Cycle Model

Additionally, two further procedural steps are defined by the International Organization for Standardization (ISO): the goal and scope definition (the planning of the LCA) and interpretation (discussion and conclusions at each step) (ISO, 1997; Hertwich, 2005). This LCA process analysis originally developed by the Society of Environmental Toxicology and Chemistry (SETAC) and the U.S. Environmental Protection Agency (EPA) uses engineering to create energy and material balances for each relevant process (generically represented in Figure 2.2.1) (Hendrickson et al., 2006). The question of relevance relates back to the planning of any LCA analysis; the determination of the goal and scope of the project. Take the life cycle of the production of an automobile for example: the facilities extracting the ores, coal, and other energy sources; the vehicles, ships, pipelines, and other infrastructure that transport the raw material, processed material, and subcomponents along the supply chain to manufacture the consumer product, and transport the products to the consumer: iron ore ships, trucks carrying steel, engines going to an automobile assembly plant, trucks carrying cars to dealers, trucks transporting gasoline, lubricating oil, and tires to service stations; the factories that make each of the components that go into the car, including replacement parts, and the car itself; the refineries and electricity generation facilities that provide energy for making and using the car; and the factories that handle the vehicle at the end of its life: battery recycling, shredding, landfills for shredder waste (Hendrickson et al., 2006). Each of these tasks requires raw materials and generates GHG emissions. Therefore, understanding the life-cycle of a certain product in this way can inform industry, consumers, and government about the potential environmental and sustainability impacts of different consumption choices or policy paradigms.

A myriad of complications arise in the application of LCA process analysis (Rebitzer et al., 2004; Reap et al., 2008a; Reap et al., 2008b). In the case of most products, analysts must identify the materials and impacts of each process in the life-cycle in great detail. This creates problems for the broad dissemination of this practice, especially in a dynamic economy. The processes employed, materials used, and impacts generated in the production of any particular product can and will change continually in response to innovations, input prices, and consumer preferences. In many cases this can lead to a situation where the design and materials used have changed significantly before an existing LCA analysis on that product has been completed. Furthermore, the time and expense necessary to perform a detailed energy and material breakdown for a process is substantial; therefore, the number of processes that is practical to analyze is limited. Performing a detailed process analysis of a complicated product, such as an automobile, is, for all practical purposes, impossible. Containing over roughly 30,000 components, each with its own process chain involving thousands of processes, tracking the material and energy balances for all of these processes is impossible (Hendrickson, et al., 2006). As a result, the ability to perform an LCA process analysis for a set of products representative of the typical consumer is also impossible. In order to go beyond this hurdle, LCA analysis can be augmented using economic input-output models, taking a more aggregated view of the sectors in the economy.

2.2.6. Economic Input-Output (EIO) Models

Simply put, input-output models focus on the interconnectedness of industry, households, and government within the economy. Building from the theoretical production function concepts established by Walras (1874) and the desire for empirical analysis in this area, Leontief (1949) developed a tractable input-output model using structural matrices of the national economy. Input-output models divide the entire economy into many distinct sectors and represent the amount of various inputs needed to produce a unit of output in each sector. In practice, these are constructed as large tables or matrices. Each sector is represented by one column and one row, enabling the researcher to trace all the direct and indirect inputs used to produce a unit of output in each sector.

Two important assumptions of EIO models must be mentioned. These models are linear and therefore assume constant returns to scale. As a result, the effects of a $1,000 purchase from one sector will be ten times greater than the effects of a $100 dollar purchase. While this assumption surely does not hold for all industries in the economy, it is a reasonable approximation over the relevant range of output for a wide range of sectors. In industries for which some degree of economies of scale is expected, such as electricity generation and distribution, natural gas distribution, and other public utilities, this assumption will have the effect of overstating input usage; for a doubling of final output will not require a doubling of input demands. Secondly, input-output models take a "snapshot" of the economy at a given moment in time and thus are static in nature, dealing only with flows of commodities, neglecting any potential changes in the stocks of those commodities. Therefore, modeling in this manner can only be a valid tool for relatively short-run analyses wherein this assumption can be deemed appropriate.

2.2.7. Economic Input-Output Life-Cycle Assessment (EIO-LCA) Models

The advantage of a pure process LCA analysis is that it can answer very detailed questions regarding the energy and material balances of each facility in question depending on the scope of the study. However, the major disadvantage, as mentioned previously, is the time and expense involved in tracking these process chains, forcing the researcher to draw relatively tight boundaries that exclude a large number of the processes involved. The advantage of the EIO-LCA approach is that no boundary must be drawn, and so covers the entire economy including all material and energy balances. However, the major drawback of using EIO tables to guide the analysis is the aggregated scope of the sector definitions. Instead of focusing on the actual steel mill involved in the production of an automobile in tracking input usage, the broad sector "iron and steel mills" must be used for example. Much of the heterogeneity in production processes among different facilities in similar sectors is lost.[13] This disadvantage is offset by the ability to expand the scope of the analysis to include the entire economy.

The incorporation of environmental and natural resource concerns into EIO analysis was first proposed by Leontief (1970), leading to a dramatic surge in research on the environmental impacts of economic activity. In theory this task is relatively simple, structural coefficients

[13] An implication of this aggregated scope is that goods of different brands or designs may often be assumed to be identical in their carbon intensity of production. For some goods, this may be plausible; but for some this may lead to an over or underestimation of the carbon intensity.

similar to those used to trace the interdependence between production and consumption can be used to explain the interdependence between levels of actual “desired” output and “undesirable” outputs (GHG emissions) (Leontief, 1970). In practice, there are two methods that can be used to implement such a technique: direct augmentation and external augmentation. In order to elaborate on and determine the potential equivalence of these methods, I will first present a general form of an input- output model based on Leontief (1949; 1970). Figure 2.2.2 shows an example structure of an economic input-output table.

Matrix entries X_{ij} are the input to sector j from sector i. Total output for each sector i is the sum (across rows) of intermediate outputs used by other sectors and final demand by consumers:

$$X_i = \sum_{i=1}^{n} O_i + Y_i$$

where

$$O_i = \sum_{j=1}^{n} X_{ij}.$$

Gross domestic product (GDP) is equal to the sum of all final demands, as well as, the sum of the value added by each sector, by definition:

$$GDP = \sum_{i=1}^{n} Y_i = \sum_{j=1}^{n} V_j$$

where

$$V_j = X_j - I_j, with\ X_j = X_i\ and\ I_j = O_i.$$

Input to sectors (j)						Intermediate Output (O)	Final Demand (Y)	Total Output (X)
Output from sectors (i)	1	2	3	…	n			
1	$\mathbf{X}_{11}$	$\mathbf{X}_{12}$	$\mathbf{X}_{13}$	…	$\mathbf{X}_{1n}$	$\mathbf{O}_1$	$\mathbf{Y}_1$	$\mathbf{X}_1$
2	$\mathbf{X}_{21}$	$\mathbf{X}_{22}$	$\mathbf{X}_{23}$	…	$\mathbf{X}_{2n}$	$\mathbf{O}_2$	$\mathbf{Y}_2$	$\mathbf{X}_2$
3	$\mathbf{X}_{31}$	$\mathbf{X}_{32}$	$\mathbf{X}_{33}$	…	$\mathbf{X}_{3n}$	$\mathbf{O}_3$	$\mathbf{Y}_2$	$\mathbf{X}_3$
⋮	⋮	⋮	⋮		⋮	⋮	⋮	⋮
n	$\mathbf{X}_{n1}$	$\mathbf{X}_{n2}$	X_{n3}	…	$\mathbf{X}_{nn}$	$\mathbf{O}_n$	$\mathbf{Y}_n$	$\mathbf{X}_n$
Intermediate input **I**	$\mathbf{I}_1$	$\mathbf{I}_2$	$\mathbf{I}_3$	…	$\mathbf{I}_n$			
Value added **V**	$\mathbf{V}_1$	$\mathbf{V}_2$	$\mathbf{V}_3$	…	$\mathbf{V}_n$		GDP	
Total input **X**	$\mathbf{X}_1$	$\mathbf{X}_2$	$\mathbf{X}_3$	…	$\mathbf{X}_n$			

Figure 2.2.2: Example Structure of EIO table[14]

However, EIO models are typically generalized in such a way that inter-industry flows can be represented as a percentage of sectoral output: technical coefficients or input-output coefficients. This is achieved by dividing the dollar value of flows from sector *i* to sector *j* by the total output of sector *j*:

$$a_{ij} = \frac{X_{ij}}{X_j}. \tag{2.2.1}$$

These coefficients are unit-less and describe the dollar amount of inputs from sector *i* in every unit of output from sector *j*. For example, if \$100 of intermediate inputs flow from sector 1 to sector 2 (X_{12}) and the total output from sector 2 (X_2) is \$1000, then $a_{12} = 0.10$. Solving the equation (1.2.1) for X_{ij} yields,

[14] Based on table presented by Hendrickson et al., 2006.

$$X_{ij} = a_{ij}X_j \tag{2.2.2}$$

therefore, the model is most often represented as a system of linear equations as follows:

$$X_i = a_{i1}X_1 + a_{i2}X_2 + \cdots + \ a_{in}X_n + Y_i. \tag{2.2.3}$$

Each term on the left has a corresponding term on the right side of the above equation. Thus, all *X* terms are typically moved to the left side, such that, final demands, Y_i, are written as a function of all intermediate inputs/outputs, and the entire system is written as follows:

$$\begin{gathered}
(1 - a_{11})X_1 - a_{12}X_2 - \cdots - a_{1n}X_n = Y_1 \\
-a_{21}X_1 + (1 - a_{22})X_2 - \cdots - a_{2n}X_n = Y_2 \\
-a_{i1}X_1 - a_{i2}X_2 - \cdots + (1 - a_{ii})X_i - \cdots - a_{in}X_n = Y_i \\
-a_{n1}X_1 - a_{n2}X_2 - \cdots + (1 - a_{nn})X_n = Y_n
\end{gathered} \tag{2.2.4}$$

Let the matrix $\boldsymbol{A}$ be a n × n matrix containing all of the technical coefficient A_{ij} terms, $\boldsymbol{x}$ be a n × 1 vector of the output X_i terms, and $\boldsymbol{Y}$ be a n × 1 vector of the final demand Y_i terms; thus equation (2.2.4) can be rewritten as

$$\boldsymbol{x} - \boldsymbol{Ax} = [\boldsymbol{I} - \boldsymbol{A}]\boldsymbol{x} = \boldsymbol{Y} \tag{2.2.5}$$

where $\boldsymbol{I}$ is the n × n identity matrix. Of prevailing interest is $\boldsymbol{x}$, the total output of each sector for various exogenous final demands $\boldsymbol{Y}$ taken as inputs to the system. In order to arrive at this solution we take the inverse of $[\boldsymbol{I} - \boldsymbol{A}]$ and pre-multiply it to both sides of equation (2.2.5), yielding the familiar result,

$$\boldsymbol{x} = [\boldsymbol{I} - \boldsymbol{A}]^{-1}\boldsymbol{Y} \tag{2.2.6}$$

where $[\boldsymbol{I} - \boldsymbol{A}]^{-1}$ is the structural matrix of the economy, or what has come to be known as the Leontief inverse matrix.

Given this general framework, we can now proceed to a comparison of the two methods for incorporating environmental elements: direct or external augmentation. The direct method, suggested by Leontief (1970) is very straightforward: simply augment the $\boldsymbol{A}$ matrix with a pollution (emissions) product rows and columns. The data limitations and computational capacity of the time somewhat limited this proposition, for adding even a single pollutant to the $\boldsymbol{A}$ matrix created problems in solving the system of equations. This, in part, led to the pursuit of a second method, externally augmented EIO models, in which the consideration of environmental effects are kept external to the input-output model; but use the Leontief inverse and output solutions to generate these results. Using this method the total supply-chain economic output is found using equation (2.2.6) above. Since $\boldsymbol{x}$ contains all output produced by each sector, an external per-dollar-output emissions function can be used to establish the environmental impact in each sector resulting from a given amount of production. These sectoral impacts can then be summed to arrive at a level of aggregate environmental impact (total pollution) resulting from an exogenous level of final demand. Specifically, the following function can be used[15]

$$h = e_1X_1 + e_2X_2 + \cdots + e_nX_n = \boldsymbol{Ex} = \boldsymbol{E}[\boldsymbol{I} - \boldsymbol{A}]^{-1}\boldsymbol{Y} \qquad (2.2.7)$$

where $\boldsymbol{E}$ is a n × 1 vector of per-dollar emissions (pollution intensities) e_i from each sector multiplied by the total output from each sector $\boldsymbol{x}$, thus yielding total pollution h. Of interest is whether or not this method yields results equivalent to the direct augmentation method. Miller and Blair (1985) maintain that external methods can generate equivalent results if done correctly, but do not prove this conclusion. Hendrickson et al. (2006) offer a proof of this hypothesis and show that the external method yields analytically identical results even when a set of m

[15] As suggested by Hendrickson et al., 2006.

environmental impacts is added to the model.[16] The EIO-LCA model used in this research to establish emissions intensities for a broad set of household expenditure items relies on the external augmentation method, thereby highlighting the importance of this equivalence.

In order to establish household level emissions and intensities we must first establish the pollution intensities of the sectors in the economy producing these household expenditure items. The EIO-LCA model used in this analysis is developed and maintained by the Green Design Institute at Carnegie Mellon University and is available as a free online tool.[17] This model uses industry-to-industry transactions in order to access the impacts of specific production processes. Industries are defined according to the North American Industry Classification System (NAICS) and the transactions among them are tracked using the benchmark input-output accounts prepared and published by the Bureau of Economic Analysis (BEA) every five years. The accounts used in the present analysis are for the years 1997 and 2002, splitting the economy into 483 and 428 disaggregated sectors, respectively. Differences across the two model years in terms of sector definitions and level of aggregation must first be reconciled to arrive at a sectoral composition consistent between the two years. The most common discrepancy between 1997 and 2002 is the level of aggregation; hence the smaller number of detailed sectors in the 2002 model. For example, in 1997 "flour milling" and "malt manufacturing" are listed as different sectors; but in 2002, "flour milling and malt manufacturing" is listed as a single sector. In situations such as this, the model provides one result for 2002, but two different results in 1997; therefore the multiple results obtained from the 1997 model were averaged to generate a single value for the impacts generated from that sector (as defined in 2002) in 1997. While some

[16] Both the external and direct augmentation methods yield equation (2.2.7). See Hendrickson et al. (2006), pages 202-206, for the exhaustive proof.
[17] The model is available on the web at www.eiolca.net.

precision in the estimation of environmental impacts is lost through this process, overall this enables us to arrive at a set of 419 sectors with reliable results across the two years.

The result reported from implementing the EIO-LCA model for $1 million of final demand from a given sector is the metric tons of carbon dioxide equivalent emissions (tCO_2e). GHGs differ in their warming influence (or radiative forcing) on the climate due to differences in their radiative properties and lifetime in the atmosphere. These differences can be expressed using the metric of CO_2 equivalent emissions, which is defined as "the amount of CO_2 emissions that would cause the same time-integrated radiative forcing, over a given time horizon, as an emitted amounted of a long-lived GHG or a mixture of GHGs" (IPCC, 2007c, p. 36). The equivalent CO_2 emissions are obtained by multiplying the emissions of multiple GHGs (in the EIO-LCA model: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and chloroflurocarbons (CFCs)) by their global warming potential (GWP)[18] for the given time horizon (in this case: 100 years) and summing the results. For example, the CO_2 equivalent emissions resulting from $1 million of final demand in the "soft drink and ice manufacturing" sector in 1997 is 709 tCO_2e. These values were determined using the 1997 and 2002 purchaser price EIO-LCA models for the 419 sectors (as redefined earlier).[19] These two values are in current prices and reflect GHG emissions resulting from $1 million dollars of final output from all sectors in 1997 and 2002 prices. The U.S. Consumer Price Index (CPI) was used to inflate the 1997 values to 2002 prices, using a conversion factor of 1.12087.[20] These values, now comparable, can be used to estimate the CO_2 equivalent emission intensities for the remaining

[18] Global warming potential (GWP) is an index that transforms the emissions of a GHG to that of an equivalent mass of CO_2. The duration of the perturbation is included by integrating radiative forcing over a time horizon (100 years in the current context) which includes the cumulative climate change and decay of the perturbation (IPCC, 2007c).
[19] A complete list of these "raw" sectoral carbon intensities can be found in Appendix 1.
[20] Data retrieved from the Bureau of Labor Statistics (BLS), at www.bls.gov/cpi.

years of data necessary (recall, consumer expenditure data has been retrieved for the years 1996 through 2009).

To estimate the remaining values, log-linear interpolation and extrapolation was used. Using logged values has two important features in this context: it bounds carbon intensities at zero and incorporates the concept of diminishing returns to technological efficiency over time. For those sectors that experienced dramatic improvements in efficiency over the period, 1997 – 2002, using actual values for extrapolation results in negative values in the most current period. By logging both the 1997 and 2002 values, differencing them, and dividing by the time period of 5 years, we arrive at a value that is interpreted as the mean percentage change in the carbon intensity for that sector per year, θ_j, where j is used to denote the sector from 1 to 419. The intuitive appeal of this method is that it incorporates the idea that efficiency gains from technology will decrease over time, or for a select few sectors, efficiency losses will also decrease over time. This process can be described mathematically as follows: let α_j be defined as the raw carbon intensity of sector j in 1997 and let β_j be defined as the raw carbon intensity of sector j in 2002. Additionally, let t be a time parameter taking on values from -1 to 12, representing the years, 1996 through 2009. Therefore,

$$\theta_j = \frac{\ln \alpha_j - \ln \beta_j}{t_{2002} - t_{1997}} = \left(\frac{1}{5}\right) ln\left(\frac{\alpha}{\beta}\right). \tag{2.2.8}$$

The estimated carbon intensity for sector j in time t can be represented as:

$$\hat{C}_{jt} = e^{(\ln \alpha_j + t\theta_j)}, \tag{2.2.9}$$

with the exponential function being necessary to convert the logged values back to levels. This method is implemented for all 419 sectors in every year from 1996 – 2009, with 1997 and 2002, of course, returning their initial values. At this point, all of these carbon intensities are being measured in constant 2002 prices, so in order to use these sectoral intensities in the calculation of household carbon intensities, we must first use the CPI to convert these values back to current year dollars, as expenditures in every year of the CEX are measured in that manner.[21] Once this procedure has been completed, we can then proceed to the matching of these estimated sectoral carbon intensities with the various expenditure categories.

The CEX Interview Survey provides data on expenditures by households over 14 broad categories: food, alcoholic beverages, housing, apparel, transportation, healthcare, entertainment, personal care, reading, education, tobacco products, cash contributions, personal insurance, and miscellaneous. These expenditures are then further disaggregated into 50 detailed expenditure categories, which must be matched to the 419 production sectors in order to determine carbon intensities for each of these categories. Since the expenditure categories are classified according to final demands and the sectors are classified according to production of output from industry; the expenditures are matched to sectors using, in some cases, only one production sector, but in other cases an average of carbon intensities from multiple production sectors must be used to match the expenditure category as closely as possible. The production sectors used in the calculation of carbon intensities and the resulting intensities are summarized in complete detail in Appendix 3.

As mentioned in Section 2.2.1, the Diary Survey is used to augment the Interview Survey to provide more detailed expenditure information. The broad expenditure category, food, is split into two components: “food at home” and “food away from home”. The Interview Survey provides one expenditure value for each component. For “food away from home” this does not

[21] See Appendix 2 for a complete list of the estimated sectoral carbon intensities in current prices for all 419 detailed sectors.

pose any significant problems; however, the "food a home" category includes cereal products, bakery products, beef, pork, other meat, poultry, seafood, eggs, milk products, other dairy, fresh fruit, fresh vegetables, processed fruit, processed vegetables, sweets, non-alcoholic beverages, oil, and other miscellaneous foods. The expenditures on these disaggregated food categories are not reported independently in the Interview Survey; only one value for "food at home" is reported. If we were to use a simple average over the sectoral carbon intensities matched with these categories, valuable information on food consumption choices of American households over the time period 1996 – 2009 would be lost. As different food categories can have dramatically different carbon intensities[22], this behavioral component cannot be overlooked. In order to incorporate changing tastes and preferences for different food items over time, the Diary Survey was used to estimate mean proportions of total "food at home" expenditures for these 18 different food categories. For example, in 1996 the average American household spent 19.1% of their grocery budget on beef, pork, poultry, and other meats and 15.6% in 2009, suggesting a declining preference for meat over the period. Therefore, weighted mean carbon intensity for "food at home" expenditures using these proportions as weights was estimated using data from the Diary Survey for each year. This provides one value for the carbon intensity of "food at home" expenditures for each year as is the case with the remaining 49 detailed expenditure categories, summarized in Appendix 3. These 50 carbon intensities, γ, can then be used in conjunction with the 50 different expenditure category values, ε, to calculate carbon intensities of consumption at the household level. Let i denote expenditure categories from 1 to 50, let j denote observations from 1 to n, and let t denote quarterly time periods, 1 to 56.[23] Household

[22] See Appendix 3.

[23] Sectoral carbon intensities are only available on an annual basis; therefore, the same carbon intensity is used for each quarter of every year in the calculation of household carbon intensities. While not ideal, this limitation does

carbon intensities are calculated by first determining the total carbon dioxide equivalent emissions, Φ, generated by household j, in time period t, by expenditures in each category i:

$$\Phi_{ijt} = \gamma_{it} \cdot \varepsilon_{ijt} . \tag{2.2.10}$$

Therefore, the total carbon intensity of consumption, Γ, for household j in time period t is:

$$\Gamma_{jt} = \sum_{i=1}^{50} \frac{\Phi_{ijt}}{\varepsilon_{ijt}} . \tag{2.2.11}$$

Lastly, in order to complete the data, households are placed into income quintiles based on their annual before-tax income. Income quintile data (Table 2.2.1) from the American Community Survey compiled by the U.S Census Bureau was used to place households into their respective

Table 2.2.1. U.S. Income Quintiles: 1996 – 2009.

	Upper Limit of Each 20% (Quintile)				Lower Limit of Top 5%
	First	Second	Third	Fourth	
2009	20,453	38,550	61,801	100,000	180,001
2008	20,712	39,000	62,725	100,240	180,000
2007	20,291	39,100	62,000	100,000	177,000
2006	20,035	37,774	60,000	97,032	174,012
2005	19,178	36,000	57,660	91,705	166,000
2004	18,486	34,675	55,230	88,002	157,152
2003	17,984	34,000	54,453	86,867	154,120
2002	17,916	33,377	53,162	84,016	150,002
2001	17,970	33,314	53,000	83,500	150,499
2000	17,920	33,000	52,174	81,766	145,220
1999	17,136	31,920	50,384	79,232	142,000
1998	16,116	30,408	48,337	75,000	132,199
1997	15,400	29,200	46,000	71,500	126,550
1996	14,768	27,760	44,006	68,015	119,540

Source: U.S. Census Bureau, Current Population Survey, Annual Social and Economic Supplements.
Note: Measured in current year dollars.

have the advantage of eliminating any seasonal variation in carbon intensities resulting from input availability, weather patterns, etc.

fifths of the income distribution on a year-by-year basis using their reported annual gross (before-tax) income.

The data now complete, we can proceed with the analysis in Section 3 which will focus on the relationship between expenditures and the proportion of those expenditures devoted to direct uses of energy. This proportion will determine the carbon intensity of household expenditures and thus the potential burden of climate policy. However, as will be shown in the following section, the composition of household expenditures is determined by many socio-demographic characteristics, in particular, a household's income and position in the life course. In Chapter 3, I investigate the changing nature of households over the life cycle and the resulting reallocation of expenditures that drives changes in carbon intensities and the level of household carbon dioxide emissions.

2.3. Economic Demography and Household Carbon Intensity of Consumption

As mentioned in Chapter 1, the regressivity of climate policy is founded in the empirical consistency that lower income households devote a larger proportion of their expenditures to direct uses of energy. This is true despite the fact that higher income households generate more CO_2 through their consumption due simply to their higher level of expenditures. As one might expect, quarterly household CO_2 emissions and expenditures are very highly correlated, a correlation coefficient of 0.9091. This correlation is present in Figure 2.3.1, displaying the highly intuitive belief that, "the more stuff one buys, the more CO_2 emissions are generated."

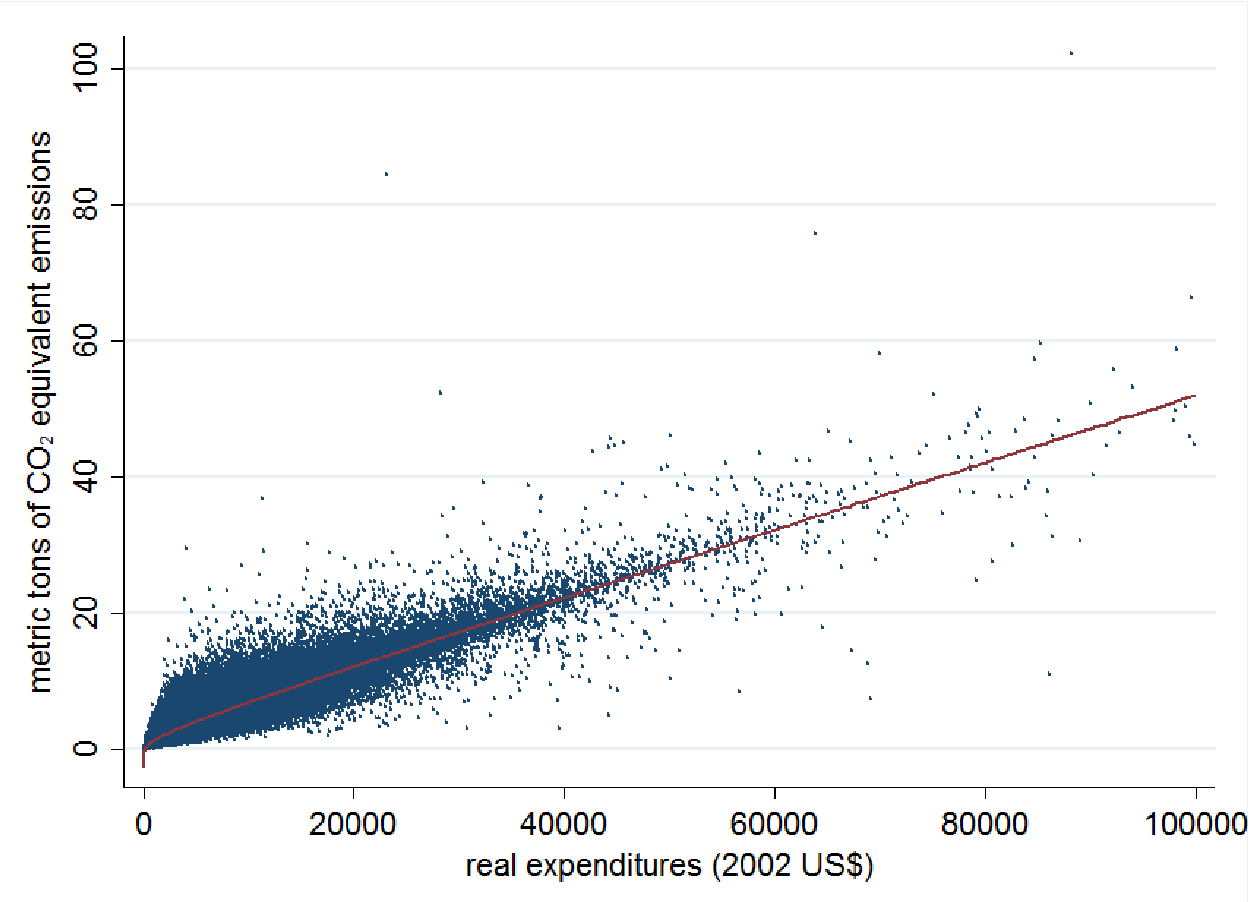


Figure 2.3.1. Quarterly Household CO_2 Emissions and Real Expenditures

More than 99% of households in the sample spend less than $100,000 per quarter, but the correlation coefficient is not significantly affected by restricting the sample in this manner (decreases to 0.9035). Therefore, household carbon dioxide emissions are largely determined by the level of expenditures. However, the degree to which each dollar of expenditures contributes to total emissions will depend upon the carbon intensity of each dollar spent. The carbon intensity of household expenditures is determined by the proportion of total expenditures devoted to direct uses of energy. This proportion varies in the sample from only 1% to nearly 34% at the 99^{th} percentile with a probability weighted mean of 8.08%. This proportion varies directly with the carbon intensity of household expenditures, as can be seen in Figure 2.3.2. This proportion is determined by household expenditure share decisions which are driven by their needs and preferences that are importantly shaped by life cycle and demographic characteristics. Therefore, understanding how and why household needs change is fundamental to an understanding of expenditure decisions and thus household carbon dioxide emissions and intensities.

