PNNL-16869

Pacific Northwest National Laboratory
Operated by Battelle for the U.S. Department of Energy

Climate Change and the Long-Term Evolution of the U.S. Buildings Sector

F. Rong
L. Clarke
S. Smith

April 2007

Prepared for the U.S. Department of Energy
under Contract DE-AC05-76RL01830

PACIFIC NORTHWEST NATIONAL LABORATORY
operated by
BATTELLE
for the
UNITED STATES DEPARTMENT OF ENERGY
under Contract DE-AC05-76RL01830

Printed in the United States of America

Available to DOE and DOE contractors from the
Office of Scientific and Technical Information,
P.O. Box 62, Oak Ridge, TN 37831-0062;
ph: (865) 576-8401
fax: (865) 576-5728
email: reports@adonis.osti.gov

Available to the public from the National Technical Information Service,
U.S. Department of Commerce, 5285 Port Royal Rd., Springfield, VA 22161
ph: (800) 553-6847
fax: (703) 605-6900
email: orders@ntis.fedworld.gov
online ordering: http://www.ntis.gov/ordering.htm

This document was printed on recycled paper.

(9/2003)

PNNL-SA-48620

Climate Change and the Long-Term Evolution of the U.S. Buildings Sector

Fang Rong
School of Public Policy
University of Maryland, College Park

Leon Clarke[a]
Joint Global Change Research Institute
Pacific Northwest National Laboratory

Steven Smith
Joint Global Change Research Institute
Pacific Northwest National Laboratory

March 2007

Prepared for the U.S. Department of Energy
under Contract DE-AC05-76RL01830

Pacific Northwest National Laboratory
Richland, Washington 99352

[a] Corresponding author. Address correspondence to Leon Clarke, Joint Global Change Research Institute, 8400 Baltimore Avenue, Suite 201, College Park, MD, 20740. Email: leon.clarke@pnl.gov. Phone: 301-314-6738. Fax: 301-314-6719.

Abstract

Buildings account for 40 percent of U.S. energy use and are the dominant driver of daily and seasonal electric load cycles. Understanding the possible long-term evolution in these energy demands, their potential response to climate policies, and the potential benefits of advances in the technologies that provide them are critical for informing climate-based policy decisions. This document presents a new, service-based approach to understanding the long-term evolution of the U.S. buildings sector within the context of a long-term, global, integrated-assessment model called MiniCAM. The buildings module explicitly represents the demands for energy services, such as heating, cooling, and lighting along with the technologies to supply these services. Future scenarios for U.S. building energy service and energy use are presented. Building final energy use increases over the 21st century with a concurrent increase in the fraction of energy supplied by electricity. Constraining carbon emissions lowers natural gas and fuel oil use, but results in little change in electricity use.

Acknowledgements

We would like to thank our colleagues who have provided data and insights into building energy use, specifically Mr. David Belzer and Mr. David Winiarski from Pacific Northwest National Laboratory. This work was funded by the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy and the California Energy Commission.

Contents

Figures

Tables

1.0 Introduction

People do not demand energy; they demand goods and services that require energy: warm homes in the winter, cool homes in the summer, cooked food, storage for perishable food (through refrigeration), Internet access, television, and so forth. Demand for these energy-based goods and services begins a causal chain that, among other things, leads to carbon dioxide (CO_2) emissions from burning fossil fuels and, ultimately, to changes in the earth's climate. Understanding the possible long-term evolution in these demands, their potential response to climate policies, and the potential benefits of advances in the technologies that provide them are critical for informing climate-based policy decisions. In addition, the buildings sector is a key determinant of both energy demand and the daily and seasonal demand profile for electricity. This document presents an approach to understand the long-term evolution of the U.S. buildings sector by developing a service-based buildings module incorporated into a long-term (through 2095) regional and global integrated assessment model (IAM), the Object-oriented Energy, Climate, and Technology Systems (O^{bj}ECTS) MiniCAM (see Section 3.1).

IAMs have been used extensively to illuminate the relationships between the underlying socioeconomic, technological, and other drivers of greenhouse gas emissions and aggregate changes in the global climate. IAMs have traditionally focused on the supply-side of the energy sector—considering, for example, electricity generation technologies or crude oil resource supplies—while treating the demand for energy in highly aggregate fashion. This lack of demand-sector detail has hampered efforts to understand the potential responses of the building sector to climate policy and the potential benefits of advanced building energy technologies, such as heat pumps or solid-state lighting.

Several other modeling efforts have attempted greater demand-side details, but these were generally constructed for other purposes. They generally do not have the century-long time frame or the global scope associated with MiniCAM. For example, the U.S. Department of Energy's (DOE) National Energy Modeling System (NEMS) (DOE 2004) and the U.S. Environmental Protection Agency's All-Modular Industry Growth Assessment (AMIGA) Modeling System (Hanson 1999) include demand-side details, but are both U.S.-focused models that are solved up to 25 and 50 years from today, respectively.

The new, service-based U.S. building sector-module explicitly represents the demands for specific building services (e.g., space cooling and lighting) and the technologies that provide these services. This detailed approach is representative of an increasing trend toward hybrid modeling approaches that integrate top-down and bottom-up modeling.

Using the buildings sector-module in MiniCAM as a vehicle, this document explores several issues that pertain to the evolution of the U.S. building sector over the coming century. What are relevant trends in the U.S. buildings sector and where are these trends leading? How might climate policies alter these trends or otherwise influence building energy demand over the long-term? What is the role of new technology in reducing demand for energy, and therefore climate impacts from this sector?

This document is organized as follows:

- Section 2.0 provides background on relevant historical trends in the U.S. building sector.
- Section 3.0 presents MiniCAM and discusses the structure of the building-sector module, along with the basis for important methodological decisions.
- Section 4.0 presents one long-term scenario and discusses the basis for the trends embodied in the scenario.
- Section 5.0 demonstrates the building-sector module under the imposition of a global carbon-constraint.
- Section 6.0 provides conclusions and additional avenues for future modeling efforts.

2.0 Current Trends in the U.S. Building Sector

It is common to split energy demand into three sectors: buildings, industry, and transportation. In the United States, the buildings sector consumes the most energy of the three. In 2003, the building sector consumed 20 exajoules of delivered energy, or roughly 40 percent of delivered energy in the United States.[a] With a U.S. population of 0.3 billion, this amounted to 70 gigajoules per capita. To give historical perspective, in 1980, building energy use was 16 exajoules in total and 70 gigajoules per capita; in 1960, building energy use was 9.5 exajoules in total and 53 gigajoules per capita. Therefore, on average, individuals in the United States are using about 30 percent more delivered energy for building services than they were 45 years ago, but per-capita energy demand has roughly stabilized over the last several decades (EIA 2005b). (Note that these figures do not include the full life-cycle energy costs associated with buildings and building equipment.)

For simplicity, we use delivered energy as the metric for total building energy use in this analysis. Delivered energy, also referred to as final energy, is the sum of inputs of electricity, natural gas, fuel oil, and other fuels as delivered to the building. This neglects transformation losses, particularly for electricity. Total energy requirements in terms of primary energy will, therefore, be higher than the final energy value. As the building sectors move more toward the use of electricity, the divergence between delivered and primary energy will increase.

To put the trends and analysis to come into context, it is useful to consider the counteracting forces that ultimately drive building energy demand. Equation (2.1) is a simple heuristic identity intended for this purpose.

$$Energy = [population]\left[\frac{floorspace}{population}\right]\left[\frac{Service}{Floorspace}\right]\left[\frac{Energy}{Service}\right] \tag{2.1}$$

In this identity, the evolution of building energy use depends on the combined effects of four interacting terms. The derivatives of the first two terms currently have a positive sign and this will probably continue for several decades and perhaps beyond. The direction of the change in the third element is ambiguous (see below). The final term has a negative derivative. Across service demands, improved energy efficiency has allowed American consumers to receive building services with lower-energy requirements.

While simplistic, this identity illuminates a meaningful dynamic in building energy use. Limiting the growth in building energy demand can be viewed as a competition between the underlying drivers of building energy use—predominantly population and per-capita floor-space growth—that drive service demands and advances in the technologies that use energy to serve these demands.

There are three salient trends from the historical record. First, per-capita floor space, both residential and commercial, has been increasing for decades. Today, residential floor space is approximately 800 square-feet per capita and commercial floor space is roughly 260 square-feet per capita. Figure 2.1 shows the historical record. Although it is unclear whether this trend will continue in incoming decades, researchers are increasingly concerned with the impacts of continued growth on building energy demand (see Wilson 1999; Laurence 2004; Battles 2004; Gerencher 2006).

---

[a] One exajoule is roughly equivalent to one quadrillion British thermal unit (quad). 1 quad = 1.055 exajoules.

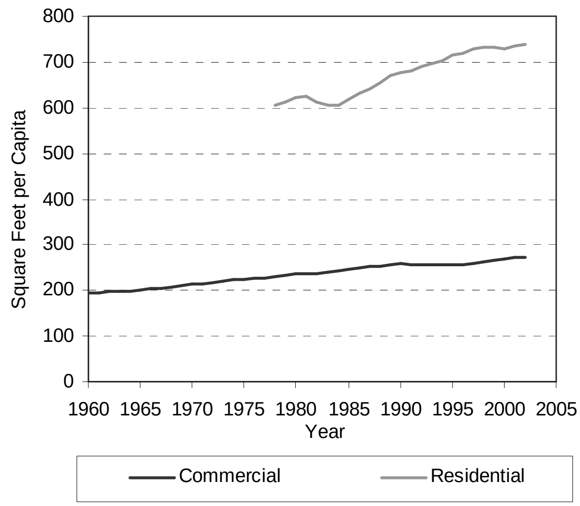


Figure 2.1. Historical Per-Capita Floor Space (DOE 2005a). Both sectors indicate a generally increasing trend in floor space per capita.

