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Pacific Northwest
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The Value of End-Use Energy Efficiency in Mitigation of U.S. Carbon Emissions

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November 2007

Prepared for the U.S. Department of Energy
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The Value of End-Use Energy Efficiency in Mitigation of U.S. Carbon Emissions

PNNL Research Report

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September 2007

Prepared for the U.S. Department of Energy
under Contract DE-AC06-76RL01830

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Abstract

This report documents a scenario analysis exploring the value of advanced technologies in the U.S. buildings, industrial, and transportation sectors in stabilizing atmospheric greenhouse gas concentrations. The analysis was conducted by staff members of Pacific Northwest National Laboratory (PNNL), working at the Joint Global Change Research Institute (JGCRI) in support of the strategic planning process of the U.S. Department of Energy (U.S. DOE) Office of Energy Efficiency and Renewable Energy (EERE).

The conceptual framework for the analysis is an integration of detailed buildings, industrial, and transportation modules into MiniCAM, a global integrated assessment model. The analysis is based on three technology scenarios, which differ in their assumed rates of deployment of new or presently available energy-saving technologies in the end-use sectors. These technology scenarios are explored with no carbon policy, and under two CO_2 stabilization policies, in which an economic price on carbon is applied such that emissions follow prescribed trajectories leading to long-term stabilization of CO_2 at roughly 450 and 550 parts per million by volume (ppmv). The costs of meeting the emissions targets prescribed by these policies are examined, and compared between technology scenarios.

Relative to the reference technology scenario, advanced technologies in all three sectors reduce costs by 50% and 85% for the 450 and 550 ppmv policies, respectively. The 450 ppmv policy is more stringent and imposes higher costs than the 550 ppmv policy; as a result, the magnitude of the economic value of energy efficiency is four times greater for the 450 ppmv policy than the 550 ppmv policy. While they substantially reduce the costs of meeting emissions requirements, advanced end-use technologies do not lead to greenhouse gas stabilization without a carbon policy. This is due mostly to the effects of increasing service demands over time, the high consumption of fossil fuels in the electricity sector, and the use of unconventional feedstocks in the liquid fuel refining sector.

Of the three end-use sectors, advanced transportation technologies have the greatest potential to reduce costs of meeting carbon policy requirements. Services in the buildings and industrial sectors can often be supplied by technologies that consume low-emissions fuels such as biomass or, in policy cases, electricity. Passenger transportation, in contrast, is especially unresponsive to climate policies, as the fuel costs are small compared to the time value of transportation and vehicle capital and operating costs. Delaying the transition from reference to advanced technologies by 15 years increases the costs of meeting 450 ppmv stabilization emissions requirements by 21%, but the costs are still 39% lower than the costs assuming reference technology.

The report provides a detailed description of the end-use technology scenarios and provides a thorough analysis of the results. Assumptions are documented in the Appendix.

Acronyms and Abbreviations

CBECS	Commercial Building Energy Consumption Survey
CCS	Carbon capture and storage
CNG	Compressed natural gas
CDD	Cooling degree days
CHP	Combined heat and power
EIA	Energy Information Administration
GDP	Gross domestic product
HDD	Heating degree days
HEV	Hybrid electric vehicle
ICE	Internal combustion engine
JGCRI	Joint Global Change Research Institute
MECS	Manufacturing Energy Consumption Survey
MiniCAM	The integrated assessment model used at PNNL
NEMS	National Energy Modeling Systems
O^{bj}ECTS	Object-oriented Energy, Climate, and Technology Systems
O&M	Operations and maintenance
PNNL	Pacific Northwest National Laboratory
RECS	Residential Energy Consumption Survey
TEDB	Transportation Energy Data Book
UEC	Unit energy consumption

2005 USD, 2005 $	U.S. dollars adjusted to the year 2005
EJ	Exajoules
GJ	Gigajoules
ppmv	parts per million by volume
TWh	Terawatt-hours
tC	Tonne carbon

MTC	Megatonne carbon

Acknowledgments

This work was funded by the U.S. Department of Energy’s Office of Energy Efficiency and Renewable Energy with additional support from the California Energy Commission and the Global Energy Technology Strategy Program. The authors would like to thank John Cymbalski and Erin Boedecker at the Energy Information Administration for their helpful insights and assistance, Emily Rauch for assistance and review comments, the buildings and industry analysis staff at PNNL for assistance in developing the model components, and William Gans for RECS data extraction.

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1. Introduction

Residents of the United States demand a range of services currently provided by technologies that use fossil fuels, contributing to increasing concentrations of greenhouse gases in the atmosphere and ultimately global climate change. To stabilize atmospheric concentrations of greenhouse gases, many aspects of the energy and climate system must be considered, from end-use demands and technologies to global energy resources and greenhouse gas warming potentials. To date, most long-term studies on climate change mitigation have focused on changes in fossil fuel energy supplies and transformation; the role of improvements in technologies used to provide end-use services is less well understood. This study addresses the value of energy-saving technologies in the U.S. buildings, industrial, and transportation sectors for reducing the costs of climate change mitigation.

Costs of mitigation will depend on future energy demand, and the characteristics of the energy technologies used to supply these demands. Future energy demand will depend on the levels and types of service demands, and the characteristics of the technologies used to provide these demands. In order to better understand the role of more energy-efficient technologies within a global context of climate change mitigation, this study uses a long-term model of energy and climate change, enhanced to incorporate explicit end-use technologies. This approach allows the role of energy efficiency to be determined on the basis of individual technologies, while consistently considering interactions within the energy system on regional and global scales.

The structure of this report is as follows. Section 2 presents the analysis approach, which is known as *integrated assessment,* as it integrates information from many disciplines across multiple spatial and temporal scales, into a common framework for analysis. Section 3 describes the structure of the detailed modules of the buildings, industrial, and transportation sectors, outlines technology assumptions, and presents results and analysis from the scenarios. The report then concludes with a summary of the findings, and identifies appropriate future research directions.

2. Project Approach

2.1. *Integrated Assessment*

The practice of integrated assessment draws together knowledge and information from different disciplines, spatial scales, and temporal scales, allowing complex questions to be addressed quantitatively. When applied to climate change, integrated assessment often produces estimates of how much climate change is likely to occur in the future, quantification of climate changes drivers (e.g. anthropogenic emissions, land-use changes), analysis of mitigation costs, identification of technologies and policies that can reduce costs, and analysis of climate impacts and the potential for adaptation. Numerous applications of integrated assessment can be found in a recent report by the Global Energy Technology Strategy Project (Edmonds et al. 2007).

With such a broad set of goals, the tools used for integrated assessment vary widely in their complexity, intended uses, and range of topics covered. This report is based on integrated assessment modeling methods used at the Joint Global Change Research Institute (JGCRI). The JGCRI's modeling approach integrates social, economic, and physical systems, to analyze in a comprehensive fashion the implications of potential future developments. Results from these models have been used by U.S. government agencies, industrial clients, international assessment activities, and have been published in peer-reviewed journals.

Integrated assessment modeling at JGCRI uses relatively simple representations of relevant processes to model the complex behaviors that result from interactions among the component systems. The framework is designed to be flexible, allowing analysis of multiple scenarios with different assumptions such as, in the present study, potential future technology strategies. This study uses scenario analysis to examine the role of energy efficiency within a changing energy system and climate policy context during the upcoming century.