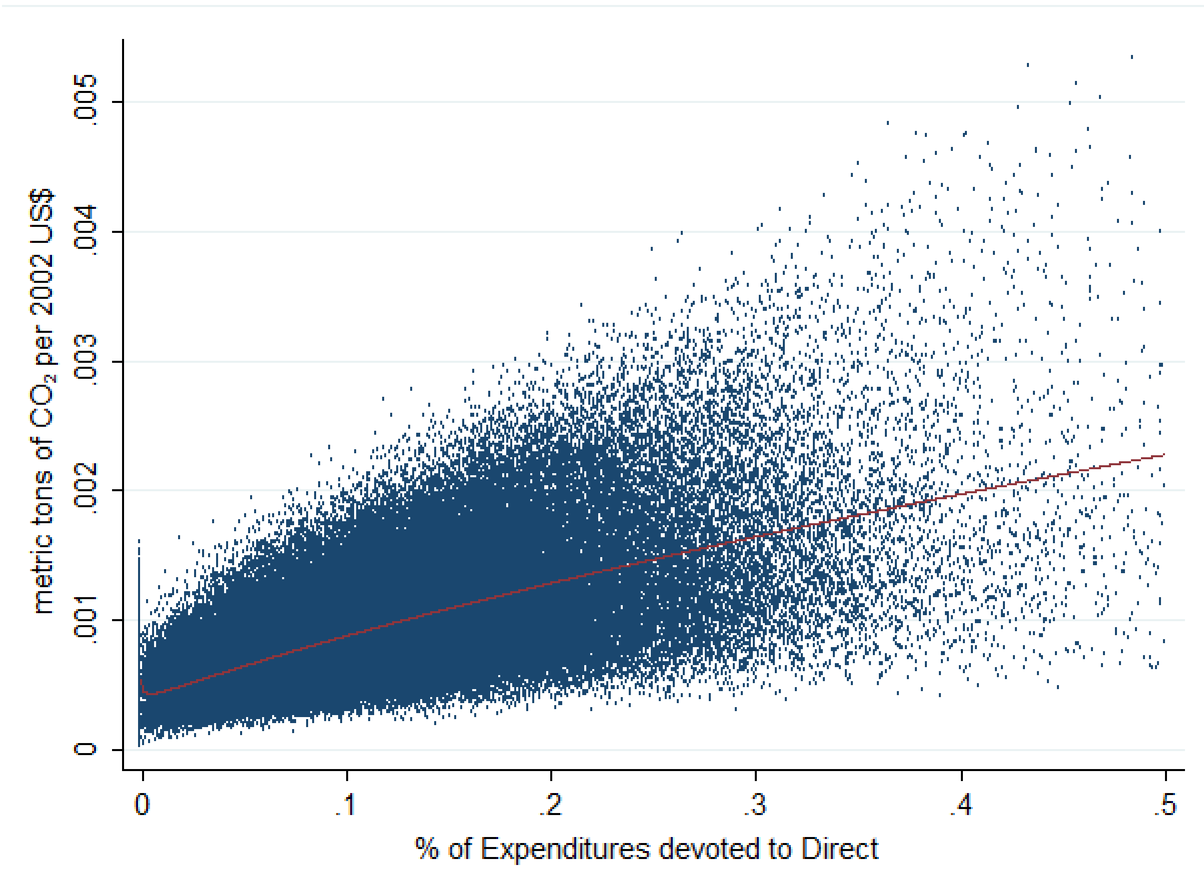
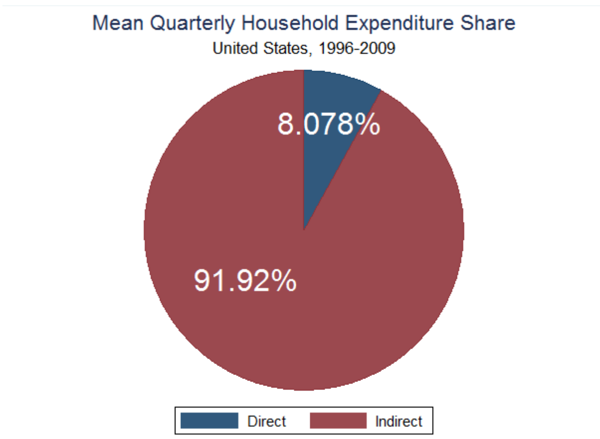
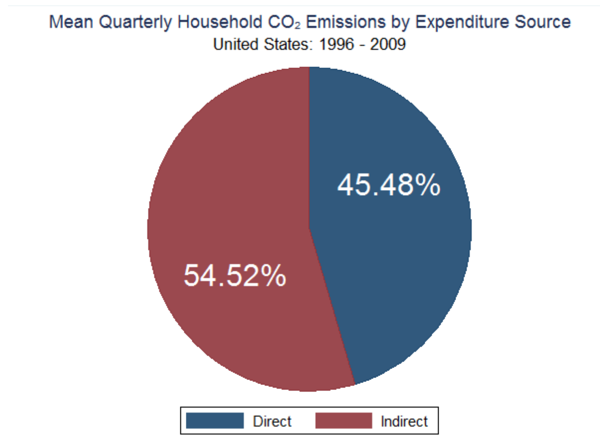


Figure 2.3.2. Carbon intensity variation with respect to the proportion of total expenditures devoted to direct uses of energy

A significant amount of research has been conducted analyzing the energy requirements of households since the 1970s, but much of this work has focused on direct uses of energy. However, households also generate GHG emissions indirectly through the purchase of other goods and services via the emissions embodied in their production processes. This component cannot be ignored; Bullard and Herendeen emphasized this point as far back as 1975. A significant proportion of household CO_2 emissions results from the indirect uses of energy through the purchase and distribution of goods and services. On average, around 90% of household expenditures are devoted to the purchase of these goods and services (Figure 2.3.3a) resulting in 54% of household CO_2 emissions, on average, (Figure 2.3.3b) over the period from 1996 – 2009 in the United States.



(a)



(b)

Figure 2.3.3. Mean quarterly household expenditure share (a) and mean quarterly CO_2 emissions by expenditure source (b).

The indirect carbon emissions resulting from the purchase of goods and services are equally important in the determination of household carbon intensity. Given the relationship in Figure 2.3.2, carbon intensity, predictably, is declining in the proportion of expenditures devoted to indirect uses of energy; doing so at an increasing rate. This relationship is shown in Figure 2.3.4.

The allocation of household expenditures between direct uses of energy (carbon intensive necessities) and all other indirect uses of energy (including both essential expenditures on food, clothing, shelter, education, and healthcare; and more discretionary expenditures on apparel, entertainment, and vacations) has been addressed in the literature starting with the "energy cost

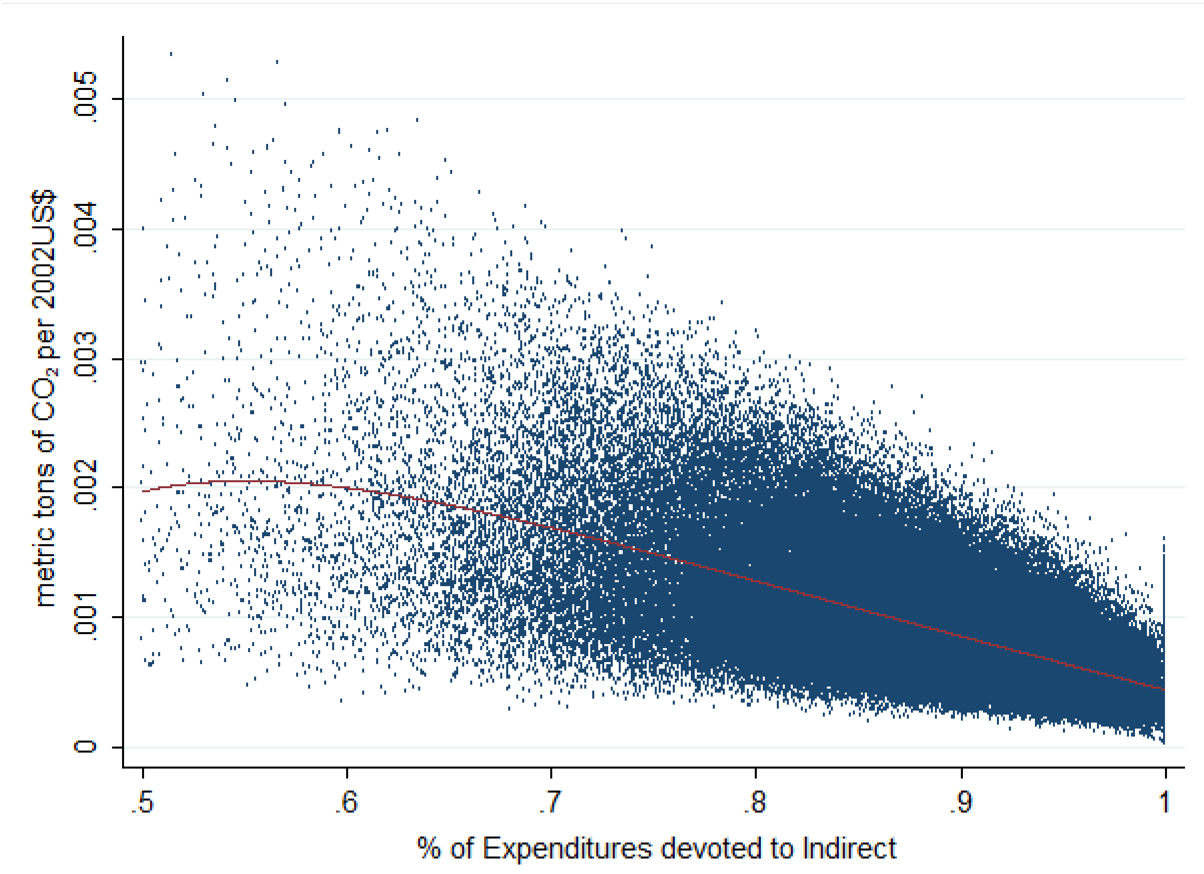


Figure 2.3.4 Carbon intensity variation with respect to the proportion of total expenditures devoted to indirect uses of energy.

of living" studies in the mid-1970s and continuing today (Bullard & Herendeen, 1975; Herendeen & Tanaka, 1976; Herendeen, 1978; Bullard et al., 1978; Herendeen et al., 1981; Vringer & Blok, 1995; Lenzen, 1998; Reinders et al., 2003; Pachauri, 2004; Carlsson-Kanyama et al., 2005; Moll et al., 2005; Bin & Dowlatabadi, 2005; Lenzen et al., 2006; Shammin & Bullard et al., 2009; Shammin et al., 2010). In order to fully understand differences in carbon intensities one needs to decompose the ratio of direct to indirect expenditures into its demographic and economic determinants. Table 2.3.1 summarizes the direct and indirect expenditure categories and their corresponding mean (over the period 1996 – 2009) carbon

Table 2.3.1. Carbon Intensity of Household Expenditure Categories

Categories	Carbon Intensity (lb CO_2e / 2002US$)
Average carbon intensity (all categories)	1.576
Average carbon intensity of direct expenditures	8.350
Average carbon intensity of indirect expenditures	0.961
Direct Expenditures	
Natural gas	5.445
Electricity	20.156
Gasoline and motor fuel	3.041
Fuel oil and other fuels	4.757
Indirect Expenditures	
Food	
Food at home	2.656
Food away from home	1.257
Housing	
Mortgage interest	0.242
Property taxes	2.005
Maintenance, repairs, insurance, and other expenses	0.242
Rent payments	0.635
Other lodging	1.253
Indirect Utilities	
Telephone	0.469
Water and other public services	3.832
Domestic services and household operations	
Domestic services excluding child care	0.764
Babysitting and child care	0.691
Other household expenses	0.532
Household equipment and supplies	
Household textiles	1.184
Furniture	1.244
Floor coverings	2.052
Major appliances	1.218
Small appliances and miscellaneous housewares	1.452
Miscellaneous household equipment	0.944
Transportation	
New and used cars and trucks	1.126
Other vehicles	1.163
Vehicle finance charges	0.254

Maintenance and repairs	1.177
Vehicle insurance	0.142
Vehicle rental, leases, licenses, and other charges	0.332
Public transportation	1.124
Clothing and footwear	
Apparel and services	0.906
Footwear	1.081
Personal Insurance	
Life and other personal insurance	0.142
Retirement, pensions, and Social Security	0.242
Healthcare	
Health insurance	0.142
Medical services	0.610
Prescription drugs	0.658
Medical supplies	0.978
Personal care	0.548
Entertainment	
Fees and admissions	1.124
Televisions, radios, and sound equipment	0.655
Pets, toys, and playground equipment	1.712
Other entertainment	0.931
Education and reading	
Reading	0.629
Education	1.106
Alcohol and tobacco	
Alcoholic beverages	0.956
Tobacco and smoking supplies	0.804
Miscelleaneous	
Miscellaneous expenditures	0.367
Cash contributions	0.686

intensities used in this analysis.[24] While the selection of which expenditures to include in direct portion seems, at first, to be arbitrary; the choice of heating fuels, electricity, gasoline, and motor

[24] Given that carbon emissions resulting from a given dollar of household expenditures are calculated using these per dollar figures, many differences in products with each category are ignored (see note 12), or more importantly, some households are assumed to have a larger (or smaller) carbon footprint than they actually do. For example, a wealthy household may spend $100 on brand-name personal care products (such as toothpaste, shampoo, etc.) while a lower income household may purchase an identical quantity of such products, but will purchase the generic brand; therefore spending less than $100. In this example, the lower income household has purchased an equal quantity of products from the "personal care" sector, but, according to the present model, has generated

oil is consistent with the bulk of the existing literature (Herendeen & Tanaka, 1976; Herendeen et al., 1981; Vringer & Blok, 1995; Reinders et al., 2003). The purchase of these goods entail the most explicit generation of carbon dioxide emissions. Electricity is the most carbon intensive good that households can purchase, resulting primarily from the reliance on coal-fired power plants in the United States (EIA, 2011). The mean carbon intensity of direct expenditures is 8.35 lb CO_2 equivalent emissions per dollar while the mean carbon intensity of indirect expenditures is a comparatively minute 0.961 lb CO_2 equivalent emissions per dollar.

The carbon intensity of consumption is driven by household characteristics that vary over the life course, most notably income and the age of the head of household. These characteristics jointly determine preferences for different goods and services that establish the composition of household expenditures among direct and indirect generation of carbon emissions. The needs of heterogeneous households within the United States population are largely determined by their position in the life course, while income will determine their ability to acquire the goods and services to fulfill those needs.

Therefore, to establish the determinants of household expenditures that give rise to GHG emissions, the focus of the study must be the household life cycle – the core element of which is that transitions in the family situation of different household groups can be meaningfully related to a systematic spending behavior. As households make transitions from one life stage to another, resources undergo a reallocation to accommodate the changing household needs and circumstances. Household expenditures follow a stable inverted U-shaped path (see Figure 2.3.5) over the life course that has been documented by much of the existing literature (Friedman, 1957; Ando & Modigliani, 1963). The permanent income hypothesis

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less CO_2 because it has lower expenditures. As a result, the income effect of expenditures and emissions may be overestimated through a lack of product specificity.

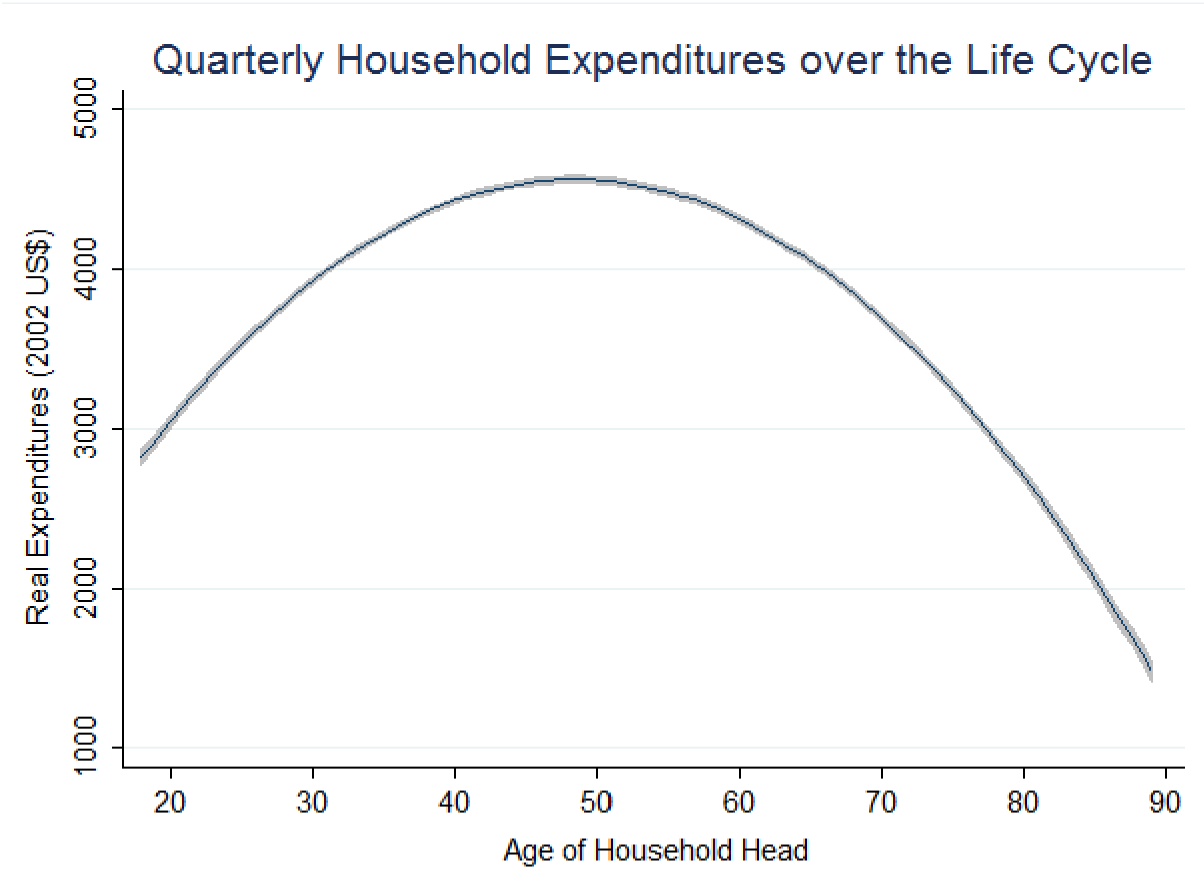

Figure 2.3.5. Quarterly Household Expenditures over the Life Cycle

implies that this is a result of changing income levels over the life course, which also follows this same inverted U-shaped path (see Figure 2.3.6). Given the correlation between expenditures and carbon emissions; quarterly household carbon emissions also follow this same inverted U-shape over the life course. Furthermore, this relationship is independent of the level of household income (see Figure 2.3.7), further emphasizing the importance of the position in the life course in determination of household expenditures and carbon emissions. These emissions trajectories over the life course are determined by the changing composition of household preferences as they transition from one life phase to the next. These changing preferences are evidenced by the consistent dynamics of household carbon intensity throughout the life course. The life cycle of

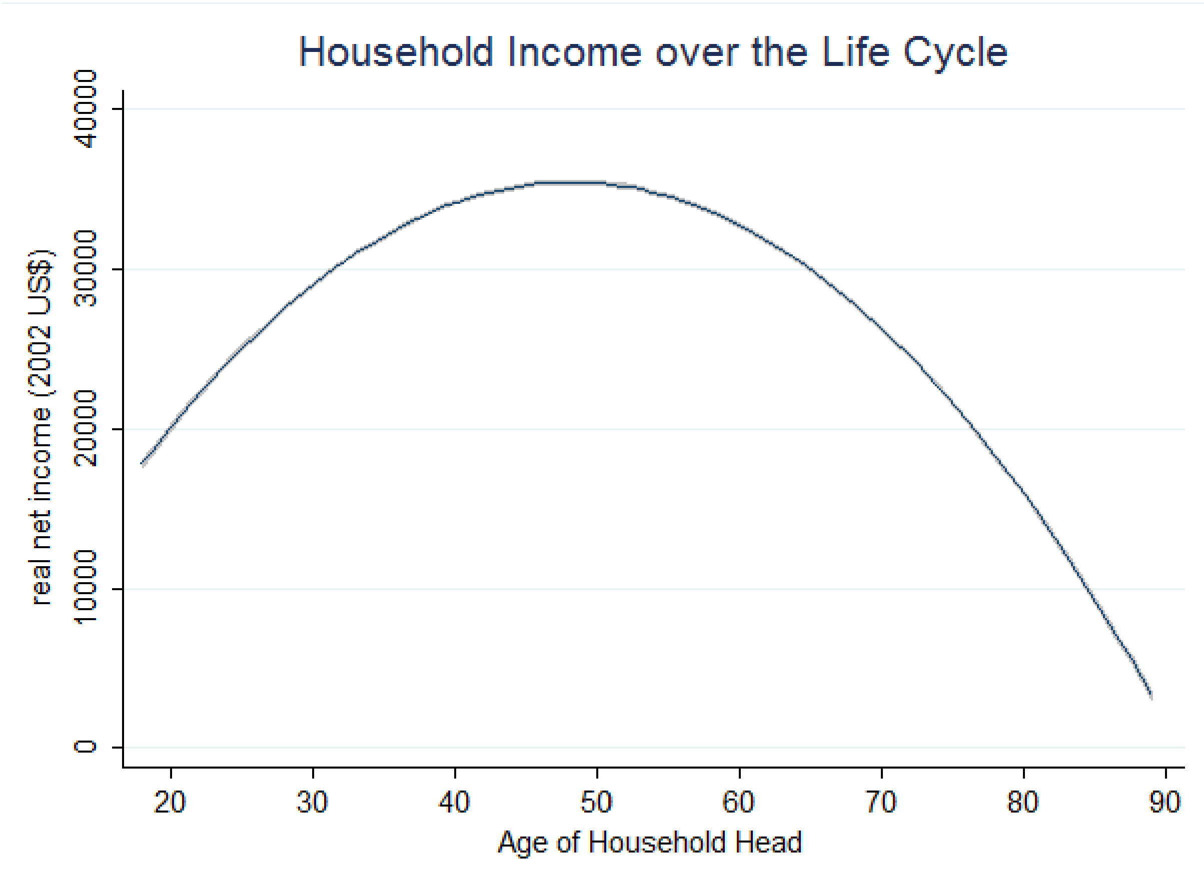

Figure 2.3.6. Real Household Income over the Life Cycle

carbon intensity is marked by three distinct phases; phase 1: ages 18 to 41, phase 2: ages 42 to 57, and phase 3: ages 58 to 89. Each life phase is classified by a consistent pattern of changing carbon intensity. Phase 1 is classified as a period of rising carbon intensity; phase 2 as a period of stable or falling intensity; and phase 3 as a period of rising intensity. The objective of Chapter 3 is to determine the reasons for the differences in preference formation giving rise to these distinct life phases. Figure 2.3.8 clearly shows the existence of these phases and their independence with respect to the level of household income. As the needs of households evolve over the life cycle the allocation of their expenditures among direct and indirect uses of energy is also evolving. This reallocation is reflected in the changing expenditure shares that households

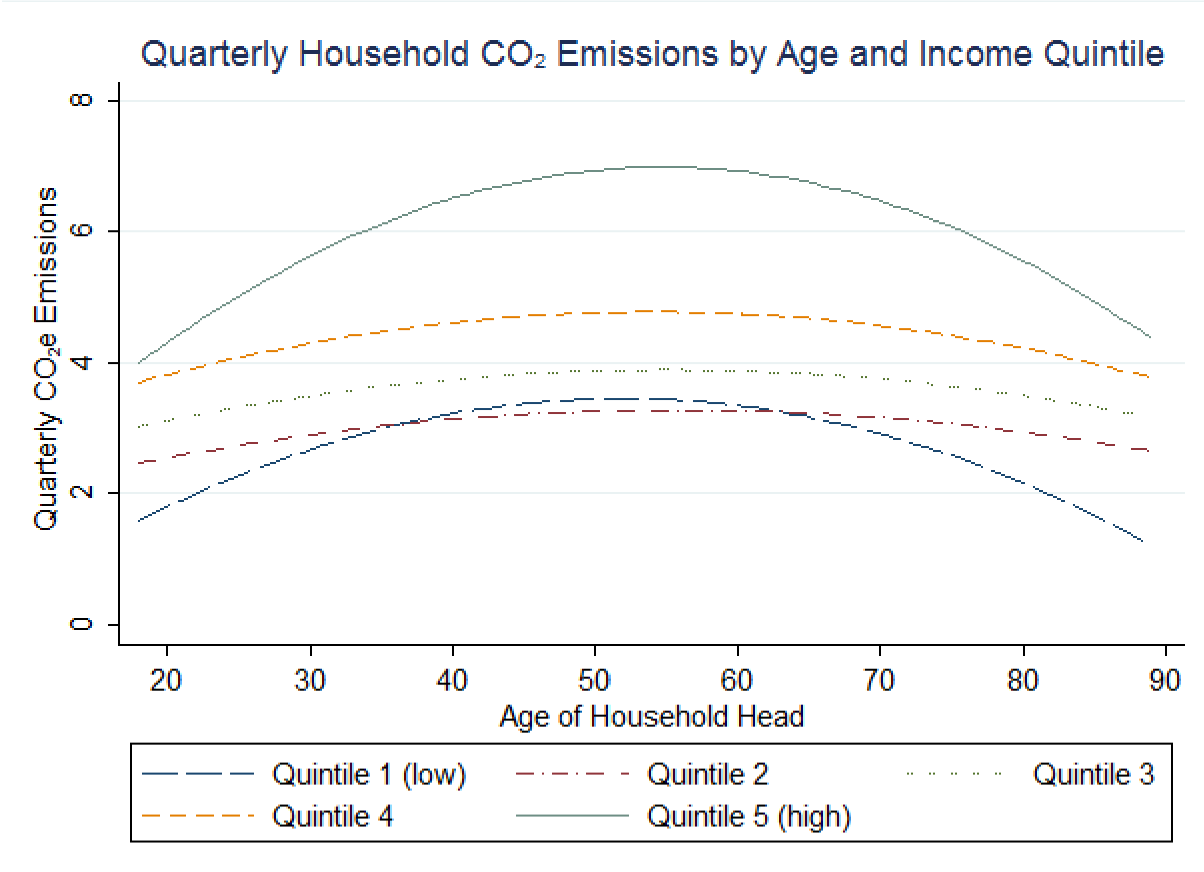

Figure 2.3.7. CO_2 Emissions by Income Quintile over the Life Cycle

choose to devote to the 13 different aggregated expenditure categories[25] over the life cycle, as presented in Table 2.3.2. As households progress through the life course (as the head of household ages) they spend relatively less on housing, personal insurance, and transportation; but more on utilities and healthcare. This reallocation of expenditures over the household life cycle is critical in the determination of household carbon intensities and emissions and will determine how a particular household will be affected by climate policy. After establishing which household demographic characteristics are most important in establishing household carbon emissions in Chapter 3, I will return to the shifting allocation of expenditures across these 13

[25] A complete list of the expenditures included in each category is available in Appendix 4.

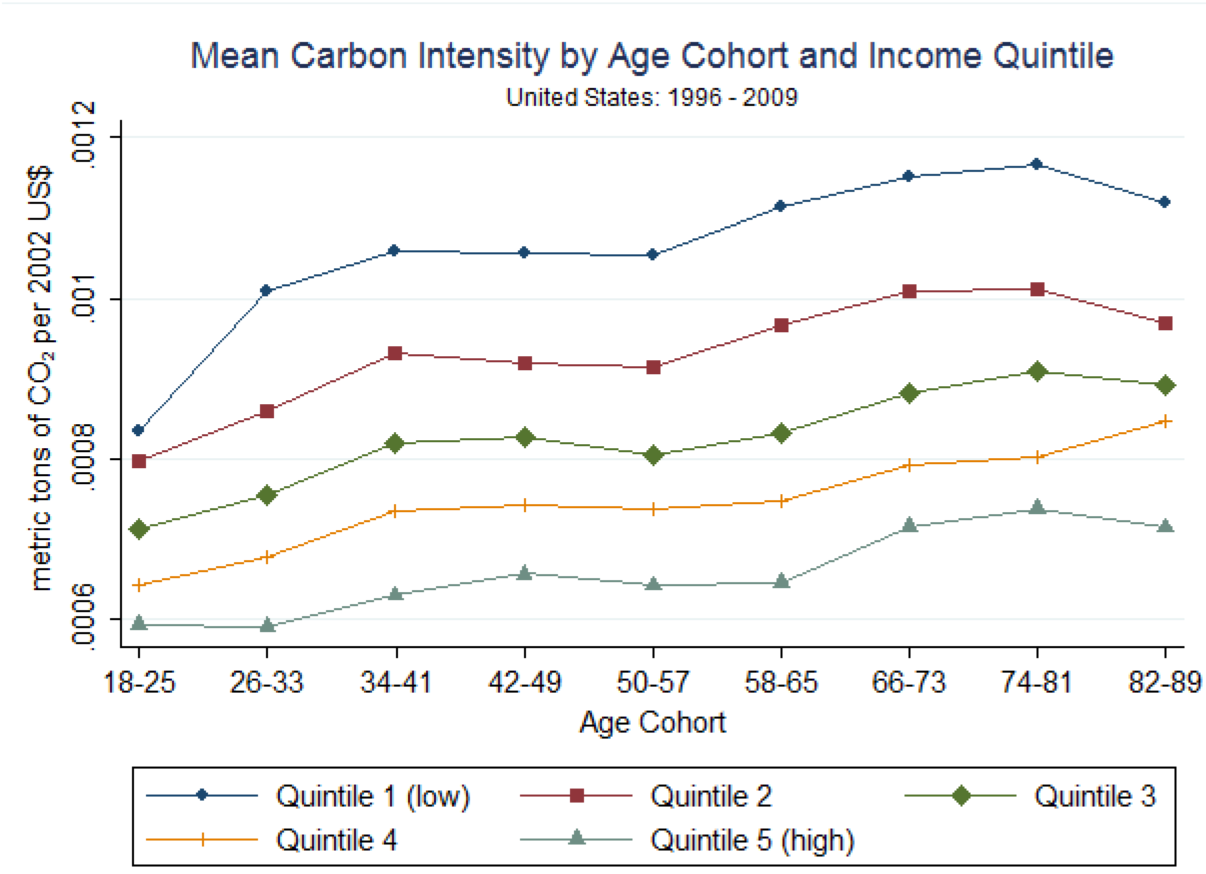

Figure 2.3.8. Carbon Intensity by Income Quintile over the Life Cycle

Table 2.3.2. Household Expenditure Shares over the Life Cycle

	Expenditure Share		
	Life Phase 1	Life Phase 2	Life Phase 3
Food & Beverage	18.46%	17.27%	18.94%
Housing	24.09%	21.87%	19.93%
Utilities	8.58%	9.58%	12.32%
Domestic Services	1.80%	1.22%	1.66%
Household Equipment	2.63%	2.57%	2.44%
Personal Insurance	10.44%	12.53%	5.77%
Clothing & Footwear	4.04%	3.00%	2.38%
Transportation	14.19%	14.38%	12.03%
Healthcare	4.38%	6.17%	13.95%
Entertainment	4.76%	4.44%	4.15%
Education	2.05%	1.67%	0.87%
Alcohol & Tobacco	2.33%	2.10%	1.51%
Miscellaneous	2.25%	3.20%	4.05%

categories over the life cycle and the contribution of each household member to these expenditures in chapter 4.

2.4. Conclusion

Differences in household income have been the focus of the great bulk of literature on the incidence of climate policy. There are indeed differences in carbon intensities across income quintiles, supporting the conclusion of the income regressivity of climate policy. However, the needs and therefore expenditure decisions of households are importantly determined by their position in the life course leading to distinct emissions and intensity trajectories over the life cycle.

The dataset compiled herein provides a comprehensive accounting of household emissions by including not only direct energy expenditures but also expenditures on other goods and services that generate emissions indirectly through the energy requirements of their production processes. This allows for an examination of preference formation through the reallocation of expenditures as households progress through the life course. I find that this progression is marked by distinct transitions in the expenditure decisions of households – generating robust trajectories of both household carbon intensities and emissions, independent of the level of household income.

To arrive at a complete understanding of household carbon dioxide emissions and climate policy incidence a more refined analysis of carbon intensities across different household groups over the life cycle is warranted. The changing needs of households throughout the life course are independent of income, but may be explained by other factors; the size and composition of the household, the region of the country, or even the education level of the household head. The objective of Chapter 3 is to disentangle the impacts of these different household characteristics in order to determine those which are most heavily impacting expenditure decisions, and thus carbon dioxide emissions and intensities.

CHAPTER III

The Demographic Determinants of Household Carbon Dioxide Emissions

3.1. Introduction

An understanding of the factors determining household expenditures and the resulting GHG emissions is crucial in explaining present levels of emissions and the potential incidence of climate policy. The household (often interchangeable with the family, but not always) is the most fundamental of all social groups and is the basic economic unit in society. The way that needs are determined and provided by the household are fundamental to an understanding of household expenditure decisions and the resulting GHG emissions. As developed in Chapter 2, the needs of households are determined primarily by the position in the life course with income providing the resources to obtain those needs. However, the evolution of needs among different households will vary according to the size of the household (number of members), the type of household (married, married with children, single persons, or multiple unrelated single persons), the age of household members, and other important demographic characteristics. In other words, the composition of the population must be considered in addition to population size when attempting to explain and project GHG emissions.

Given the level of correlation among these demographic characteristics with household income, meaningful empirical investigations into household expenditures and GHG emissions are lacking due to the complexities inherent in attempting to decompose these effects. The present goal is to successfully disentangle the impact of demographic characteristics from the impact of income differences in determination of household carbon intensities and emissions. Section 2 summarizes and discusses the previous empirical literature on this topic. Section 3 describes the demographic characteristics of United States households over the study period and discusses the expected results of the analysis. Section 4 estimates the relative importance of a wide range of demographic characteristics in determination of household expenditures and the resulting emissions and discusses those results. Finally, in Section 5 I discuss the implications of these results for population policy and its implications for future carbon emissions and the potential implications for the analysis of climate policy incidence.