The second salient trend is increasing electrification of the U.S. building sector, as shown in Figure 2.2. While natural gas is a principal energy source used in U.S. residential buildings, accounting for about half of total delivered energy consumption in 2003, the share of electricity has been steadily increasing from roughly 10 percent in the 1950s to approximately 40 percent today. Energy Information Administration (EIA) projects that residential electricity demand will match natural gas demand around 2020 (EIA 2005a). The commercial sector has exhibited similar trends, with electricity becoming the dominant delivered energy source in the early 1990s. Increasing electrification has been a function of increased deployment of cooling technology, increased use of electricity in heating applications, and increased demand for services that demand electricity such as appliances, office equipment and information technology.

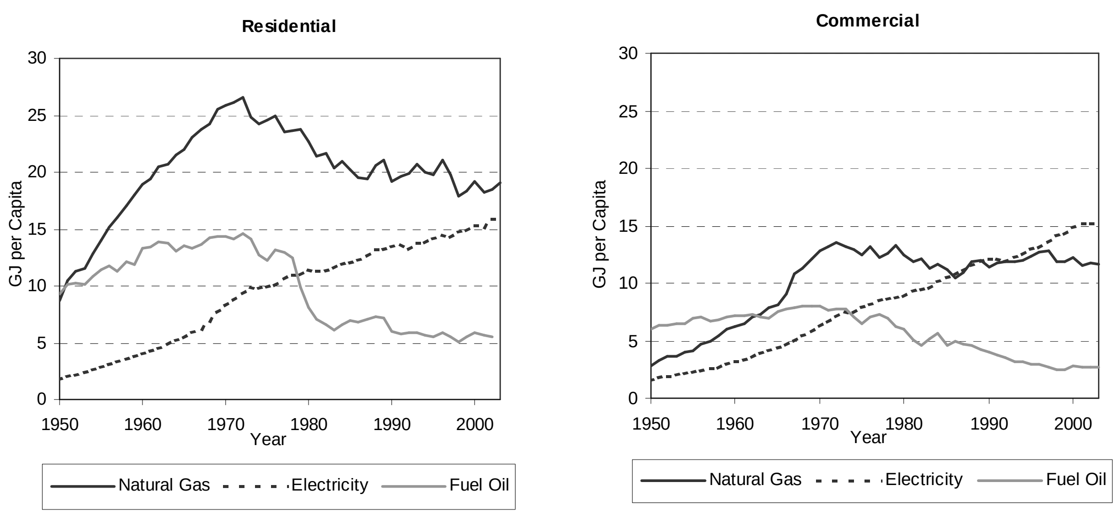


Figure 2.2. Per-Capita Delivered Energy Use by Fuel, 1950-2002. The historical record shows increasing electrification in both residential and commercial sectors.

The final trend is the evolution of demands for energy along individual service dimensions. Figure 2.3 shows energy demand per square foot by end use (EIA 2003; EIA 2005b). It is important to interpret these trends with some caution, as there are substantial uncertainties in the underlying data. This is particularly true for commercial data, where variations from year to year reflect both real-world trends and methodological differences (Section 3.3.4). Nonetheless, whatever trends do exist reflect a competition between increased efficiencies on the one hand, and increased demand for services per square foot on the other. In most cases, these two forces have fought roughly to a draw, with a few exceptions. Across both the residential and commercial sectors, the demand for energy for appliances, office equipment, and similar services has been increasing faster than the growth in floor space. This trend will figure prominently in the scenario presented in Section 4.0.

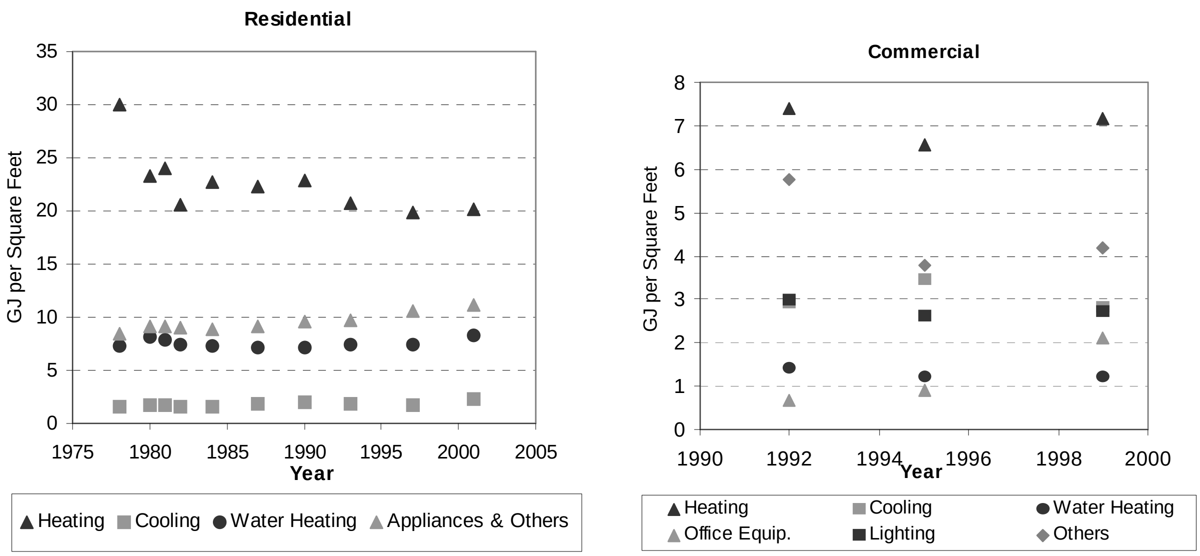


Figure 2.3. Historical Energy Consumption Per Square Foot by End Use (EIA 2003; EIA 2005b). Figures for heating and cooling are adjusted for temperature in the given year.

In concluding this section, we return to the identity with which it began: Equation (2.1). Figure 2.4 illustrates the full competition between forces in the case of residential hot water consumption using energy consumption data from the Residential Energy Consumption Survey (EIA 2005b)[b]. The figure shows that the total energy demand for hot-water heating has been steadily increasing since the early 1980s, as has the demand for hot water itself. At the same time, if the effects of increasing square footage per capita are stripped out, the trends are very different. The service demand per square foot has remained relatively constant, and the energy per square foot has generally been decreasing as a result of

[b] To develop these estimates of service demand, a linear relationship was assumed for those years when survey data were not available. The stock efficiency data are from National Energy Modeling System's vintage database. The stock efficiency was the average efficiency for all existing and new water heaters including those fueled by natural gas, electricity, fuel oil, and liquid petroleum gas. The average efficiency for new gas water heaters in markets, for example, was calculated to be 0.49 in 1980, 0.55 in 1990, and 0.56 in 2000, and the average efficiency for new electricity water heaters in markets was taken to be 0.81 in 1980, 0.88 in 1990, and 0.88 in 2000. Using a simple vintage model, the NEMS database estimates the stock efficiency of all water heaters to be 0.49 in 1980, 0.52 in 1990, and 0.55 in 2000.

improvements in the efficiency of water heaters, which were estimated to have increased by roughly 15 percent in the past two decades.

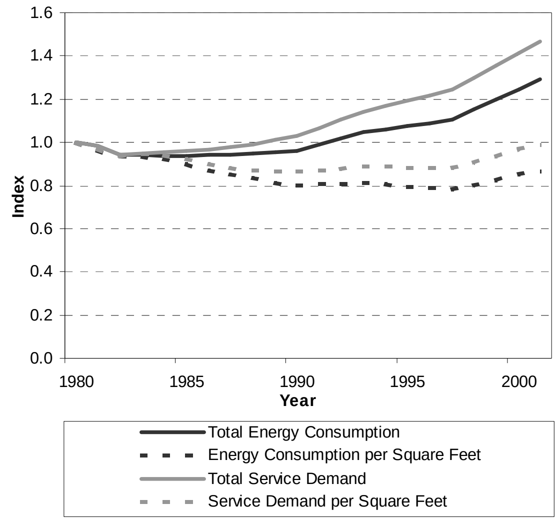


Figure 2.4. Historical Service and Energy Demands for Hot Water. The figure demonstrates the effect of increasing floor space and energy efficiency on the demand for hot water on total energy hot water energy demand

It is important to note that trends in floor space and service demands depend on a range of sociological, demographic, and economic changes. For example, both gross domestic product (GDP) per capita and median household income have been increasing; population densities have shifted from the northern census regions to the south and west; the size of the average family has decreased over time; and increases in energy prices have greatly exceeded the rate of inflation (Laurence 2004). Any future scenario for building energy use has to consider, either explicitly or implicitly, how these trends might change over time and what other new trends might emerge in the future.

3.0 Buildings Sector in O^{bj}ECTS MiniCAM

3.1 Overview of O^{bj}ECTS MiniCAM

The analysis of long-term, U.S. building-sector energy demand in this document was conducted within MiniCAM IAM, as implemented within the O^{bj}ECTS framework (Kim et al. 2006). The O^{bj}ECTS framework is an object-oriented architecture that allows for an implementation of MiniCAM model that incorporates additional bottom-up technology detail within a globally consistent economic market framework.

MiniCAM is referred to as an IAM because it combines representations of emissions producing sectors with a global climate model in order to allow analysis of drivers of emissions all the way through to concentrations, radiative forcing, and temperature change. MiniCAM (Edmonds et al. 2004) is a partial-equilibrium model that includes submodels of the global energy system and global land-use (Sands and Leimbach 2003) and uses the MAGICC climate model (Wigley and Raper 2002). Population growth and labor productivity are exogenous inputs. The O^{bj}ECTS MiniCAM as used here has 14 regions, 1 of which is the United States. The model looks forward from 1990 to 2095 in 15-year time periods.

Decisions in MiniCAM are myopic: they are made based on current market characteristics rather than through an assessment, optimal or otherwise, of future conditions. Technologies are incorporated within this framework by exogenously specifying available technologies at each point in time and allowing an endogenous selection of specific technologies using a price-based logit formulation. This selection method is based on the least-cost selection of technologies under the assumption that technology costs and other non-modeled characteristics have a statistical distribution. Note that costs here represent the average annual costs of a technology, in which any one-time costs (e.g., capital costs) are amortized over the lifetime of the equipment. The buildings module is calibrated to historical data in 1990 and 2005 for each technology, and new technologies are allowed to compete in the future.