2.2. *O^{bj}ECTS MiniCAM*

MiniCAM is a partial-equilibrium model structure that is designed to examine long-term, large-scale changes in global and regional energy systems. MiniCAM is based on Edmonds and Reilly (1985), and has been updated over time (Edmonds et al. 1996, Kim et al. 2006). The MiniCAM model has a strong focus on energy supply technologies and has been recently expanded to include a comprehensive suite of end-use technologies. MiniCAM was one of the models used to generate the Special Report on Emissions Scenarios of the Intergovernmental Panel on Climate Change (Nakicenovic and Swart 2000). This model has also been used in a number of national and international assessment and modeling activities such as the Energy Modeling Forum (Edmonds et al. 2004, Smith and Wigley 2006), the U.S. Climate Change Technology Program (Clarke et al. 2006a) and the U.S. Climate Change Science Program (Clarke et al. 2007a).

The MiniCAM model is calibrated to historical data in 1990 and 2005, and operates in 15-year time steps to the year 2095. In each modeled time step, it solves for supply and demand equilibria in energy, agriculture, and greenhouse gas markets. It takes inputs such as labor productivity growth, population, fossil and non-fossil fuel resources, energy technology characteristics, and productivity growth rates. It generates outputs of prices, supplies, and demands of energy by fuel (9 primary and 5 final), agricultural land, and emissions of greenhouse gases and other radiatively important compounds. MiniCAM also incorporates MAGICC, a model of the carbon cycle, atmospheric processes, and global climate change (Wigley and Raper 1992; Raper et al. 1996), allowing simultaneous consideration of the energy and agricultural systems and climate change.

The version of the model used in this project is the Object-oriented Energy, Climate, and Technology Systems (O^{bj}ECTS) framework, which uses a flexible, object-oriented modeling structure to implement an enhanced version of MiniCAM (Kim et al. 2006). The framework is intended to bridge the gap between “bottom-up” technology models and “top-down” macroeconomic models. The O^{bj}ECTS framework allows individual sectors of the model to be created and refined as needed, while still retaining interactions between all model components, allowing exploration into system-level feedbacks and interactions. By using object-oriented programming techniques, the model is structured to be data-driven, meaning that new model configurations can be created by changing only input data, without changing the underlying model code.

In MiniCAM, different technologies compete for market share of service provision primarily according to the costs of providing a given service. MiniCAM uses a logit choice formulation to determine market shares of different fuels and technologies. The market share of a given technology is computed according to the following equation:

$$S_{i,L} = sw_{i,L} P_{i,L}^{r_L} / \sum_{i}^{N} sw_{i,L} P_{i,L}^{r_L} \qquad (1)$$

where, $S_{i,L}$ is market share of each technology, $sw_{i,L}$ is the share weight, $P_{i,L}$ is cost per unit of output of each technology, r_L is a distribution parameter, and N is the number of competing technologies. The share weight captures current consumer preferences, the availability of the technology, and geographic heterogeneities that are not explicitly modeled. Share weights are calibrated from data for current technologies or set as scenario parameters for future technologies that are not in widespread use at present. While the methodology allocates market shares based on prices, it also ensures that higher-priced goods can gain some share of the market, which is consistent with real observations (McFadden 1974; McFadden 1981).

MiniCAM does not model the processes by which technological efficiency improves over time, such as learning-by-doing, or research and development. Instead, the present and future characteristics of technologies are inputs to the model. This means that developments that affect energy prices such as resource depletion, or policies to address climate change, may affect the deployment and use of technologies, but not the characteristics of the technologies themselves.

The O^{bj}ECTS MiniCAM therefore produces projections with technological detail, such as the fraction of electricity produced by various fossil fuel and renewable technologies, or the fraction of refined liquid fuels produced from different feedstocks such as crude oil, “unconventional” oil, biomass, and coal. The model also generates projections of energy consumption and greenhouse gas emissions. Because it operates using fundamental economic principles, it allows analysis of the costs of meeting greenhouse gas emissions objectives.

3. Project Results

3.1. *Climate Stabilization and the Energy System*

The goal of the United Nations Framework Convention on Climate Change is the stabilization of atmospheric concentrations of greenhouse gases at a level that avoids dangerous anthropogenic interference with the climate system (UNFCCC 1992, Article 2). Because of uncertainty in the response of climate to increasing greenhouse gases, the stabilization level that would achieve this goal is not known. Still, the general characteristics of climate stabilization can be described.

Figure 3.1 shows global carbon emissions pathways that lead to stabilization of atmospheric concentrations of CO_2 at levels ranging from 450 to 750 parts per million by volume (ppmv). Because some portion of any CO_2 emitted to the atmosphere will remain for centuries, concentration stabilization requires that emissions eventually continually decrease. The point at which emissions begin to decrease is determined primarily by the stabilization level and the assumed details of the carbon cycle. Note that for stabilization at 450 ppmv, global carbon emissions begin to decline within the next decade or two, which would require a significant departure from the present historical trend.

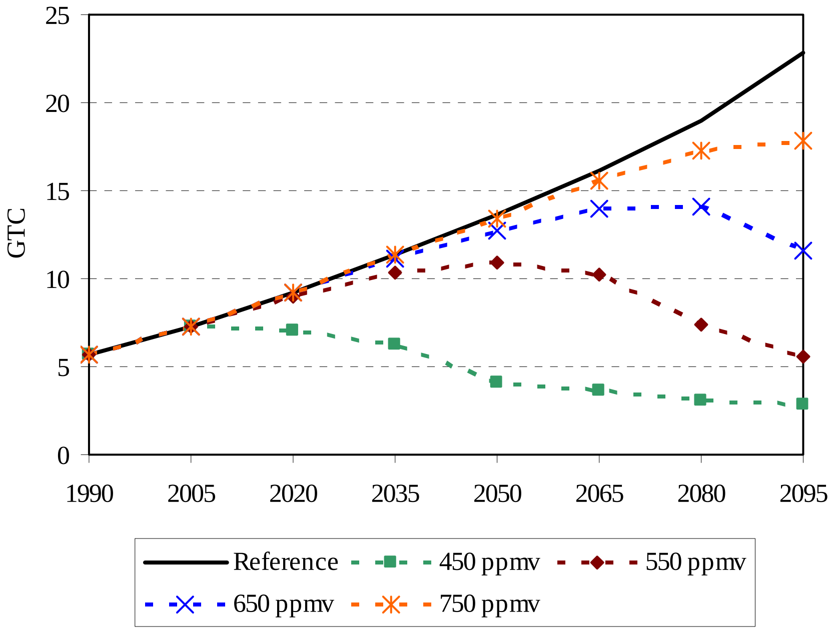

Figure 3.1. Global carbon emissions paths leading to stabilization of atmospheric CO_2 concentrations, ranging from 450 ppmv to 750 ppmv.