3.2. Previous Empirical Literature

A significant amount of research has been conducted in related areas, albeit through a variety of different threads; the energy cost of living studies beginning in the 1970s (Bullard & Herendeen, 1975; Herendeen & Tanaka, 1976; Herendeen, 1978; Bullard et al., 1978; Herendeen et al., 1981), studies analyzing the direct and indirect energy requirements of households (Vringer & Blok, 1995; Reinders et al., 2003), those studies which explicitly analyze the impact of demographic characteristics on household energy use (Ironmonger, et al., 1995; O'Neill, 2000; O'Neill & Chen, 2002; Jiang & O'Neill, 2007), and those studies that extend the analysis to carbon emissions and climate change (Dalton et al., 2008; Shammin & Bullard, 2009; Shammin et al., 2010; Zagheni, 2011). Therefore, the goal of this section is to illuminate the intersection of these different literature threads in order to analyze household expenditures in such a way as to focus existing knowledge of household energy use and its demographic determinants toward a valid understanding of household carbon emissions and the potential incidence of climate policy.

Herendeen and Tanaka (1976) emphasize the importance of including not only direct uses of energy (electricity, home heating fuels, and gasoline) by households, but also indirect uses of energy through the purchase of other goods and services in any analysis of household energy use. The focus of their study is on the differences in energy requirements of households of different incomes and sizes and a brief discussion on the effect of urbanization on energy use. They find that the energy requirements of households with similar incomes are statistically identical regardless of the number of people in the household, with single person households being the only exception (significantly lower energy requirements). While not mentioned in their study, this suggests the existence of significant economies of scale within the household, a topic I will return to shortly. The results of their analysis on energy requirements with respect to households of different incomes state that the proportion of total energy requirements resulting from direct uses of energy falls from 65% to 35% when going from poor to rich. This increase in indirect energy expenditures is dominated by increases in education, travel, housing, and investments – a key insight into the determination of carbon intensities for households of different income levels. Their results also suggest that urban households are less energy intensive than rural households, a result of the fact that urban households spend 20% less of their budget on residential energy and automobile fuel. This is consistent with the intuitive idea that urban households tend to live in smaller dwellings, such as apartments, and to drive less.

A similar study, Herendeen, Ford, and Hannon (1981), confirms many of the results from the Herendeen and Tanaka (1976) study but fails to account for income differences when estimating the impact of household size on household energy requirements. This oversight can blur the importance of household size and its implications for the generation of economies of scale within the household. The basic rational for economies of scale within the household is based on the observation that energy use (and emissions) rises less than proportionately with increases in household size due to the "sharing" of energy made possible by cohabitation. A two-person household, in general, does not use twice the energy for heating or electricity of a single-person household. These household economies of scale are critical to understanding past energy use and emissions as well as developing accurate projections of future energy demand and emissions. If economies of scale are not present, then household energy use will vary significantly with household size. If economies of scale exist, and are quite large, then household energy use will not vary with household sizes of two or more people.

Ironmonger et al. (1995) analyze cross-sectional data on adult-only households in Australia and find that economies of scale exist in direct residential energy expenditures, including transportation. They conclude that single-person households use 30% more energy per adult than do two-person households which use 15% more energy per adult than do households with three or more people. This result is robust to differences in income, meaning that estimates of these economies of scale are not biased as a result of any correlation between the level of income per adult and the size of the household. Lastly, they find that these patterns of expenditure and economies of scale are nearly identical across households of different age compositions, with mixed households (no children, with adults both older and younger than 45 years) being the main beneficiaries of these economies of scale in expenditures.

Vringer and Blok (1995) in a similar study on Dutch households include expenditures on indirect uses of energy through the purchase of goods and services in their analysis. This is an important distinction, as mentioned previously; they find that, on average, 54% of household energy use is a result of indirect expenditures on goods and services. They also find that significant economies of scale exist. As household size increases beyond two people, no significant differences in total energy requirements are observed. Just as in Ironmonger et al. (1995) they find that age does not play a significant role in the relationship between energy consumption and income; households with heads aged 40 to 50 have the highest average energy requirements, but also the highest average net income. Counter to Ironmonger et al. they find a significant income effect in energy requirements. This is a likely result of the inclusion of indirect expenditures on goods and services that one would expect to more responsive to income differences since these expenditures are decidedly more discretionary than those included in the Ironmonger et al. analysis of direct expenditures.

O'Neill (2000) also finds evidence of economies of scale within the household for the United States using 1997 data from the Residential Energy Consumption Surveys (RECS). He finds a less than proportional increase in household energy consumption with household size, or equivalently, this is also shown as a decline in per capita energy consumption with increasing household size. Importantly, O'Neill also focuses on the complications that arise due to the possible correlation between income, the age of the household head, and household size. If per capita income is correlated with household size, then differences in energy consumption may be due to income differences rather than the number of persons in a household. Also, the age composition of households may create the appearance of economies of scale due to the fact that a larger household size often implies the presence of children who consume less energy than an adult. This suggests that the number of children in a household or the familial ties within a household may determine the presence or level of economies of scale. O'Neill finds that economies of scale are less dramatic for adult-only households, but still present. It remains to be determined why households with children tend to consume less energy than adult-only households of the same size. It may be that households with children share more energy-related consumption than others. O'Neill also finds that the impact of household size on energy consumption is independent of income, consistent with the findings of Vringer and Blok (1995). This suggests additional research on the existence of economies of scale in total expenditures (including indirect expenditures) and decomposing the inter-related effects of income, age, and household size.

O'Neill and Chen (2002) take the decomposition challenge head on in a study again using RECS data for the United States in 1993-94. They focus here on per capita energy consumption, although the household is still the unit of analysis. They do this in order to estimate the effect on aggregate energy consumption of alternative distributions of households by various characteristics, *holding population size constant*.[26] They divide energy uses into residential (natural gas, electricity, etc.) and transportation (fuel consumption and expenditures for personal vehicles) to better inform their analysis. The exclusion of indirect expenditures in this analysis must be noted, as over half of total household energy use is ignored. They find that mean per capita energy consumption does indeed follow a clear pattern with respect to the age of the household head. Residential expenditures rises consistently with age, but transportation expenditures rise until age 51-55 and then fall to low levels at older ages. However, as previously noted several factors are likely to contribute to this relationship: income, household size, and household composition.

O'Neill and Chen focus on the presence of children in their analysis of household composition, mainly due to data limitations. They find that households with children use 35 percent less energy per capita for transportation and 44 percent less residential energy per capita than adult-only households. This effect is more pronounced when looking into households of varying size, suggesting that the energy use of any household of a particular size will be

[26] Emphasis by O'Neill and Chen (2002). This implies that changes in household distributions will only affect aggregate energy consumption if they affect overall per capita energy use. If per capita consumption varies significantly across households categorized by a particular variable, then changes in the distribution of households across different household groups will lead to changes in overall per capita consumption. This has important implications for future projections of energy use and emissions for a variety of different demographic changes.

dependent on its composition. For example, a household of five adults will have significantly different energy expenditure patterns than a household with two adults, two children under 15, and one child age 17. O'Neill and Chen also find that per capita energy use generally declines with household size, with two-person households using 17 percent less energy per capita than one-person households and three-person households using over a third less energy per capita than those living alone. This result tends to support the hypothesis of economies of scale within the household, as suggested by Vringer and Blok (1995) and Ironmonger et al. (1995). However, this result could be explained by other factors confounding the analysis. First, since income and energy use are so strongly correlated and per capita income falls with household size, it may be an income effect explaining these differences. Second, larger households tend to consist of more children and since children can be assumed use less energy than an adult this compositional effect may explain the decrease in per capita energy use as household size rises. Finally, energy use changes with life phase, so if the distribution of households by age (a marker for the position in the life course) varies across household size then this age effect may contribute to the observed pattern in energy use. O'Neill and Chen analyze each of these confounding factors in turn.

They find that one-person households on average have higher per capita incomes than larger households, so given the variation in energy use with income, at least some of the reason that energy use falls with household size is the result of an income effect. Larger households tend to have lower per capita incomes and thus lower rates of energy consumption per household member. In order to quantify this effect, O'Neill and Chen use a standardization method (Kitagawa, 1964; Dasgupta, 1994; Chevan & Sutherland, 2009) to arrive at estimates of income-standardized per capita energy use. Income-standardized per capita energy use still falls substantially with household size, suggesting that the observed decline is unlikely to be explained primarily by an income effect. While data limitations[27] somewhat restrict the level at which they can test for the presence of a compositional effect, as expected larger households tend to contain more children and less elderly. Using a similar standardization method they find that the presence of children in the household significantly reduces per capita transportation energy use as household size rises. This is a result of the fact that most children are not themselves drivers so contribute proportionately less to household demands for transportation related expenses and energy use. Interestingly, the compositional effect on residential energy use is found to be much weaker, suggesting that a child's contribution to demand for heating and electricity is nearly equal to that of an adult. The total effect of household composition on energy use is modest, albeit stronger than the income effect (which may itself be influenced by composition since the decline in per capita income as household size increases is most likely due to the increased prevalence of children in larger households) implying that economies of scale may still be present.

O'Neill and Chen also find that the distribution of the population by the age of household head varies substantially across household size, thus some difference in energy expenditures across household size is likely due to variations in age, which is a good marker for the position in life course. The effects of age standardization are somewhat ambiguous given the age distribution among households of different sizes. One- and two-person households have a bimodal distribution of young and elderly households, while larger households display peaks in the age distribution at more narrow age bands. They conclude their cross-sectional analysis by stating that energy consumption varies strongly with age, some aspects of household

[27] O'Neill and Chen use 1993-94 RECS data which only has information on the presence and number of children (defined as under age 18) in a household.

composition, and household size. While income, age, and composition all impact the relationship between energy use and household size there is still a significant amount of variation remaining that could be explained by the existence of economies of scale within the household.

I extend upon this existing literature in three important ways. First, the amount of cross-sectional data available allows for empirically viable estimation of carbon intensities and emissions for households of various positions in the life course, sizes, incomes, and compositions. Second, the comprehensive nature of the Consumer Expenditure Survey allows for an analysis of indirect energy expenditures as well as direct expenditures, an often ignored component in the existing literature. The potential of economies of scale in indirect energy expenditures has implications for a complete understanding of household carbon emissions. Finally, the data I have obtained on the 1996 – 2009 period enables the leveraging of not only the cross-sectional variation in household energy use, but also the longitudinal variation, in order to assess the impacts of demographic change within the sample period. In the following section, I summarize the data coverage and the demographic characteristics of households over the study period.

3.3. Economic Demography and Household CO_2 Emissions

A large majority of the research conducted on the potential impacts of climate policy on households has focused on the variation in income among different households – a very important component determining household carbon intensities and emissions, but not the only one. The impact of income on household energy use has been well-documented; however, these analyses are often naïve in their treatment of other demographic factors that impact household expenditure decisions and the ensuing carbon emissions. As mentioned in Section 2, income, age, and household size and composition all impact the expenditure decisions of households and therefore are important determinants of household carbon emissions and intensities. In this section I will first highlight the impact of each of these household characteristics in turn, and then disentangle these effects in an attempt to establish the relative importance of those determinants.

As discussed in Chapter 2, there is a very strong relationship between the level of household income and carbon emissions. This relationship is robust over time, as seen in Figure 3.3.1, and is also accelerating in time as evidenced by the income elasticity of household carbon emissions increasing from 0.266 over the period 1996-1999 to 0.305 over the period 2007-2009, a statistically significant difference.[28] Furthermore, an important check of the developing intuition on household carbon emission determination is the relative responsiveness to income of indirect carbon emissions and direct carbon emissions. Over the period 1996-1999, the income elasticity of indirect carbon emissions is 0.340 and 0.145 for direct emissions, meaning indirect expenditures (and emissions) are more than twice as responsive to changes in household income – a ratio of 2.35. This result is expected given the discretionary nature of indirect expenditures relative to the necessity of direct expenditures. Over the period 2007-2009, this ratio remained relatively unchanged at 2.36 with an income elasticity of indirect carbon emissions of 0.418 and an income elasticity of direct carbon emissions of 0.177.[29]

[28] The elasticity estimate over the 1996-1999 period of 0.266 has a 95% CI of [0.254,0.277], and the elasticity estimate over the 2007-2009 period of 0.305 has a 95% CI of [0.292,0.318].

[29] All elasticities are evaluated at the sample mean of after-tax real household income within each period, 1996-1999 and 2007-2009: $32,740.69 and $41,028.14, respectively. We would expect these elasticities to differ according to income level, the income elasticity of total carbon emissions for the lowest income quintile is -0.129, 95% CI = [-0.135, -0.122], and 0.380, 95% CI = [0.348, 0.411], for the highest income quintile over the entire sample period 1996-2009.

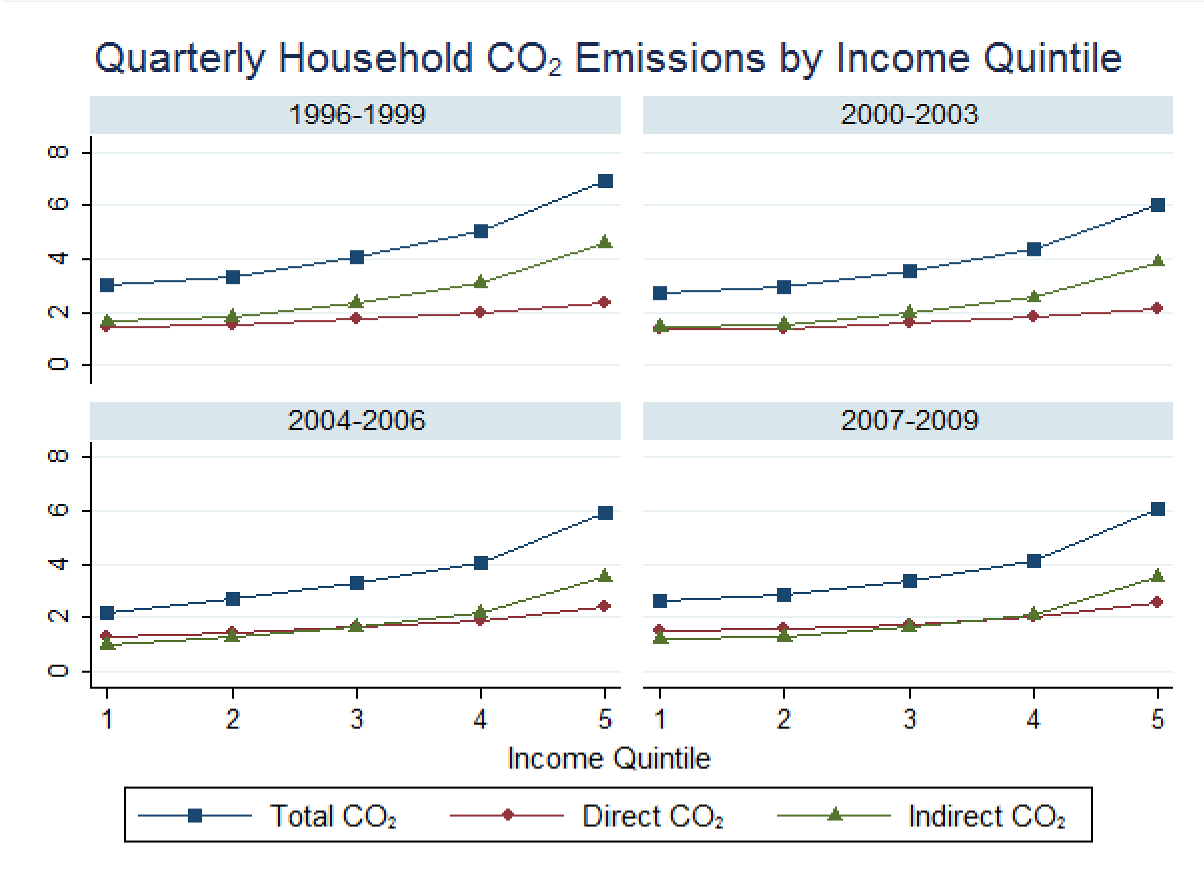

Figure 3.3.1. Quarterly Household CO_2 Emissions by Income Quintile over time.

One reason for the overall increased responsiveness in the 2007-2009 period is due to the recession, as one would expect households to be more responsive in their expenditures (and thus, emissions) to income changes during a period of economic hardship. However, the general increase in these income elasticities over time can also be attributed to the rise in real incomes corresponding with declining personal savings rates over the period (Guidolin & La Jeunesse, 2007). As households spend an increasingly larger proportion of their income, one would expect the income elasticity of total carbon emissions to increase.

In this discussion of income it must be noted that household carbon intensities do, in fact, differ across households in different income quintiles. However, there has been substantial technological progress over the sample period that has reduced the carbon intensity of production for a vast majority of goods and services. As a result, we observe significant reductions in carbon intensities across households in all income quintiles, but the differences among quintiles remain, as seen in Figure 3.3.2. This is the fundamental explanation for the income regressivity of climate policy; however, as previously mentioned, income only provides households with the ability to purchase goods and services. Other demographic characteristics of households, such as the age of the household head and household size and composition, will determine the wants and needs that necessitate those expenditures.

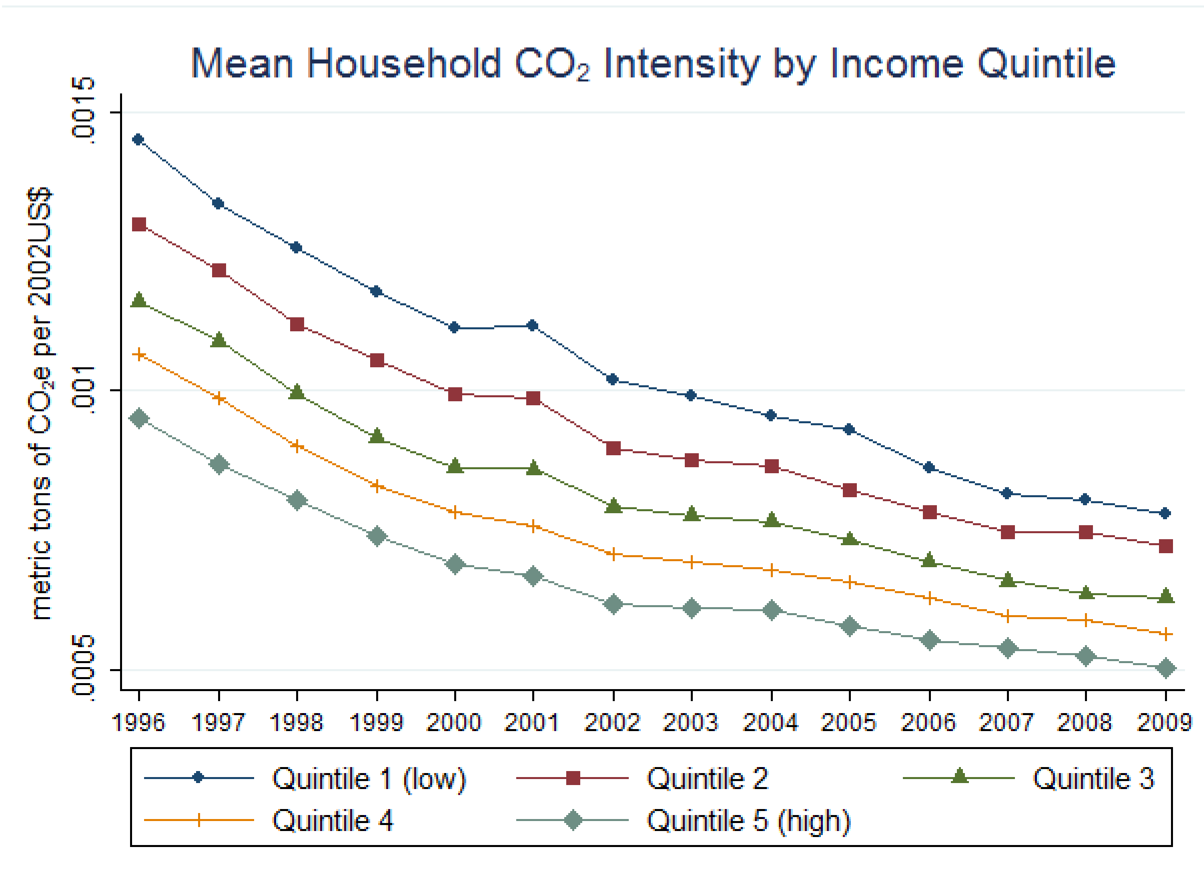

Figure 3.3.2. Mean Household CO_2 Intensity by Income Quintile over time.

The position in the life course is a key indicator for the needs of households and the age of the household head can be used as a proxy for a given household's position. This has significant implications in the determination of household needs. Now, it must be noted that while age can provide insight into a household's carbon intensity and the resulting emissions, these effects can be confounded by the size and composition of that household. With these correlations in mind, we can proceed to summarize the population age structure of the sample, and the effects of age on carbon emissions. The age structure of the adult population (see Figure 3.3.3) reflects the fact that the United States adult population is aging. The mean age of a household head during the period 1996-1999 is 47.69 years while the mean age during the period 2007-2009 is 48.98 years, constituting a 2.7% increase in mean age – a very large shift in demographic terms over a relatively short period of time.[30] As eluded to at the end of Chapter 2, the life course is marked by three distinct phases resulting in different carbon intensities (see Figure 2.3.8); therefore, the proportion of the population residing in each of the phases at any moment in time will largely determine the mean household carbon intensity and resulting emissions. The proportions can be observed in Figure 3.3.3 by the "fattening" of the right tail of the population age structure histogram over time, as well as the gradual shift in modal age rightward, reflecting the aging of the baby boomer generation. The middle of the life course (ages 42-57) is characterized by stable or falling carbon intensities, yet quarterly household carbon emissions peak around age 50 (see Figure 2.3.7 and Figure 3.3.4). As the majority of the United States adult population approaches this period of peak expenditures, one can expect aggregate emissions to continue to grow at a rapid pace, even with carbon intensities at their most stable position. Recall, that these emissions trajectories are consistent across all income quintiles, suggesting that it is more than simply the level of income that determines household expenditures and emissions. However, there is obviously a significant level of correlation between age, income, and household size as these all tend to peak in the middle of the life

[30] These estimates are significantly different from one another: the mean of 47.69 during the 1996-1999 period has a 95% CI = [47.57, 47.81], while the mean of 48.98 during the 2007-2009 period has a 95% CI = [48.85, 49.10].

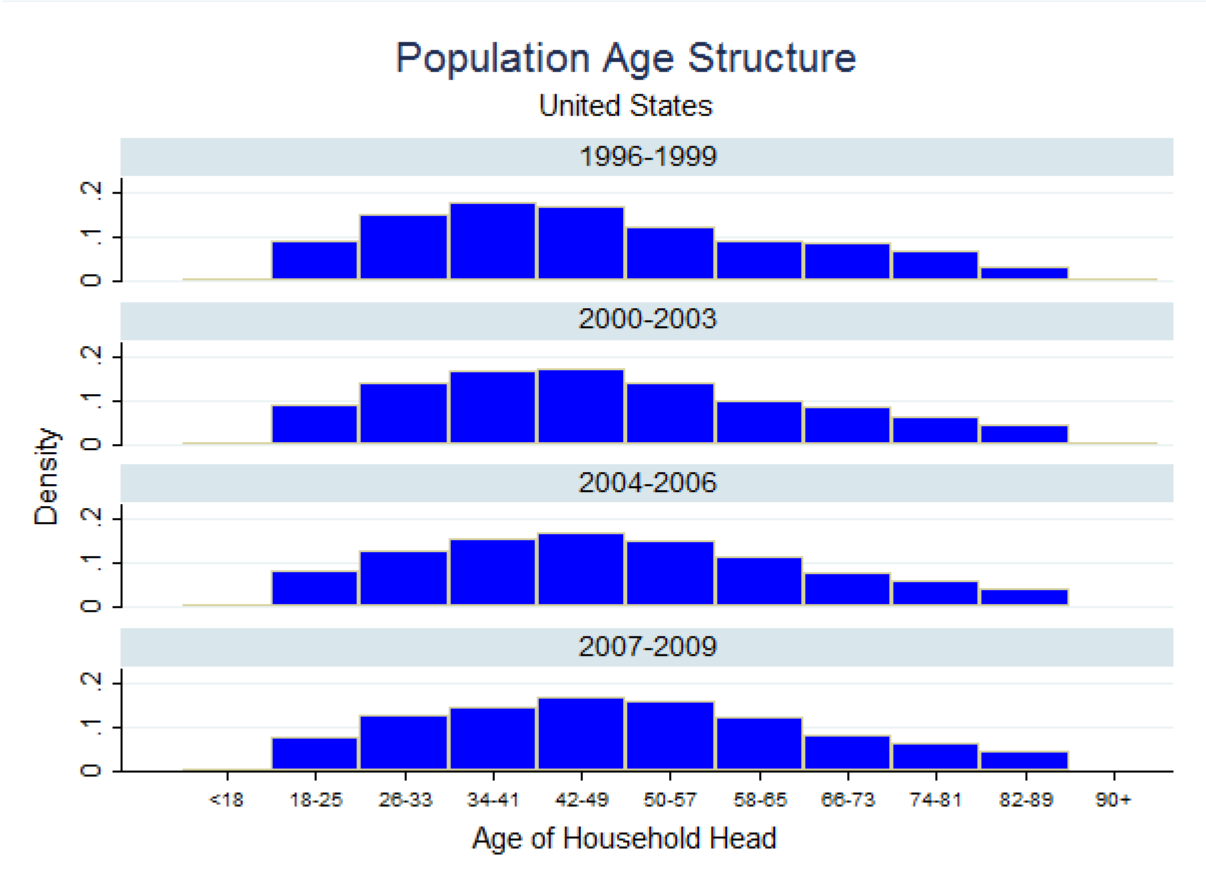

Figure 3.3.3. Population Age Structure over time, *age of household heads.*

course. The data show that household size peaks within the 34-41 year old age band, but we are seeing a drift of this peak to later in the life course over time, a result consistent with the delay of marital onset and family formation in the United States. As expected the mean household size is falling in time, from 2.53 members during the 1996-1999 period to 2.49 over the 2007-2009 period.[31] Figure 3.3.5 highlights two points: the drift in peak household size to later in the life course over time and the consistency of this maximum with respect to income. However, it should also be noted that higher income does seem to facilitate larger household size, or it may

[31] While this difference is small, it is statistically significant. The mean of household size of 2.53 during the 1996-1999 period has a 95% CI = [2.52, 2.54] and the mean household size of 2.49 during the 2007-2009 period has a 95% CI = [2.48, 2.50].

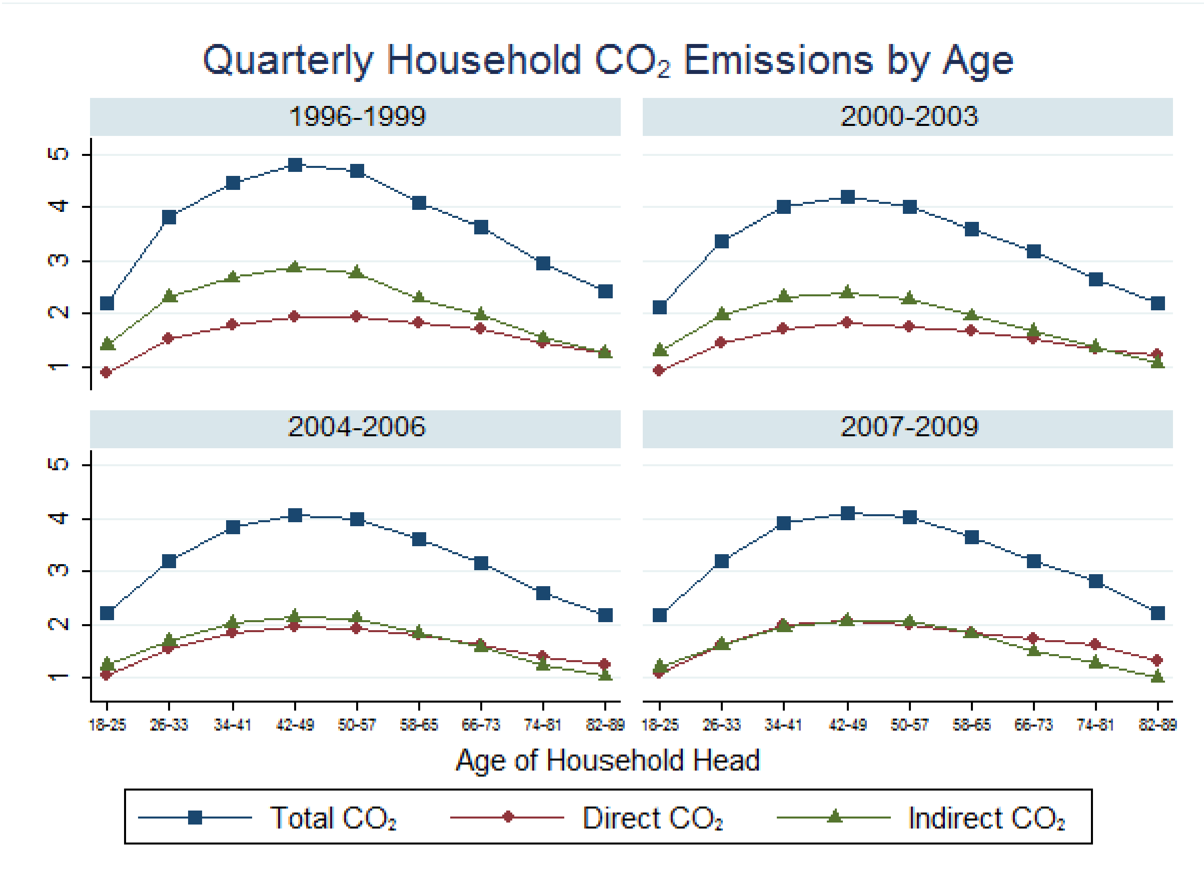

Figure 3.3.4. Quarterly Household CO_2 Emissions by Age of Household Head

be the case that larger household size necessitates a larger incomes to sustain, forcing increased labor force participation in the form of a second or third job or increased hours worked.[32] The causal direction of this result is, as of now, unclear. The dominating household size over the entire time period is a household comprised of two members, a class of households consisting primarily of either young or elderly members. Figure 3.3.6 shows the distribution of households across different household sizes over the four time periods, showing the dominating class of two-person households.

[32] The mean household size over the entire 1996-2009 period for households in the lowest income quintile (quintile 1) is 2.117 members, 95% CI = [2.109, 2.125], and the mean household size for households in the highest income quintile (quintile 5) is 3.132 members, 95% CI = [3.120, 3.145].