The approach used in MiniCAM to model future building energy use differs somewhat from detailed building optimization models. In these detailed models, technological details for a specific building at a specific location are adjusted to determine the least cost solution to some constraint (e.g., lowest total-cost, zero net-energy consumption, etc.). While it is not feasible to incorporate this high level of detail into an aggregate, global model operating on time scales up to a century, these detailed models can provide valuable insights.

3.2 Conceptual Structure of the U.S. Buildings Sector

For every MiniCAM region, energy demand is formed from three individual components: transportation, buildings, and industry. Prior to the enhancements discussed in this document, building energy demand was based on a simplified, constant elasticity relationship with regional GDP and energy prices, along with an exogenously specified autonomous rate of energy intensity improvement.

The conceptual structure of the new, U.S. buildings-sector module is shown in Figure 3.1. In the version presented here, two building subsectors are assumed for the United States: residential buildings and commercial buildings. There are no regional breakouts; each sector represents building energy demand for the entire country. In essence, each sector is an aggregate representative building. Associated with each of these sectors is information such as floor space and building-shell thermal characteristics. Each of the two sectors demands a suite of building energy services.

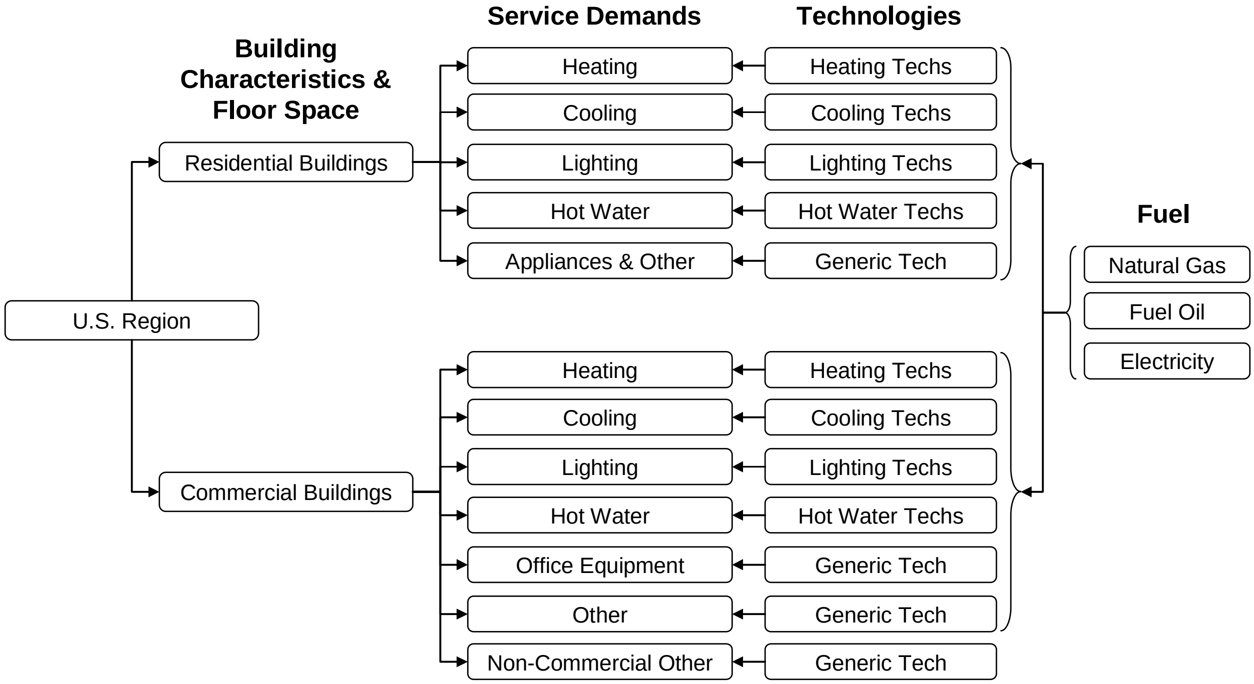


Figure 3.1. Conceptual Structure of the U.S. Building-Sector Module. The United States is split into two aggregate building sectors, residential and commercial buildings, each of which demands a range of services. These services are supplied by associated technologies that require fuel inputs to do so.

Both sectors demand heating, cooling, lighting, and hot water, and an “other category” that captures all other demands, including demands for information services such as those provided by computers and televisions, as well as refrigeration, clothes washers and dryers, and so forth. The commercial sector also demands a “noncommercial” other category that includes energy use that is categorized by the EIA as lying with the commercial sector, but represents demand such as parking lot lighting. This additional commercial category is included in the overall model, but is not presented further in this document.

Demands for these services in MiniCAM are expressed not in terms of input energy, such as electricity or natural gas, but in terms of the actual services provided, when feasible. For example, lighting demand can be expressed in lumens; heating and cooling demands are expressed in terms of the heat-transfer demands of the sector. All service demands for “other” categories are simply indexed. By specifying demand for services rather than input energy, MiniCAM is able to disentangle changes in the demand for services and the efficiency of the technologies that provide these services.

A number of technologies might provide any service. For example, lighting can be supplied by incandescent lamps, fluorescent lamps, or, in the future, solid-state lighting. Heating can be supplied by electric-resistance heating, electric heat pumps, natural gas furnaces, natural gas heat pumps, and fuel oil furnaces. For this analysis, three primary fuels are assumed to serve the buildings sector: electricity, natural gas, and fuel oil. Wood used in buildings also included in the model, but is not discussed in this document.

3.3 Formulas and Assumptions

3.3.1 Floor Space

As discussed in Section 2.0, floor space is a primary driver of service and energy demand in the buildings sector. In the building-sector module, floor space per capita is a constant-elasticity function of income and the price of floor space, as shown in Equation (3.1):

$$s = \sigma_S \, I^{\beta_{S,I}} \, P_S^{-\beta_{S,P}} \tag{3.1}$$

where *s* is floor space, σ_S is a calibration parameter, *I* is per-capita income (represented by per-capita GDP), P_S is the price of floorspace, and the two β's are positive elasticities. Although the elasticity parameters are calibrated to be consistent with past information, a range of possible parameterizations could feasibly fit the past. In addition, it is virtually impossible to project how the preference for floor space might change over time, whether suburbanization will continue, or how prices might vary as more buildings are constructed. Therefore, it is critical that floor-space scenarios used for the buildings module be considered just that—scenarios. The module is not intended as an exploration of the drivers of floor space as much as an exploration of the implications of potential future floor space demands for building-sector energy demand.

3.3.2 Service Demands

The core of the buildings module is the explicit representation of service demands. The formulation for heating and cooling is the most complex of the service demands, because it must consider the implications of internal gains, building shells, and climate. Heating and cooling demands in both residential and commercial sectors are based on the following specifications in Equations (3.2) and (3.3):

$$d_H = \sigma_H \, u \, a \, HDD \, P_H^{-\beta_H} - G \tag{3.2}$$

$$d_C = \phi_C \left(\sigma_C \, u \, a \, CDD \, P_C^{-\beta_C} + G \right) \tag{3.3}$$

Where d_H and d_C are the demands for heating and cooling per square foot of floor space in terms of the thermal loads, the σ's are calibration coefficients, ϕ_C is a "saturation" parameter that captures the penetration of cooling technology over time, *u* is the thermal heat characteristics of the building, *a* is building shell area per square foot, *HDD* and *CDD* are heating degree days and cooling degree days, P_H and P_C are the service prices (discussed below), the β's are price elasticities, and *G* represents the internal gains from other demands, such as lighting.

Several aspects of this formulation bear note. First, the demand for heating and cooling services on a per-square-foot basis is independent of per-capita income. In this specification, the income effect is indirect. Income affects floor space, and heating and cooling service per floor space is a function of the prices of these services. The prices for these services are the weighted average of the prices from the different technologies that provide the services (discussed below). Second, demand is temperature-driven, through heating and cooling degree-days. This means that any changes in temperature that might occur through climate change could be reflected in energy demands. However, for the version of the module discussed here, heating and cooling degree-days were assumed invariant over time. Third, energy demands are a function of the building shell thermal characteristics. This means that technological improvements might take place not only in the technologies that provide the services, but also in the building shells, reducing the demand for heating and cooling. Fourth, the demand for cooling is modified by a "saturation parameter" to capture increasing utilization of cooling over time. This parameter is implicitly assumed to be unity for heating in the United States, meaning that heating technology is assumed to be employed already in all regions where it might be applicable. For this document, it was assumed that all those needing cooling services will be able to use these service by 2020, meaning that ϕ_C in 2020 will be 100 percent.

Finally, the module allows for the effects of internal gains in reducing heating loads and increasing cooling loads. For this analysis, it was assumed that 90 percent of lighting energy demands, 50 percent of appliances energy demands, 10 percent of hot water energy demands, and 80 percent of office equipment energy demands lead to the internal gains.

The demands for all other services are based on a simplified generic formulation, as seen in Equation (3.4):

$$d_i = \phi_i \ \sigma_i \ P_i^{-\beta} \tag{3.4}$$

This formulation is a simplified version of the heating and cooling formulations, and the same logical structure applies.

3.3.3 Technology Choice

Many building services can be provided by multiple technologies. For example, lighting might be provided by incandescent bulbs, fluorescent lamps, and solid-state lighting. The MiniCAM framework is highly flexible in this regard; therefore, technologies can easily be added or subtracted from the module. The technologies included in the version of the module in this document are shown in Table 3.1.

Every model with multiple technologies must include an approach to manage choices among discrete options such as these. The O^{bj}ECTS MiniCAM uses a price-based logit formulation based on the price at which they can provide the service. This price is a function of technology cost and performance characteristics along with the price of input fuel. Together, these factors define a price of providing the service; for example, cost per lumen of lighting or cost per British thermal unit of heat energy transferred in or out of a building for space heating or cooling. These service prices change over time as technology cost and performance improve and as fuel prices change (More details on the price-based technology choice mechanism could be found on Clarke and Edmonds, 1993).