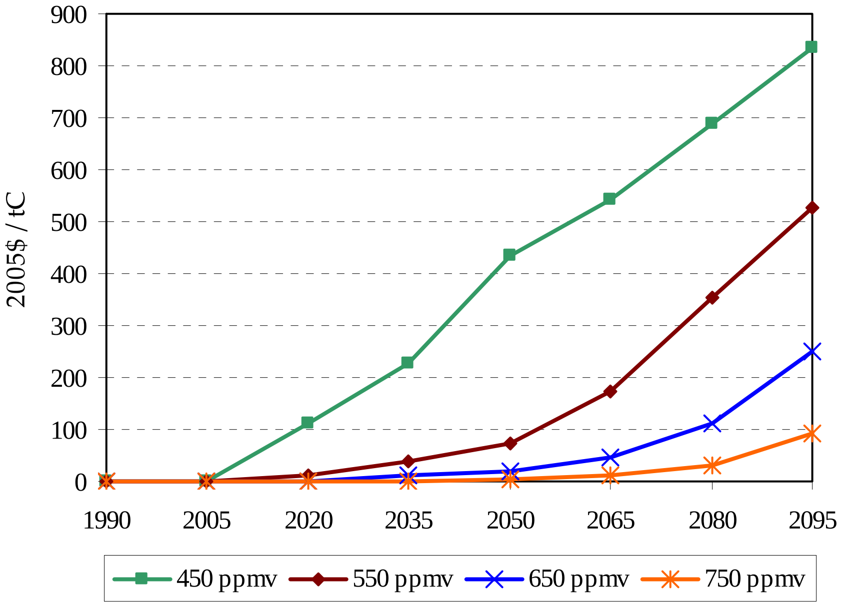

Figure 3.2. Carbon price paths for CO_2 stabilization. The carbon price increases at a level close to the long-term interest rate until the concentration stabilization target is approached.

Because of the general abundance and relative cost-effectiveness of fossil fuels, the changes necessary to stabilize greenhouse gas concentrations at any of the prescribed levels do not occur without political intervention, such as an economic price on the emission of CO_2 to the atmosphere. Figure 3.2 shows the global carbon prices over time necessary to induce the transition to an energy system with stabilized greenhouse gas concentrations, in the reference technology scenario detailed later in this report. In this study, carbon taxes raise the costs of fuels in proportion to their carbon content, so natural gas prices increase less than coal prices, for example. The increases in fuel prices then influence technology choices and levels of service consumption.

The responses of the U.S. electricity sector and liquid fuel refining sector to the carbon taxes in the reference technology scenario with a 450 ppmv CO_2 stabilization policy are shown in Figure 3.3. The technology assumptions for these energy supply sectors are detailed in Clarke et al. (2007b). In summary, electricity can be generated from nuclear energy, wind, hydroelectricity, biomass, and fossil fuels, with or without carbon capture and storage (CCS). Refined liquid fuels are currently produced almost entirely with crude oil, but alternative feedstocks include biomass, shale oil, natural gas, and coal. Note that even without a climate policy, there is a shift towards shale oil and coal over time, as crude oil resources are depleted. These technologies release emissions in addition to the "tailpipe" emissions when the fuels are used by end-use consumers.

The climate policy induces large changes in both of the energy supply sectors, inducing a shift towards low-emissions technologies starting in 2020. For instance, in 2095, fossil fuel generation with CCS accounts for more than half of the electricity produced, whereas these technologies barely enter the market without a carbon tax. Note also that electricity generation increases in the policy scenario, in response to fuel switching towards electricity in the end-use sectors (buildings, industry, transportation). This is the result of extensive technology switching and service demand responses, the subject of the following section.

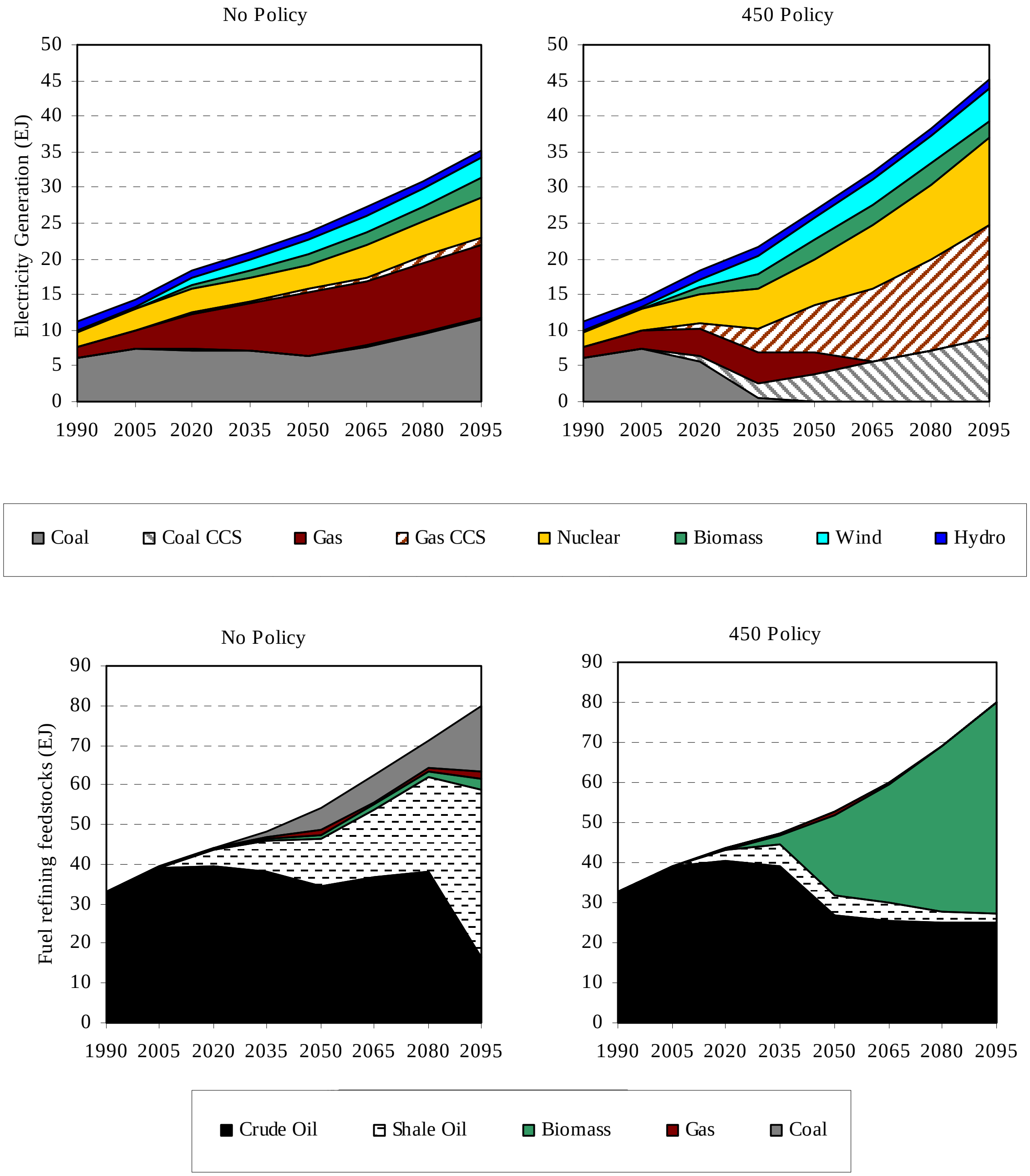

Figure 3.3. U.S. electricity generation technologies and liquid fuel refining feedstocks, with and without a 450 ppmv CO_2 stabilization policy. Note that the policy induces the entry of low-emissions technologies that otherwise are too expensive to compete.