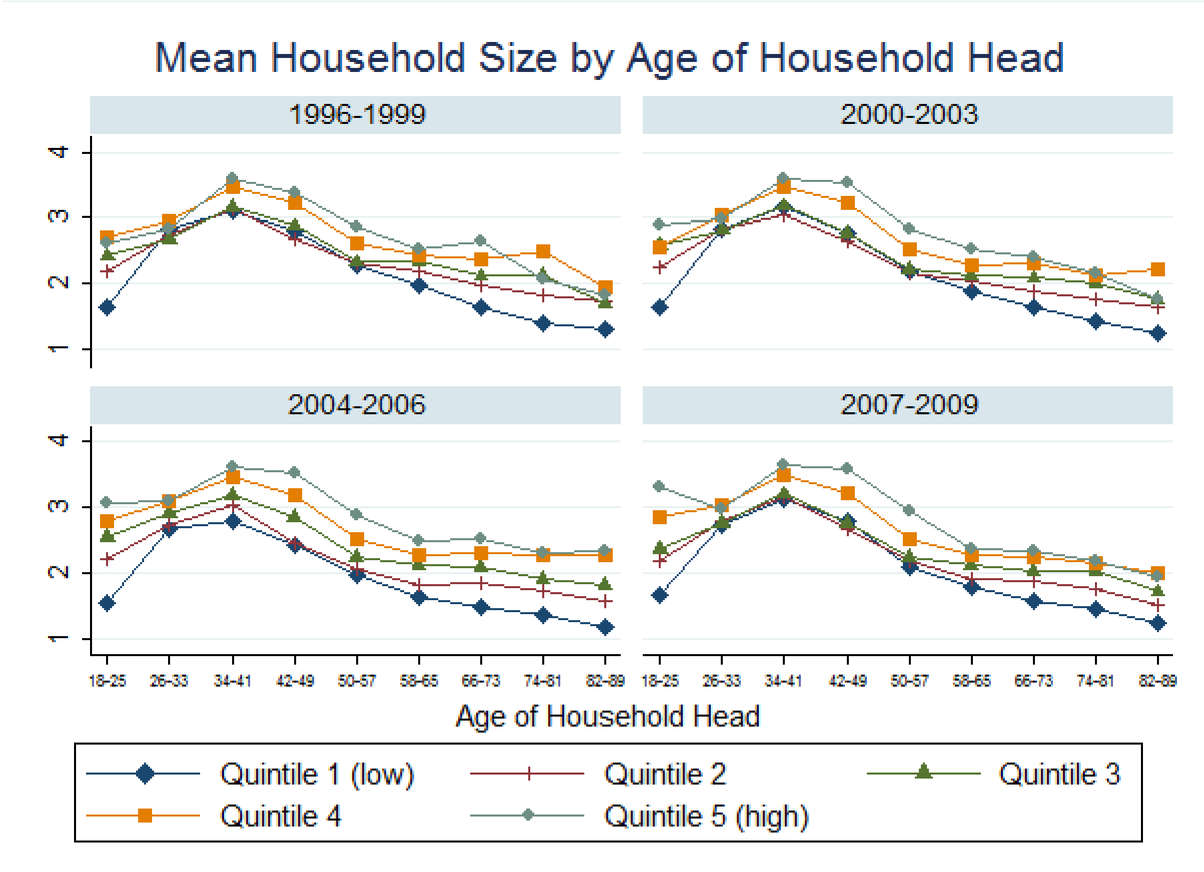

Figure 3.3.5. Mean Household Size by Age of Household Head

Interestingly, we observe the increased prevalence of two-person households over time, suggestive of both the aging of the population (baby boomers that have increasingly empty nests over the period) and the delay of family formation (young couples choosing to wait until later in the life course to have children).

The impact of household size on carbon dioxide emissions is one of the most interesting components. As mentioned in the review of the empirical literature, many authors have found that economies of scale exist within the household which enables households to add a member to the household and increase household carbon emissions less than proportionately. One extension provided by this research is an analysis of these economies of scale in both direct and indirect

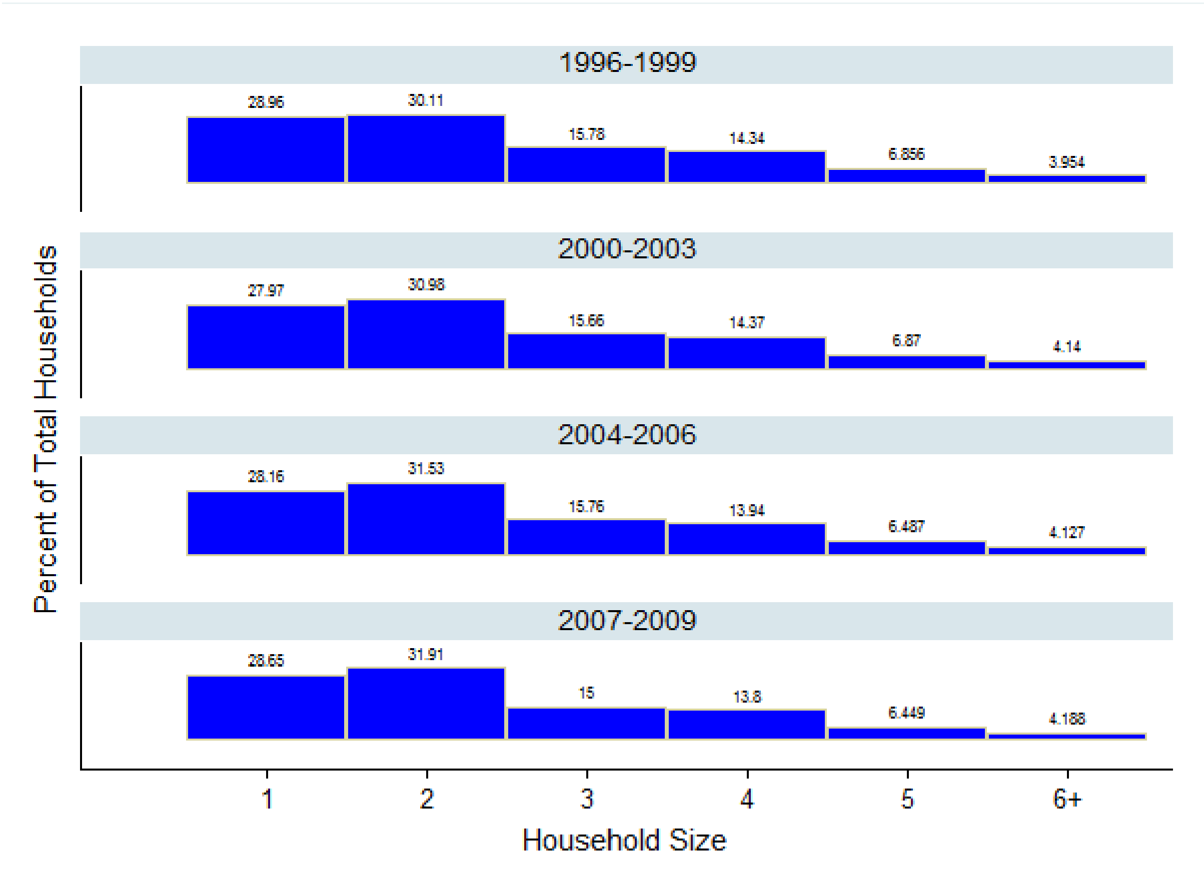

Figure 3.3.6. Distribution of Households across Household Size over time.

expenditures. While one would expect these effects to be stronger in direct uses of energy as household members share the heating and cooling within the home, share the benefits of light (generated by electricity), and share the benefits provided by many appliances (televisions, refrigerators, microwaves, etc.). It is less clear as to why or how indirect expenditures may provide the possibility of scaling, but the effect seems to be present for these indirect expenditures as well. This is evidenced by the less than proportional increase in carbon dioxide emissions as household size increases from one to households with six or more members, as seen in Figure 3.3.7. Furthermore, the diagram suggests that economies of scale within direct expenditures are diminishing over time (curve becoming steeper in time) while the economies of scale within indirect expenditures are actually increasing in time (the curve becoming flatter in

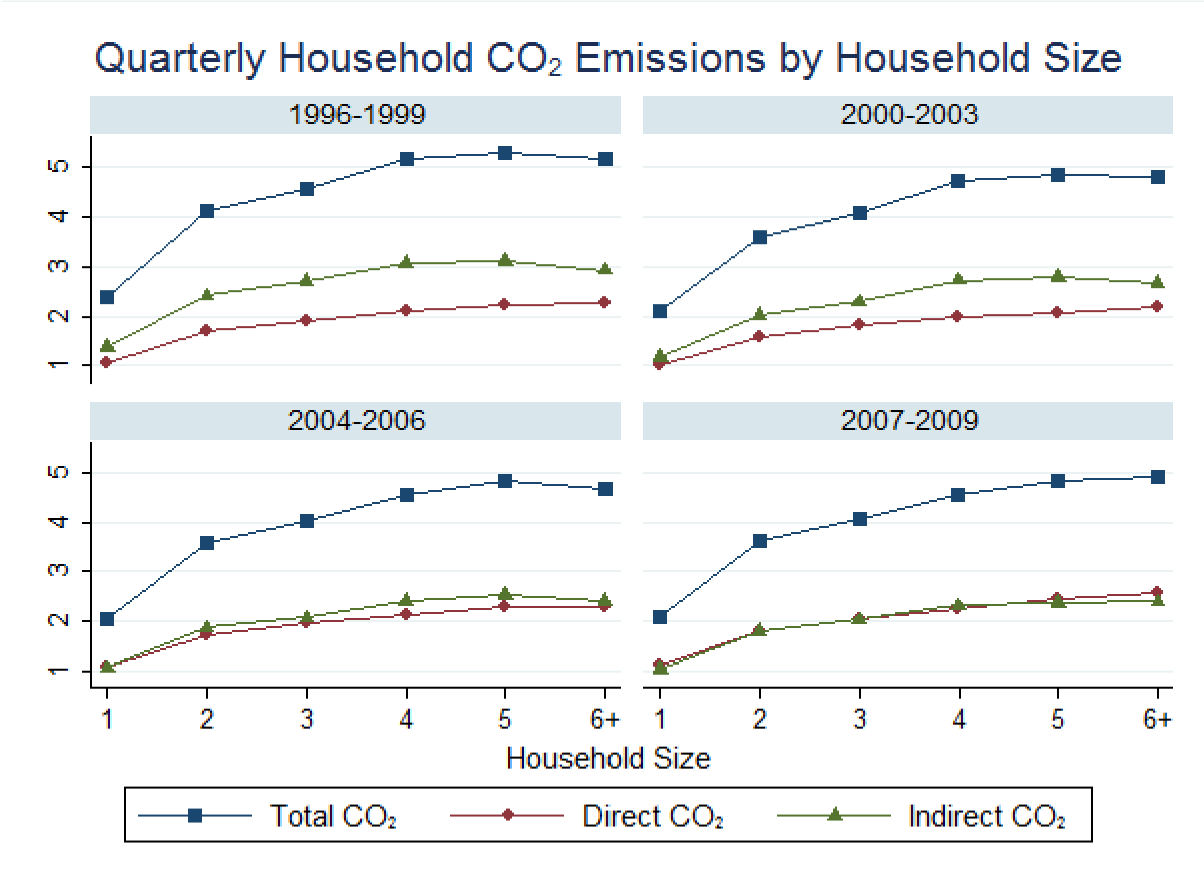

Figure 3.3.7. Household CO_2 Emissions by Household Size

time). This may be a result of shifts in the allocation of expenditures from indirect goods (such as food) into indirect services (such as child care). These shifts would be reflected in changes of household carbon intensities across different household sizes in time. I will return to this discussion in Chapter 4. The composition of a household may be the key to understanding the importance of household size in determination of carbon emissions. The composition of household members between adults and children is critical to the ability of a household to generate an income to facilitate expenditures and its ability to scale those expenditures. As the size of the household rises the proportion of adult-only households (defined as households with all members age 18 or older) decreases. This result is expected given the belief that larger households tend to be large due to the presence of children. This is evident in Figure 3.3.8, and

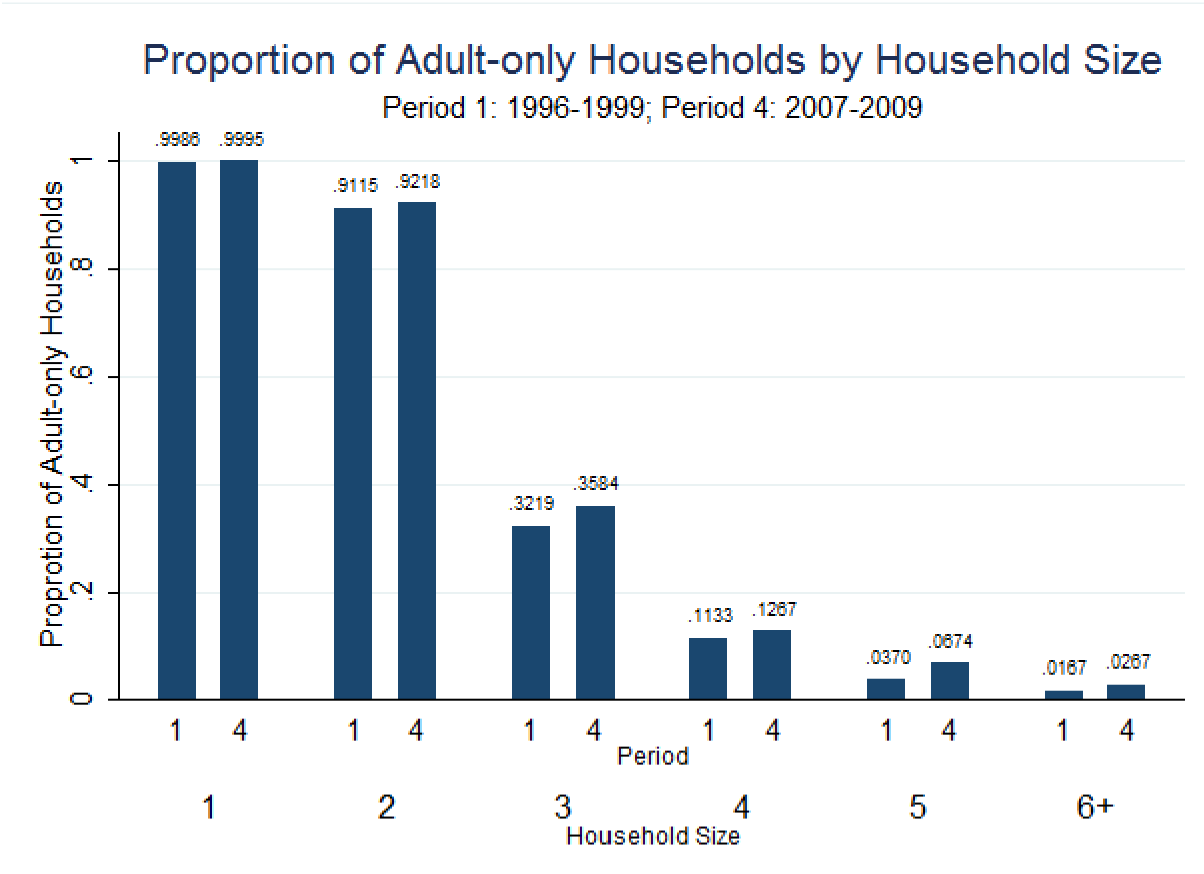

Figure 3.3.8 Proportion of Adult-only Households by Household Size

interestingly there is a decreased prevalence of children within households of all sizes over time. Over all household sizes the mean proportion of adult-only households over the 1996-1999 period is 0.639, while the mean proportion over the 2007-2009 period is 0.666, an increase of 4.2 percent.[33] Household composition affects carbon emissions by determining the degree to which the expenditures allocated to each member of the household contribute to total household emissions. On average, over the entire period 1996 – 2009, adult-only households generate more quarterly carbon emissions than households with children age 17 or younger of the same size, a result shown in Table 3.3.1 and reflected in Figure 3.3.9. This implies that the carbon cost of a

[33] These proportions are significantly different reflecting the decreased presence of children in the household over time. The mean of 0.639 over the 1996-1999 period has a 95% CI = [0.636, 0.642] and the mean of 0.666 over the 2007-2009 period has a 95% CI = [0.663, 0.669].

Table 3.3.1. Mean Quarterly CO_2 Emissions by Household Size and Composition

	Household Size				
	2	3	4	5	6+
Mean Quarterly CO_2 Emissions					
Households with children <18	2.786	4.027	4.717	4.927	4.886
Adult-only households	3.808	4.509	5.065	5.495	5.399
F - Statistic (difference of means)	1103.59	175.09	28.58	7.37	5.53
Probability > F	0.0000	0.0000	0.0000	0.0066	0.0187

N = 259,646

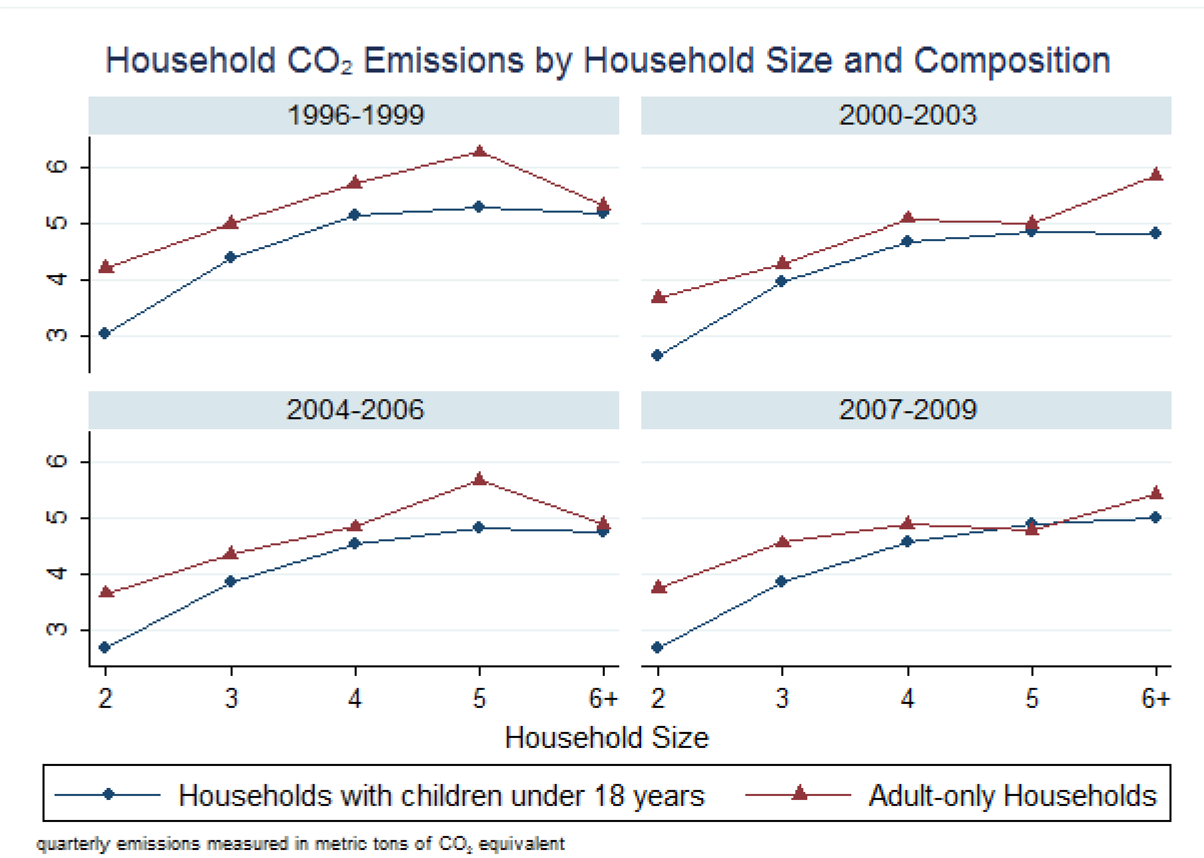

Figure 3.3.9. Household CO_2 Emissions by Household Size and Composition

child is lower than that of an adult in a household of identical size. The difference in quarterly carbon emissions between adult-only households and those with children seems to be diminishing in time, especially among those household sizes with the lowest proportion of adult-only households. The presence of children in the household generally provides more opportunities for the scaling of expenditures and the resulting emissions; however, results indicate that the ability to scale expenditures (emissions) in both adult-only households and those with children is increasing in time. This is a result of increasing energy efficiency over time, but may also be the result of demographic shifts in the population. The effect of household composition on the ability to achieve economies of scale in expenditures (both direct and indirect) and the resulting emissions will be the topic of discussion and analysis in Chapter 4.

The results presented thus far have pointed to the importance of household income, household size, the age of the household head, and the composition of the household in determination of expenditures and the resulting carbon intensities and emissions. The correlation that exists between these demographic characteristics presents difficulties in attempting to arrive at the relative importance of these determinants; however, in the following section I will begin to disentangle these effects using multiple regression analysis.

3.4. Empirical Model and Results

Any attempt to estimate the relative importance of the demographic determinants of household carbon emissions is plagued by problems of collinearity resulting from the intrinsic correlations between age, income, and household size and composition. The descriptive statistics presented in the preceding section have highlighted the importance of these demographic characteristics and the relationships that exist among them. Household carbon dioxide emissions tend to increase with the level of income, while household carbon intensities are inversely related to the level of income. Emissions follow an inverted U-shaped path over the life course, with the age of the household head used as a proxy for a household's position, regardless of the level of income. Household carbon intensities, however, tend to increase over the life course, following a distinct path throughout the different life phases. Household carbon dioxide emissions increase with the size of the household, albeit at a less than proportional rate, suggestive of economies of scale in energy use within the household. This relationship is also dependent upon the composition of the household, with adult-only households, on average, generating more quarterly carbon dioxide emissions than households with children of an identical size. While many of these relationships are robust over time, they are confounded by the correlations among the demographic characteristics. Emissions tend to peak in the middle of the life course, but this could be explained by incomes peaking around age 50, household size peaking around age 40, or by the changing composition of households throughout the life course. In the following analysis I decompose these effects and estimate expenditure and emissions profiles by age of household members to determine the contribution of those members to total household emissions and how those contributions have changed over time.

3.4.1 The Impact of Age and Income on Household CO_2 Emissions

First, we must first determine the relative importance of age, independent of the income effect, in the determination of household expenditures and the resulting carbon dioxide emissions. To achieve this, the following least squares regression of total quarterly household carbon dioxide emissions (C_j) is estimated

$$C_j = \beta' \boldsymbol{X}_j + \alpha t + u_j \tag{3.4.1}$$

where $\boldsymbol{X}_j$ is a vector of household characteristics including both regional dummy variables and socio-demographic information and t is a linear time trend. Variable definitions are listed in Table 3.4.1. The model in equation 3.4.1 is estimated using balanced repeated replicate (BRR) survey weights to efficiently determine the regression coefficients, a method first introduced by

Table 3.4.1. Variable Definitions

Variable	Description	Measurement
realco2	Real quarterly household CO_2 emissions	Continuous, measured in metric tons of CO_2 equivalent emissions
realincatax	Real annual after-tax household income	Continuous, measured in constant 2002 US dollars
age_ref	Age of household head	Continuous, measured in years
famsize	Number of members in the household	Categorical, takes on values 1-6, with 6 = HH of *6 or more* members
adult	Adult-only households, defined as HH with no members under age 18	adult = 1 if HH is adult-only adult = 0 if otherwise
northe	Northeast Census region dummy variable	northe = 1 if HH is in NE region northe = 0 if otherwise
midwest	Midwest Census region dummy variable	midwest = 1 if HH is in MW region midwest = 0 if otherwise
south	South Census region dummy variable[34]	South = 1 if HH is in South region South = 0 if otherwise
ownhome	Home ownership dummy variable	ownhome = 1 if HH is homeowner ownhome = 0 if otherwise
sexref	Sex of reference person (household head)	sexref = 1 if ref person is male sexref = 0 if female
whiteref	Race of reference person (household head)	whiteref = 1 if ref person is white whiteref = 0 if non-white
college	Education of reference person	college = 1 if college degree college = 0 if otherwise
year	Linear time trend	Categorical, takes on values 1-14 representing years 1996 – 2009

McCarthy (1966). The BRR variance estimator tends to give more reasonable estimates than the linearized variance estimator, which can result in large values and wide confidence intervals.

The regression results are presented in Table 3.4.2. On average, adult-only households generate 0.284 metric tons of CO_2 equivalent emissions (626.1 lbs. CO_2) more per quarter than an equivalent household with children. For reference, this is approximately equivalent to spending an additional 31 dollars[35] on electricity per quarter. If the household head has a college degree, on average, the household generates 0.544 metric tons of CO_2 equivalent emissions

[34] The West census region is the excluded category for the regional dummy variables.
[35] Measured in constant 2002 U.S. dollars.

Table 3.4.2. Regression Results: Total Household CO_2 Emissions

VARIABLES	realco2
realincatax	1.60e-05***
	(8.19e-07)
realincatax^2	0***
	(0)
age_ref	0.0653***
	(0.00324)
age_ref^2	-0.000613***
	(2.96e-05)
famsize	1.110***
	(0.0328)
famsize^2	-0.0923***
	(0.00476)
adult	0.284***
	(0.0370)
northe	0.222***
	(0.0596)
midwest	-0.0179
	(0.0656)
south	0.232***
	(0.0566)
ownhome	0.867***
	(0.0228)
sexref	0.113***
	(0.0204)
whiteref	0.245***
	(0.0333)
college	0.544***
	(0.0236)
year	-0.0641***
	(0.00467)
Constant	-1.385***
	(0.103)
Observations	219,361
R-squared	0.223

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

(1199.3 lbs. CO_2) more per quarter than an equivalent household with a household head without a college degree.

To analyze the results of this regression more completely, marginal effects of income and age are calculated and presented in Table 3.4.3 and Table 3.4.4. The marginal effect of income is measured as the resulting change in household CO_2 emissions from an additional $1000 of real

Table 3.4.3. Marginal effects of household income on CO_2 emissions by quintile

Income Quintile	Mean Income	Marginal Effect	Delta-method Standard error	95% Confidence Interval	
1	$5,596	0.0162	0.000782	0.0146	0.0177
2	$24,236	0.0166	0.000666	0.0153	0.0179
3	$40,029	0.0169	0.000579	0.0158	0.0181
4	$62,096	0.0174	0.000485	0.0165	0.0184
5	$121,988	0.0188	0.000522	0.0178	0.0198

NOTE: measured as the change in household CO_2 emissions resulting from an additional $1000 of real after-tax household income.

Table 3.4.4. Marginal effects of the age of the household head on CO_2 emissions

Age of Household Head	Marginal Effect	Delta-method Standard error	95% Confidence Interval	
20	0.04078	0.00209	0.03669	0.04487
30	0.02852	0.00153	0.02552	0.03153
40	0.01627	0.00102	0.01427	0.01826
50	0.00401	0.00065	0.00274	0.00528
60	-0.00825	0.00071	-0.00964	-0.00686
70	-0.02051	0.00114	-0.02273	-0.01828
80	-0.03276	0.00167	-0.03603	-0.02950

after-tax household income and is evaluated at the mean of each income quintile. While the impact of an additional thousand dollars of income on household carbon dioxide emissions rises with the level of income, there is little evidence of meaningful differences in these estimated marginal effects across income quintiles.[36] The observed differences are negligible and only

[36] This result seems to contradict the presumption of the income regressivity of carbon abatement policies. However, what this result shows is that this regressivity disappears when controlling for other demographic characteristics of the household, corroborating the argument being made in Chapter 2. If we simply estimate the relationship between household income and carbon dioxide emissions, as follows:

$$C_j = \beta_1 + \beta_2 realincatax_j + \beta_3 realincatax_j^2 + u_j$$

and calculate the resulting marginal effects of income at the mean of each income quintile (measured as the change in household CO_2 emissions resulting from an additional $1000 of real after-tax household income), as in Table 3.4.3, then we obtain the following results (marginal effect followed by standard error in parentheses), Q1: 0.0365 (0.000805); Q2: 0.0352 (0.000683); Q3: 0.0342 (0.000588); Q4: 0.0327 (0.000478); Q5: 0.0287 (0.000460). Therefore, when not controlling for other demographic factors, we obtain the expected result – the marginal effect significantly different among those households with the highest and lowest incomes.[37] The variation in household carbon dioxide emissions, independent of other demographic characteristics, is not sufficiently explained by variation in the level of household income. This implies that differences in household CO_2 emissions are driven primarily by other demographic factors. In Table 3.4.4 marginal effects of age on household CO_2 emissions are estimated for ages of the household head ranging from 20 to 80 years. The impact of aging one year on household emissions falls as household heads move through the life course, becoming negative at an age of around 55 years. Therefore, *independent of the income effect*, household CO_2 emissions vary significantly depending on the household's position in the life course.

While not directly comparable these calculated marginal effects suggest that age is more essential in explaining the variation in carbon dioxide emissions among different households. For example, on average, an additional $1000 of household income for a household in the third income quintile results in an additional 0.0169 metric tons of CO_2 equivalent emissions (37.3 lbs. CO_2) per quarter, roughly equivalent to the emissions generated from spending an additional $1.85 on electricity. This result varies from $1.77 to $2.05 for income quintiles one and five, respectively. On average, the household head of an equivalent household aging one year from age 20 to 21 results in an additional 0.0408 metric tons of CO_2 equivalent emissions (89.9 lbs. CO_2) per quarter, equivalent to $4.46 of additional electricity expenditures. While aging one year from age 80 to 81 results in a reduction of 0.0328 metric tons of CO_2 equivalent emissions (72.3 lbs. CO_2) per quarter, equivalent to $3.59 *fewer* electricity expenditures. Relative to the marginal effects of income, these marginal effects of age are both larger in magnitude and vary

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of income decreases as household income incomes increases. In other words, any carbon pricing policy would be income regressive.

[37] Wald test chi-squared statistic = 8.38, p-value = 0.0038 for test of equality of marginal effects of income for the first and fifth income quintiles.

significantly across households headed by members of different ages. To substantiate and examine the robustness of this result the impact of household size and composition must be examined to determine the driving forces behind this sensitivity of household emissions to a household's position in the life course. To analyze the degree to which members of different ages within households contribute to total household emissions, age profiles of emissions by age of the household members are constructed and estimated in Chapter 4.

3.5. Conclusion

In this chapter, I have established the significant demographic changes experienced by the United States over the period from 1996 to 2009, discussed the implications of these changes on household carbon dioxide emissions, and estimated the impact these demographic characteristics have on the level of carbon dioxide emissions generated by households.

The demographic shifts that have occurred in the United States over the relatively brief period from 1996 to 2009 are significant. The average age of a household head has increased by 2.7 percent reflecting the general aging of the population. The delay of marital onset and family formation is reflected in the fact that average household size has decreased by 1.6 percent and the corresponding results that the proportion of adult-only households has increased by 2.7 percent and the proportion of two-person households has risen by 1.8 percent. These changing household formation and cohabitation patterns have a significant impact on the ability of the average household to experience economies of scale in expenditures and the resulting emissions.

I have shown that the degree to which aging impacts household carbon emissions is different depending on the household's position in the life course, as represented by the age of the household head, *independent of the income effect.* In order to more accurately estimate future household CO_2 emissions, age-emissions profiles which account for the fact that larger households can scale their expenditures must be constructed. In this manner, changes in household formation and cohabitation patterns will be reflected in these profiles. These concerns will be the focus of the analysis in Chapter 4.

CHAPTER IV

The Impact of Demographic Change on Economies of Scale in Household Expenditures and CO_2 Emissions

4.1. Introduction

In this chapter, I build off the intuition and analysis developed in the first few chapters to determine the degree to which demographic changes in the United States impact the amount of carbon dioxide emissions resulting from household expenditures. As established in Chapter 3, an understanding of the factors determining household expenditures and the resulting greenhouse gas (GHG) emissions is crucial to explaining present levels of emissions and the potential incidence of climate policy.

This analysis establishes the degree to which demographic changes such as the rise in single-person households, the delay of marital onset and family formation, and shrinking average household size are having on the ability of households to generate economies of scale in their expenditures and emissions. I find that these demographic changes are indeed decreasing this ability since 2003, resulting in the rise of mean household carbon dioxide emissions despite continued improvements in energy efficiency and conservation. In the absence of these demographic changes, I estimate that mean household carbon dioxide emissions would be 10.68% lower than the baseline predicted values, if the ability of households to experience economies of scale had remained unchanged at 2003 levels. As a result, climate projections using naïve models of population size and growth that fail to account for household size and composition effects may be inaccurately projecting energy use and emissions in the future.