Table 3.1. Technologies Included in the Buildings Module[a]

Residential	Commercial
Residential Heating	**Commercial Heating**
Gas Furnace	Gas Furnace/Boiler
Gas Heat Pump (beginning in 2020)	Gas Heat Pump (beginning in 2020)
Electric Resistance Heater	Electric Resistance Heater
Electric Heat Pump	Electric Heat Pump
Fuel Oil Furnace	Fuel Oil Furnace/Boiler
Wood Furnace	
Residential Cooling	**Commercial Cooling**
Electric AC	Electric AC
Residential Lighting	**Commercial Lighting**
Incandescent	Incandescent
Fluorescent	Fluorescent
Solid State (beginning in 2020)	Solid State (beginning in 2020)
Residential Hot Water	**Commercial Hot Water**
Gas Water Heater	Gas Water Heater
Gas Heat Pump Water Heater (beginning in 2020)	Gas Heat Pump Water Heater (beginning in 2020)
Electric Resistance Water Heater	Electric Resistance Water Heater
Electric Heat Pump Water Heater (beginning in 2020)	Electric Heat Pump Water Heater (beginning in 2020)
Fuel Oil Water Heater	Fuel Oil Water Heater
Residential Appliances & Other	**Commercial Office Equipment**
Generic Electric	Generic Electric
Generic Natural Gas	
Generic Fuel Oil	**Commercial Other**
	Generic Electric
	Generic Natural Gas
	Generic Fuel Oil

[a]Some services are served by real-world technologies where others, such as aggregate multiple services, are supplied by a generic technology.

Fuel prices change over time in MiniCAM for two reasons. One reason is the normal supply and demand workings of the energy markets. A second reason is that fuel prices are the primary means by which constraints on carbon emissions make their way into technology choice. Carbon emissions are constrained by placing an additional cost on fossil fuels based on their carbon content.

Because the technology options in MiniCAM are discrete, the primary technological response to changes in technology characteristics or fuel prices is a shift between these discrete technologies rather than changes in the characteristics of the technologies themselves. So, for example, when the price of electricity increases through a price on carbon, consumers will switch toward solid-state lighting from fluorescent or incandescent lighting, but they will not use more efficient versions of any of these technologies. This is a common characteristic of models that are based on discrete technologies. The treatment of intra-technology switching in this paradigm can be generally handled by adding multiple technologies with different characteristics. For simplicity this has not been done in this analysis, but may be explored in future work.

3.3.4 Data and Assumptions

Two classes of inputs are needed to model future building energy use: (1) historical data on the building stock, energy consumption by end use, stock efficiencies of equipment providing services, and the nonenergy costs of this equipment; and (2) scenario assumptions for all these over 100 years into the future. Historical data used in this study served two purposes. First, trend analysis based on historical data provided valuable insights on the key drivers of energy service demands. Secondly, historical data on the characteristics of the current building stock and technologies were used as starting points for calibrating the model.

The Energy Information Administration's Residential Energy Consumption Survey (EIA 2005c) and Commercial Building Energy Consumption Survey (CBECS) (EIA 2003) are the two major sources for historical data on the floor space of building stock and energy consumption by end use in the United States. The two surveys are national sample surveys that collect energy-related building characteristics data and energy consumption and expenditures data for residential and commercial buildings in the United States. Data on stock efficiencies and nonenergy costs of technology equipment providing the services mainly come from Technology Forecast Updates – Residential and Commercial Building Technologies – Reference Case (2003 Installed Base) (Navigant Consulting 2004) and National Energy Modeling System's (NEMS) detailed reference case data tables (DOE 2004). These data were supplemented with additional sources, including 2004 Buildings Energy Databook (DOE 2005b) and U.S. Lighting Market Characterization (Navigant Consulting 2002). Technology assumptions are provided in Table A-1 of the Appendix.

The process of collecting and reviewing the historical data showed that in the United States there are severe data gaps and limitations. For example, CBECS collects total energy consumption for natural gas, electricity, and fuel oil, but does not collect end-use consumption data for these sources. The end-use energy consumption data were estimated in CBECS by using statistical modeling. The methodologies used in different survey years were different, and thus the estimated end-use consumption data were not consistent. Overall, compared with end-use consumption data, it is much more difficult to get reliable data on the stock efficiencies and nonenergy costs for technologies providing the services, a challenge that is compounded by the need to aggregate multiple technologies into the discrete representations used in the building-sector module. For example, estimates of the nonenergy costs of different lighting technologies such as incandescent, fluorescent and solid-state vary with lamp, operating hours, and other factors. For this reason, technology data—particularly cost information—are best interpreted in comparison to other technologies within the sector rather than in absolute terms. That is, what matters is the relative average cost of fluorescent technologies relative to solid-state lighting.

The total demand for services responds to the prices at which these services can be delivered. For example, the more expensive it is to heat a house, the lower people will set their thermostats. This service-price response is captured in the service-price elasticity parameters from Equations (3.1), (3.2), and (3.3). This service-price response encompasses only the long-term adjustment in service demands; it does not encompass long-term adjustments in energy demand, as these are based not only on adjustments in service demand, but also fuel and technology switching, which are an endogenous component of the model. For the scenarios discussed in Section 4.0, a service price elasticity of 0.4 was assumed across the board.

This service-price elasticity was informed by the fuel-price responsiveness in the Annual Energy Outlook (AEO 2003) NEMS residential and commercial building-sector models (Wade 2005) and the battery of research that helped inform the assumptions in NEMS (Dahl 1993). In the AEO2003 NEMS, own-price elasticities range from 0.10 for initial year, short-run responses (commercial electricity) to 0.60 for long-run responses (residential distillate oil). The fuel-price elasticities cited in Dahl (1993) exhibit a substantially higher range than this, underscoring the uncertainty in appropriate choice of parameters.

Fuel-price elasticity numbers are a useful input to this analysis, but they are not perfectly transferable because the focus here is on service prices rather than fuel prices. Several countervailing factors complicate the link between fuel-price elasticities and service-price elasticities. Service prices include capital and other costs in addition to energy costs. In this basis, service price elasticities should be higher than energy price elasticities. On the other hand, long-run fuel-price elasticities include fuel and technology changes over time that will lead to larger changes in energy demand than in service demand. All other things being equal, this would imply that long-run fuel-price elasticities should be larger than long-run service-price elasticities. Using short-term fuel-price elasticity numbers should eliminate these fuel and technology changes, but may not be representative of the long-term behavior that is captured in the buildings model. Taking these factors into account, the assumption of 0.4 for service-price elasticities should be viewed as non inconsistent with historical data, but there are a range of other service-price elasticities that could meet this same qualification.

4.0 A Scenario of the U.S. Building Sector

This section presents the results from one illustrative scenario using the building-sector module in the ObjECTS MiniCAM. A discussion of aggregate results is presented, followed by a discussion of results in each service demand area.

4.1 Aggregate Results

This scenario assumes moderate population growth and robust economic growth. As shown in Figure 4.1, by 2095 total U.S. population is assumed to increase by approximately one-half from today with an annual growth rate 0.5 percent, while GDP per capita is assumed to almost triple from today with an annual growth rate of 1.3 percent.

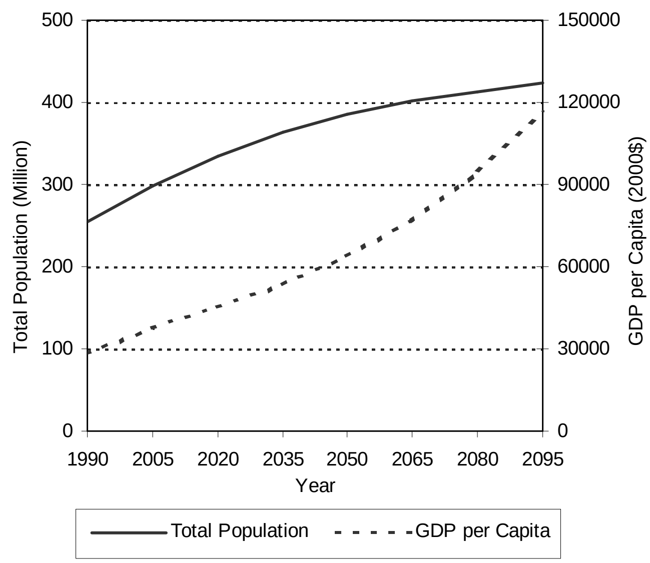


Figure 4.1. The Future U.S. Population and Gross Domestic Product Assumptions Underlying the Scenario Discussed in this Document

Associated with this economic and population growth are increasing trends in total and per-capita floor space, as shown in Figure 4.2. By the end of the century, per-capita residential floor space has risen from roughly 800 square feet today to more than 1300 square feet by 2095. In the commercial sector, floor space expands from roughly 250 square feet per capita today to roughly 400 square feet per capita in 2095. This growth may seem substantial, but is consistent with historical trends (Figure 2.1); however, it is critical in century-long projections not to simply extrapolate from the past under the assumption that the underlying dynamics will not change. Nonetheless, floor space is a fundamental driver of building energy demand and it is highly uncertain, so it should be considered here as a scenario parameter and not a prediction. A range of floor-space scenarios could be considered equally likely given what we know today about the potential movements and preferences over the coming century, which might include an expansion of urban sprawl or perhaps movement back toward cities with smaller dwellings.

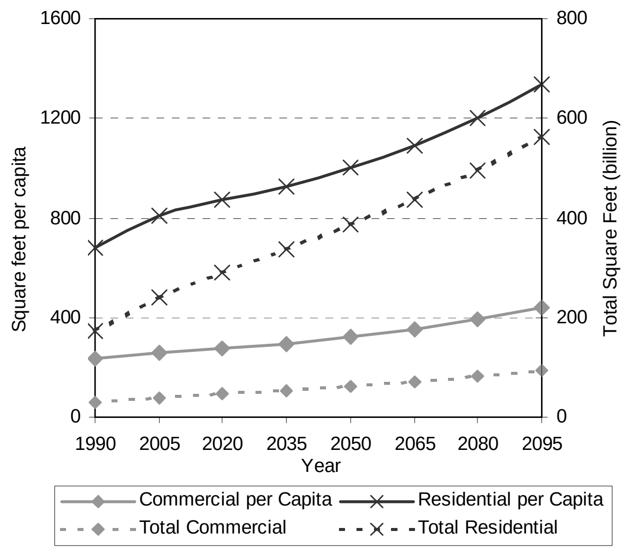


Figure 4.2. The Future Commercial and Residential Floor-Space Projections Underlying the Reference Scenario in this Chapter. These projections are functionally tied to United States GDP growth, but the parameterization of this relationship should not be considered a prediction; the floor space projections are a fundamental scenario assumption.