3.2. End-Use Service and Final Energy Consumption

3.2.1. Introduction

The purpose of final energy consumption is the provision of end-use services and goods to people. In MiniCAM, future levels of service demand are driven primarily by gross domestic product (GDP). Future GDP in each region is calculated based on assumptions about future population, labor force participation rates, and labor productivity.

End-use services are supplied by technologies that consume final (or delivered) energy. This energy can be in the form of a secondary fuel such as electricity, or a primary fuel such as natural gas, depending on the technology being used and the service being provided. Reducing energy consumption, and therefore greenhouse gas emissions, can be accomplished through three primary methods: (1) reducing the level of services supplied, (2) producing the energy in forms that result in lower net emissions (supply-side), and (3) using technologies that consume less energy (demand-side).

It is a general goal of most policies to balance costs and benefits so that undue costs are not borne by consumers. For this reason, reducing the level of services (e.g. restrictions on driving) constitute the least politically favorable options for reducing emissions. While reductions in service demand can be expected to occur as a result of any measure that increases the price of a service, this is generally an effect that policy-makers seek to minimize.

Supply-side methods have generally received the most attention from researchers and policy-makers, in large part due to their convenience. For example, if electricity generation were shifted to technologies with zero net carbon emissions to the atmosphere, then carbon emissions would be substantially reduced and, aside from likely electricity price increases, the change would be largely transparent to consumers. The policies could achieve emissions reductions by inducing substantial changes in the technologies used by electric utilities, but for individual consumers, there would be little adjustment necessary.

Demand-side measures, such as the deployment of a more energy-efficient stock of end-use technologies, also have the potential to decrease overall emissions, and have the benefit that they do not necessarily reduce levels of service provision. At present, there are state and national energy efficiency standards on certain types of end-use equipment (e.g. air conditioners, automobiles). However, the difficulty with the demand-side approach, from both a practical and analytical perspective, is that there are myriad end-use technologies deployed in a wide range of applications. Potential energy-use reductions differ by each service, so each technology and service must be addressed individually. Still, improved energy efficiency reduces the scale of any problems associated with energy use, and can be implemented in a way that is transparent to consumers. In fact, the deployment of more energy-efficient technologies can actually result in a net gain in welfare, by reducing energy costs, which for a variety of reasons are often not appropriately considered at the consumer level (IEA 2007; Meier and Eide 2007). Note, however, that this kind of analysis can be complicated by differences in the quality of the services provided by different technologies.

Long-term integrated assessment models have generally not included detailed analysis of end-use energy-efficient technologies (e.g. Nakicenovic and Swart 2000). This study uses a sufficient level of end-use technological detail to be able to analyze the contribution of efficiency improvements over a century time frame. While the results are in the context of a global energy model, the analysis focuses on the U.S., where detailed representations of energy demands by the buildings, industry, and transportation sectors have been developed. The present study examines the impact of the deployment of advanced end-use technologies, relative to a reference scenario in which energy efficiency improvement generally takes place at projected or extrapolated historical rates. These scenarios are also compared to an illustrative scenario in which no improvements in end-use technologies take place from 2005 through the end of the upcoming century.

3.2.2. End-Use Model Components

Buildings

The U.S. buildings sector module, detailed in Rong et al. (2006), is shown schematically in Figure 3.4. It consists of two sectors, residential and commercial, each of which is modeled as an aggregate representative building. This means that, for example, the aggregate residential building represents multi-family buildings, single-family homes, and mobile homes. There are no regional breakouts; each sector represents the entire U.S.

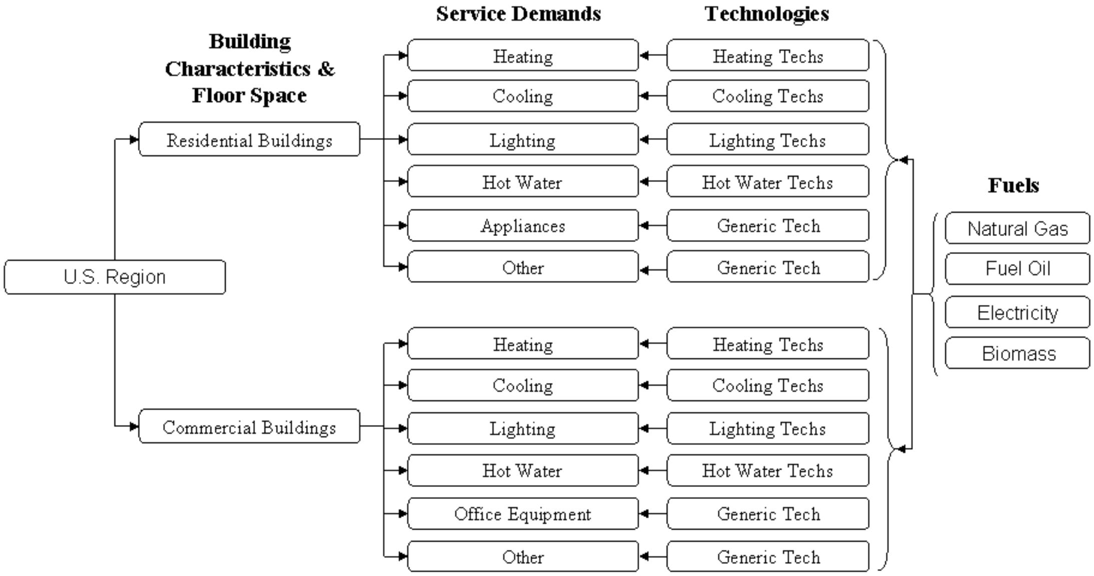

Figure 3.4. Conceptual structure of the U.S. buildings module. Two sectors, residential and commercial, demand a range of services, which are supplied by competing technologies. Technologies consume either natural gas, fuel oil, electricity, or biomass.

Associated with each sector are a range of service demands, shown in Figure 3.4. Each service is provided by competing technologies, each of which consumes energy in the form of electricity, natural gas, fuel oil, or biomass. The amount of energy required for a technology to meet a given level of service demand depends on the efficiency of the technology. This separation between services and technologies is important, as it allows the effects of changes in technology to be isolated from changes in service demand.

As shown in Figure 3.4, the residential and commercial building sectors tend to demand similar types of services; for instance, each sector demands space heating, space cooling, lighting, and water heating services. In the residential sector, “appliances” consist of refrigerators, freezers, clothes washers, clothes dryers, and dishwashers. The residential “other” category consists of many disparate services, listed in Table A.6; the largest energy users are televisions and set-top boxes, cooking equipment, and home office equipment. The commercial “other” demands, listed in Table A.11, consist mostly of ventilation, cooking, refrigeration, distribution transformers, and water treatment and pumping. In the commercial sector, office equipment is a large and fast-growing energy consumer, and as such is considered as a separate service demand.