While income, age, and composition all impact the relationship between energy use and household size there is still a significant amount of variation remaining that could be explained by the existence of economies of scale within the household. Much of this previous literature has addressed the existence of economies of scale, but has failed to fully develop its impacts on household expenditures and energy use. Furthermore, this chapter will address the still unanswered question: Has the ability to experience these economies of scale changed, independent of the income effect, as a result of demographic change? Previous studies have been static in nature and have not addressed the dynamics of these economies of scale.

4.2. Age Profiles of Emissions

To determine the degree to which household members of different ages contribute to total household carbon dioxide emissions, I first construct age profiles of emissions. Let c_{ijt} be the CO_2 emissions resulting from expenditures on good i by household j in year t, then

$$c_{ijt} = \sum_{m=1}^{M} c_{ijtm} \tag{4.3.1}$$

where c_{ijtm} is the contribution of the mth member in year t, and M is the total number of people in the household. Therefore, I am assuming that household emissions are an additive function of the emissions resulting from expenditures by the various members of the household, similar to the method used by Mankiw and Weil (1989) to model the demand for housing. The contribution of each household member is a function of age; each age has its own contribution parameter, so the individual contribution of member m in year t is:

$$c_{ijtm} = \beta_{it0} D(h)_m + \beta_{it1} D(h)_m + \cdots + \beta_{it80} D(h)_m, \tag{4.3.2}$$

where $D(h)_m = 1$ if household member m is of age h, with household members ranging in age from 0 (less than one year old) to 80 years. The parameter β_{ith} is the contribution to household emissions from expenditures on good i in year t by a person of age h. Combining equation 4.3.1

with equation 4.3.2, the regression function for total CO_2 emissions by household j in year t becomes

$$c_{ijt} = \beta_{it0} \sum_{m} D(0)_m + \beta_{it1} \sum_{m} D(1)_m + \cdots + \beta_{it80} \sum_{m} D(80)_m + u_{ijt} \tag{4.3.3}$$

where u_{ijt} is an error term. The parameters in equation 4.3.3 are estimated for total household CO_2 emissions using least squares regression with suppression of the constant.[38] These estimated age-emissions profiles are then appropriately smoothed using a robust non-linear smoother, wherein smoothed values are obtained by taking medians of each data point and a few points around it. In this case a span-five smoother is implemented repeatedly until convergence, that is, until repeated applications produce the same series. Median smoothers are resistant to outliers, and therefore provide robustness to spikes in the data (Tukey, 1977). The smoothed age-emissions profiles for the years 1996, 2000, 2004, and 2009 are displayed in Figure 4.3.1. Notice the dramatic rise in household member emissions contributions as that member ages from 20 to 40. This relationship is quite robust over time, highlighting the importance of age in household CO_2 emissions determination, but it is also being compressed over time, a likely result of the increased energy efficiency of production. This confirms the results of Zagheni (2011) and O'Neill and Chen (2002) in which the demand for most consumption goods tends to increase with age until the person reaches the adult life stage, at which point emissions (expenditures) stabilize and begin to decrease as the person enters the elderly life stage.

[38] Complete age profile regression results are available upon request to the author.

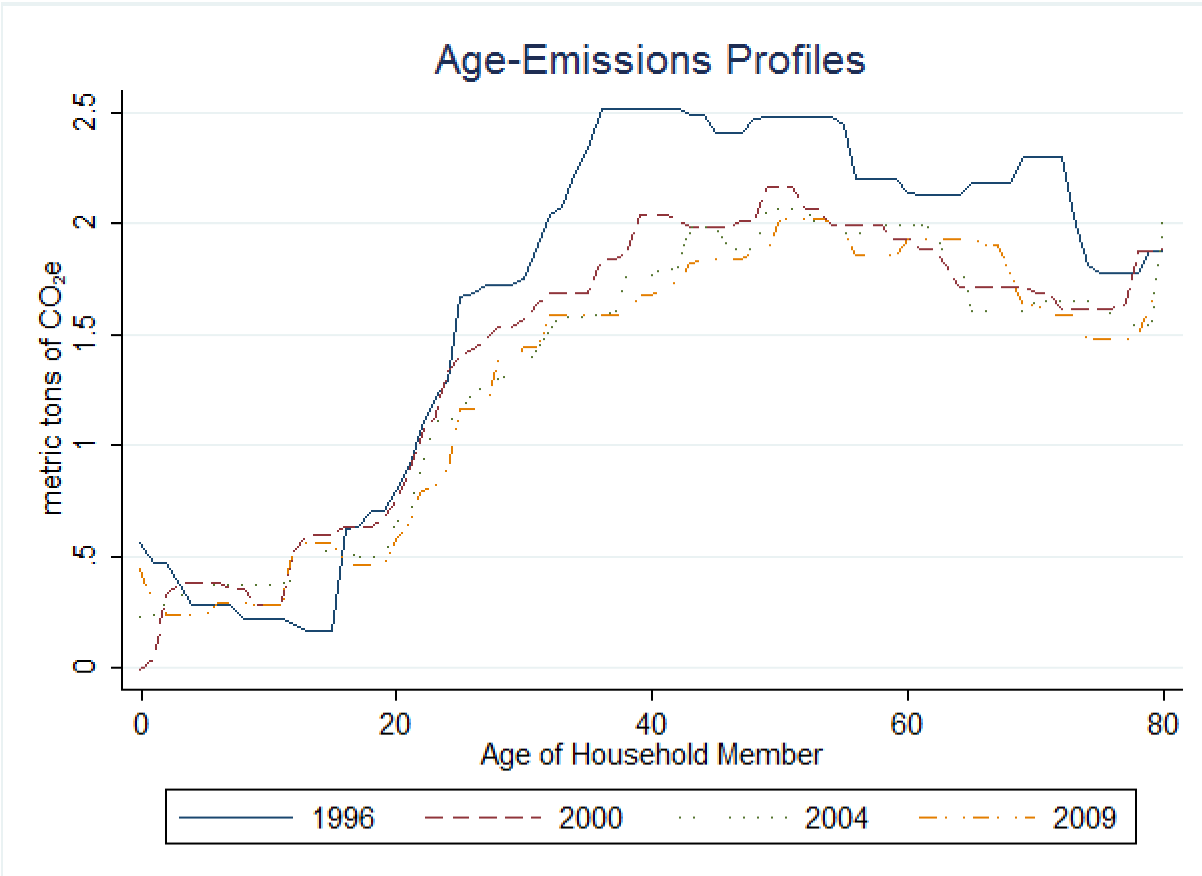

Figure 4.2.1 Age-Emission Profiles, total household CO_2 emissions

The estimation of these age-emissions profiles treats each household member as an autonomous consumer unit, meaning member contributions are independent of the size and composition of their household. To the extent that there are not significant economies of scale in household energy use and no change in household formation and average household size, one would expect this approach to be fairly accurate. However, given the demographic changes experienced in the United States over the period, 1996 – 2009, the increase in single-person households, the delay of marital onset and family formation, decreased average household size, and the aging of the population, this approach may be overestimating the contribution of individual household members to total household carbon dioxide emissions. The size and age composition of a household will largely determine its needs and how those needs will change over the life course of the household, while income provides the ability to obtain those needs. Shifts in the demographic characteristics of the average United States household will significantly alter the shape and position of these age-emissions profiles and ultimately determine how mean household carbon dioxide emissions will change over time.

4.3. Theoretical and Empirical Modeling

To incorporate the impact of household size and age composition in the generation of economies of scale in the household, I develop a parametric equivalence scale model, similar to Zagheni (2011). Parametric methods of estimating equivalence scales are one of the most straightforward methods for achieving meaningful comparisons of households of different sizes and compositions (Buhmann et al., 1988; Coulter et al., 1992). The most common form of a parametric equivalence scale, which only takes into account household size *n* has the following form,

$$c_{ijt} = n_{jt}^{\theta_{it}} \tag{4.3.1}$$

where c_{ijt} is the CO_2 emissions resulting from expenditures on good *i* by household *j* in year *t* and n_{jt} is the number of people in household *j* and θ_{it} is the scale relativity parameter measuring the intensity of economies of scale in household emissions (Buhmann et al., 1988; Coulter et al., 1992). This parametric specification relates actual household emissions c_{ijt} to equivalent emissions, those emissions resulting from the additional expenditures necessary to maintain an constant level of well-being when an additional member is added to the household, $CO2_{ijt}$, in the following way,

$$CO2_{ijt} = \frac{c_{ijt}}{n_{jt}^{\theta_{it}}} \tag{4.3.2}$$

for a given value of θ_{it}. If $\theta_{it} = 1$, then equivalent emissions are simply per capita emissions, as nominal household emissions would be divided by household size n. In this case, any additional household member would require as much expenditures (emissions) as any other member for the household to maintain a constant level of well-being. If, however, $0 < \theta_{it} < 1$, then an additional household member would not require a proportional increase in emissions due the sharing made possible by cohabitation. Given the importance of age in determining emissions, I further develop this model to incorporate elements of the age composition of the household.

Let n_{cj} be the number of children in household j, let n_{aj}, be the number of adults in household j, and let n_{ej} be the number of elderly in household j. Children are those household members 15 years old and younger, adults are those between 16 and 64 years, and elderly are those 65 years and older. Furthermore, let S_{ait} be the average carbon dioxide emissions resulting from the consumption of good i by an adult living alone in year t. This average, S_{ait}, has been estimated from the age emission profile which assumes, implicitly, that each household member is an autonomous consumer unit. An equivalence scale for carbon dioxide emissions resulting from expenditures on good i by household j in year t is then written as

$$c_{ijt} = (n_{cj}\gamma_{it}S_{ait} + n_{aj}S_{ait} + n_{ej}\alpha_{it}S_{ait})^{\theta_{it}} + \varepsilon_{ijt}\,, \tag{4.3.3}$$

where ε_{ijt} is an error term. γ_{it} represents the carbon contribution of children within households relative to that of adults. If $\gamma_{it} = 0$, then adults are considered to be solely responsible for the carbon dioxide emissions resulting from the consumption of good i, yet if $\gamma_{it} = 1$, no distinction can be made between children and adults in the consumption of that good. The parameter α_{it} represents the carbon contribution of the elderly relative to that of an adult within the household. The scale relativity parameter θ_{it} measures the intensity of household economies of scale resulting from cohabitation. If θ_{it} lies between zero and one, then cohabitation generates economies of scale; if $\theta_{it} = 0$, then economies of scale are at their maximum, meaning an additional household member does not warrant any additional expenditures on good *i* in year *t*; if $\theta_{it} = 1$, then economies of scale are not present, meaning an additional household member requires a proportional increase in expenditures on good *i* in year *t* and the resulting emissions. While unlikely, if $\theta_{it} > 1$, then an additional household member will require a more than proportional increase in household carbon dioxide emissions resulting from expenditures on good *i*, in other words, expenditures on good *i* generate diseconomies of scale in the household. Therefore, the scale relativity parameter θ_{it} can be thought of as an estimation of the degree of rivalry inherent in the consumption of good *i* within the household. The two extremes, $\theta_{it} = 0$ or $\theta_{it} = 1$, represent situations when good *i* is either a pure public good or pure private good, respectively, in household consumption.

The equivalence scale in equation 4.4.3 is a non-linear model, therefore I estimate the parameters, γ_{it}, α_{it}, and θ_{it} using a non-linear least squares technique. Given the estimated value for S_{ait}, I choose the set of parameters $(\widehat{\gamma_{it}}, \widehat{\alpha_{it}}, \widehat{\theta_{it}})$ such that the sum of squared residuals is minimized. Once estimates for the set of parameters have been produced, age-emissions profiles based on the equivalence scale could be reconstructed, so the equivalence scale now becomes

$$c_{ijt} = (n_{cj}\widehat{\gamma_{it}}CO2_{ijt} + n_{aj}CO2_{ijt} + n_{ej}\widehat{\alpha_{it}}CO2_{ijt})^{\widehat{\theta_{it}}} \tag{4.3.4}$$

where $CO2_{ijt}$ is the average carbon contribution from consumption of good *i* by an adult in household *j* in year *t*. It can be retrieved as

$$CO2_{ijt} = \frac{c_{ijt}^{\left(1/\widehat{\theta_{it}}\right)}}{\left(n_{cj}\widehat{\gamma_{it}} + n_{aj} + n_{ej}\widehat{\alpha_{it}}\right)} \tag{4.3.5}$$

For household j in year t, the average contribution of a child is $CO2_{ijt}\widehat{\gamma_{it}}$, and the average contribution of the elderly is $CO2_{ijt}\widehat{\alpha_{it}}$. In this chapter I focus on the values and dynamics of θ_{it}, but additional research into the values and dynamic properties of these contribution parameters can provide additional insight. An analysis of the estimated values of the scale relativity parameter θ will determine whether economies of scale exist in household expenditures, in which expenditure categories, and how this ability has changed, on average, as a result of demographic change over time.

4.3.1 Household Economies of Scale

First, we must establish the existence of economies of scale in the household and further disaggregate the expenditure categories to determine the degree to which goods and services of different types can successfully be shared by household members to enjoy the economies of scale from cohabitation. Due to the inherent rivalry in consumption of many goods and services, a priori, we can make some statements about the potential results. We would expect households to have very strong economies of scale in direct uses of energy, specifically, expenditures on natural gas and fuel oil for home heating and electricity for lighting and the use of home electronics. Households share the heat provided from the burning of fuel oil and natural gas and as the size of the household increases, ceteris paribus, there is no reason to expect the amount of heating necessary to increase proportionally. While natural gas is also used in home water heaters, stoves, and clothes dryers, fuel oil is used almost exclusively to heat homes and not for other purposes; therefore we expect fuel oil to have a lower scale relativity parameter (less rival) than that of natural gas. Households with natural gas appliances need to increase hot water generation as households become large and additional members need to take showers and wash and dry their clothing. Electricity expenditures will behave in much the same manner;

households can share these expenditures by using the same light in the living room, watching the same television, and using the same computer. However, as with natural gas, there are also uses of electricity that are more rivalrous in their consumption than that of fuel oil, such as each household member needing their own bedroom light and personal electronics. On the other hand, some household goods and services have a very high degree of rivalry, such as clothing and indirect utilities (water, telephone, and other public services). With the exception of "hand-me-downs", each household member needs their own clothing and footwear. Each member takes their own shower, flushes their own toilet, and makes their own phone calls. So these expenditures we would expect to rise nearly proportionally with the size of the household – the degree of economies of scale in these expenditures is very low.

The estimation of the equivalence scale model in equation 4.3.3 for total household emissions and the remaining 19 disaggregated expenditure categories listed in Appendix 3 for each year from 1996 to 2009 provides results on the existence and temporal dynamics of household economies of scale. In Table 4.3.1, the estimated mean scale relativity parameters (θ) and relative contribution parameters (α and γ) over the entire period are listed with their corresponding standard errors. Recall, a value of θ equal to zero represents the situation when economies of scale are at their maximum, while of value of θ equal to one signifies the situation where economies of scale do not exist in the emissions resulting from consumption of that good or service.

On average, household economies of scale from cohabitation do in fact exist, consistent with the historical estimates of Logan (2011). The scale relativity parameter for total household emissions (expenditures) is equal to 0.913 and is statistically different from one.[39] From the

[39] 95% Confidence Interval = [0.912955, 0.913051].

table we can see, consistent with expectations, that the least rival of household expenditures is fuel oil with an estimated scale relativity parameter of 0.231, meaning expenditures on fuel oil provide the greatest opportunity for households to experience economies of scale resulting from cohabitation. However, also consistent with expectations, the most rivalrous of all household

Table 4.3.1. Mean Scale Relativity and Contribution Parameters: 1996 – 2009

Expenditure Category	θ	se(θ)	α	se(α)	γ	se(γ)
Total	**0.913**	0.00002	**1.213**	0.01138	**0.366**	0.01422
Direct	**0.746**	0.00008	**1.483**	0.01456	**0.518**	0.01870
Natural Gas	**0.648**	0.00012	**1.361**	0.02685	**0.209**	0.01320
Electricity	**0.559**	0.00014	**1.832**	0.03471	**0.917**	0.04563
Gasoline and Motor Fuel	**0.883**	0.00004	**0.615**	0.00800	**0.037**	0.00831
Fuel oil and Other Fuels	**0.231**	0.00019	**1.872**	0.32377	0.008	0.06460
Indirect	**0.829**	0.00007	**1.113**	0.01948	**0.428**	0.02325
Indirect Utilities	**0.967**	0.00001	**1.193**	0.02171	**0.181**	0.00762
Food	**0.645**	0.00006	**0.818**	0.01057	**0.341**	0.01738
Housing	**0.769**	0.00015	**0.771**	0.03660	**-0.025**	0.00785
Domestic Services	**0.837**	0.00017	**1.585**	0.08525	**1.571**	0.08815
Household Equipment	**0.619**	0.00004	**0.806**	0.04817	0.036	0.04116
Transportation	**0.717**	0.00017	**0.710**	0.03160	-0.013	0.02286
Clothing and Footwear	**0.848**	0.00001	**0.740**	0.01439	**0.210**	0.02658
Personal Insurance	**0.918**	0.00018	**0.437**	0.03601	-0.014	0.00734
Healthcare	**0.929**	0.00010	**1.814**	0.05008	0.009	0.00804
Entertainment	**0.932**	0.00004	**0.811**	0.04194	**0.139**	0.03253
Education	**0.667**	0.00013	**0.255**	0.05613	**-0.058**	0.02089
Alcohol and Tobacco	**0.792**	0.00012	**0.773**	0.01507	**-0.117**	0.01758
Miscellaneous	**0.779**	0.00009	**1.817**	0.18528	**-0.076**	0.02769

Note: Parameters in bold are those statistically significant (different from zero) at 95% confidence.

expenditures is indirect utilities with an estimated scale relativity parameter of 0.967, meaning that expenditures on water, telephone, and other public services rise nearly proportionally with household size. Generally, the results are intuitively appealing and consistent with a priori notions of rivalry; however, some are surprising. Food is generally used as the classic example of a private good due to its high degree of excludability and rivalry. While an inspection of the results shows that food expenditures have a scale relativity parameter of 0.645, nearly identical to that of natural gas. Significant economies of scale exist in emissions resulting from food expenditures. At first glance, this seems invalid and puzzling, as pointed out in previous empirical studies (Deaton and Paxson, 1998; Logan, 2011); however, it is rarely the case that cooking a meal for 4 or 5 people involves dramatically greater expenditures than a meal prepared for two people. It is possible for this to result in less waste (leftovers) and any additional expenditure may enable the household to take advantage of wholesale pricing by buying in bulk. With the presence of economies of scale and the validity of the results established we can proceed to analyze how these economies of scale have changed over time.

4.3.2 Demographic Change and the Dynamics of Household Economies of Scale

The United States has experienced significant demographic change over the past few decades, especially with regard to household formation. Much of this change is due to the aging of the baby boomers, in this sample the mean age of a head of household has increased from 47.27 to 49.01[40] over the period 1996 to 2009, many of whom have progressed though the period of family stability. Many baby boomers have seen their children leave home during this period resulting in "empty nest" two-person households. During this same period the United States has been undergoing a significant change in the timing and pace of household formation at the beginning of the life course. Young individuals are pursuing more advanced degrees[41], partially out of economic and financial necessity resulting in the delay of marital onset and a dramatic increase in the number of single-person households. According to the U.S. Census Bureau, the

[40] Statistically significant difference. 1996, 95% confidence interval = [46.96, 47.58]; 2009, 95% confidence interval = [49.14, 49.67]. Adjusted Wald test for difference of means, p-value = 0.0000.

[41] Enrollment in degree granting institutions increased by 11 percent between 1990 and 2000 and increased 37 percent between 2000 and 2010 (U.S. Department of Education, National Center for Education Statistics. (2012). *Digest of Education Statistics, 2011* (NCES 2012-001), Chapter 3).

median age at first marriage increased to 28.2 for men and 26.1 for women in 2010, an increase from 26.8 and 25.1 in 2000 and the proportion of one-person households rose from 25 percent in 2000 to 27 percent in 2010, more than double the percentage in 1960 (13 percent).[42] Young couples also are choosing to wait until later in life to start a family for a variety of cultural, social, financial, or personal reasons contributing to the rise in two-person households and the increasing proportion of adult-only households (Stevenson and Wolfers, 2007). The proportion of adult-only households in the U.S. population has increased from 63.3 to 66.4 percent[43] and the proportion of two-person households has increased from 30.6 to 32.7 percent[44] from 1996 to 2009. Overall, average household size has decreased from 2.54 to 2.49 members over the same period, a decrease of nearly two percent[45]. Among households with children the average number of children per household has decreased from 1.85 to 1.80 children, a decrease of 2.7 percent[46]. The number of adults per household has remained relatively constant over the period at 1.62.[47] The average number of elderly people, ages 64 to 80, per household has also remained relatively constant over the period at 0.233.[48]

The size and composition of households is crucial to the ability to experience economies of scale in their expenditures and the resulting emissions. These demographic shifts are changing this ability which has implications for mean household carbon dioxide emissions and

[42] U.S. Census Bureau, "America's Families and Living Arrangements: 2010". Housing and Household Economic Statistics Division, Fertility & Family Statistics Branch.
[43] Statistically significant difference. 1996, 95% confidence interval = [62.44, 64.12]; 2009, 95% confidence interval = [65.72, 67.17]. Adjusted Wald test for difference of means, p-value = 0.0000.
[44] Statistically significant difference. 1996, 95% confidence interval = [29.79, 31.44]; 2009, 95% confidence interval = [31.93, 33.38]. Adjusted Wald test for difference of means, p-value = 0.0003.
[45] Statistically significant difference. 1996, 95% confidence interval = [2.517, 2.568]; 2009, 95% confidence interval = [2.474, 2.519]. Adjusted Wald test for difference of means, p-value = 0.0077.
[46] Statistically significant difference. 1996, 95% confidence interval = [1.823, 1.879]. 2009, 95% confidence interval = [1.773, 1.823]. Adjusted Wald test for difference of means, p-value = 0.0054.
[47] Adjusted Wald test for difference of means between 1996 and 2009, shows an insignificant change, p-value = 0.2597.
[48] Adjusted Wald test for difference of means also shows an insignificant change, p-value = 0.8756.

the way in which population growth will impact total emissions in the United States. To determine how this demographic change has had an effect on economies of scale I examine how the scale relativity parameters have changed over time and for which expenditures categories the change has been most dramatic. The ability of households to scale their total expenditures (emissions) has remained relatively constant until 2003, but since has been declining. There have been significant changes in the ability to scale direct and indirect expenditures. These trends are shown in Figure 4.3.1. Household economies of scale in indirect expenditures and the resulting CO_2 emissions have generally been increasing over the period, as reflected in the fairly consistent decrease in the scale relativity parameter. However, the scale relativity parameter for direct expenditures experienced steady declines until 2003 when it began to rapidly increase.

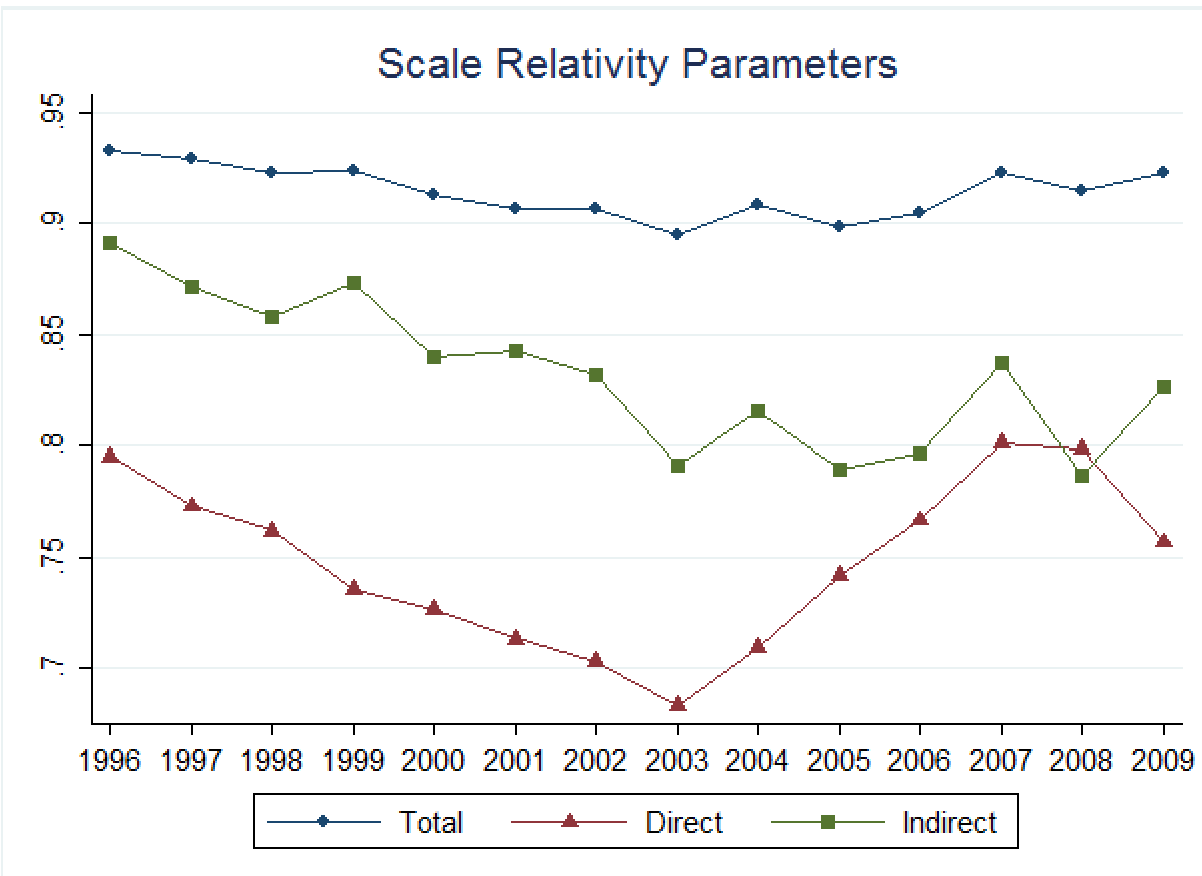

Figure 4.3.1 Household Economies of Scale, 1996 – 2009

Interestingly, from 2003 until 2009 the scalability of indirect expenditures was essentially constant which coincided with the dramatic decrease in scalability of direct expenditures, resulting in a net increase in the scale relativity parameter for total expenditures and emissions.

To fully understand these changes I further disaggregate these expenditures to determine changes in the scalability of which expenditure categories are driving these changes in direct and indirect economies of scale. In Figure 4.3.2 direct expenditures, which, on average, account for 8 percent of total household expenditures and 45 percent of total household emissions, are disaggregated into its four components: natural gas, electricity, gasoline, and fuel oil and other fuels. The most dramatic increase in the scale relativity parameter is in natural gas expenditures, which is the smallest component of direct expenditures and emissions, accounting for, on average, 7.6 percent of total direct emissions. However, the use of natural gas has been declining over the period, from 10.8 to 4.6 percent of total direct emissions. Electricity, however, accounts for 69 percent of total direct emissions, on average, increasing from 64.6 to 74.7 percent[49] over the period. The dramatic increase in the scalability of direct expenditures prior to 2003 was driven by the increase in the scalability of electricity. The subsequent decrease in scalability post-2003 was driven by the decreases in economies of scale in both natural gas and electricity which account for, on average, over 75 percent of household emissions resulting from direct expenditures. Since 2003 the ability of households to experience economies of scale in total emissions is declining; fueled by these decreases in direct scalability, but this effect would be less dramatic if the ability to scale indirect expenditures had continued to increase as it did prior to 2003.

[49] Statistically significant difference. 1996, 95% confidence interval = [64.11, 65.05]; 2009, 95% confidence interval = [74.31, 75.03]. Adjusted Wald test for difference of means, p-value = 0.0000.

From 1996 to 2003 the United States greatly improved its ability to scale indirect expenditures, but has remained relatively constant since. To determine which indirect expenditure categories have experienced the most dramatic changes in their scalability resulting from demographic change, Figure 4.3.3 disaggregates indirect emissions into the top five expenditure categories in terms of their average contribution to total indirect emissions: food

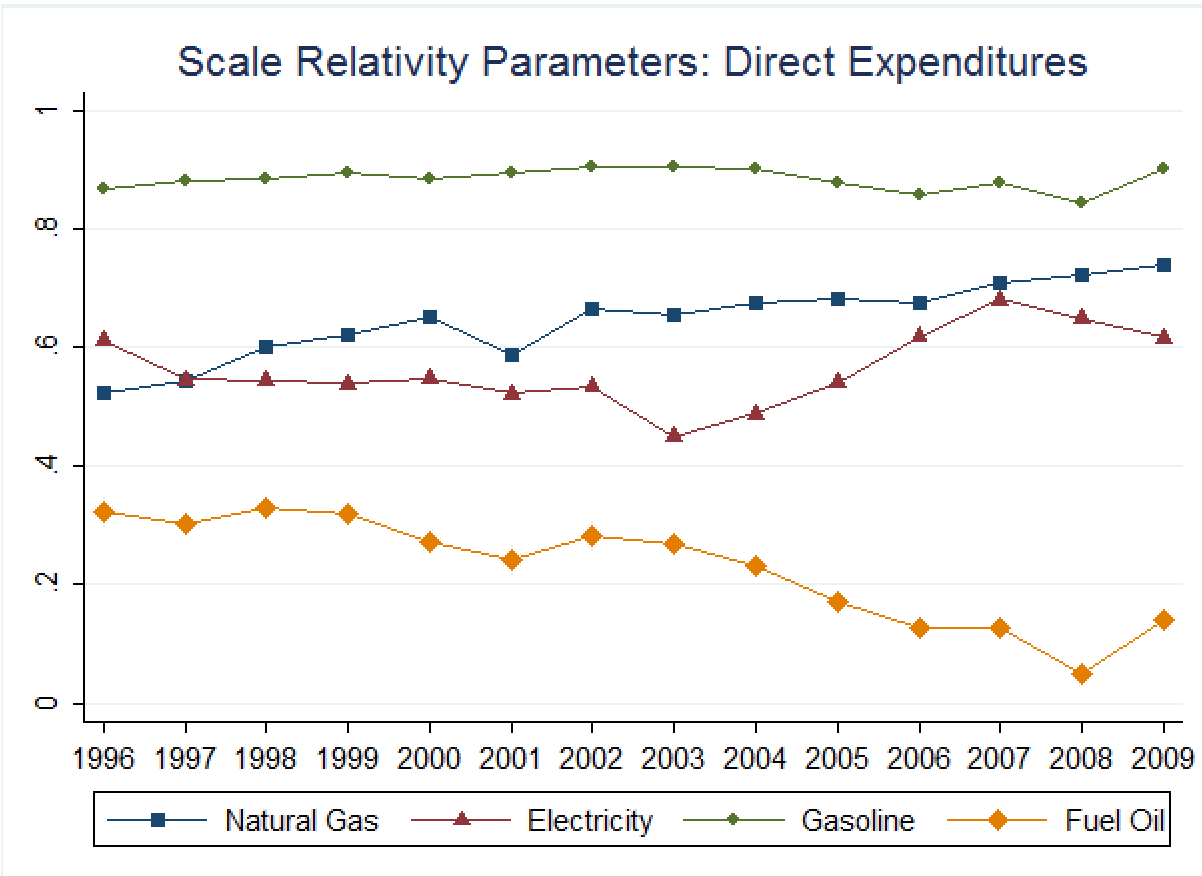

Figure 4.3.2 Household Economies of Scale: Direct Expenditures, 1996 – 2009

(44.3%), housing (18.2%), transportation (6.6%), indirect utilities (6.4%), and entertainment (5.1%). From the figure we can see that the scalability of indirect utilities and entertainment have remained relatively constant, while after slight improvements in the first few years of the period food, housing, and transportation have seen their scalability decline. Food and housing have remained relatively constant since 2003, but the ability of households to scale emissions resulting from transportation expenditures (excluding gasoline) has continued to decline.