These two forces—population growth and growth in per-capita floor space—constitute the first two terms of the identity in Equation (2.1). Together, these two forces imply that total residential floor space increases by 135 percent and commercial floor space increases by 140 percent from 2005 to 2095. This is a large part of the challenge faced by new technology. Assuming no change in service demand per unit of floor space, new technology would need to be at least 135 percent more efficient and 140 percent more efficient in the residential and commercial sectors by the end of the century simply to keep pace with the growth in floor space. Any increases in service demand per square foot would exacerbate this requirement.

Table 4.1 shows the energy technology shares and average technology efficiencies[a] that emerge in this illustrative scenario. Average efficiencies are the result of (1) the technology cost and performance assumptions that were used, and (2) any price-induced choices among these technologies that occur within the model.

Table 4.1 shows that the efficiency gains in the reference case are quite substantial. Despite these substantial improvements in installed efficiency, total energy consumption almost doubles in the residential sector and more than doubles in the commercial sector in this scenario (Figure 4.3).

[a] The unit % means energy out (J) by energy in, which is converted from such units as seasonal energy efficiency ratio used for central cooling systems, coefficient of performance, or heating season performance factor used for heat pumps and chillers in their heating modes, and annual fuel utilization efficiency used for gas furnaces and boilers. The units for appliances, office equipment, and the other catetegory are in Appendix A.

Table 4.1. Aggregate Fuel Shares and Efficiencies by Fuel.(1)

Residential Services		2005 Electricity	2005 Natural Gas	2050 Electricity	2050 Natural Gas	2095 Electricity	2095 Natural Gas
Residential Heating	Energy Fraction	8%	71%	23%	58%	39%	48%
	Efficiency (%)	1.37	0.87	1.67	1.01	2.01	1.13
Residential Cooling	Energy Fraction	100%	0%	100%	0%	100%	0%
	Efficiency (%)	2.80	-	3.50	-	4.39	-
Residential Lighting	Energy Fraction	100%	0%	100%	0%	100%	0%
	Efficiency (lumen/watt)	25	-	88	-	129	-
Residential Hot Water	Energy Fraction	21%	69%	26%	65%	30%	61%
	Efficiency (%)	0.88	0.56	0.97	0.71	1.26	1.15
Residential Appliances & Other	Energy Fraction	14%	80%	22%	74%	34%	64%
	Efficiency (Index)	1	1	1.17	1.17	1.37	1.37
Commercial Services							
Commercial Heating	Energy Fraction	8%	80%	18%	73%	36%	59%
	Efficiency (%)	1.27	0.76	1.87	0.89	2.51	1.11
Commercial Cooling	Energy Fraction	100%	0%	100%	0%	100%	0%
	Efficiency (%)	2.79	-	3.49	-	4.37	-
Commercial Lighting	Energy Fraction	100%	0%	100%	0%	100%	0%
	Efficiency (lumen/watt)	56	-	92	-	173	-
Commercial Hot Water	Energy Fraction	17%	74%	25%	67%	38%	58%
	Efficiency (%)	0.88	0.81	2.10	1.34	3.18	2.30
Commercial Office Equipment	Energy Fraction	100%	0%	100%	0%	100%	0%
	Efficiency (Index)	1	--	1.25	--	1.57	--
Commercial Other	Energy Fraction	46%	32%	26%	69%	26%	72%
	Efficiency (Index)	1	1	1.17	1.17	1.37	1.37

(1) Where more than one technology is available for each fuel (Table 3.1) the weighted average is shown. The 2005 values are estimated using historical data. See also note (a) on previous page.

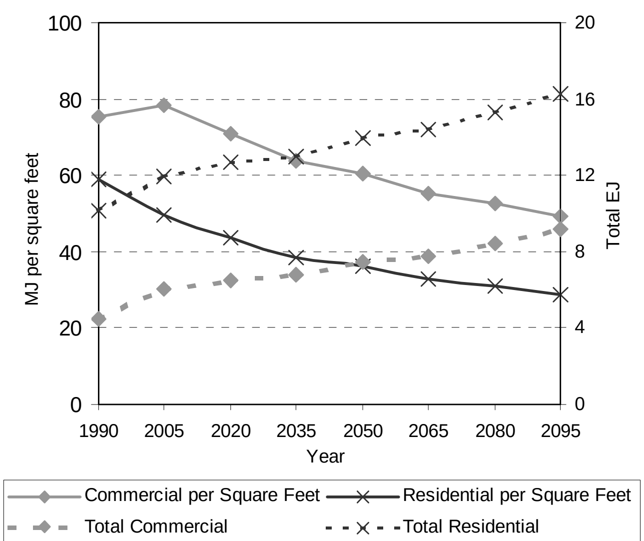
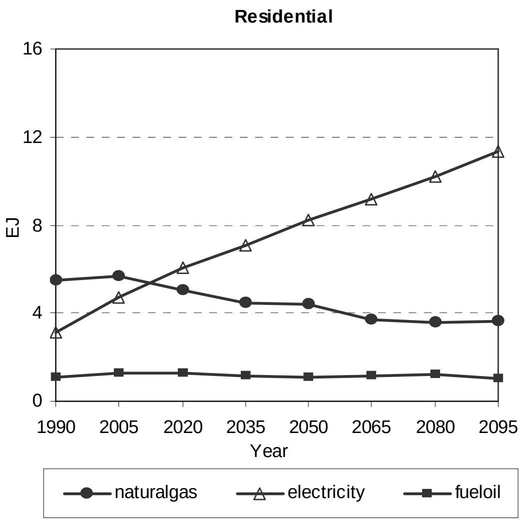


Figure 4.3. Building Energy Consumption in the Illustrative Scenario. Although energy consumption per square foot decreases, largely through energy efficiency, this is outweighed by the increase in floor space, leading to an increase in total energy consumption in both the commercial and residential sectors.

The resulting fuel mix continues an increasing trend toward electrification in both sectors, as shown in Figure 4.4. The primary drivers of electrification are a movement toward electric technologies particularly in heating because of the relatively higher efficiency these technologies can provide along with a substantial increase in the demand for appliances, office equipment, and similar demands that are largely met by electricity.



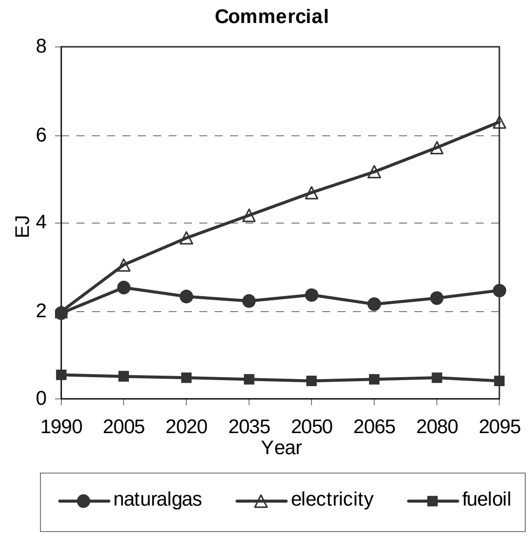


Figure 4.4. Total Delivered Energy by Fuel in the Residential and Commercial Sectors in the Illustrative Scenario. Both sectors continue the historical trend of increasing electrification.

4.2 Results by Service Demand

Underlying the aggregate changes in energy use are changes in the energy required for individual building services per square foot of floor space (Figure 4.5) and the demands for the services themselves (Figure 4.6). The demands for energy result from the combined effect of the last two terms in Equation (2.1), changes in unit of service per floor space and the efficiency at which services are delivered. In this scenario, energy demands per square foot are decreasing for all service categories except for the "other" categories in both residential (appliances and other) and commercial (office equipment and other) sectors. The remainder of this section discusses results and drivers for each major service demand area.

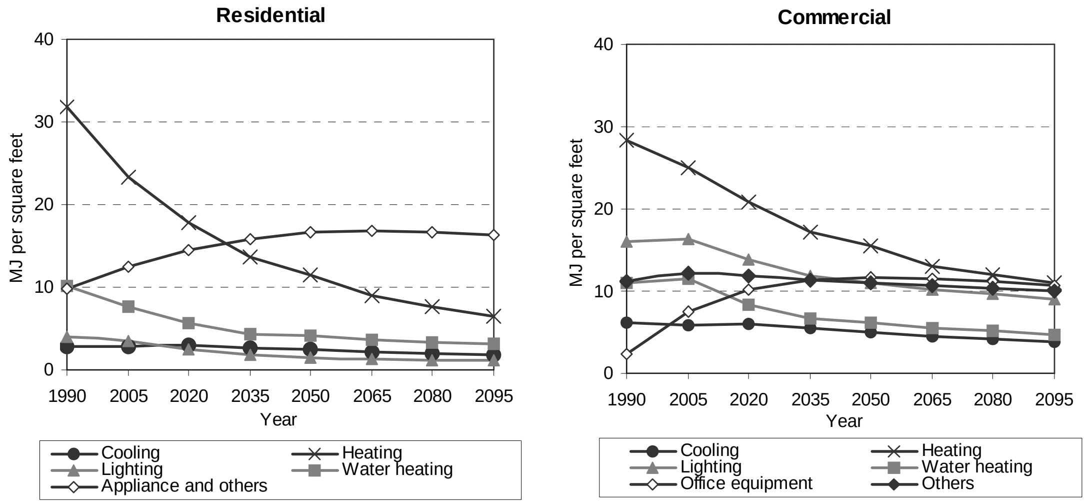


Figure 4.5. Delivered Energy Per Square Foot in the Residential and Commercial Sectors in the Illustrative Scenario