Future levels of service demand are based on floorspace. Income and population only affect service demands through the demand for floorspace. However, the future evolution of U.S. floorspace demands is quite uncertain, as it will depend on a range of unforeseeable socioeconomic, political, cultural, and demographic factors. A simple formulation is used in this study, based on future population, income, and floorspace price. The market price and demand for floorspace are assumed to be based on the market equilibrium of the following supply and demand relationships:

$$\begin{aligned} &Supply = \alpha_S \ P_S^{\beta_S} \\ &Demand = \alpha_D \ Pop \ i^{\lambda} \left(P_S + P_O + P_E\right)^{\beta_D} \end{aligned} \tag{2}$$

where β_S is the price elasticity of floorspace supply, β_D is the price elasticity of floorspace demand, and λ is the income elasticity of floorspace demand. *Pop* is the population, i is the income per capita, and α’s are the calibration coefficients. P_S and P_O represent the capital and other non-energy operating costs, and P_E represents the energy costs, determined endogenously in the model. Given P_O and P_E, the model solves for P_S such that supply is equal to demand in each time period.

Per unit of floorspace, all service demands except for heating and cooling are assumed to grow according to the following equation:

$$d_i = \phi_i \ \sigma_i \ P_i^{-\beta} \tag{3}$$

where d_i is the demand for the service per unit of floorspace, ϕ_i is a “saturation” parameter that captures the market penetration of the service over time, and σ is a calibration coefficient. P_i is the weighted average price of delivering the service from all technologies providing the service, and β is the price elasticity of the service demand.

The saturation parameter allows accelerated future growth of certain service demands whose growth is expected to outpace that of floorspace, such the “other” demands, as this category includes future services that do not currently exist. The price term stands for the price of the service, which consists of the sum of the levelized capital costs, operating costs, and energy costs, represented in dollars per unit of service output.

The formulations for heating and cooling demands are more complex, because they account for the interactions of internal gains, building shells, and climate. Heating and cooling demands per unit of floorspace in both the residential and commercial sectors are based on the following formulations:

$$d_H = \sigma_H \, u \, a \, HDD \, P_H^{-\beta_H} - G \tag{4}$$

$$d_C = \phi_C \left(\sigma_C \, u \, a \, CDD \, P_C^{-\beta_C} + G \right) \tag{5}$$

where *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 (allowing for scenarios with climate change-induced warming, for example), and *G* represents the internal gains from equipment servicing all other demands within the building shell. Internal gains tend to decrease heating demands and increase cooling demands, and are calculated by multiplying the energy consumption for a given service demand by the fraction of energy consumption assumed to be dissipated as heat within the building. The internal gain energy is only subtracted from heating demands or added to cooling demands during the fraction of the year during which these services are used. For the entire U.S., this was estimated to be 5.5 months for heating and 4 months for cooling, based on analysis of heating and cooling degree day trends.

Industry

The U.S. industrial sector spans a large and heterogeneous range of individual industries, producing materials such as chemicals and metals, and finished goods such as automobiles. The U.S. industrial module, detailed in Wise et al. (2006), disaggregates the sector into 12 industry groups (nine manufacturing and three non-manufacturing). The designation of the 12 industry groups was informed by patterns of service demands and fuel consumption in the Manufacturing Energy Consumption Survey (MECS; EIA 1999).

Figure 3.5 shows the nine O^{bj}ECTS U.S. manufacturing industry groups and energy end-uses, with energy consumption data for 1998. Although it is relatively small in terms of energy use, the cement industry is considered separately because of its non-combustion emissions of CO_2. Similarly, the other non-metallic minerals category includes the production of lime and other processes that produce non-combustion carbon emissions. Aluminum smelting is treated separately from other metals due to the large amount of electro-chemical services demanded in this industry.

As shown in Figure 3.5, most of the energy demanded can be assigned to a relatively small set of general services, such as boilers (steam), process heat (dry heat), machine drive, and feedstocks. The categorization of the general industrial end-use services, shown in Figure 3.5, is based on MECS (EIA 1999). There is heterogeneity across industries in the fuel mixes used to provide some of the services. For example, boilers in the pulp, paper, and wood industries tend to be fueled mostly by waste biomass, a readily available by-product of the manufacturing processes. Similarly, the petroleum refining industry uses a greater share of oil-based boiler fuels than any other industry group. Because of such differences in fuel mixtures between industry groups, boilers and machine drive services are considered on an industry-by-industry basis. All other service types are assumed to use a consistent fuel blend across industries; for example, process heat is generally supplied by natural gas, as a clean-burning fuel is required for this purpose.

The non-manufacturing industry groups consist of agriculture, mining, and construction. Energy use in these non-manufacturing industries is not disaggregated into services, with the exception of construction consumption of fossil fuels for feedstocks, mostly for paving. This category is treated separately because a certain portion of the fuel consumed can be assumed to not be emitted to the atmosphere.

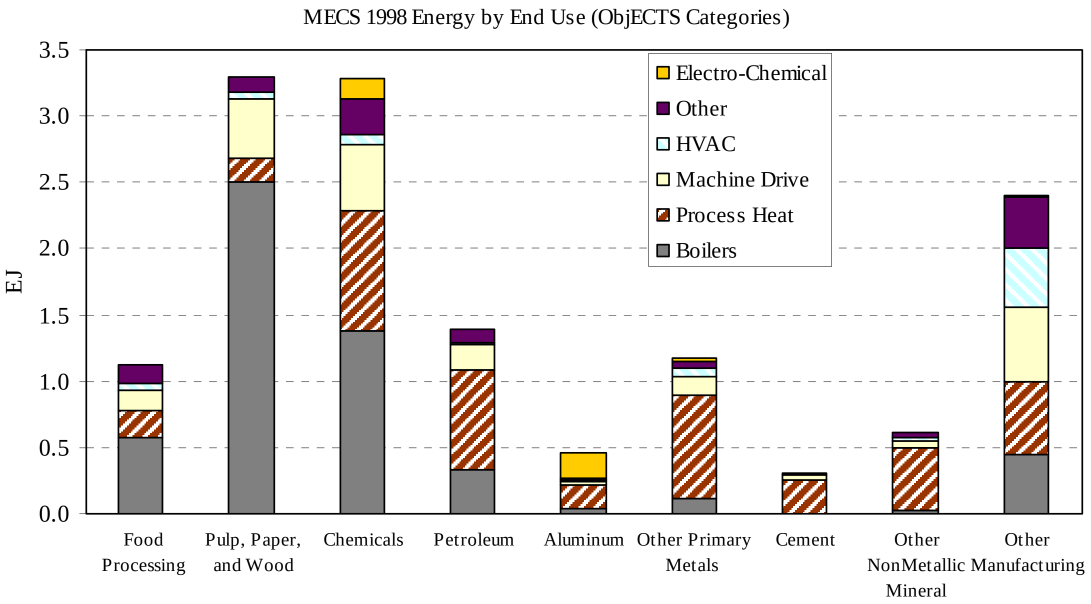

Figure 3.5. U.S. annual energy consumption in 1998, by industry group and energy service. Source: EIA 1999.