There has been substantial demographic change in the United States over the period from 1996 to 2009 which has led to significant changes in the ability of households to experience economies of scale in carbon dioxide emissions resulting from their expenditures, especially for

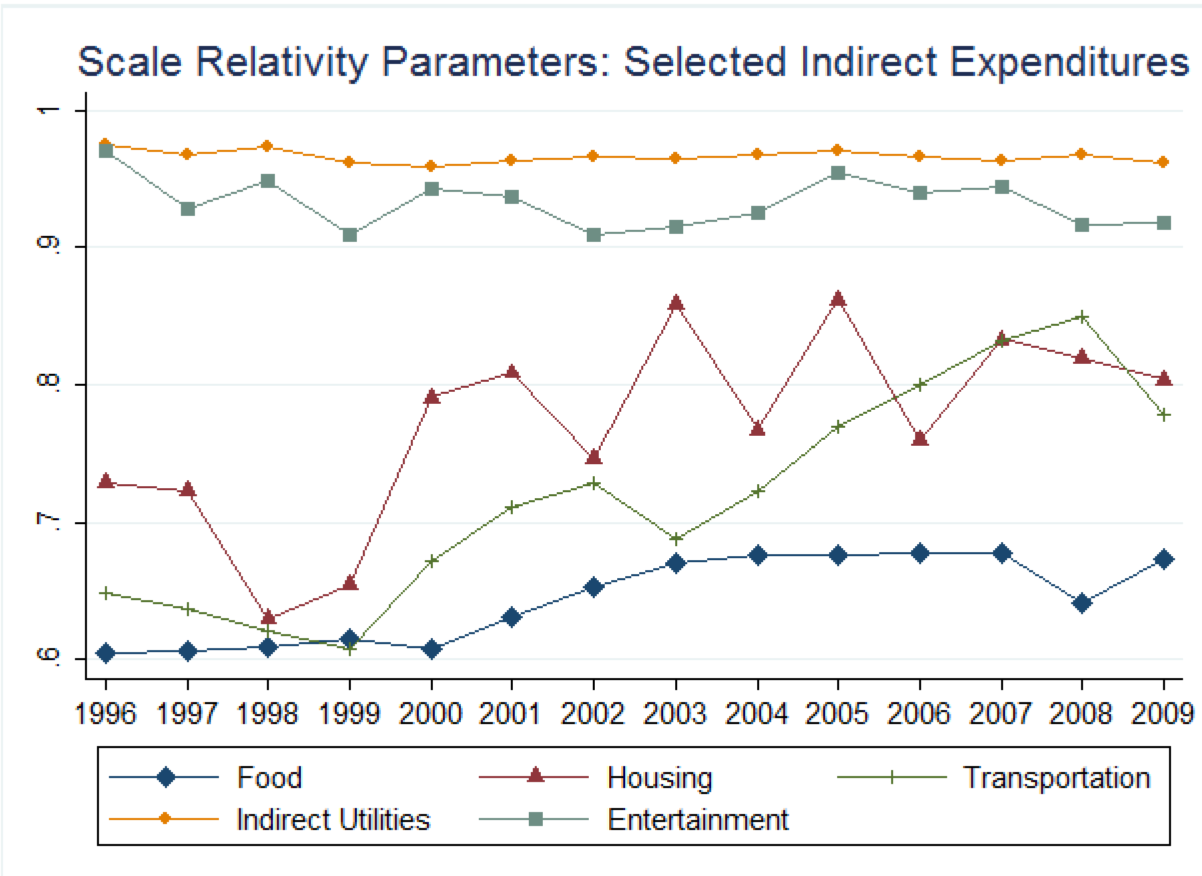

Figure 4.3.3. Household Economies of Scale: Selected Indirect Expenditures, 1996 – 2009

certain expenditure categories that are more sensitive to these demographic changes, such as natural gas, electricity, food, and transportation. Ultimately, the reason it is so important to understand the impact of demographic change on these household economies of scale is that it has implications for how mean household carbon emissions change over time and impacts the shape of the age-emissions profile by changing the carbon contributions of children, adults, and elderly household members.

The United States has experienced dramatic improvements in energy efficiency (as measured by quadrillion BTUs per million dollars of real GDP) over the period 1996 to 2003, from 11.81 to 9.80, a decrease of 17 percent. As a result, despite rising mean household expenditures, mean household carbon dioxide emissions resulting from those expenditures were falling until 2003, see Figure 4.3.4. However, while energy efficiency continued to improve to 8.68 by 2009, starting in 2003 mean household carbon dioxide emissions began to increase, at quite an alarming rate. As seen in Figure 4.3.4, after increasing over the five year period

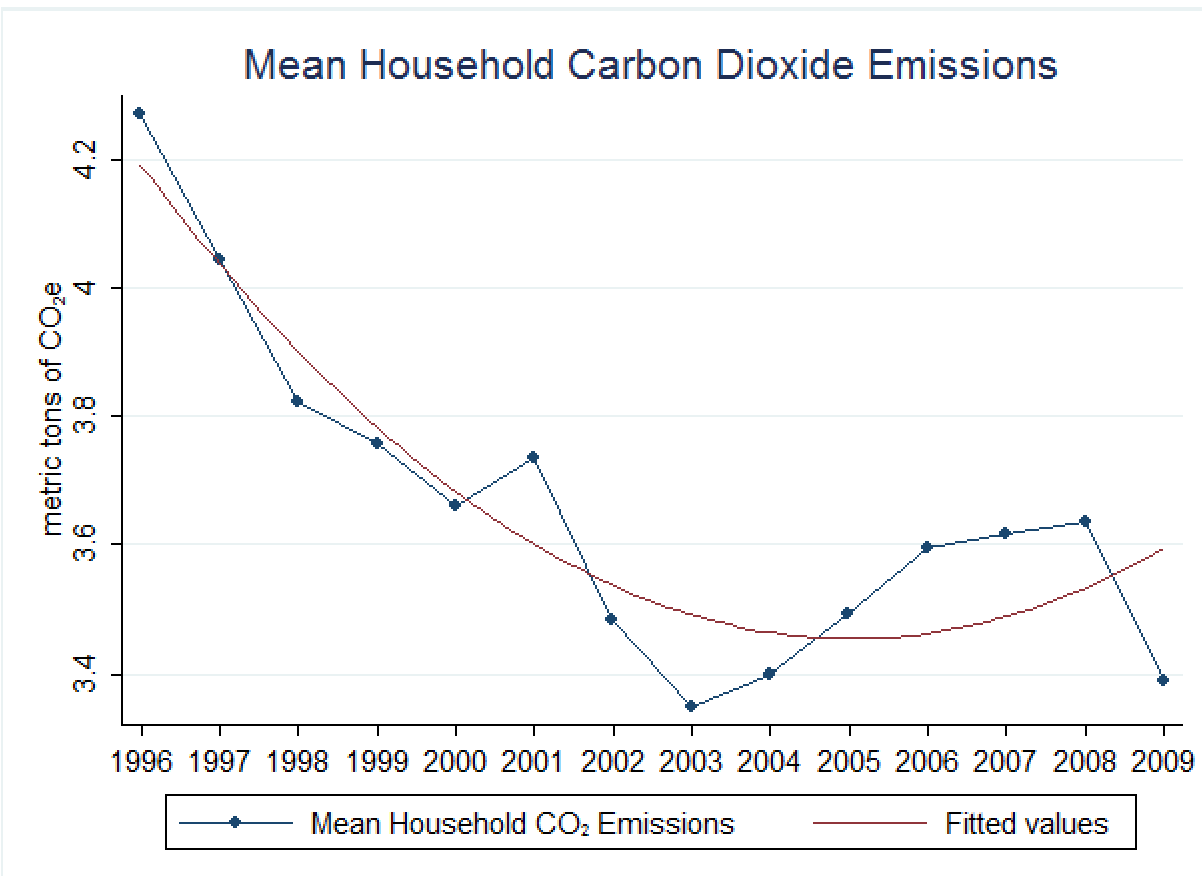

Figure 4.3.4. Mean Household Carbon Dioxide Emissions, 1996 – 2009

between 2003 and 2008 mean household emissions decrease in 2009 which is the result of decreased expenditures due to the Great Recession. Energy efficiency improved by 9.4 percent from 2003 to 2008, but mean household carbon dioxide emissions increased by 7.2 percent. This reversal of trend is a result of the decreased ability of households to experience economies of scale since 2003 (see Figure 4.3.1). Over the period from 2003 to 2008, the scale relativity parameter for total household carbon dioxide emissions increased from 0.894 to 0.915, an increase of 2.35 percent while mean household carbon dioxide emissions increased by 7.2 percent. This result can be strengthened by estimating a modified version of the least squares regression in Equation 3.4.1 using the entire pooled cross-section from 1996 to 2009:

$$ln\, C_j = \alpha_1 + \alpha_2\, ln\, \theta_j + \alpha_3\, ln\, realinc_j + \boldsymbol{\gamma X} + u_j \qquad (4.3.1)$$

where $\boldsymbol{X}$ is a vector of regional and household characteristics, the results of which are presented in Table 4.3.1. The scale relativity parameter (theta_co2) subsumes the variables for household size, age of household head, and household composition; as it itself is a function of these household characteristics. The remaining variables are defined as in Table 3.4.1. I implement a log-log functional form on the continuous variables (real_co2, theta_co2, and realincatax) and the dummy variables and time trend variable are included in linear form. Therefore the estimated parameter on the scaling variable can be interpreted to mean that for every one percent increase in the scale relativity parameter, household carbon dioxide emissions will increase by 4.24 percent, independent of the income effect. This result substantiates the more anecdotal result we found earlier when simply comparing the mean growth rates of the scale relativity parameter and mean household carbon dioxide emissions.

Table 4.3.1 Modified Regression Results: Total Household CO_2 Emissions

VARIABLES	l_realco2
l_realincatax	0.116***
	(0.00424)
l_theta_co2	4.235***
	(0.306)
northe	0.0157
	(0.0243)
midwest	-0.0476*
	(0.0255)
south	0.0765***
	(0.0241)
ownhome	0.515***
	(0.0110)
sexref	0.0677***
	(0.00625)
whiteref	0.0112
	(0.00927)
college	0.195***
	(0.00726)
year	-0.0141***
	(0.00162)
Constant	-0.155***
	(0.0557)
Observations	232,723
R-squared	0.225

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

To further illuminate the importance of this result I use the above regression model to predict mean household carbon dioxide emissions from 1996 to 2009. Initially, I predict household emissions while allowing all regressors to vary in time (unrestricted prediction). Then, to determine the impact of decreasing economies of scale since 2003 I predict mean household emissions while holding the scale relativity parameter constant at 2003 levels and allowing all other regressors to vary (2003 scaling). The comparison of these predictions is displayed in Figure 4.3.5. In the absence of demographic change resulting in the diminished ability of households to experience economies of scale since 2003, mean household carbon dioxide

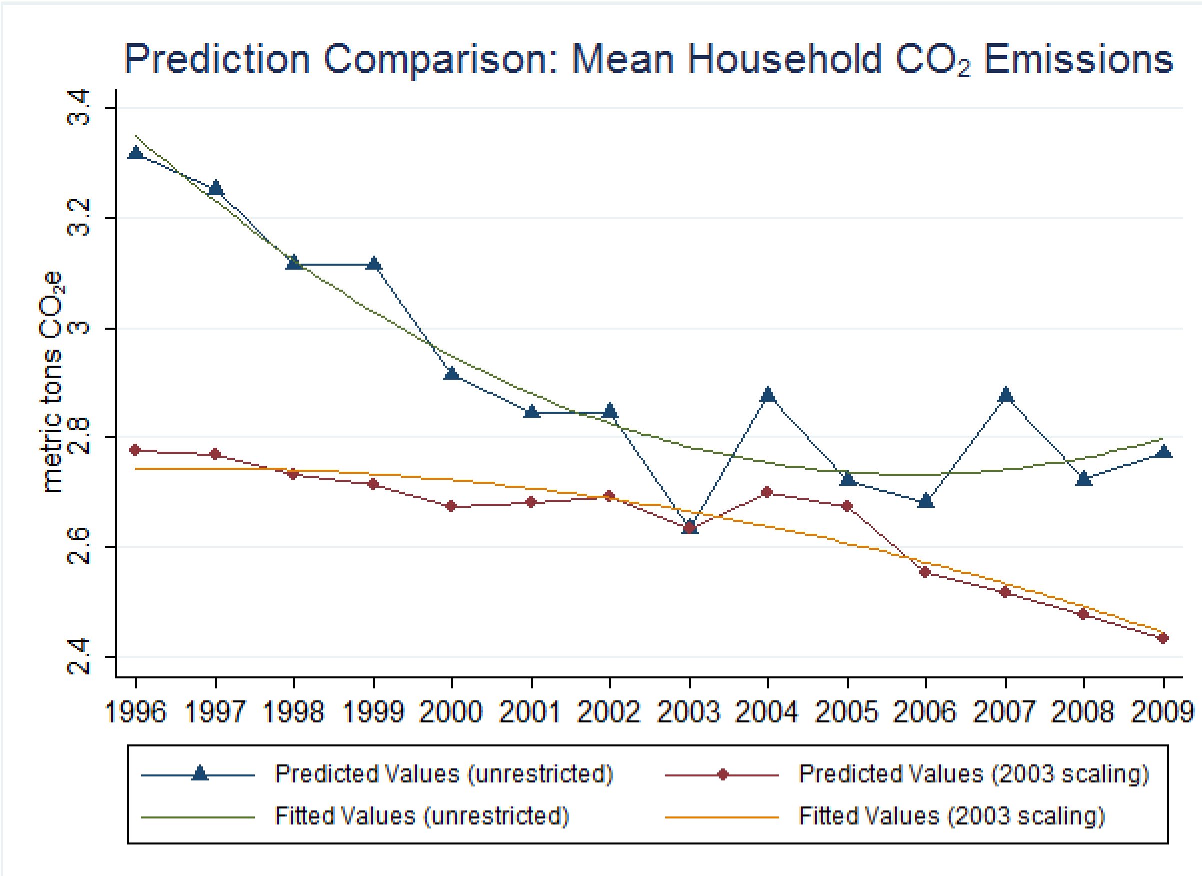

Figure 4.3.5. Prediction Comparison: Mean Household CO_2 Emissions

emissions are estimated to be 10.68% lower in 2009, relative to the unrestricted prediction.[50] In the presence of rising household expenditures and continued improvements in energy efficiency since 2003, mean household carbon dioxide emissions are increasing. This increase is a result of the diminished ability of households to enjoy economies of scale from cohabitation driven by changes in household size and composition.

4.4. Conclusion

Changes in household formation patterns alter the way in which household members can share their expenditures to experience economies of scale in the resulting emissions. These

[50] The estimated 2009 value in the unrestricted prediction is 2.724 metric tons of CO_2e with a 95% confidence interval = [2.710, 2.738]. The estimated 2009 value in the restricted 2003 scaling prediction is 2.433 metric tons of CO_2e with a 95% confidence interval = [2.420, 2.446].

benefits of cohabitation entail energy savings and reduce household emissions. As more people choose to wait until later in life to cohabitate or get married, young couples continue to delay or forego reproduction, and baby boomers continue to age and form "empty nests", the ability of the average United States household to experience economies of scale in their expenditures and resulting emissions will continue to diminish. Despite ongoing improvements in energy efficiency and continued conservation efforts, mean household carbon dioxide emissions are rapidly increasing since 2003. This increase has been attenuated by decreased expenditures, as a result of the Great Recession. In addition, people seeking to take advantage of the cost savings provided by cohabitation may have stabilized mean household size. However, a sustained economic recovery and growth period may to lead to continued increases in household emissions.

This chapter shows that a household's needs are determined by their position in the life course, revealed by the age composition of the household, and progression through the life course has more profound impacts on household expenditure decisions than do changing household incomes. Changes in the population age structure and household formation patterns change the composition and size of the average U.S. household, decrease the ability of households to experience economies of scale, and increase the mean household carbon dioxide emissions of the U.S. population. On average, household carbon dioxide emissions were over 10 percent higher in 2009 as a result of reductions in the scalability of household expenditures and emissions.

These results are significant and seem to be fairly large in magnitude; as a result it is natural to be somewhat skeptical of these results. One potential limitation of this empirical methodology is the possible endogeneity arising from the two-stage analysis. In this methodology, due mainly to limited computational capacity, I estimated the equivalence scale model to obtain estimates of the scale relativity parameters and then controlled for other household and regional characteristics in the second stage. Using the estimated scale relativity parameters as a regressor in the second stage creates potential endogeneity, as these parameters are themselves a function of household carbon dioxide emissions, the logged value of which is the dependent variable in the second stage. This potential endogeneity may explain the seemingly large estimated coefficient on the scale relativity parameter variable in the second stage.

To address this issue, in the future, I plan to combine the first and second stage into a single econometric model. By including the other household and regional control variables linearly in the equivalence scale model, the estimated scale relativity and contribution parameters will be robust to differences in household income and other characteristics. While this adjustment is not likely to change the implications and directionality of the results, it will make for a more robust and reliable set of estimates on which to base conclusions and develop policy implications.

It is important to point out that demographic changes such as those described herein are an inevitable stage of development, so no policy recommendation can be made to reverse this trend. However, these demographic changes have, and continue to, eliminate the gains we have achieved through energy efficiency and conservation, so if we are to attempt to dramatically change the trajectory of total U.S. carbon dioxide emissions into the future, gains must be made in the carbon intensity of production, especially with respect to the most carbon intensive direct expenditures. The gains in energy efficiency are becoming increasingly smaller and are no longer substantial enough to outweigh the losses in economies of scale resulting from demographic change. The only path to dramatically lower household carbon dioxide emissions is through dramatic reductions in the carbon intensity of direct expenditures.

Climate projections using naïve models of population size and growth that fail to account for household size and composition effects may be inaccurately projecting energy use and emissions in the future. Much of the developing world can be expected to undergo similar demographic and cultural transitions. To develop accurate projections of carbon dioxide emissions in the developing world, elements of household size and composition must be considered.

CHAPTER V

Conclusion

As discussed in Chapter 1, increasing evidence from the Intergovernmental Panel on Climate Change (IPCC), the world's leading body on climate change, which includes over 2500 scientists from 150 countries, indicates that global warming is occurring, mostly due to greenhouse gas (GHG) emissions related to human activities (IPCC, 2007a). Most of this warming is very likely due to GHG emissions with a confidence level of over 90 percent (IPCC, 2007a). Considerable progress has been made in developing a better understanding of how human actions lead to global climate change, in particular, the anthropogenic drivers of this change. This literature focuses on two main themes: land use changes and human activities. Studies regarding land use changes focus primarily on changes in albedo[51], the supply of ecosystem services, including carbon sequestration, and GHG emissions resulting from agriculture (Rosa & Dietz, 2012). As there have been several excellent reviews of this literature, I will not discuss these findings here (DeFries et al., 2010; Rudel et al., 2005; Williams, 2008).

The human drivers of GHG emissions have been discussed and debated for centuries, dating back to the writings of Thomas Malthus in the eighteenth and nineteenth centuries: population, affluence, technology, institutional structure, and culture. Growing human population puts stress on the environment through both its sheer size and its rate of growth. The degree of environmental impact resulting from population increases will depend upon the patterns of consumption within the population. While cultural differences may have a mitigating impact on the pattern of consumption, over the course of many decades, varying patterns of consumption tend to converge towards a Western pattern of affluence increases (Wilk, 1997;

[51] The amount of solar radiation reflected from the earth's surface, typically expressed as a percentage.

2002). However, the degree of environmental impacts produced by a rising population and its corresponding consumption also depend on the technologies used in production. This point, that population, affluence, and technology act jointly, in a multiplicative fashion, in driving environmental impact, was elucidated decades ago by Ehrlich and Holdren (1971) in the I-PAT model and its extended Kaya Identity (Kaya, 1990). However, these models assume unit elasticity with respect to the three components, meaning that an equal percent change in any component produces an equal change in environmental impact. The STIRPAT model (Dietz & Rosa, 1994; 1997), based on both the I-PAT model and Kaya Identity, is somewhat more sophisticated by allowing researchers to test statistically the elasticity of each component with respect to emissions; yet interactions between population dynamics, economic growth, and technology are not considered. In a cross-national panel study of carbon dioxide emissions from 1960-2005, Jorgenson and Clark (2010) found population elasticities ranging from 1.27 to 1.86, indicating an elastic impact on carbon dioxide emissions which is consistent with the bulk of previous studies finding population elasticities between one and two (Cole & Neumayer, 2004; Dietz & Rosa, 1997; Rosa et al., 2004; Shi, 2003; York et al., 2003). However, these analyses conducted mainly by economists, demographers, sociologists, or ecologists do not use the type of language or "integrated assessment models" familiar to climatologists and have therefore been largely ignored or not taken seriously by the climate research community.

Even the IPCC's Special Report on Emission Scenarios (SRES) identifies population growth, economic growth, technological change, and changes in the patterns of energy and land use as the major drivers of the growth in GHG emissions. In nearly all integrated assessment models, population size is the only demographic variable considered. The implied assumption is that each individual in a population shares the same productive and consumptive behavior – an assumption that, as I have shown in the previous few chapters – is inaccurate and potentially misleading. These behavioral attributes differ among various population groups and as the proportion of these various groups in a population change, the amount of GHG emissions that a population emits will also change. Over the past two decades many studies have been conducted to determine whether or not different consumption and emissions behaviors exist in population groups with various characteristics (Cole & Neumayer, 2004; Dietz et al., 2007; York et al., 2003) and whether the proportion of these different groups will change significantly in the future (Jiang & O'Neill, 2007; Lutz et al., 2001; Mackellar et al., 1995; Zagheni, 2011;). Fan et al. (2006) find that the effect of population dynamics, especially the percentage of the population aged 15 to 64, on carbon dioxide emissions vary greatly with the level of economic development, highlighting the importance of considering the role that productive and consumptive behaviors play at various income levels when constituting long-term strategies for emission reductions.

The consideration of both heterogeneous consumption behaviors among population groups and how the proportion of these groups within the population will change in the future is crucial to predications of future carbon dioxide emissions, both in the United States and globally. For example, it would not be necessary to consider the impact of urbanization if there are no substantial differences in productive and consumptive behavior between rural and urban populations. It would be sufficient to use mean per capita emissions when estimating or predicting the total emissions of a given population. Furthermore, even if significant behavioral differences are found between rural and urban populations, it would not be necessary to account for these differences in the analysis if urban/rural proportions of the population are not expected to change in the future (Jiang & Hardee, 2011).

According the United Nations' most recent population projections, the global population will increase from 6.97 billion in 2011 to 9.31 billion in 2050, with 97 percent of this growth occurring in the developing world (UN, 2011). Urban areas of the world are expected to absorb all of this expected population growth while at the same time drawing in some from rural populations and this growth will be concentrated in cities and towns of less developed regions (UN, 2012). Therefore, the percentage of the world's population living in urban areas is expected to increase from 52 percent in 2011 to about 67 percent in 2050. Furthermore, the demographic consequence of expected fertility decline and life expectancy increases associated with global development is population aging, a process through which the proportion of older persons in the population will increase and that of younger persons will decrease. As a result the median age of the world population is expected to increase from 29.4 years in 2011 to 37.9 in 2050 and the proportion of persons aged 60 years or older in the world's population is expected to increase from 11.2 percent to 22 percent. Lastly, household projections for major developed and developing countries also show that an increasing proportion of these populations will be living in smaller households (Dalton et al., 2008; Jiang & O'Neill, 2007; Pachauri & Jiang, 2008; Zeng et al., 2008).

As I and an increasing number of other studies have shown, households, rather than individuals, should be used as the unit of analysis when analyzing the impact of demographic trends on carbon dioxide emissions, as households are the units of consumption (Cramer 1997, 1998; Jiang, 1999; Liu et al., 2003; Mackellar et al., 1995; O'Neill & Chen, 2002). A study of energy consumption in developed countries from 1970 to 1990 shows that using either the number of households or population size as the demographic variable leads to significantly different results regarding the demographic impact on energy use. This study decomposes total energy consumption into demographic, economic, and technological effects and finds that when population size is used as the demographic variable in the analysis, demographic factors account for only one-third of total energy consumption (Mackeller et al., 1995). However, when the number of households is used, demographic factors contribute to 76 percent of the total increase in energy consumption. This difference stems mainly from the compositional changes of the population, especially with respect to the proportion of smaller households – which has increased. Therefore, the number of households has increased more rapidly than the increases in the population. As I have shown in Chapter 4, this reduction in household size results in a loss of economies of scale meaning that per capita energy consumption (or emissions) is higher for smaller households than that of larger households. As a result, total energy consumption (emissions) has increased in the developed world even though the rate of population increase has slowed and energy efficiency has continued to improve.

To highlight the importance of these changes in population composition I will use a simplified illustrative example using data from the United States. For simplicity, I will assume that per capita emissions across household size are constant at their respective mean levels over the period 1996 to 2009 (i.e. efficiency is constant over the period). Notice the reduction in per capita emissions as household size increases (Table 5.1). Using sample proportions of

Table 5.1. Per Capita CO_2 Emissions and Household Size

	Household Size					
	1	2	3	4	5	6+
Mean CO_2	2.17	3.72	4.19	4.76	4.96	4.90
Mean CO_2 per capita	2.17	1.86	1.40	1.19	0.99	0.75
Proportions 1996	0.285	0.309	0.154	0.148	0.066	0.037
Proportions 2009	0.288	0.328	0.148	0.137	0.059	0.040

Note: Carbon dioxide emissions measured as metric tons of CO_2 equivalent emissions households of different sizes obtained from my data and total population data from the U.S. Census Bureau, I estimate total carbon dioxide emissions in the United States for 1996 and 2009, using the corresponding yearly proportions (Table 5.2). Over this period the U.S. population

Table 5.2. Illustrative example of emissions under different compositional scenarios

	U.S. population (thousands)	Total Emissions (thousand metric tons CO2e)	Total Emissions (1996 proportions)	Percent difference
1996	269,386	452,182.7	452,182.7	-
2009	307,206	520,259.4	515,666.2	-0.88%
% Change	14.04%	15.06%	14.04%	

increases by 14 percent and total estimated carbon dioxide emissions increase by 15 percent, a population elasticity of 1.07. If however, these changing population demographics were ignored in estimating total emissions in 2009, in other words, if 1996 proportions were used, then estimated total emissions in the United States would be nearly a full percent (0.88%) lower than the actual value in 2009. While this scenario is over-simplified and does not consider interactions with affluence and technology, given the changes in total population and population composition over this short period, inaccuracy in emission projections will compound over longer time horizons. In the context of the dramatic global demographic changes expected over the next century, the failure of climate researchers and policymakers to incorporate these changes in modeling global emissions may result in drastic inaccuracies of projections and will impede attempts to mitigate and adapt to the effects of changes in the climate system.

Strong evidence exists showing that demographic change is closely associated with greenhouse gas emissions and future trends in population dynamics will play a key role in attempts to develop mitigation and adaptation strategies in a changing global climate. The social science literature on the drivers of anthropogenic climate change is relatively fixed across disciplines. As the group of researchers in any one discipline examining the human drivers of greenhouse gas emissions is relatively small, a multi-disciplinary and cooperative dialogue is warranted. While many aspects of this literature are reasonably robust, with many studies converging on the same conclusion regarding the importance of population and demographic dynamics, there seems to be little evidence that this growing body of literature has had any impact on the development of emissions scenarios – a key component in all climate assessments, including the IPCC. In mapping plausible climate futures, these assessments could be dramatically enhanced if emissions calculations were based on well-founded empirical estimates of driver weights (affluence, technology, and population) rather than the *a priori* proportionality assumptions stemming from the I-PAT model.

The population and economic growth anticipated in the next century will tend to push greenhouse gas emissions ever upward – a scale effect. As shown herein, based off data from the United States, improvements in energy efficiency and the demographic forcing resulting from development, especially changes in household economies of scale tend to act as countervailing forces. Most policy proposals for limiting the magnitude of climate change address only strategies for improvements in technological efficiency, while taking the scale effect as given. However, it has yet to be demonstrated that these technological and compositional changes can consistently produce such a strong counteracting effect as to neutralize the scale effect. In fact, as suggested by the demographic changes in the United States discussed in this dissertation, it is possible that at a certain point in global development demographic pressures will overwhelm the mitigating effects of efficiency improvements and compositional changes in consumption. Indeed, much of the resistance to climate change mitigation policy, beyond its incidence on different groups in the population, stems from the large-scale changes in technology and forms of consumption that will be required to stabilize the concentration of greenhouse gases in the atmosphere. The dramatic changes in population and affluence over the next century will occur primarily in the developing world necessitating these huge changes, but also highlighting the resistance to these changes in the developed world. Regardless, it is clear that reductions in greenhouse gas emissions need to occur, but adopting these policies in the face of this scale effect will be extremely difficult in the context of the institutional, political, and cultural forces that have prevailed so far.

Nonetheless, it is clear, in addition to population size, that analyzing the compositional changes of the population, specifically the age composition, the distribution of people living in urban and rural areas, and household size and composition, is very important in understanding current carbon intensities of, and total emissions resulting from, consumption behaviors and for understanding future needs and potential mitigation strategies.