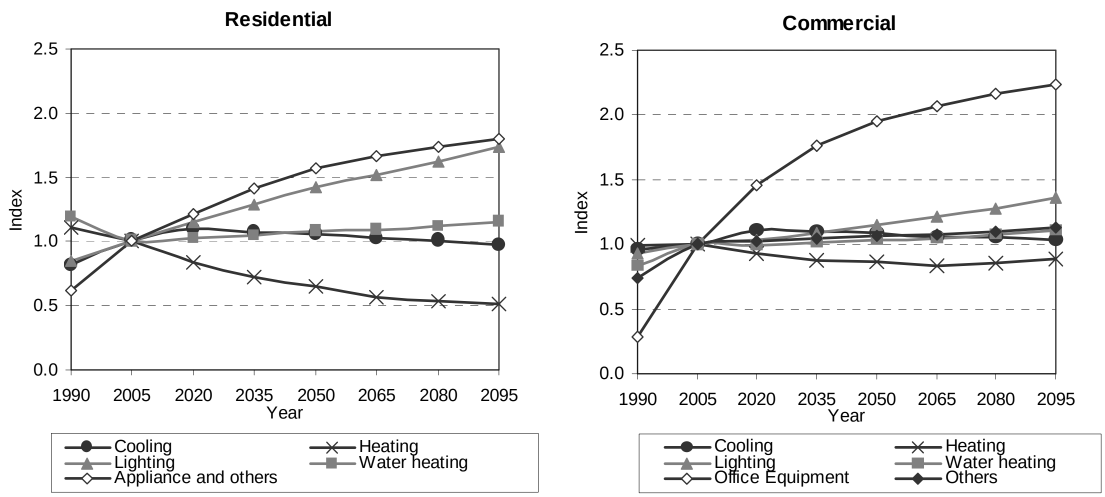


Figure 4.6. Service Demand Per Square Foot in the Residential and Commercial Sectors in the Illustrative Scenario

Heating and Cooling Demands: Overall, unit energy demands for heating and cooling decrease over the century. There are three major trends that combine to give this result. First, improved building shell technologies decrease the required service demands for both services. The thermal characteristics of the building stock in this scenario, for example, are assumed to improve by 50 percent from today to the end of the century. The effect is larger in the residential sector because much of heating and cooling load in commercial buildings is driven by internal gains rather than external thermal loads.

The second factor is increasing internal gains from appliances and other services in the residential sector and office equipment in the commercial sector. The growth in internal gains in the commercial sector is particularly large. Internal gains asymmetrically affect heating and cooling loads, decreasing the former and increasing the latter. To some extent, this can be seen in the service demand results. Heating service demands decrease more substantially than do cooling service demands due to the effects of internal gains.

The service demands as reported are the demands for the energy service as seen by the technology, that is, with internal gains taken into account. The heating service demand as shown, for example, has been reduced from the value it would have been without internal gains.

The final trend is improvements in the efficiency of the underlying service technologies. The aggregate trend is due in large part to increases in technology efficiency, although in some sectors, fuel switching, which manifests itself as a change in technology shares in this model, also plays a role. Cooling technology remains entirely electric as it is today but heating switches from gas technologies today to a much more even balance of electricity and natural gas by the end of the century. This change is driven partly by the relative growth in natural gas and electricity prices and partially by decreases in the cost of more efficient heat-pump-based electric heating technologies. The slight increase in residential cooling through 2020 is due to a continued penetration of cooling technologies into the marketplace (Sailor and Pavlova 2003).

Hot Water Demand: Hot-water service demand per square foot slightly increases over the century in these scenarios, with energy consumption for hot water decreasing substantially. This decrease is driven by improvements in the efficiency of hot water equipment, which include a move toward more efficient electric- (heat pump) based technologies, along with, in these scenarios, the adoption of natural gas heat-pump technologies.

Appliances, Office Equipment, and Other Demands: The demand for energy for electricity-based services such as office equipment, appliances, and information technology is an important characteristic of this scenario. The demand for these services continues the increasing historical trend. This trend is manifest through scenario construction by assuming that the use of these technologies continues to increase over the century. As a result, the total energy demand for these services almost doubles over the century in the residential sector and more than doubles in the commercial sector. To be clear, this is a scenario assumption rather than an endogenous output of the model. At the same time, it is assumed that the efficiency at which these various services are supplied increases by almost 40 percent over the century. The efficiency increase does not fully counter the service demand increase, resulting in a substantial increase in the energy demand per unit of floor space for these services. Note that will almost certainly include the addition of new "other" energy services not anticipated today. Consequently, there is substantial uncertainty in the demand for other energy services.

Lighting Demand: The role of technology in reducing the energy required to supply building services is clearly demonstrated in lighting. The per-square-foot demands for both residential and commercial lighting services increase, but the energy demand per square foot in both sectors dramatically decreases. The basis for this decrease in the long term is a shift to solid-state lighting, which has substantially higher efficiency than incandescent and fluorescent lighting. Under the illustrative scenario with solid-state lighting technology, the stock efficiencies of residential and commercial lighting equipment improve five-fold in the residential sector and three-fold in the commercial sector. The result is a dramatic decrease in the energy demand per square foot, along with an increase in the service per square foot associated with lower prices of the lighting services.

Figure 4.7 shows the mechanisms that drive increasing lighting efficiency. In the residential sector, three phases are apparent. The current phase in which lighting is predominantly supplied by incandescent bulbs is followed by a period in which fluorescent technologies become dominant, which is then followed by the emergence of solid-state lighting. Over the full period, the efficiency of the system transitions from that of incandescent lights (typically not more than 20 lumen/watt) to that of a combination of fluorescent and solid-state lighting. In this scenario, solid-state lighting is assumed to achieve efficiencies of over 170 lumens/watt. The commercial sector story is similar, except that we begin with largely fluorescent use, with a transition to solid-state technologies.

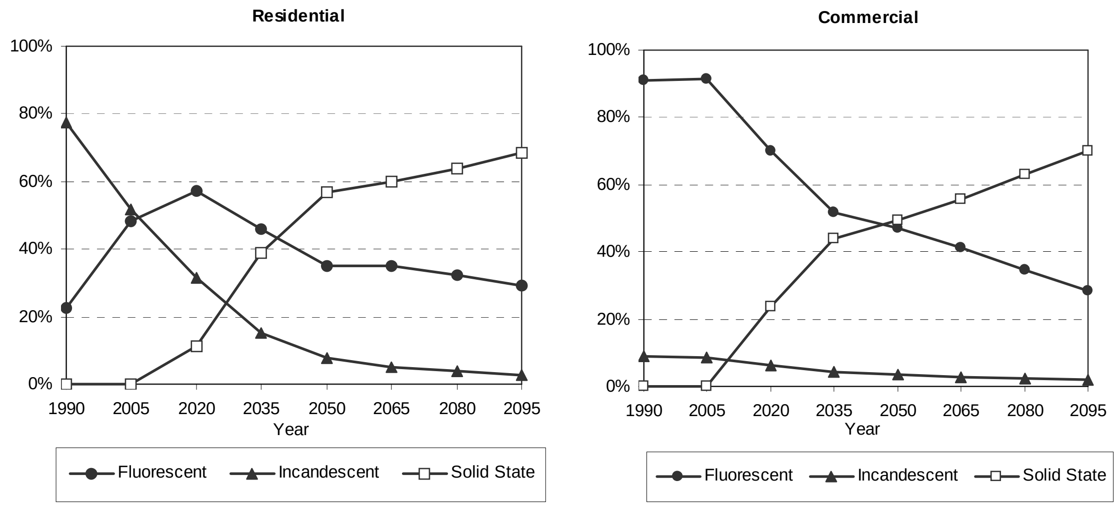


Figure 4.7. Technology Shares for Residential and Commercial Lighting in the Illustrative Scenario

To illustrate the importance of solid-state lighting, and to demonstrate the value of the modeling structure more generally for exploring the value of demand-side technologies, a scenario was constructed in which solid-state lighting did not materialize and was therefore not an option. Energy demand for lighting with and without solid-state lighting is presented in Figure 4.8. Without solid-state lighting, the stock efficiencies of residential and commercial lighting equipment improve approximately 400 percent and 100 percent from 2005 through 2095, respectively, compared with 600 percent and 200 percent with solid-state lighting scenario. The energy demands for lighting in both building sectors still decrease and the energy demand per square foot is higher than the scenario with solid-state lighting. Under the scenario with solid-state lighting, the per-square-foot energy demand for commercial lighting in 2095, for example, is 13.6 million joules, compared with 8.4 million joules with solid-state lighting. The total annual energy savings for building lighting at the end of the century is 1.1 exajoules of delivered energy and the reduction of carbon emissions in 2095 is 11 million tons.

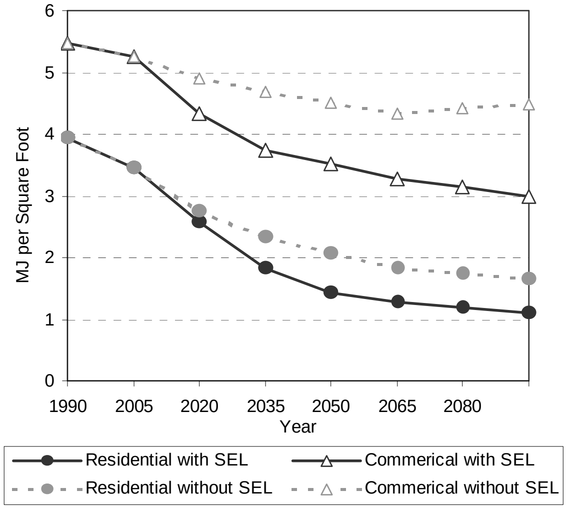


Figure 4.8. Energy Demand per Square Foot for Lighting With and Without Solid-State Lighting

5.0 Climate Policy and Building Energy Demand

MiniCAM is an integrated assessment model, designed specifically to explore the impact of technological advances on the climate challenge over a century-long time horizon. To explore these impacts on the buildings sector, the model was run for a climate policy scenario where carbon dioxide emissions were constrained to follow a path resulting in stabilization of atmospheric concentrations at 550 parts-per-million by volume (ppmv).