Future demand growth in each of the industry groups is modeled econometrically, based on historical relationships between income and population growth, and demand for the products of these industries. Each industry group is assigned to one of two formulations, GDP-based or per-capita-based, shown in the following equations:

(7)
$$\eta_{GDP} = \frac{\ln(E)}{\ln(Y)}$$
$$\eta_{percapita} = \frac{\ln(E_{percapita})}{\ln(Y_{percapita})}$$

where η is the elasticity of energy with respect to income, E is the energy demand of a given industry, and Y is the real GDP. Demand from the food processing and from the pulp, paper, and wood industry groups is assumed to be per-capita-based; demand for output from all other industry groups is assumed income-based.

Within each industry, the production process is modeled as the set of end-use services required to produce each unit of output. For example, to produce one unit of output from the chemicals industry requires 0.52 units of feedstocks, 0.16 units of steam, 0.14 units of process heat, and 0.18 units of all other service categories. The input-output coefficients required by these production processes are determined by MECS data; each column in Figure 3.5 shows roughly the blend of services required by that industry.[1] Future process improvements are modeled by decreasing the coefficients of specific end-uses.

Multiple technology options compete to provide each service based on relative economics, using a logit choice mechanism, as with all technology and fuel competition in MiniCAM. This allows examination of the impact of fuel price changes on technology choice. As an illustrative schematic, Figure 3.6 shows the technologies competing to provide steam in the chemicals industry. Coal, oil, natural gas, and biomass can all be used as fuel for steam-only boilers, and biomass, coal and gas can be used in cogeneration systems (combined heat and power, or CHP). The relative economics of each option is determined by non-energy costs (levelized capital plus operating costs), fuel costs, and in the case of CHP, the value of the electricity produced. This electricity can be used on-site or sold to the grid. While more capital-intensive, CHP requires approximately 40% less primary energy, and generates 15% less carbon emissions, than separate heat and power systems (Kaarsberg and Roop 1998).

Transportation

The transportation sector is a large and growing source of greenhouse gas emissions, responsible for a third of total CO_2 emissions in the U.S. (EIA 2006). The sector consists of four services: passenger, freight, and pipeline transportation, and military fuel use. A full description of the structure and capabilities of the U.S. transportation module are given in Kim et al. (2006). The schematic in Figure 3.7 shows the two transportation services that are modeled explicitly, down to the technology level: passenger transport

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[1] The figure shows fuel consumption by each service category; actual service supplied is equal to fuel consumption times efficiency. Efficiencies are shown in Table A.20; averaged across all technologies, boiler efficiency is approximately 80%, machine drive is 90%, and all other service efficiencies are indexed to the base years (and therefore equal to 100%).

and freight transport. Future demand for passenger transportation is assumed to be dependent on both population and income (GDP), whereas demand for freight services depends only on income.

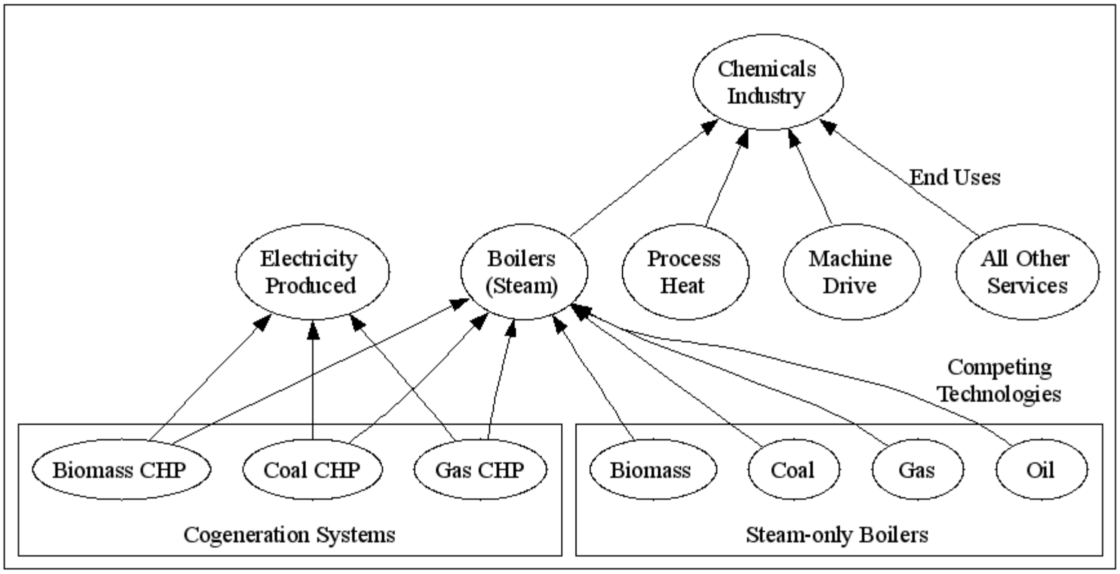

Figure 3.6. Simplified schematic of structure of end uses and technologies in the U.S. chemicals industry. As shown, cogeneration technologies compete directly with steam-only boiler technologies for supplying steam.

Passenger and freight services are each provided by a number of modes that compete for share based on relative costs, using a logit choice mechanism. The per-mile costs of transportation services are calculated as the sum of the fuel cost, the non-fuel cost (levelized capital plus operating costs), and in passenger transportation, the time value of transportation, determined by the average vehicle speed and the wage rate (Edwards 1992). Average vehicle speed is an exogenous input assigned to each mode, and the wage rate is calculated as the per-capita GDP divided by the number of working hours in a year. The time value therefore puts a cost premium on faster modes of transportation. The fuel and non-fuel costs of each mode are determined by the fuel and non-fuel costs of the technologies within each mode, weighted by the shares of each technology. Technologies (e.g. hybrid electric and internal combustion engine vehicles within the passenger auto mode) also compete based on relative service costs, calculated as the sum of per-mile fuel costs and non-fuel costs.

The formulation of the cost of passenger transportation is shown below:

$$(8) \qquad P_{i,L} = (P_{f,L} / Eff_{i,L} + P_{nf,i,L}) / LF_{i,L} + W_L / T_m$$

where, $P_{i,L}$ is cost of passenger transport service, $P_{f,L}$ is fuel cost, $Eff_{i,L}$ is vehicle fuel efficiency, $P_{nf,i,L}$ is vehicle non-fuel cost, $LF_{i,L}$ is load factor, W_L is wage rate, and T_m is average vehicle transit speed. Vehicle non-fuel cost, $P_{nf,i,L}$, includes all costs of owning, operating, and maintaining the vehicle excluding fuel costs.

The fuel cost and wage rates are determined endogenously by the model; all other variables in Equation 8 are exogenous inputs. Vehicle fuel efficiency is the inverse of vehicle fuel intensity and is expressed in terms of vehicle miles per unit of fuel. The load factor refers to the average number of persons per vehicle, and for freight transportation, it refers to the average number of tons per vehicle. The load factor allows calculation from vehicle fuel intensity to the service fuel intensity of transportation, or fuel used per amount of passenger/freight service provided.