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APPENDICES

Appendix 1. Raw Sectoral Carbon Intensities

Broad Production Sector		**tCO$_2$e per $mil**	
Detailed Production Sector	**Sector ID**	**1997 (1997$)**	**2002 (2002$)**
Agriculture, Livestock, Forestry, and Fisheries			
Oilseed Farming	1	2540	2760
Grain Farming	2	4950	3240
Vegetable & Melon Farming	3	1120	856
Tree Nut Farming	4	1230	1010
Fruit Farming	5	1080	886
Greenhouse & Nursery Production	6	659	667
Tobacco Farming	7	2140	3400
Cotton Farming	8	3370	3540
Sugarcane & Sugar Beet Farming	9	2160	2250
All Other Crop Farming	10	2410	2440
Milk Production	11	NA	3930
Cattle Ranching & Farming	12	6270	7390
Poultry & Egg Production	13	2420	2260
Other Animal Production	14	3900	3440
Logging	15	654	669
Forest Nurseries, Forest Products & Timber Tracts	16	823	1050
Fishing	17	996	1200
Hunting & Trapping	18	758	604
Agriculture & Forestry Support Activities	19	1730	1450
Mining and Utilities			
Oil & Gas Extraction	20	1880	2170
Coal Mining	21	3080	3150
Iron Ore Mining	22	2740	2350
Copper, Nickel, Lead, & Zinc Mining	23	1490	1460
Gold, Silver, & Other Metal Ore Mining	24	1390	1640
Stone Mining & Quarrying	25	1350	1250
Sand, Gravel, Clay & Refractory Mining	26	1550	1360
Other Nonmetallic Mineral Mining	27	2310	1600
Drilling Oil & Gas Wells	28	766	984
Support Activities for Oil & Gas Operations	29	591	649
Support Activities for Other Mining	30	1200	977
Power Generation & Supply	31	9530	9370
Natural Gas Distribution	32	4160	2430
Water, Sewage, & Other Systems	33	2330	1780
Construction			
*Nonresidential, Commercial, & Health Care Structures**	34	599	589

Broad Production Sector		**tCO_2e per $mil**	
Detailed Production Sector	**Sector ID**	**1997 (1997$)**	**2002 (2002$)**
*Nonresidential Manufacturing Structures**	35	588	437
*Other Nonresidential Structures**	36	602	612
*Residential, Permanent, Single & Multi-Family Structures***	37	602	659
*Other Residential Structures**	38	602	580
*Nonresidential Maintenance & Repair**	39	430	624
*Residential Maintenance & Repair**	40	743	698
Food, Beverage, & Tobacco			
Dog & Cat Food Manufacturing	41	1050	1530
Other Animal Food Manufacturing	42	2400	2030
*Flour Milling & Malt Manufacturing***	43	3290	2050
Wet Corn Milling	44	3970	3650
Fats & Oils, Refining & Blending	45	1960	2060
*Soybean & Other Oilseed Processing***	46	2420	2340
Breakfast Cereal Manufacturing	47	1160	713
Beet Sugar Manufacturing	48	NA	2330
*Sugarcane Mills & Refining**	49	1780	2050
Confectionary Manufacturing from Cacao Beans	50	874	1050
Confectionary Manufacturing from Purchased Chocolate	51	646	707
Non-chocolate Confectionary Manufacturing	52	659	769
Frozen Food Manufacturing	53	873	1000
*Fruit & Vegetable Canning, Pickling, & Drying**	54	810	745
Cheese Manufacturing	55	2600	1760
Dry, Condensed, & Evaporated Dairy Products	56	1670	1350
*Fluid Milk & Butter Manufacturing***	57	2390	1650
Ice Cream & Frozen Dessert Manufacturing	58	1550	1070
Poultry Processing	59	1310	1120
Animal (except poultry) Slaughtering & Processing	60	2553	2870
Seafood Product Preparation & Packaging	61	992	970
*Bread & Bakery Product Manufacturing***	62	700	656
Cookie, Cracker, & Pasta Manufacturing	63	833	763
Tortilla Manufacturing	64	981	870
*Snack Food Manufacturing***	65	853	744
Coffee & Tea Manufacturing	66	682	609
Flavoring Syrup & Concentrate Manufacturing	67	537	411
*Seasoning & Dressing Manufacturing***	68	770	771
All Other Food Manufacturing	69	1090	838
Soft Drink & Ice Manufacturing	70	709	651
Breweries	71	569	568
Distilleries	72	421	316
Wineries	73	544	450

Broad Production Sector *Detailed Production Sector*	Sector ID	tCO$_2$e per $mil 1997 (1997$)	 2002 (2002$)
*Tobacco Product Manufacturing***	74	830	309
Textiles, Apparel, & Leather			
Fiber, Yarn, & Thread Mills	75	1670	1500
Broad woven Fabric Mills	76	1310	1180
Narrow Fabric Mills & Schiffli Embroidery	77	916	806
Nonwoven Fabric Mills	78	1130	1140
Knit Fabric Mills	79	1240	1180
Textile & Fabric Finishing Mills	80	1340	1040
Fabric Coating Mills	81	914	899
Carpet & Rug Mills	82	819	735
Curtain & Linen Mills	83	677	552
Textile Bag & Canvas Mills	84	721	550
All Other Miscellaneous Textile Product Mills	85	638	807
*Hosiery & Sock Mills***	86	745	424
*Cut & Sew Apparel Contractors**	87	557	375
Men's & Boys' Cut & Sew Apparel Manufacturing	88	NA	381
Women's & Girls Cut & Sew Apparel Manufacturing	89	NA	403
Other Cut & Sew Apparel Manufacturing	90	NA	383
Accessories & Other Apparel Manufacturing	91	585	437
Leather & Hide Tanning & Finishing	92	2270	2350
Footwear Manufacturing	93	614	504
Wood, Paper, & Printing			
*Sawmills & Wood Preservation***	94	725	695
Reconstituted Wood Product Manufacturing	95	1190	1250
Veneer & Plywood Manufacturing	96	759	717
Engineered Wood Member & Truss Manufacturing	97	541	522
*Wood Windows, Doors, & Millwork**	98	535	558
Wood Container & Pallet Manufacturing	99	708	675
Manufactured Home, Mobile Home, Manufacturing	100	553	710
Prefabricated Wood Building Manufacturing	101	636	567
Miscellaneous Wood Product Manufacturing	102	600	577
Pulp Mills	103	2000	1670
*Paper Mills**	104	1750	1520
Paperboard Mills	105	NA	1790
Paperboard Container Manufacturing	106	1180	1010
*Coated & Laminated Paper, Packaging Materials, & Plastic Films**	107	910	813
*All Other Paper Bag & Coated and Treated Paper**	108	1120	952
*Stationery Product Manufacturing***	109	796	711
Sanitary Paper Product Manufacturing	110	875	631
All Other Converted Paper Product Manufacturing	111	791	809

Broad Production Sector *Detailed Production Sector*	Sector ID	tCO$_2$e per $mil 1997 (1997$)	2002 (2002$)
*Printing***	112	648	542
*Support Activities for Printing***	113	433	389
Petroleum, Coal, & Basic Chemical			
Petroleum Refineries	114	1200	1260
Asphalt Paving Mixture & Block Manufacturing	115	1900	1450
Asphalt Shingle & Coating Materials Manufacturing	116	1250	1090
Petroleum Lubricating Oil & Grease Manufacturing	117	2340	1530
All Other Petroleum & Coal Products Manufacturing	118	1720	2160
Petrochemical Manufacturing	119	1920	2690
Industrial Gas Manufacturing	120	7930	4640
Synthetic Dye & Pigment Manufacturing	121	2650	1880
Alkalis & Chlorine Manufacturing	122	NA	2100
Carbon Black Manufacturing	123	NA	3780
*All Other Basic Inorganic Chemical Manufacturing**	124	1970	2060
Other Basic Organic Chemical Manufacturing	125	1820	2540
Resin, Rubber, Artificial Fibers, Agricultural Chemicals, & Pharmacuticals			
Plastics Material & Resin Manufacturing	126	1650	2380
Synthetic Rubber Manufacturing	127	1750	1780
*Artificial & Synthetic Fibers & Filaments Manufacturing***	128	2190	1700
*Fertilizer Manufacturing***	129	6610	5750
Pesticide & Other Agricultural Chemical Manufacturing	130	987	776
Medicinal & Botanical Manufacturing	131	NA	409
*Pharmaceutical Preparation Manufacturing**	132	420	304
In-Vitro Diagnostic Substance Manufacturing	133	NA	361
Biological Product (except diagnostic) Manufacturing	134	NA	300
Paint, Adhesives, Cleaning, & Other Chemicals			
Paint & Coating Manufacturing	135	1110	988
Adhesive Manufacturing	136	1200	1180
*Soap & Cleaning Compound Manufacturing**	137	608	569
Toilet Preparation Manufacturing	138	456	481
Printing Ink Manufacturing	139	1190	1130
*All Other Chemical Product & Preparation Manufacturing***	140	1192	960
Plastic, Rubber, & Nonmetallic Mineral Products			
Plastics Packaging Materials, Film & Sheet	141	1050	1240
*Unlaminated Plastics Profile Shape Manufacturing**	142	884	915
*Plastics Pipe & Pipe Fitting Manufacturing**	143	884	1060
Laminated Plastics, Plate, Sheet, & Shapes	144	786	799
*Polystyrene Foam Product Manufacturing**	145	851	1150
*Urethane & Other Foam Product Manufacturing (except Polystyrene)**	146	851	966

Broad Production Sector *Detailed Production Sector*	Sector ID	tCO_2e per $mil 1997 (1997$)	 2002 (2002$)
Plastics Bottle Manufacturing	147	1050	1330
*Other Plastics Product Manufacturing***	148	834	748
Tire Manufacturing	149	933	565
Rubber & Plastics Hose & Belting Manufacturing	150	834	845
Other Rubber Product Manufacturing	151	915	836
*Pottery, Ceramics, & Plumbing Fixture Manufacturing***	152	793	624
*Brick, Tile, and Other Structural Clay Product Manufacturing***	153	1125	1220
*Clay & Non-Clay Refractory Manufacturing***	154	1165	1190
*Flat Glass Manufacturing**	155	839	1650
*Other Pressed & Blown Glass & Glassware Manufacturing**	156	839	1070
Glass Container Manufacturing	157	1610	1510
Glass Product Manufacturing Made of Purchased Glass	158	NA	904
Cement Manufacturing	159	6020	9220
Ready-Mix Concrete Manufacturing	160	1980	2150
*Concrete Pipe, Brick, & Block Manufacturing***	161	1215	1470
Other Concrete Product Manufacturing	162	1090	1140
*Lime & Gypsum Product Manufacturing***	163	5635	4200
Abrasive Product Manufacturing	164	807	645
Cut Stone & Stone Product Manufacturing	165	653	629
Ground or Treated Minerals & Earths Manufacturing	166	1200	1360
Mineral Wool Manufacturing	167	1280	1340
Miscellaneous Nonmetallic Mineral Products	168	1440	1770
Ferrous & Nonferrous Metal Production			
Iron & Steel Mills	169	2160	3110
*Iron, Steel Pipe, & Tube Manufacturing from Purchased Steel***	170	2135	1780
Secondary Smelting & Alloying of Aluminum	171	NA	3490
*Alumina Refining & Primary Aluminum Production***	172	3375	3220
*Aluminum Product Manufacturing from Purchased Aluminum***	173	1565	1450
Primary Smelting & Refining of Copper	174	1120	1200
*Primary Smelting & Refining of Nonferrous Metal (expect Cu & Al)**	175	2080	2070
*Copper Rolling, Drawing, Extruding, & Alloying**	176	835	880
*Nonferrous metal (except Cu & Al) Rolling, Drawing, Extruding, & Alloying**	177	971	999
Ferrous Metal Foundries	178	928	1030
Nonferrous Foundries	179	NA	1170
Custom Roll Forming	180	1160	1440
All Other Forging, Stamping, & Sintering	181	1060	1450
Crown, Closure, & Metal Stamping Manufacturing	182	NA	1010
Cutlery, Hand tools, Structural & Metal Containers			
*Cutlery, Utensils, Pots, & Pans Manufacturing***	183	526	453

Broad Production Sector *Detailed Production Sector*	Sector ID	tCO$_2$e per $mil 1997 (1997$)	 2002 (2002$)
*Hand tool Manufacturing***	184	588	648
*Platework & Fabricated Structural Product Manufacturing***	185	890	932
*Ornamental & Architectural Metal Products Manufacturing***	186	755	735
Power Boiler & Heat Exchanger Manufacturing	187	711	784
Metal Tank, Heavy Gauge, Manufacturing	188	816	945
Metal Can, Box, & Other Container Manufacturing	189	1410	1230
Other Metal Hardware and Ordnance Manufacturing			
Hardware Manufacturing	190	615	600
Spring & Wire Product Manufacturing	191	852	906
Machine Shops	192	541	529
Turned Product & Screw, Nut, & Bolt Manufacturing	193	542	602
Coating, Engraving, Heat Treating & Allied Activities	194	1020	1140
*Plumbing Fixture Fitting & Trim Manufacturing**	195	504	440
*Valve & Fittings Other than Plumbing**	196	504	541
Ball & Roller Bearing Manufacturing	197	606	665
Fabricated Pipe & Pipe Fitting Manufacturing	198	806	796
Ammunition Manufacturing	199	753	407
*Ordnance & Accessories Manufacturing***	200	524	362
*Other Fabricated Metal Manufacturing***	201	765	699
Machinery & Engines			
Farm Machinery & Equipment Manufacturing	202	606	576
Lawn & Garden Equipment Manufacturing	203	531	412
Construction Machinery Manufacturing	204	680	617
*Mining & Oil & Gas Field Machinery Manufacturing***	205	614	656
Plastics & Rubber Industry Machinery	206	448	581
Semiconductor Machinery Manufacturing	207	573	496
Other Industrial Machinery Manufacturing	208	523	571
Optical Instrument & Lens Manufacturing	209	409	397
Photographic & Photocopying Equipment Manufacturing	210	446	423
Other Commercial & Service Industry Machinery	211	542	456
*Vending, Commercial, Industrial, & Office Machinery**	212	574	339
Heating Equipment (except warm air furnaces) Manufacturing	213	519	508
Air Conditioning, Refrigeration, & Warm Air Heating Equipment	214	609	493
*Air Purification & Ventilation Equipment Manufacturing***	215	642	640
Industrial Mold Manufacturing	216	551	626
Special Tool, Die, Jig, & Fixture Manufacturing	217	530	610
Cutting Tool & Machine Tool Accessory Manufacturing	218	607	566
*Metal Cutting & Forming Machine Tool Manufacturing***	219	497	531
Rolling Mill & Other Metalworking Machinery Manufacturing	220	461	491
Turbine & Turbine Generator Set Units Manufacturing	221	535	408

Broad Production Sector *Detailed Production Sector*	Sector ID	tCO2e per $mil 1997 (1997$)	 2002 (2002$)
*Speed Changer, Industrial High-Speed Drive, & Gear**	222	608	548
*Mechanical Power Transmission Equipment Manufacturing**	223	608	601
Other Engine Equipment Manufacturing	224	622	597
*Pump & Pumping Equipment Manufacturing***	225	591	530
Air & Gas Compressor Manufacturing	226	487	509
*Material Handling Equipment Manufacturing***	227	689	702
Power-Driven Hand tool Manufacturing	228	449	409
Packaging Machinery Manufacturing	229	411	458
Industrial Process Furnace & Oven Manufacturing	230	496	508
*Fluid Power Process Machinery***	231	614	582
*Process & Oven, Not Fluid Power Machinery***	232	533	559
Computers, Audio-Video, & Communications Equipment			
Electronic Computer Manufacturing	233	403	276
Computer Storage Device Manufacturing	234	333	347
*Computer Terminals & Other Computer Peripheral Equipment***	235	449	330
Telephone Apparatus Manufacturing	236	315	313
Broadcast & Wireless Communications Equipment	237	327	319
Other Communications Equipment Manufacturing	238	366	340
Audio & Video Equipment Manufacturing	239	502	446
Electron Tube Manufacturing	240	846	685
Bare Printed Circuit Board Manufacturing	241	NA	542
Semiconductors, Electronic Equipment, Media Reproduction			
Semiconductor & Related Device Manufacturing	242	435	557
Electronic Connector Manufacturing	243	NA	582
Printed Circuit Assembly (Electronic Assembly) Manufacturing	244	NA	390
*Other Electronic Component Manufacturing**	245	469	416
Electronic Capacitor, Resistor, Coil, Transformer, & Other Inductor Manufacturing	246	NA	536
Electro-medical Apparatus Manufacturing	247	385	346
Search, Detection, & Navigation Instruments	248	320	312
Automatic Environmental Control Manufacturing	249	443	453
Industrial Process Variable Instruments	250	354	448
Totalizing Fluid Meters & Counting Devices	251	563	454
Electricity & Signal Testing Instruments	252	295	298
Analytical Laboratory Instrument Manufacturing	253	381	337
Irradiation Apparatus Manufacturing	254	402	377
Watch, Clock, & Other Measuring & Controlling Device Manufacturing	255	408	310
Magnetic and Optical Recording Media Manufacturing	256	779	489
*Software, Audio, & Video Reproduction***	257	402	575

Broad Production Sector *Detailed Production Sector*	Sector ID	tCO$_2$e per $mil 1997 (1997$)	 2002 (2002$)
Lighting, Electrical Components, Batteries			
Electric Lamp, Bulb, & Part Manufacturing	258	499	422
Lighting Fixture Manufacturing	259	595	511
*Small Electrical Appliance Manufacturing***	260	586	463
Household Cooking Appliance Manufacturing	261	609	597
Household Refrigerator & Home Freezer Manufacturing	262	744	584
Household Laundry Equipment Manufacturing	263	689	554
Other Major Household Appliance Manufacturing	264	666	533
Electric Power & Specialty Transformer Manufacturing	265	768	733
Motor & Generator Manufacturing	266	630	582
Switchgear & Switchboard Apparatus Manufacturing	267	483	400
Relay & Industrial Control Manufacturing	268	459	305
Storage Battery Manufacturing	269	816	950
Primary Battery Manufacturing	270	513	422
*Communication & Energy Wire & Cable Manufacturing***	271	668	668
Wiring Device Manufacturing	272	564	541
Carbon & Graphite Product Manufacturing	273	840	1100
Miscellaneous Electrical Equipment Manufacturing	274	546	370
Vehicles & Other Transportation Equipment			
*Automobile Manufacturing**	275	611	488
*Light Truck & Utility Vehicle Manufacturing**	276	611	562
Heavy Duty Truck Manufacturing	277	676	642
Motor Vehicle Body Manufacturing	278	888	546
Truck Trailer Manufacturing	279	852	748
Motor Home Manufacturing	280	622	518
Travel Trailer & Camper Manufacturing	281	654	632
Motor Vehicle Parts Manufacturing	282	769	710
Aircraft Manufacturing	283	464	373
Aircraft Engine & Engine Parts Manufacturing	284	442	365
Other Aircraft Parts & Equipment	285	544	522
Guided Missile & Space Vehicle Manufacturing	286	408	310
*Other Guided Missile & Space Vehicle Parts & Auxiliary Equipment Manufacturing**	287	578	352
Railroad Rolling Stock Manufacturing	288	787	518
Ship Building & Repairing	289	621	443
Boat Building	290	531	468
Motorcycle, Bicycle, & Parts Manufacturing	291	645	543
Military Armored Vehicles & Tank Parts Manufacturing	292	1500	538
All Other Transportation Equipment Manufacturing	293	578	500
Furniture, Medical Equipment, & Supplies			

Broad Production Sector *Detailed Production Sector*	**Sector ID**	**tCO$_2$e per $mil** **1997 (1997$)**	**2002 (2002$)**
Wood Kitchen Cabinet & Countertop Manufacturing	294	479	489
Upholstered Household Furniture Manufacturing	295	552	469
Non-upholstered Wood Household Furniture Manufacturing	296	509	433
Institutional Furniture Manufacturing	297	555	613
*Metal & Other Household Non-upholstered Furniture***	298	623	613
Custom Architectural Woodwork & Millwork	299	456	601
Showcases, Partitions, Shelving, & Lockers	300	742	910
*Office Furniture Manufacturing***	301	537	535
Mattress Manufacturing	302	529	481
Blind & Shade Manufacturing	303	582	548
Laboratory Apparatus & Furniture Manufacturing	304	522	387
Surgical & Medical Instrument Manufacturing	305	357	384
Surgical Appliance & Supplies Manufacturing	306	425	483
Dental Equipment & Supplies Manufacturing	307	477	624
Ophthalmic Goods Manufacturing	308	379	288
Dental Laboratories	309	558	273
Other Miscellaneous Manufacturing			
Jewelry & Silverware Manufacturing	310	570	532
Sporting & Athletic Goods Manufacturing	311	543	451
Doll, Toy, & Game Manufacturing	312	509	447
Office Supplies (except paper) Manufacturing	313	497	391
Sign Manufacturing	314	752	614
Gasket, Packing, & Sealing Device Manufacturing	315	805	686
Musical Instrument Manufacturing	316	425	328
Broom, Brush, & Mop Manufacturing	317	613	519
*All Other Miscellaneous Manufacturing***	318	629	505
Trade, Transportation, & Communications Media			
Wholesale Trade	319	279	192
Air Transportation	320	1780	1980
Rail Transportation	321	1120	1200
Water Transportation	322	1430	2780
Truck Transportation	323	2100	1400
Transit & Ground Passenger Transportation	324	NA	1870
Pipeline Transportation	325	4010	4400
Scenic & Sightseeing Transportation & Support Activities for Transportation	326	837	505
Postal Service	327	257	256
Couriers & Messengers	328	1040	1230
Warehousing & Storage	329	1330	483
Retail Trade	330	382	265

Broad Production Sector *Detailed Production Sector*	Sector ID	tCO$_2$e per $mil 1997 (1997$)	 2002 (2002$)
Newspaper Publishers	331	407	325
Periodical Publishers	332	385	309
Book Publishers	333	370	257
*Directory, Mailing List, & Other Publishers**	334	370	277
Software Publishers	335	151	108
Motion Picture & Video Industries	336	281	156
Sound Recording Industries	337	281	248
Radio & Television Broadcasting	338	242	176
*Cable & Other Subscription Programming**	339	192	182
Internet Publishing & Broadcasting	340	NA	238
Telecommunications	341	179	213
Internet Service Providers & Web Search Portals	342	NA	172
*Data Processing, Hosting, & Related Services**	343	153	160
*Other Information Services**	344	225	225
Finance, Insurance, Real Estate, Rental & Leasing			
Non-depository Credit Intermediation & Related Activities	345	211	110
Securities, Commodity Contracts, Investments	346	219	100
Insurance Carriers	347	85.1	66.2
Insurance Agencies, Brokerages, & Related	348	71.6	117
Funds, Trusts, & Other Financial Vehicles	349	231	97.9
Monetary Authorities & Depository Credit Intermediation	350	116	72.6
Real Estate	351	476	285
Automotive Equipment Rental & Leasing	352	308	137
Video Tape & Disc Rental	353	336	439
*Commercial & Industrial Machinery & Equipment Rental & Leasing**	354	152	245
General & Consumer Goods Rental Except Video Tapes & Discs	355	198	230
Lessors of Nonfinancial Intangible Assets	356	7.33	175
Professional & Technical Services			
Legal Services	357	134	98.9
Accounting & Bookkeeping Services	358	146	118
Architectural & Engineering Services	359	144	186
Specialized Design Services	360	198	155
Custom Computer Programming Services	361	149	183
Computer Systems Design Services	362	150	173
Other Computer Related Services, Including Facilities Management	363	150	132
Management Consulting Services	364	167	129
Environmental & Other Technical Consulting Services	365	194	143
Scientific Research & Development Services	366	284	346

Broad Production Sector *Detailed Production Sector*	**Sector ID**	**tCO_2e per \$mil 1997 (1997\$)**	**2002 (2002\$)**
Advertising & Related Services	367	326	239
Photographic Services	368	252	233
Veterinary Services	369	408	294
All Other Miscellaneous Professional & Technical Services	370	133	117
Management, Administrative, & Waste Services			
Management of Companies & Enterprises	371	259	170
Office Administration Services	372	142	159
Facilities Support Services	373	178	236
Employment Services	374	41.2	88.1
Business Support Services	375	328	186
Travel Arrangement & Reservation Services	376	548	245
Investigation & Security Services	377	183	159
Services to Buildings & Dwellings	378	447	491
Other Support Services	379	315	237
Waste Management & Remediation Services	380	7620	2570
Education & HealthCare Services			
Elementary & Secondary Schools	381	401	374
Colleges, Universities, & Junior Colleges	382	286	768
Other Educational Services	383	262	194
Home Health Care Services	384	197	235
Offices of Physicians, Dentists, & Other Health Practitioners	385	169	157
*Healthcare & Social Assistance**	386	378	243
Hospitals	387	400	366
Nursing & Residential Care Facilities	388	443	366
Community Food, Housing, & Other Relief Services, Rehabilitation Services*	389	585	325
Child Day Care Services	390	525	309
*Individual & Family Services**	391	585	253
Arts, Entertainment, Hotels, & Food Services			
Performing Arts Companies	392	248	164
Spectator Sports	393	198	223
Independent Artists, Writers, & Performers	394	212	91.6
Promoters of Performing Arts & Sports & Agents for Public Figures	395	170	274
Museums, Historical Sites, Zoos, & Parks	396	559	496
Fitness & Recreational Sports Centers	397	515	566
Bowling Centers	398	711	791
*Amusement Parks & Arcades**	399	401	394
*Other Amusement, Gambling, & Recreation Industries**	400	401	671
Hotels & Motels, including Casino Hotels	401	400	559

Broad Production Sector *Detailed Production Sector*	**Sector ID**	**tCO_2e per $mil** **1997 (1997$)**	 **2002 (2002$)**
Other Accommodations	402	809	565
Food Services & Drinking Places	403	813	580
Other Services, Except Public Administration			
Car Washes	404	398	569
Automotive Repair & Maintenance, Except Car Washes	405	233	328
Electronic Equipment Repair & Maintenance	406	233	190
Commercial Machinery Repair & Maintenance	407	311	263
Household Goods, Repair & Maintenance	408	324	306
Personal Care Services	409	321	284
Death Care Services	410	387	445
Dry-cleaning & Laundry Services	411	674	323
Other Personal Services	412	359	220
Religious Organizations	413	224	176
Grantmaking, Giving, & Social Advocacy Organizations	414	294	242
Civic, Social, Professional, & Similar Organizations	415	428	398
Government & Special Services			
Other Federal Government Enterprises	416	283	257
Other State & Local Government Enterprises	417	852	923
Scrap	418	361	145
Used & Secondhand Goods	419	159	164

Source: Carnegie Mellon University Green Design Institute. (2011) Economic Input-Output Life Cycle Assessment (EIO-LCA) US 2002 (428) model [Internet], Available from: <http://www.eiolca.net/> [Accessed 30 Sep, 2011]

*defined and labeled differently in 1997 model; **averaged from multiple sectors in 1997; NA: not available

Appendix 2. Estimated Sectoral Carbon Intensities in Current Prices

Note: Sector IDs correspond to those listed in Appendix 1.

	Carbon Intensity of Production Sector in Current Year Dollars (tCO_2e per $mil)													
Sector ID	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
1	2498	2540	2564	2604	2675	2734	2760	2805	2862	2941	3017	3084	3182	3151
2	5389	4950	4514	4143	3846	3552	3240	2976	2743	2547	2361	2181	2033	1820
3	1182	1120	1054	997	955	910	856	811	771	739	706	673	647	597
4	1280	1230	1174	1127	1095	1058	1010	971	936	910	882	853	832	779
5	1124	1080	1030	989	961	928	886	851	821	798	773	747	729	683
6	658	659	656	657	665	670	667	668	672	681	689	694	706	690
7	1951	2140	2330	2554	2831	3122	3400	3729	4105	4550	5037	5554	6185	6608
8	3337	3370	3378	3408	3478	3530	3540	3574	3622	3696	3766	3824	3919	3855
9	2143	2160	2162	2177	2218	2248	2250	2268	2294	2338	2378	2410	2466	2422
10	2404	2410	2398	2402	2433	2451	2440	2445	2460	2492	2521	2540	2585	2524
12	6068	6270	6432	6640	6933	7202	7390	7635	7917	8268	8621	8956	9394	9455
13	2454	2420	2370	2335	2327	2308	2260	2229	2206	2199	2189	2170	2173	2087
14	4000	3900	3775	3678	3624	3553	3440	3354	3282	3234	3182	3120	3088	2933
15	651	654	652	654	664	671	669	672	677	687	697	704	717	702
16	784	823	858	900	954	1007	1050	1102	1161	1232	1305	1377	1468	1501
17	960	996	1026	1064	1116	1164	1200	1245	1297	1360	1425	1487	1566	1583
18	793	758	719	686	663	637	604	577	553	534	515	495	480	447
19	1792	1730	1658	1599	1559	1513	1450	1399	1355	1322	1288	1250	1224	1151
20	1827	1880	1921	1974	2053	2124	2170	2233	2305	2398	2490	2576	2690	2696
21	3067	3080	3071	3082	3128	3158	3150	3163	3189	3237	3280	3313	3377	3304
22	2826	2740	2638	2555	2504	2441	2350	2278	2217	2173	2126	2072	2040	1927
23	1496	1490	1473	1466	1475	1476	1460	1454	1453	1462	1469	1471	1487	1442
24	1345	1390	1426	1473	1538	1598	1640	1695	1758	1836	1915	1990	2087	2101
25	1371	1350	1320	1298	1292	1278	1250	1231	1216	1210	1202	1190	1189	1141
26	1591	1550	1499	1459	1436	1406	1360	1325	1295	1275	1253	1227	1213	1151
27	2486	2310	2131	1978	1857	1734	1600	1486	1386	1301	1220	1140	1075	973
28	729	766	799	840	892	943	984	1034	1091	1159	1230	1300	1387	1420
29	580	591	598	608	626	642	649	661	676	696	715	733	758	752
30	1251	1200	1143	1096	1063	1025	977	937	903	876	848	818	797	745
31	9564	9530	9428	9387	9452	9469	9370	9336	9336	9403	9455	9473	9582	9301
32	4633	4160	3708	3327	3019	2725	2430	2182	1966	1784	1617	1460	1330	1164
33	2459	2330	2192	2075	1986	1892	1780	1686	1603	1535	1468	1398	1345	1241
34	601	599	593	590	594	595	589	587	587	591	594	596	602	585
35	624	588	550	518	493	467	437	412	389	371	353	334	319	293
36	600	602	600	601	609	614	612	614	618	627	634	640	651	637
37	591	602	608	619	637	652	659	671	685	705	725	742	767	760

38	607	602	593	588	590	589	580	576	573	575	576	575	579	560
39	399	430	460	495	539	583	624	672	727	791	860	931	1018	1068
40	752	743	728	719	717	712	698	689	683	682	679	674	676	650
41	974	1050	1124	1211	1319	1429	1530	1649	1784	1944	2115	2292	2509	2634
42	2482	2400	2304	2226	2175	2114	2030	1963	1905	1861	1816	1766	1733	1632
43	3617	3290	2971	2700	2482	2270	2050	1864	1702	1565	1436	1313	1213	1075
44	4038	3970	3875	3807	3782	3738	3650	3588	3541	3518	3491	3451	3444	3298
45	1941	1960	1965	1983	2023	2054	2060	2080	2108	2152	2193	2226	2282	2245
46	2437	2420	2386	2368	2376	2373	2340	2324	2316	2325	2330	2327	2346	2269
47	1279	1160	1045	947	868	792	713	647	589	540	494	451	415	367
49	1731	1780	1818	1868	1941	2007	2050	2108	2176	2262	2348	2428	2535	2539
50	843	874	900	933	978	1019	1050	1089	1134	1188	1244	1297	1366	1380
51	635	646	653	664	683	699	707	720	735	757	777	796	822	815
52	639	659	675	695	724	751	769	793	821	855	890	923	966	970
53	850	873	890	914	949	980	1000	1027	1059	1100	1140	1178	1228	1229
54	824	810	791	777	772	763	745	732	723	718	713	705	703	674
55	2811	2600	2387	2206	2061	1916	1760	1627	1510	1412	1318	1225	1150	1036
56	1743	1670	1589	1521	1473	1419	1350	1293	1244	1205	1165	1122	1092	1019
57	2574	2390	2203	2044	1917	1790	1650	1532	1427	1339	1255	1171	1104	998
58	1669	1550	1429	1325	1243	1161	1070	993	926	868	814	760	716	647
59	1352	1310	1260	1220	1195	1164	1120	1085	1055	1034	1011	985	969	914
60	2495	2553	2595	2653	2744	2824	2870	2937	3017	3121	3223	3317	3446	3436
61	997	992	980	975	981	981	970	965	964	970	975	975	985	955
62	709	700	686	676	675	669	656	647	641	640	637	632	633	609
63	848	833	812	798	792	782	763	750	739	734	728	719	717	686
64	1005	981	951	927	915	898	870	849	832	821	808	793	786	747
65	877	853	824	801	787	770	744	724	707	695	682	667	659	625
66	698	682	662	646	638	627	609	595	584	577	569	559	555	528
67	567	537	505	479	458	437	411	389	370	355	339	323	311	287
68	770	770	765	764	772	776	771	771	774	782	789	794	806	785
69	1149	1090	1027	973	933	890	838	795	757	726	695	662	638	589
70	721	709	692	680	675	667	651	640	631	627	622	615	613	587
71	569	569	565	564	569	572	568	568	569	575	580	583	592	576
72	446	421	395	372	355	337	316	298	283	270	257	244	234	215
73	565	544	520	500	486	471	450	433	418	407	395	383	374	351
74	1011	830	676	554	460	379	309	254	209	173	143	118	99	79
75	1706	1670	1623	1587	1569	1544	1500	1468	1442	1426	1408	1385	1376	1312
76	1338	1310	1273	1246	1233	1214	1180	1155	1135	1124	1110	1093	1086	1036
77	940	916	886	863	850	833	806	785	768	757	744	729	721	685
78	1128	1130	1124	1125	1138	1146	1140	1142	1148	1162	1174	1183	1202	1173
79	1253	1240	1219	1206	1206	1200	1180	1168	1160	1161	1160	1155	1160	1119
80	1410	1340	1264	1201	1153	1102	1040	988	943	906	869	830	801	741
81	917	914	904	900	907	908	899	896	896	902	907	909	920	893