In MiniCAM, emissions reductions are achieved by placing an additional cost—a carbon price—on carbon-emitting fuels. The price makes its way through the energy system, causing price-induced reductions in energy use, fuel switching and changes in technology adoption. The scenario described above was run for a policy case where global carbon dioxide emissions are constrained to follow a 550 ppmv stabilization path consistent with those of Wigley et al. (1996). The carbon price increases at a roughly exponential rate until the concentration target is approached near the end of the century.

Figure 5.1 shows the U.S. total carbon emissions with and without the carbon constraint along with the associated price on carbon. In the climate policy scenario, U.S. carbon dioxide emissions peak in 2020 and decline thereafter. For simplicity, the climate policy was applied to all world regions beginning in 2005.

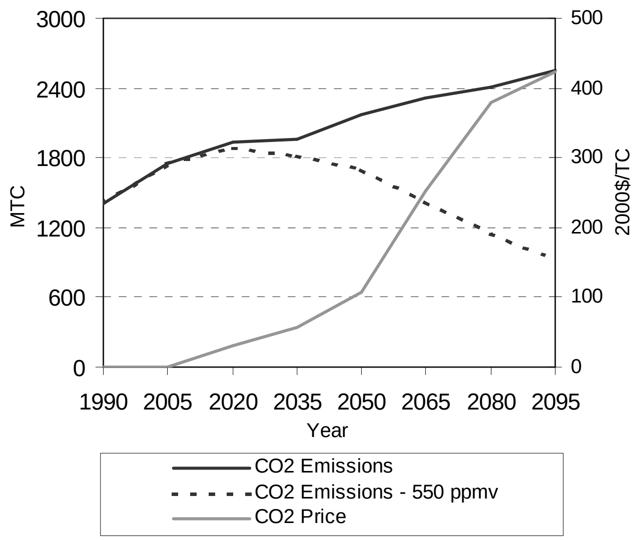


Figure 5.1. U.S. Carbon Emissions With and Without the Constraint

Figure 5.2 shows the associated energy prices, which influence service demands and technology choices. Not surprisingly, fuel prices increase as the constraint on carbon becomes more stringent through the century, and the increases are substantial. Of importance, the increase in fuel oil and natural gas prices (roughly 70 percent by 2095) is far more substantial than the increase in electricity (roughly 20 percent). Electricity is less influenced by the carbon price because, as a secondary fuel, there are multiple low or zero-carbon options (e.g., wind or solar power, nuclear power, electricity from biomass, and fossil electricity equipment with carbon capture and storage technology) for producing electricity, many of which are assumed to experience substantial cost and performance improvements over the century.

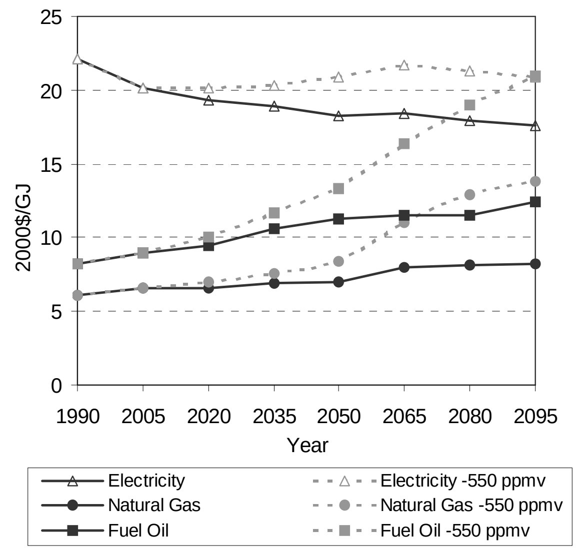


Figure 5.2. Energy Prices With and Without the Constraint on Carbon Emissions

Within MiniCAM, there are two main avenues by which the buildings sector might respond to these price changes: (1) reductions in service demand, and (2) changes in the technologies for supplying these services. Changes in technologies may also result in fuel switching. Figure 5.3 shows the aggregate results of these responses across fuels. Overall, increasing prices must decrease energy demand as compared to the reference case. However, as Figure 5.3 illustrates, stabilization accelerates the shift toward electricity. In both the residential sector and commercial sector, electricity demands barely change, and natural gas and fuel oil demands gradually decrease. The basis for this electrification arises in large part from the fuel price changes in response to the climate policy. As discussed above, the prices of fuel oil and natural gas increase more than the price of electricity. Hence, in addition to an overall decrease in service demand, there is also a shift toward electricity. This results in a significant decrease in direct fossil fuel use. Fuel switching is most important for heating demand, as other demands are already largely electricity-based.

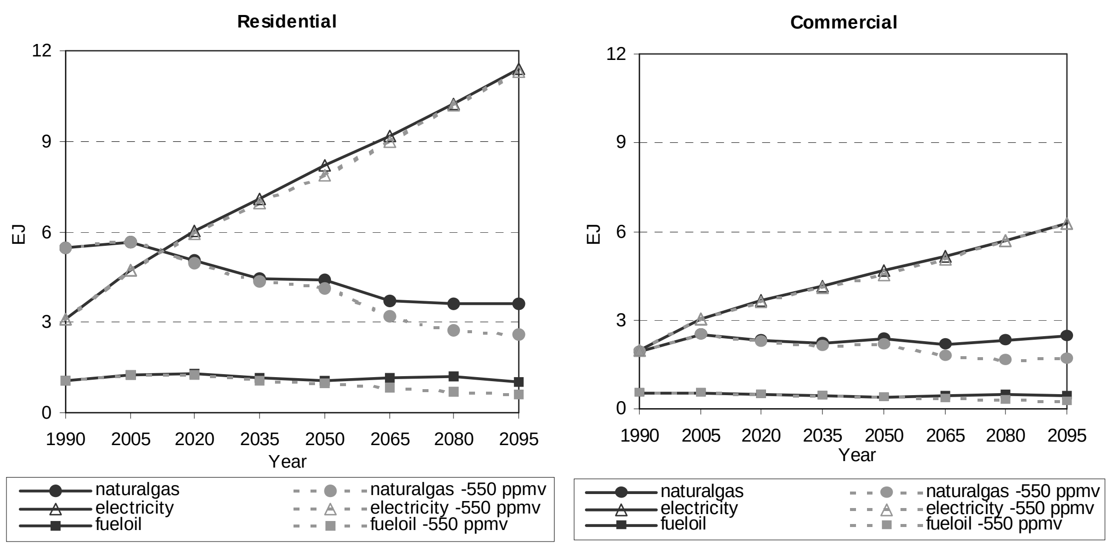


Figure 5.3. Total Delivered Energy Consumption in the Buildings Sector With and Without the Imposition of the Carbon Constraint

6.0 Conclusions and Discussion

This document has used a newly constructed, detailed building-sector module within the O^{bj}ECTS MiniCAM to explore national building sector energy demand evolution over the coming century. The module is based on explicit representations of the services that building users demand and the technologies that provide these services. This more detailed approach represents another step toward "hybrid" integrated assessment modeling. It conveys the advantage of allowing exploration of the impact of specific technologies on future energy use and the costs of stabilization of carbon emissions, thereby forging a stronger link between research and development planning efforts and integrated assessment modeling. While this link has been available for supply-side technologies, the demand side has until recently received only limited treatment within long-term, century-scale modeling.

This module has been employed to explore one scenario of the future evolution of the U.S. building sector and its associated energy and carbon emissions impacts. In conclusion, we would like to highlight three themes that have emerged from this exercise.

First, several factors may combine to put substantial upward pressure on building energy demand. For one, the U.S. population continues to grow and, in most published scenarios, will be higher by the end of the century than it is today. In addition, there exists a strong trend toward greater floor space per capita. Finally, the demand for a number of services associated broadly with appliances, office equipment, and information technology has increased substantially over the last several decades and seems likely to continue to increase, perhaps quite substantially, over the coming century. In the scenario presented here, the energy required to support these demands outstrip heating energy demand by the end of the century. In fact, in the scenario here, these are the only services that demand more energy per unit of floor space over time, a behavior that is consistent with recent historical experience in the U.S. (Figure 2.3). There is only a limited amount of information available on the breakdown of these services (Wenzel et al. 1997; Kawamoto et al. 2001), and further analysis of historical trends in this area is warranted.

The second theme is that these increasing trends set the challenge for energy efficiency. If energy efficiency were, for example, to fully balance the effect of the factors sited above, it would require substantial increases in the efficiency across the board. In the scenario presented in this document, substantial efficiency gains are not sufficient to decrease total building energy demand. The scenario assumed that over the century, the total U.S. population and total floor space will increase by roughly 40 percent and 140 percent, which results in a 40 percent increase in energy demands despite substantial efficiency gains (see Table 4.1).

The final theme is an increasing electrification of the building sector. Previous, more aggregate studies using earlier versions of MiniCAM attributed this change to a "preference for electricity." The approach presented in this document allows for a more coherent glimpse of the forces that drive the change. In general, they are three-fold. The first driver is a larger increase in the price of fuel oil and natural gas relative to electricity, changing the cost balance between electric and fossil-based technologies. The second factor is the emergence of more advanced electric technologies, particularly for heating, that can allow for substantial efficiency improvements above those of today. The third factor is the substantial increase in the demand for services associated with appliances, office equipment, and information technology that are largely served by electricity.

This trend toward electrification was found to be stronger in the scenarios with a constraint on carbon emissions. While the prices for all fuels increased as a response to the imposition of the emissions constraint, the increase in the electricity price was more modest than for fuel oil and natural gas because, as a secondary fuel, there are multiple low- or zero-carbon options for producing electricity, many of which are assumed to experience substantial cost and performance improvements over the century. This, combined with the availability of high efficiency heating technologies further accelerates the trend toward electrification.

The new buildings module represents a substantial step forward in integrating demand-side detail into a long-term, global IAM. However, there are a number of possible additional avenues for expansions to the module. These include: (1) inclusion of a greater range of technologies that could be available in the future, such as gas-cooling technologies; (2) explicit consideration of government programs, such as energy star and appliance standards, which may play important roles in future energy use; and (3) explicit consideration of different building vintages that will allow for a better understanding of shell efficiencies over time. Further work could also consider more explicitly the connections between building energy use and the electric generation system through demand-side management and time of day pricing.