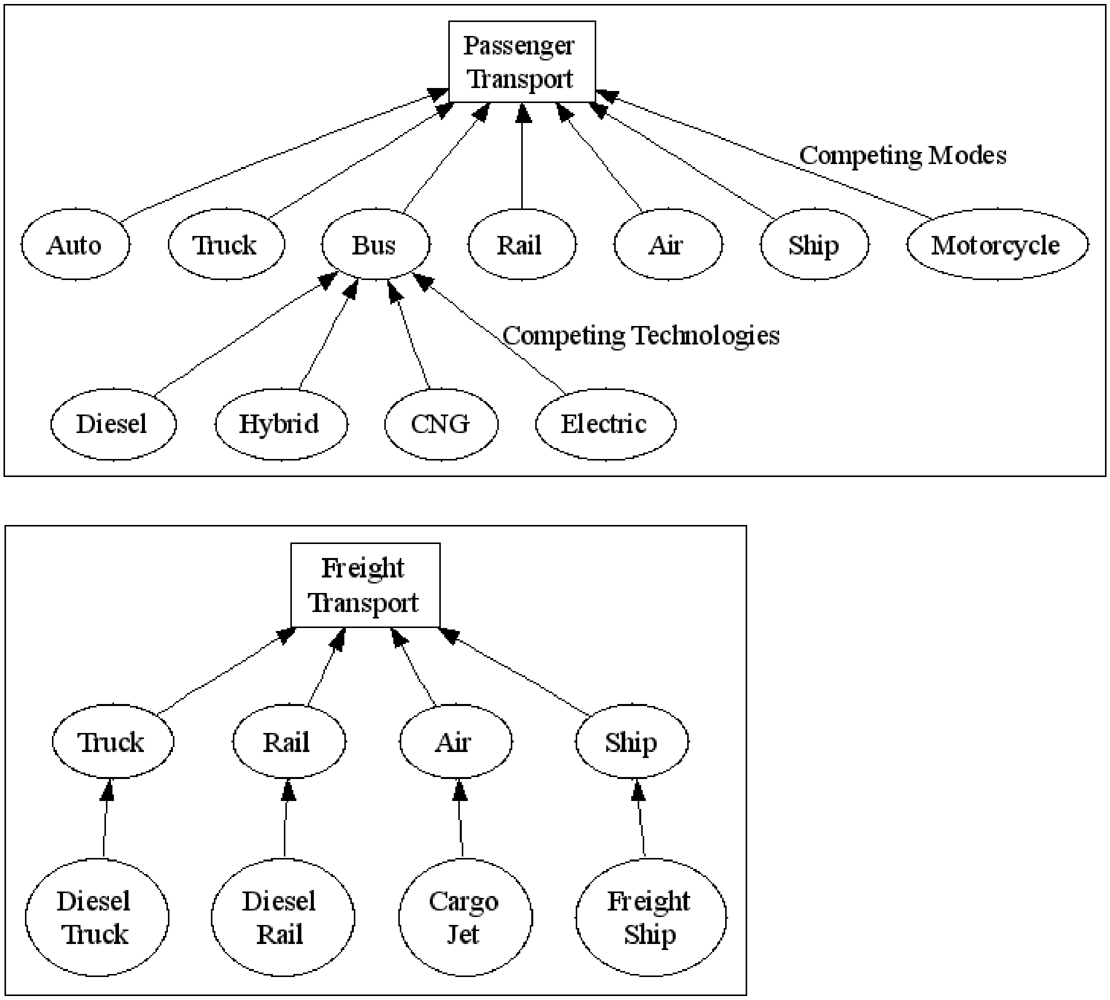

Figure 3.7. Structure of U.S. passenger and freight service demands. Services are supplied by competing modes, which may also be supplied by competing technologies.

3.2.3. Scenario Descriptions

Scenarios are based on many wide-ranging assumptions, related to future demographics, labor force productivity, technological development, technology availability, and environmental policies. While this study focuses on the impacts of varying assumptions related to end-use technologies and environmental policy, these assumptions are made within a larger framework of variables held constant.

Background Assumptions

For all regions other than the U.S., demographic and labor productivity assumptions are identical to those in the MiniCAM scenarios described in Clarke et al. (2007b). The U.S. estimates for total population have been updated to the most recent Census projection (U.S. Census Bureau 2000), adjusted to be consistent with the most recent mid-term projections (U.S. Census Bureau 2004). Labor productivity growth in the U.S. from 2005-2020 has also been revised to reflect more recent data. Following this time period, the labor productivity growth rate is assumed to be 1.5% per year, which combined with declining population growth rates results in a long-term slowdown in the GDP growth rate. Increasing energy prices also lower GDP through a long-term energy-price feedback, though this effect is small as energy costs only constitute a small fraction of total service costs.

All assumptions pertaining to energy resources and energy supply technologies are identical to Clarke et al. (2007b), with the exception that this study does not include the option of hydrogen technologies. For non-U.S. regions, future service demands are modeled as three aggregate sectors within each region: buildings, industry, and transportation. Cement production in each region is considered separately due to the potential for the use of CCS for reducing CO_2 emissions. Each of these sectors is assigned price and income elasticities, which generally remain constant over time. Demands are met by a number of competing technologies (fuels). Energy efficiency across all technologies is assumed to improve at approximately 1% per year for all regions.

In the U.S., however, the buildings, industrial, and transportation sectors are dis-aggregated into service demands and specific technologies. Assumptions about end-use technological efficiency, future technological improvement, income elasticities, and price elasticities in these scenarios differ from Clarke et al. (2007a; 2007b). Therefore, results from these detailed end-use scenarios should not be assumed to be consistent with the aggregate version presented in Clarke et al. (2007a; 2007b).

U.S. Buildings Technology Assumptions

The elasticities that influence the future floorspace trajectories are equal between the reference and advanced technology scenarios, and are shown in Table A.1. Assumptions about saturation of services, fractions of energy consumption released into the building envelope as internal gain energy, and the service demand price elasticities are shown in Table A.2. Heating, water heating, and lighting services in both sectors are assumed nearly saturated in the base years. The “others,” which represent services that do not currently exist, reach 100% saturation in 2050. Office equipment also does not reach 100% saturation until 2050, reflecting a continuation of the economic trend towards information services, as well as declining costs of computing technologies allowing greater deployment throughout the commercial sector.

The buildings sector is not assumed to have energy-free technologies such as solar water heaters or day-lighting, so technology-driven emissions reductions are most likely to come from switching to fuels with low carbon intensity, and improvements in energy requirements of end-use technologies. Most buildings technologies have improved in energy use requirements in the past few decades, detailed in National Energy Modeling System (NEMS) stock models. However, increases in demands for certain services, such as office equipment, have increased substantially over the same time. Continuation of both of these trends seems likely in the future.

All technologies and future efficiencies in the reference and advanced scenarios are shown in Table 3.1. Formulations, methodological assumptions, and data sources of all assumed efficiencies, non-energy costs, and building stock shell efficiencies are found in the Appendix (Section A.1). In the reference technology scenario, the stock average energy efficiencies of most technologies are assumed to improve at projected annual rates through 2035 (EIA 2007). Thereafter, rates of improvement are assumed to decline, and already in some cases, efficiency gains are limited due to physical or thermodynamic limits.

Table 3.1. Technology efficiency assumptions in the U.S. buildings module. Values for shell efficiency, appliances, office equipment, and others are indexed to 2005. Values for heating, cooling, and water heating are unitless, representing energy out (service) divided by energy in (fuel consumption). Lighting values are in lumens per watt.