82	837	819	796	778	769	756	735	719	706	698	689	678	674	642
83	705	677	645	619	600	579	552	530	510	495	480	463	451	422
84	761	721	678	642	614	585	550	521	495	474	453	431	415	383
85	609	638	664	695	736	775	807	846	889	942	996	1050	1117	1140
86	834	745	661	590	532	478	424	379	339	306	276	248	225	196
87	603	557	511	472	440	409	375	346	321	300	280	260	243	219
91	620	585	548	516	492	467	437	412	390	372	354	336	321	295
92	2255	2270	2269	2283	2322	2350	2350	2366	2390	2432	2471	2502	2557	2507
93	639	614	586	563	546	528	504	484	467	454	440	425	415	389
94	731	725	714	707	708	706	695	689	686	687	687	685	689	666
95	1179	1190	1193	1204	1228	1247	1250	1262	1279	1305	1330	1350	1384	1361
96	768	759	745	736	735	730	717	709	703	702	701	696	699	673
97	545	541	533	529	531	530	522	518	516	518	519	518	522	505
98	531	535	536	540	550	557	558	563	569	580	590	598	613	602
99	715	708	696	689	689	686	675	668	664	665	665	662	665	642
100	526	553	577	606	644	680	710	746	787	836	887	937	1000	1024
101	651	636	617	602	595	584	567	554	543	537	529	520	516	491
102	605	600	591	586	587	586	577	572	570	571	572	571	575	555
103	2074	2000	1915	1845	1798	1744	1670	1610	1559	1519	1479	1434	1404	1319
104	1800	1750	1689	1640	1611	1575	1520	1477	1441	1416	1389	1358	1340	1268
106	1217	1180	1135	1100	1077	1049	1010	979	952	933	912	889	875	826
107	931	910	883	863	852	837	813	795	780	770	760	747	741	706
108	1157	1120	1076	1041	1018	990	952	921	895	875	855	832	818	771
109	814	796	773	755	745	732	711	695	682	674	664	653	648	617
110	934	875	814	761	721	678	631	591	555	526	497	468	445	406
111	788	791	789	792	803	811	809	812	819	831	843	851	867	849
112	672	648	621	598	583	566	542	523	506	494	481	466	457	429
113	442	433	421	411	407	400	389	381	374	370	365	359	357	340
114	1189	1200	1203	1213	1238	1257	1260	1272	1289	1315	1340	1360	1394	1371
115	2006	1900	1787	1691	1619	1542	1450	1373	1306	1250	1195	1138	1094	1010
116	1285	1250	1207	1174	1154	1128	1090	1060	1035	1018	999	977	965	915
117	2548	2340	2134	1958	1817	1678	1530	1405	1295	1202	1114	1029	959	858
118	1644	1720	1787	1868	1976	2079	2160	2260	2374	2510	2651	2789	2963	3020
119	1795	1920	2039	2179	2355	2533	2690	2877	3088	3339	3604	3875	4208	4384
120	8828	7930	7072	6347	5760	5202	4640	4167	3757	3410	3091	2792	2545	2227
121	2839	2650	2456	2291	2161	2028	1880	1755	1644	1551	1461	1371	1300	1182
124	1953	1970	1973	1989	2027	2056	2060	2078	2104	2145	2184	2215	2268	2229
125	1703	1820	1931	2062	2227	2393	2540	2714	2912	3145	3392	3645	3955	4117
126	1534	1650	1762	1895	2060	2228	2380	2560	2764	3006	3263	3530	3855	4040
127	1744	1750	1743	1747	1771	1787	1780	1786	1798	1823	1846	1862	1896	1853
128	2304	2190	2067	1963	1885	1801	1700	1616	1541	1480	1420	1357	1309	1212
129	6798	6610	6381	6200	6091	5955	5750	5590	5455	5361	5261	5143	5077	4809
130	1036	987	934	889	856	820	776	739	707	681	655	627	607	563

132	448	420	391	366	347	327	304	285	268	254	240	226	215	197
135	1136	1110	1076	1051	1037	1019	988	965	946	934	921	904	897	853
136	1204	1200	1187	1182	1190	1192	1180	1176	1176	1184	1191	1193	1207	1172
137	616	608	596	587	585	581	569	561	556	554	552	548	548	527
138	451	456	458	462	472	479	481	486	493	503	513	522	535	527
139	1203	1190	1169	1156	1156	1150	1130	1118	1110	1111	1109	1103	1108	1068
140	1245	1192	1133	1084	1049	1010	960	919	883	855	826	795	773	721
141	1016	1050	1078	1113	1162	1208	1240	1282	1330	1389	1449	1506	1580	1591
142	878	884	884	889	904	915	915	921	931	947	962	974	995	976
143	853	884	910	943	988	1030	1060	1099	1143	1198	1254	1307	1376	1389
144	784	786	783	785	795	802	799	801	807	818	828	835	850	831
145	801	851	897	952	1021	1091	1150	1221	1301	1397	1497	1598	1723	1782
146	830	851	866	888	920	949	966	991	1019	1057	1094	1128	1174	1173
147	1002	1050	1093	1145	1212	1278	1330	1394	1467	1554	1644	1732	1843	1882
148	852	834	810	792	783	770	748	732	718	710	701	690	685	653
149	1032	933	838	757	692	629	565	511	464	424	387	352	323	285
150	832	834	830	831	842	849	845	847	852	863	873	880	896	875
151	932	915	892	875	868	857	836	821	809	803	796	785	783	749
152	832	793	750	715	688	659	624	595	569	548	527	505	488	453
153	1107	1125	1135	1152	1183	1209	1220	1240	1264	1298	1331	1360	1403	1389
154	1160	1165	1161	1165	1182	1193	1190	1195	1204	1222	1238	1250	1274	1246
155	733	839	953	1091	1261	1452	1650	1888	2169	2510	2899	3337	3877	4323
156	799	839	874	917	973	1026	1070	1123	1183	1255	1330	1403	1495	1529
157	1631	1610	1578	1556	1552	1540	1510	1490	1476	1473	1467	1456	1459	1403
159	5529	6020	6508	7080	7789	8527	9220	10038	10969	12071	13263	14520	16049	17022
160	1948	1980	1998	2029	2084	2130	2150	2185	2229	2290	2349	2401	2477	2453
161	1170	1215	1253	1300	1365	1425	1470	1527	1591	1671	1751	1829	1928	1951
162	1080	1090	1092	1101	1122	1138	1140	1150	1164	1187	1209	1226	1256	1234
163	5977	5635	5274	4968	4733	4486	4200	3959	3746	3569	3396	3219	3081	2829
164	844	807	766	732	707	679	645	617	592	572	551	530	514	479
165	658	653	643	638	640	638	629	624	622	623	624	623	628	607
166	1170	1200	1221	1251	1296	1336	1360	1394	1434	1486	1538	1585	1649	1647
167	1268	1280	1282	1293	1318	1337	1340	1352	1369	1396	1422	1442	1478	1452
168	1382	1440	1490	1551	1633	1711	1770	1844	1928	2031	2135	2237	2366	2402
169	2008	2160	2306	2478	2693	2912	3110	3344	3610	3924	4258	4604	5027	5266
170	2214	2135	2044	1969	1918	1859	1780	1716	1660	1618	1574	1526	1493	1403
172	3407	3375	3319	3285	3287	3274	3220	3189	3170	3174	3172	3159	3176	3065
173	1589	1565	1530	1505	1498	1483	1450	1428	1411	1404	1395	1381	1381	1325
174	1105	1120	1127	1142	1170	1192	1200	1216	1237	1268	1297	1322	1360	1343
175	2082	2080	2063	2059	2078	2087	2070	2067	2073	2092	2109	2118	2148	2090
176	826	835	838	846	863	877	880	889	902	921	939	954	978	963
177	966	971	969	974	990	1000	999	1004	1014	1030	1045	1057	1079	1057
178	909	928	941	959	990	1016	1030	1051	1077	1112	1145	1176	1218	1212

180	1111	1160	1202	1254	1323	1389	1440	1503	1575	1662	1751	1838	1948	1981
181	996	1060	1120	1192	1282	1372	1450	1543	1649	1774	1906	2040	2204	2285
183	542	526	507	491	482	470	453	440	428	420	411	401	395	374
184	577	588	595	606	624	640	648	661	676	696	716	734	760	755
185	882	890	892	899	917	930	932	940	952	971	989	1004	1028	1011
186	759	755	745	741	744	744	735	731	729	733	736	736	743	720
187	697	711	720	733	755	774	784	799	818	843	867	889	920	914
188	793	816	834	858	893	924	945	973	1005	1046	1087	1125	1176	1180
189	1449	1410	1362	1324	1302	1273	1230	1197	1168	1149	1128	1103	1090	1033
190	618	615	607	604	607	607	600	597	596	599	602	602	608	589
191	842	852	856	866	886	901	906	917	931	953	973	991	1018	1004
192	544	541	535	532	535	535	529	526	526	529	531	532	537	521
193	531	542	549	561	578	594	602	615	630	650	670	688	713	709
194	998	1020	1035	1058	1092	1123	1140	1165	1196	1235	1275	1310	1360	1354
195	518	504	487	473	465	455	440	428	418	411	404	395	390	370
196	497	504	507	514	527	537	541	549	558	572	586	597	615	607
197	595	606	613	624	642	657	665	677	692	713	733	750	776	770
198	808	806	798	795	802	804	796	794	795	801	806	808	818	795
199	852	753	661	584	522	464	407	360	319	285	254	226	203	175
200	564	524	483	448	421	393	362	336	313	294	275	257	242	219
201	779	765	746	732	726	717	699	686	676	671	665	657	655	626
202	612	606	595	589	589	586	576	570	566	566	566	563	566	545
203	559	531	501	476	457	437	412	392	373	359	344	329	317	294
204	693	680	662	649	643	634	617	605	595	590	584	576	573	547
205	606	614	618	625	640	652	656	665	676	692	707	721	741	732
206	425	448	468	493	525	556	581	612	647	688	732	775	828	850
207	590	573	553	536	526	514	496	482	470	461	452	441	435	412
208	514	523	528	537	552	565	571	581	593	610	627	641	662	656
209	411	409	404	401	403	402	397	395	394	395	397	396	400	387
210	451	446	438	433	433	431	423	418	415	415	415	413	414	399
211	561	542	520	502	490	475	456	440	427	417	406	394	387	364
212	638	574	513	461	419	379	339	305	275	251	228	206	188	165
213	521	519	513	510	513	514	508	506	505	508	511	511	517	501
214	635	609	580	555	538	518	493	472	454	440	426	410	399	373
215	642	642	637	636	642	645	640	639	641	648	653	656	665	648
216	537	551	561	575	596	615	626	642	661	685	709	731	761	761
217	515	530	541	556	578	597	610	627	647	673	698	722	754	755
218	616	607	594	585	583	578	566	558	552	550	547	543	543	522
219	491	497	500	506	518	528	531	538	547	560	573	583	600	592
220	455	461	463	469	480	488	491	497	505	517	528	538	553	545
221	565	535	503	476	456	434	408	386	367	352	336	320	308	284
222	621	608	591	578	572	564	548	537	527	522	516	508	505	482
223	609	608	602	600	605	607	601	599	600	605	609	611	619	601

224	627	622	612	607	608	606	597	592	589	591	591	589	593	573
225	604	591	574	561	555	546	530	518	509	503	497	489	485	463
226	483	487	488	492	501	508	509	513	520	530	539	547	560	550
227	687	689	687	688	698	704	702	704	710	720	729	735	749	732
228	458	449	437	429	425	420	409	401	395	392	388	383	382	365
229	402	411	417	426	439	451	458	468	480	495	511	525	544	542
230	494	496	495	497	504	509	508	510	515	522	530	535	546	534
231	621	614	603	596	596	592	582	576	571	571	570	567	570	549
232	528	533	534	539	549	558	559	564	572	583	594	603	618	607
233	435	403	371	343	322	300	276	256	238	223	209	194	183	165
234	330	333	333	336	342	347	347	350	354	361	367	372	380	374
235	478	449	419	394	374	353	330	310	293	278	264	249	238	218
236	315	315	312	312	314	316	313	313	313	316	319	320	324	315
237	329	327	323	321	323	323	319	317	317	319	320	320	323	313
238	371	366	358	352	351	348	340	335	331	330	328	325	325	312
239	514	502	487	475	468	460	446	435	427	421	415	407	404	384
240	883	846	805	771	747	720	685	656	632	612	592	570	555	518
242	414	435	454	476	506	534	557	585	617	655	694	733	782	800
245	480	469	455	443	437	429	416	406	398	392	387	379	376	357
247	393	385	374	366	362	356	346	339	333	329	325	320	318	303
248	322	320	316	314	316	316	312	310	310	312	313	313	316	306
249	441	443	442	443	450	454	453	455	459	465	472	476	486	475
250	338	354	368	386	409	430	448	469	494	523	553	583	620	633
251	588	563	535	512	496	477	454	435	418	405	391	376	366	341
252	294	295	293	294	297	300	298	299	300	304	307	310	315	307
253	391	381	369	360	355	348	337	329	322	317	312	307	304	288
254	407	402	394	389	388	385	377	372	369	368	366	364	364	350
255	431	408	383	363	347	330	310	293	279	267	255	242	233	215
256	855	779	705	641	590	541	489	445	407	375	345	316	292	259
257	374	402	429	460	499	539	575	617	666	723	783	846	922	965
258	516	499	479	463	452	440	422	408	396	387	377	367	360	339
259	613	595	573	555	544	531	511	496	482	473	463	451	444	420
260	614	586	555	529	510	489	463	442	423	408	392	376	364	338
261	612	609	602	599	603	604	597	594	594	598	601	602	608	590
262	781	744	704	670	645	617	584	556	532	512	492	471	456	423
263	720	689	655	626	606	583	554	530	509	493	476	458	445	415
264	696	666	632	604	584	561	533	510	489	473	456	439	426	397
265	775	768	755	748	748	745	733	726	722	723	722	719	723	698
266	640	630	616	605	602	596	582	573	566	563	559	553	552	529
267	502	483	462	444	432	418	400	385	372	362	352	341	333	312
268	498	459	420	387	360	333	305	281	260	242	225	208	195	175
269	792	816	835	860	896	928	950	979	1013	1055	1097	1137	1190	1195
270	534	513	490	471	457	442	422	406	392	381	369	357	348	326

271	668	668	663	662	669	673	668	668	670	677	683	687	697	679
272	569	564	555	550	551	549	541	536	534	535	535	534	537	519
273	796	840	880	928	989	1050	1100	1161	1229	1311	1396	1481	1587	1631
274	590	546	501	463	433	403	370	342	318	297	277	258	242	218
275	639	611	580	554	535	514	488	466	447	432	417	401	389	362
276	621	611	596	586	582	576	562	553	545	542	538	532	531	508
277	683	676	664	657	657	653	642	635	631	631	630	627	630	607
278	979	888	800	725	665	606	546	495	451	413	378	345	318	281
279	875	852	824	802	789	773	748	729	712	701	689	675	668	634
280	645	622	595	573	558	541	518	499	483	471	458	444	434	408
281	659	654	645	640	642	641	632	628	625	628	629	628	633	612
282	781	769	751	739	734	727	710	699	690	686	681	674	673	645
283	485	464	441	422	408	392	373	357	343	332	320	308	300	279
284	459	442	422	406	395	382	365	351	339	330	320	310	303	284
285	549	544	536	531	532	530	522	518	515	516	517	515	518	501
286	431	408	383	363	347	330	310	293	279	267	255	242	233	215
287	638	578	520	470	430	391	352	319	290	265	242	220	203	179
288	856	787	719	660	613	567	518	476	440	409	379	351	327	293
289	664	621	576	538	508	477	443	414	388	367	346	325	308	281
290	545	531	514	501	493	483	468	456	446	440	433	424	420	399
291	668	645	619	597	583	566	543	524	508	496	484	470	461	434
292	1842	1500	1213	987	812	665	538	438	358	295	242	198	164	130
293	595	578	557	541	531	518	500	486	473	465	455	445	439	415
294	477	479	477	479	486	490	489	491	495	502	509	513	523	512
295	570	552	530	513	502	488	469	454	441	431	421	410	403	379
296	526	509	489	473	463	450	433	419	407	398	389	379	372	351
297	544	555	562	573	590	605	613	625	640	660	679	696	721	716
298	625	623	616	614	618	619	613	611	611	615	619	620	627	609
299	432	456	478	505	539	573	601	635	673	719	767	814	874	899
300	712	742	767	798	840	880	910	948	991	1043	1096	1148	1213	1231
301	537	537	533	532	537	539	535	534	536	541	546	548	556	541
302	539	529	515	505	501	494	481	472	465	461	456	450	448	428
303	589	582	571	563	562	559	548	541	537	536	534	531	532	512
304	554	522	488	459	437	414	387	364	344	328	312	295	282	259
305	352	357	360	365	374	381	384	390	397	407	416	425	437	432
306	414	425	433	444	460	474	483	495	510	529	547	564	588	587
307	452	477	500	527	561	596	624	658	697	743	791	839	899	924
308	400	379	356	337	322	306	288	273	259	248	236	225	216	199
309	644	558	480	416	364	317	273	237	206	180	158	137	121	102
310	578	570	558	550	548	543	532	525	519	517	515	511	511	491
311	564	543	519	500	487	471	451	434	420	409	398	385	377	354
312	522	509	492	479	472	462	447	435	426	419	412	404	399	379
313	521	497	470	448	431	413	391	373	356	343	330	316	306	284

314	783	752	717	688	667	644	614	589	568	551	534	515	502	470
315	831	805	774	749	733	713	686	664	646	632	617	601	591	557
316	448	425	401	380	365	348	328	311	297	285	273	260	251	232
317	634	613	589	569	556	540	519	502	487	476	465	452	444	418
318	657	629	598	571	552	531	505	483	464	449	433	417	405	377
319	301	279	257	238	223	208	192	178	166	156	146	136	128	116
320	1743	1780	1805	1842	1901	1952	1980	2022	2073	2140	2205	2265	2348	2336
321	1105	1120	1127	1142	1170	1192	1200	1216	1237	1268	1297	1322	1360	1343
322	1252	1430	1621	1850	2135	2451	2780	3174	3638	4200	4840	5557	6442	7167
323	2278	2100	1922	1771	1650	1529	1400	1291	1194	1113	1035	960	898	807
325	3937	4010	4055	4127	4248	4350	4400	4481	4581	4716	4847	4964	5133	5093
326	926	837	751	678	619	563	505	456	414	378	345	313	287	253
327	257	257	255	254	257	258	256	256	256	259	261	262	266	259
328	1006	1040	1068	1103	1152	1198	1230	1272	1320	1379	1439	1496	1570	1581
329	1629	1330	1078	880	726	596	483	394	323	267	220	180	149	119
330	411	382	352	327	307	287	265	246	230	216	202	189	178	161
331	426	407	386	369	356	342	325	311	298	288	278	267	259	241
332	402	385	366	350	338	325	309	296	284	275	265	255	248	231
333	398	370	341	317	298	278	257	239	223	209	196	184	173	157
334	392	370	347	327	312	296	277	261	247	236	225	213	204	188
335	161	151	140	131	124	116	108	101	95	90	84	79	75	69
336	316	281	248	220	198	177	156	139	124	111	100	89	80	70
337	288	281	272	265	261	256	248	242	237	233	230	225	223	212
338	258	242	225	211	200	189	176	165	155	147	140	132	125	115
339	194	192	189	186	186	185	182	180	179	179	178	177	178	172
341	173	179	184	190	199	207	213	220	229	240	250	261	274	276
343	152	153	153	154	157	160	160	161	163	167	170	172	176	173
344	225	225	223	223	225	227	225	225	226	228	230	231	235	229
345	240	211	184	161	143	126	110	97	85	75	67	59	53	45
346	256	219	186	159	137	118	100	85	73	63	55	47	41	34
347	89	85	80	76	73	70	66	63	60	58	55	53	51	47
348	65	72	78	86	96	107	117	129	143	159	177	197	220	237
349	274	231	193	163	138	117	98	82	70	59	50	43	36	30
350	127	116	105	95	88	80	73	66	60	56	51	47	43	38
351	527	476	426	384	351	318	285	257	233	212	193	175	161	141
352	362	308	260	221	190	162	137	116	99	85	73	63	54	45
353	319	336	352	371	395	419	439	463	490	522	556	590	631	649
354	138	152	166	182	203	224	245	269	297	331	367	406	453	486
355	192	198	203	208	217	225	230	237	245	255	265	275	287	288
356	4	7	14	26	49	93	175	330	625	1191	2266	4296	8225	15109
357	142	134	125	118	112	106	99	93	88	84	79	75	72	66
358	152	146	139	133	129	124	118	113	109	105	102	98	95	89
359	137	144	150	158	168	178	186	196	207	220	233	247	264	271

360	208	198	187	178	171	164	155	148	141	136	130	125	121	112
361	143	149	154	160	169	177	183	191	199	210	221	231	244	248
362	146	150	153	157	164	169	173	178	184	191	198	205	214	215
363	154	150	145	141	139	136	132	129	126	124	122	119	118	112
364	176	167	157	149	143	137	129	122	117	112	107	102	99	91
365	206	194	181	170	162	153	143	134	127	121	115	108	103	95
366	273	284	293	305	320	335	346	360	376	395	414	433	458	464
367	347	326	304	286	271	256	239	225	212	201	191	180	172	157
368	256	252	246	242	241	238	233	229	227	225	224	222	221	212
369	436	408	379	355	336	316	294	275	259	245	231	218	207	189
370	136	133	129	125	123	121	117	114	112	110	108	106	105	99
371	282	259	236	217	202	186	170	156	144	134	124	115	107	96
372	139	142	144	147	152	157	159	163	167	173	178	183	190	189
373	168	178	187	198	211	225	236	250	265	283	302	322	346	356
374	35	41	48	55	65	76	88	103	120	141	166	194	229	260
375	367	328	291	259	234	210	186	166	149	134	121	108	98	85
376	644	548	463	394	339	290	245	209	178	153	132	113	97	81
377	188	183	177	172	169	165	159	155	151	148	145	142	140	133
378	439	447	452	460	474	485	491	500	511	527	541	555	574	569
379	333	315	295	279	266	253	237	224	212	203	193	183	176	162
380	9471	7620	6086	4892	3977	3217	2570	2067	1669	1357	1102	891	728	570
381	407	401	393	387	385	382	374	369	365	364	362	359	359	345
382	235	286	346	421	518	635	768	935	1144	1408	1731	2121	2622	3112
383	278	262	245	230	219	207	194	183	173	164	156	148	141	129
384	190	197	203	210	219	228	235	243	253	265	277	288	303	306
385	172	169	165	163	162	160	157	155	153	152	151	150	150	144
386	413	378	343	314	291	267	243	222	204	189	175	161	149	133
387	407	400	390	383	380	375	366	359	354	352	349	344	343	329
388	460	443	423	407	396	383	366	352	340	331	321	311	304	285
389	658	585	516	459	412	368	325	289	258	232	208	186	168	145
390	584	525	469	421	383	346	309	278	251	228	207	187	171	150
391	692	585	491	415	354	301	253	214	182	155	132	113	97	80
392	269	248	227	208	194	179	164	151	139	130	120	112	104	93
393	193	198	201	206	213	219	223	228	235	243	251	258	268	268
394	251	212	178	150	128	109	92	77	66	56	48	41	35	29
395	155	170	186	204	227	251	274	301	333	370	411	454	507	543
396	573	559	542	528	521	512	496	484	474	468	461	453	448	426
397	505	515	521	530	546	559	566	577	590	607	624	640	662	657
398	696	711	721	736	759	780	791	808	828	855	881	905	938	933
399	402	401	397	395	398	398	394	393	392	395	397	398	403	391
400	362	401	441	489	547	610	671	744	827	926	1036	1155	1299	1402
401	374	400	425	454	490	527	559	598	641	693	747	803	872	908
402	869	809	747	695	653	611	565	526	491	462	434	406	383	347

403	870	813	754	704	665	625	580	542	508	480	453	425	404	367
404	371	398	424	455	494	534	569	611	659	715	775	836	912	954
405	218	233	248	265	287	309	328	351	377	408	441	475	516	538
406	243	233	222	213	207	199	190	182	176	170	165	159	155	145
407	322	311	299	288	282	274	263	254	247	241	235	229	224	211
408	328	324	318	314	314	312	306	302	300	300	299	297	298	287
409	329	321	311	303	299	293	284	277	271	268	263	258	256	243
410	376	387	395	406	422	436	445	457	472	491	509	526	549	550
411	781	674	578	498	434	377	323	279	241	211	183	159	139	117
412	396	359	323	293	268	244	220	199	181	166	152	139	128	113
413	235	224	212	202	194	186	176	168	160	154	148	142	138	128
414	306	294	281	270	262	253	242	233	225	218	212	205	200	187
415	434	428	419	412	411	407	398	392	388	386	384	381	381	365
416	289	283	276	270	268	264	257	252	248	246	243	240	239	228
417	839	852	859	872	896	915	923	938	956	982	1007	1028	1060	1049
418	433	361	299	249	209	175	145	121	101	85	71	60	51	41
419	158	159	159	160	162	164	164	165	167	169	172	174	178	174

Note: Sectors missing from this list are those for which no data could be obtained in one of the model years.

Appendix 3. Matching of Expenditure Categories and Resulting Intensities

Note: Sector IDs correspond to those listed in Appendix 1. Expenditure Category	Production Sector ID(s)	Mean Carbon Intensity (1996-2009) metric tons CO_2e / 1 million 2002US$	lb CO2e / 2002US$
Direct Expenditures			
Natural gas	32	2469.832	5.445
Electricity	31	9142.816	20.156
Gasoline and motor fuel	114, 117	1379.261	3.041
Fuel oil and other fuels	20	2157.866	4.757
Indirect Expenditures			
Food			
Food at home (weighted mean)		1204.626	2.656
Cereal	47	736.017	1.623
Bakery products	62, 63	711.064	1.568
Beef	60	2945.115	6.493
Pork	60	2945.115	6.493
Other meat	60	2945.115	6.493
Poultry	59	1119.492	2.468
Seafood	61	976.183	2.152
Eggs	13	2266.115	4.996
Milk products	57	1671.025	3.684
Other dairy	55, 56, 58	1407.010	3.102
Fresh fruit	5	885.827	1.953
Fresh vegetables	3	858.398	1.892
Processed fruit	53, 54	888.114	1.958
Processed vegetables	53, 54	888.114	1.958
Sweets	49, 50, 51, 52	1180.754	2.603
Non-alcoholic beverages	66, 70	630.697	1.390
Oils	45	2090.860	4.610
Miscellaneous food	69	840.035	1.852
Food away from home	403	569.985	1.257
Housing			
Mortgage interest	349	109.651	0.242
Property taxes	417	909.344	2.005
Maintenance, repairs, insurance, and other expenses	40	109.651	0.242
Rent payments	351	288.134	0.635
Other lodging	401, 402	568.279	1.253
Indirect Utilities			
Telephone	341	212.936	0.469
Water and other public services	33	1737.983	3.832
Domestic services and household operations			

Domestic services excluding child care	411	346.499	0.764
Babysitting and child care	390	313.543	0.691
Other household expenses	406, 408	241.351	0.532
Household equipment and supplies			
Household textiles	83	536.984	1.184
Furniture	294, 295, 296, 298, 299, 300, 302	564.277	1.244
Floor coverings	76, 82	930.568	2.052
Major appliances	261, 262, 263, 264	552.436	1.218
Small appliances and miscellaneous housewares	156, 183, 260	658.694	1.452
Miscellaneous household equipment	184 ,203, 228, 233, 236, 255, 258, 259 ,301, 303	428.292	0.944
Transportation			
New and used cars and trucks	275, 276	510.829	1.126
Other vehicles	291	527.742	1.163
Vehicle finance charges	345	115.041	0.254
Maintenance and repairs	149, 282, 405	533.780	1.177
Vehicle insurance	347	64.555	0.142
Vehicle rental, leases, licenses, and other charges	352	150.735	0.332
Public transportation	326	509.744	1.124
Clothing and footwear			
Apparel and services	86, 87, 91	410.766	0.906
Footwear	93	490.171	1.081
Personal Insurance			
Life and other personal insurance	347	64.555	0.142
Retirement, pensions, and Social Security	349	109.651	0.242
Healthcare			
Health insurance	347	64.555	0.142
Medical services	385, 386, 387, 388	276.707	0.610
Prescription drugs	132	298.660	0.658
Medical supplies	305, 306, 307, 308	443.700	0.978
Personal care	409, 412	248.660	0.548
Entertainment			
Fees and admissions	393, 396, 397, 398, 399, 400, 415	509.849	1.124
Televisions, radios, and sound equipment	237, 238, 239, 257, 316, 338, 339, 353, 406	297.181	0.655
Pets, toys, and playground equipment	41, 312, 369	776.464	1.712
Other entertainment	280, 281, 291, 311, 318, 352, 368	422.098	0.931
Education and reading			

Reading	331, 332, 333, 334	285.383	0.629
Education	313, 381, 382, 383	501.805	1.106
Alcohol and tobacco			
Alcoholic beverages	71, 72, 73	433.795	0.956
Tobacco and smoking supplies	74	364.905	0.804
Miscellaneous			
Miscellaneous expenditures	345, 357, 358, 410	166.509	0.367
Cash contributions	414, 415	311.255	0.686

Appendix 4. List of Broad and Detailed Expenditure Categories

Broad Expenditure Category Detailed Expenditure Category	
Food and Beverage	**Clothing and footwear**
Food at home (weighted mean)	Apparel and services
Food away from home	Footwear
Housing	**Personal Insurance**
Mortgage interest	Life and other personal insurance
Property taxes	Retirement, pensions, and Social Security
Maintenance, repairs, insurance, and other expenses	**Healthcare**
Rent payments	Health insurance
Other lodging	Medical services
Utilities	Prescription drugs
Natural gas	Medical supplies
Electricity	Personal care
Fuel oil and other fuels	**Entertainment**
Telephone	Fees and admissions
Water and other public services	Televisions, radios, and sound equipment
Domestic services and household operations	Pets, toys, and playground equipment
Domestic services excluding child care	Other entertainment
Babysitting and child care	**Education and reading**
Other household expenses	Reading
Household equipment and supplies	Education
Household textiles	**Alcohol and tobacco**
Furniture	Alcoholic beverages
Floor coverings	Tobacco and smoking supplies
Major appliances	**Miscellaneous**
Small appliances and miscellaneous housewares	Miscellaneous expenditures
Miscellaneous household equipment	Cash contributions
Transportation	
New and used cars and trucks	
Other vehicles	
Gasoline and motor fuel	
Vehicle finance charges	
Maintenance and repairs	
Vehicle insurance	
Vehicle rental, leases, licenses, and other charges	
Public transportation	