The model presented here incorporates a physically-based representation of building energy use so that energy end use technologies can be explicitly represented. Both building shell characteristics and internal thermal loads are explicitly included. Future work could explore more fully the effect of integrated, whole building design by including such options as daylighting to reduce lighting demands.

7.0 References

Battles SJ. 2004. "Housing Trends as an Indicator of Future Housing Stock and Energy Use: 1990 and 2001 RECS Comparisons." *Breaking Out of the Box: Proceedings, 2004 ACEEE Summer Study on Energy Efficiency in Buildings*, Energy Information Administration, Washington, D.C.: American Council for an Energy-Efficient Economy. Accessed March 27, 2007, at http://www.eceee.org/conference_proceedings/ACEEE_buildings/2004/Panel_1/p1_2/.

Blok K. 2005. "Enhanced Policies for the Improvement of Electricity Efficiencies." *Energy Policy* 33:1635-1641.

Clarke, J and J. Edmonds. 1993. "Modeling Energy Technologies in a Competitive Market." *Energy Economics* 15(2): 123-129.

Dahl C. 1993. *A Survey of Energy Demand Elasticities in Support of the Development of the NEMS*. Prepared for the U.S. Department of Energy by the Department of Mineral Economics, Golden, Colorado.

DOE. 2004. *The National Energy Modeling System: An Overview 2003*. U.S. Department of Energy, Washington, D.C. Accessed March 27, 2007, at http://www.eia.doe.gov/oiaf/aeo/overview.

DOE. 2005a. *Energy Intensity Indicators*. U.S. Department of Energy, Washington, D.C. Accessed March 27, 2007, at http://intensityindicators.pnl.gov.

DOE. 2005b. *2005 Buildings Energy Databook*. U.S. Department of Energy, Washington, D.C. Accessed March 27, 2007, at http://buildingsdatabook.eren.doe.gov.

Edmonds JA, JF Clarke, JJ Dooley, SH Kim, and SJ Smith. 2004. "Stabilization of CO_2 in a B_2 World: Insights on the Roles of Carbon Capture and Disposal, Hydrogen, and Transportation Technologies." *Energy Economics* 26(4):517-537.

EIA. 2003. *Commercial Buildings Energy Consumption Survey (CBECS).* Energy Information Administration, Washington, D.C. Accessed March 27, 2007, at http://www.eia.doe.gov/emeu/cbecs/enduse_consumption/intro.html.

EIA. 2005a. *Annual Energy Outlook 2005 with Projections to 2025.* DOE/EIA-0383, Energy Information Administration, Washington, D.C. Accessed March 27, 2007, at http://tonto.eia.doe.gov/FTPROOT/forecasting/0383(2005).pdf.

EIA. 2005b. *Annual Energy Review 2004.* Energy Information Administration, Washington, D.C. Accessed March 27, 2007, at http://www.eia.doe.gov/emeu/aer/consump.html.

EIA. 2005c. *Residential Energy Consumption Survey (RECS)*. Energy Information Administration, Washington, D.C. Accessed March 27, 2007, at http://www.eia.doe.gov/emeu/recs/contents.html.

Gerencher K. 2006. *Bigger Houses Bring Energy Woes: Efficient Materials, Appliances Have Limited Cost Effects.* Accessed March 27, 2007, at http://www.marketwatch.com/news/story/energy-efficiency-limited-big-houses/story.aspx?guid=%7BCAE75E92%2D7226%2D466C%2D9092%2D9F065E60BE42%7D.

Hanson DA. 1999. *A Framework for Economic Impact Analysis and Industry Growth Assessment: Description of the AMIGA System.* Decision and Information Sciences Division, Argonne National Laboratory, Argonne, Illinois.

Kawamoto K., JG Koomey, B Nordman, RE Brown, MA Piette, M Ting, and AK Meier. 2001. *Electricity Used by Office Equipment and Network Equipment in the U.S.: Detailed Report and Appendices*. LBNL-45917, Lawrence Berkeley National Laboratory, Berkeley, California. Accessed March 27, 2007, at http://enduse.lbl.gov/Info/LBNL-45917b.pdf.

Kim SH, J Edmonds, J Lurz, SJ Smith, and M Wise. In Press. "The Object-oriented Energy Climate Technology Systems (ObjECTS) Framework and Hybrid Modeling of Transportation in the MiniCAM Long-Term, Global Integrated Assessment Model." *Energy Journal* (Special Issue #2).

Laurence MT. 2004. "Changes in the Patterns of Energy Consumption and Expenditures over the Past Quarter Century." Presentation a*t Breaking Out of the Box: Proceedings*, *2004 ACEEE Summer Study on Energy Efficiency in Buildings,* Energy Information Administration, Washington, D.C.; American Council for an Energy-Efficient Economy.

Navigant Consulting, Inc. 2002. *U.S. Lighting Market Characterization. Volume I: National Lighting Inventory and Energy Consumption Estimate.* Prepared for the U.S. Department of Energy by Navigant Consulting, Inc., Washington, D.C. Accessed March 27, 2007, at http://www.eere.energy.gov/buildings/info/documents/pdfs/lmc_vol1_final.pdf.

Navigant Consulting, Inc. 2004. *EIA – Technology Forecast Updates – Residential and Commercial Building Technologies – Advanced Adoption Case.* Navigant Consulting, Inc., Washington, D.C.

Sailor DJ and AA Pavlova. 2003. "Air Conditioning Market Saturation and Long-Term Response of Residential Cooling Energy Demand to Climate Change." *Energy* (28):941-951.

Schubert EF and JK Kim. 2005. "Solid-State Light Sources Getting Smart." *Science* 308 (5726):1274-1278.

Sands R and M Leimbach. 2003. "Modeling Agriculture and Land Use in an Integrated Assessment Framework." *Climatic Change* 56(1):185-210.

Wade SH. 2005. *Price Responsiveness in the AEO2003 NEMS Residential and Commercial Buildings Sector Models*. Accessed March 27, 2007, http://www.eia.doe.gov/oiaf/analysisdocument/elasticity.

Wenzel TP, JG Koomey, GJ Rosenquist, M Sanchez, and JW Hanford. 1997. Energy Data Sourcebook for the U.S. Residential Sector. LBL-40297, Lawrence Berkeley National Laboratory, Berkeley, California.

Wigley TML, R Richels, and JA Edmonds. 1996. "Economic and Environmental Choices in the

Stabilization of Atmospheric CO_2 Concentrations." *Nature* 379(6562):240-243.

Wigley TML and SCB Raper. 2002. "Reasons for Larger Warming Projections in the IPCC Third Assessment Report." *Journal of Climate* 15(20):2945-2952.

Wilson A. 1999. "Small is Beautiful: House Size, Resource Use, and the Environment." *Environmental Building News* 1(8).

Appendix A

Appendix A

		2005		2050		2095	
Residential		Efficiency	Non-energy Cost	Efficiency	Non-energy Cost	Efficiency	Non-energy Cost
Residential Heating	Gas Furnace	0.87	2.8	0.96	2.5	0.96	2.3
	Gas Heat Pump	-	-	1.75	11.8	2.19	9.4
	Electric Resistance Heat Furnace	0.98	2.8	0.99	2.5	0.99	2.2
	Electric Heat Pump	2.14	9.5	2.68	7.6	3.35	6.0
	Fuel Oil Furnace	0.82	3.0	0.92	2.7	0.96	2.4
	Wood Furnace	0.58	4.0	0.65	3.6	0.73	3.2
Residential Cooling	Electric AC	2.80	7.0	3.50	5.6	4.39	4.4
Residential Lighting	Incandescent	15	1.3	19	1.2	20	1.1
	Fluorescent	75	0.9	94	0.8	100	0.7
	Solid State	-	-	143	1.3	205	0.6
Residential Hot Water	Gas Water Heater	0.56	5.9	0.70	5.3	0.88	4.7
	Gas Heat Pump Water Heater	-	-	2.20	17.1	2.76	13.6
	Electric Resist Water Heater	0.88	3.9	0.96	3.5	0.96	3.1
	Electric Heat Pump Water Heater	-	-	2.75	11.7	3.45	9.3
	Fuel Oil Water Heater	0.56	6.5	0.70	5.8	0.88	5.2
Residential Appliances & Other	Generic Electric	1.00	70.0	1.17	62.5	1.37	55.9
	Generic Natural Gas	1.00	40.0	1.17	35.7	1.37	31.9
	Generic Fuel Oil	1.00	40.0	1.17	35.7	1.37	31.9
Commercial							
Commercial Heating	Gas Furnace/Boiler	0.76	1.0	0.85	0.9	0.95	0.8
	Gas Heat Pump	-	-	1.75	11.1	2.19	8.8
	Electric Resistance Heat Furnace/Boiler	0.98	2.4	0.99	2.2	0.99	1.9
	Electric Heat Pump	2.14	10.4	2.68	8.3	3.35	6.6
	Fuel Oil Furnace/Boiler	0.77	0.4	0.86	0.4	0.96	0.3
Commercial Cooling	Electric AC	2.79	6.7	3.49	5.3	4.37	4.3
Commercial Lighting	Incandescent	15	1.1	17	1.0	20	0.9
	Fluorescent	75	0.7	94	0.7	100	0.6
	Solid State	-	-	143	1.1	205	0.5
Commercial Hot Water	Gas Water Heater	0.81	2.0	0.91	1.8	0.96	1.6
	Gas Heat Pump Water Heater	-	-	2.20	8.0	2.76	1.6
	Electric Resist Water Heater	0.88	1.4	0.96	1.3	0.96	1.1
	Electric Heat Pump Water Heater	-	-	2.63	6.4	3.29	5.1
	Fuel Oil Water Heater	0.76	1.9	0.85	1.7	0.95	1.5
Commercial Office Equipment	Generic Electric	1.00	120	1.25	107	1.57	96
Commercial Other	Generic Electric	1.00	20.0	1.17	17.9	1.37	16.0
	Generic Natural Gas	1.00	20.0	1.17	17.9	1.37	16.0
	Generic Fuel Oil	1.00	20.0	1.17	17.9	1.37	16.0

Note: For lighting technologies, the unit of efficiencies is lumens/watt and the unit of nonenergy costs is $2000/million lumen-hours.