	Historical		**Reference**		**Advanced**	
	1990	**2005**	**2050**	**2095**	**2050**	**2095**
Residential Technologies						
Shell efficiency	0.92	1.00	1.34	1.70	1.50	2.45
Heating						
Gas furnace	0.70	0.82	0.88	0.91	0.88	0.91
Gas heat pump	na	na	na	na	1.94	2.37
Electric furnace	0.98	0.98	0.99	0.99	0.99	0.99
Electric heatpump	1.61	2.14	2.49	2.58	2.81	3.00
Fuel oil furnace	0.76	0.82	0.85	0.87	0.85	0.87
Wood furnace	0.52	0.58	0.66	0.68	0.66	0.68
Cooling						
AC	2.16	2.81	3.76	3.90	4.18	4.47
Water Heating						
Gas water heater	0.52	0.56	0.80	0.91	0.80	0.91
Gas heatpump water heater	na	na	na	na	1.73	1.96
Electric resistance water heater	0.84	0.88	0.95	0.96	0.95	0.96
Electric heatpump water heater	1.95	2.20	2.69	2.80	2.92	3.13
Fuel oil water heater	0.51	0.55	0.56	0.58	0.56	0.58

Lighting						
Incandescent lighting	14	14	16	17	16	17
Fluorescent lighting	60	60	79	85	79	85
Solid-state lighting	na	100	122	127	152	186
Appliances and others						
Gas appliances	0.96	1.00	1.66	1.72	1.66	1.72
Electric appliances	0.67	1.00	1.41	1.47	1.59	1.80
Gas other	0.99	1.00	1.12	1.25	1.12	1.25
Electric other	1.00	1.00	1.02	1.05	1.40	1.46
Fuel oil other	0.99	1.00	1.05	1.09	1.05	1.09
Commercial Technologies						
Shell efficiency	0.97	1.00	1.18	1.22	1.34	1.43
Heating						
Gas furnace	0.69	0.76	0.85	0.89	0.85	0.89
Gas heat pump	na	na	na	na	1.94	2.37
Electric furnace	0.98	0.98	0.99	0.99	0.99	0.99
Electric heatpump	2.67	3.10	3.69	3.83	3.95	4.10
Fuel oil furnace	0.73	0.77	0.81	0.84	0.81	0.84
Cooling						
AC	2.44	2.80	3.72	3.87	4.29	4.87
Water Heating						
Gas water heater	0.72	0.82	0.93	0.93	0.93	0.93
Gas heatpump water heater	na	na	na	na	1.73	1.96
Electric resistance water heater	0.96	0.97	0.98	0.98	0.98	0.98
Electric heatpump water heater	na	na	na	na	2.69	2.80
Fuel oil water heater	0.74	0.76	0.80	0.82	0.80	0.82
Lighting						
Incandescent lighting	14	14	16	17	16	17
Fluorescent lighting	76	76	101	108	101	108
Solid-state lighting	na	100	122	127	152	186
Office and Other						
Office equipment	1.00	1.00	1.12	1.15	1.56	1.61
Gas other	1.00	1.00	1.12	1.15	1.33	1.51
Electric other	1.00	1.00	1.12	1.15	1.33	1.51
Fuel oil other	1.00	1.00	1.12	1.15	1.12	1.15

Future capital and operating costs of most building technologies are assumed to decrease at the rate of efficiency increase. Exceptions include new technologies, which have faster rates of cost decrease in the future, and the other energy services, for which costs are assumed to remain constant. Building shell efficiency improves at modest rates in both the residential and commercial sectors, and with the exception of the commercialization of solid-state lighting, no new technological breakthroughs are assumed to take place.

The advanced technology scenario differs from the reference in several key areas, starting in the first future time period (2005-2020). Building stock shell efficiency is assumed to improve at an accelerated rate due to new construction being substantially more energy efficient. In 2050 and 2095, average new residential building shells are assumed to improve over new construction in 2005 by factors of 2.0 and 3.4, respectively, as compared with factors of 1.4 and 1.8 in the reference scenario. These factors correspond to least-cost energy-saving optima calculated using the BEopt program (Christensen et al. 2005), and have the effect of increasing the stock average residential shell efficiencies in the advanced scenario in 2095 by 59% relative to the reference.

Several specific technologies are also assumed to improve in energy use requirements and/or affordability in the advanced technology scenario. Commercial office equipment becomes 50% more energy-efficient by 2035 (as in NCI 2004a), and the residential other equipment matches appliances in annual efficiency improvement rates. As well, the following heat pump technologies are commercialized, entering the market in 2020: gas heat pumps, electric heat pump water heaters, and gas heat pump water heaters. Advances in solid-state lighting reduce costs over time, and allowing the technology to compete with incandescent and fluorescent lighting technologies.

U.S. Industry Technology Assumptions

Demand elasticities of each industry are assumed constant for all time periods and are shown in Table A.18. Technological sources of industrial emissions reductions could potentially develop in several areas. However, the specific technologies that provide the general industrial services are already highly efficient. For example, current efficiencies to produce steam or heat from burning natural gas exceed 80% (Council of Industrial Boiler Owners 2003), and average electric motor efficiencies exceed 90% (EIA 2005). As a result, the potential role of increased energy efficiency in final end-use technologies is quite limited as a means of making reductions in industrial energy use or CO_2 emissions.

Because of the high energy efficiencies of the service technologies, future reductions in industrial energy intensity are more likely to come from redesigns and fundamental changes in the processes used to manufacture industrial products. Potential process improvements are more industry-specific than the general industrial services, and difficult to foresee. Still, a number of cross-industry energy-saving process technologies are presently available, but not currently widespread. Assuming feasible rates of market penetration, Worrell et al. (2004) show that five available improvements, such as using membranes for materials separation, have the potential to reduce projected U.S. industrial energy consumption by 8% in 2025.

In the present study, the difference between the reference and advanced technology scenarios is found in the rates of deployment of process improvements that reduce service requirements per unit of output. In the reference technology scenario, the service (and therefore energy) requirements for each unit of industrial output, across all industry groups, are assumed to decrease by 9% between 2005 and 2095. In the advanced scenario, this decrease in service requirements is 31% over the same time period.

U.S. Transportation Technology Assumptions

In contrast to end-use equipment in the industrial sector, which is already highly efficient, road vehicles in the passenger and freight sectors are generally thought to be inefficient relative to technological possibilities (e.g. DeCicco et al. 2001; NRC 2002; Elliott et al. 2006). These low efficiencies in part reflect consumer preferences for qualitative services in excess of service miles (e.g. comfort, safety, performance). Still, efficiency may be improved in the future by reducing vehicle weight, rolling resistance, aerodynamic drag, or fuel consumption while idling, for example (NRC 2002).

In this study, the reference case assumes that future efficiencies of transportation technologies improve through 2020 at rates projected in the Annual Energy Outlook (EIA 2007). Thereafter, the EIA (2007) projected rate of improvement between 2020 and 2030 is assumed to continue through 2095. See Appendix for all input parameters and data sources in the transportation module. Table 3.2 shows vehicle fuel economy (in miles per gallon) of selected road transportation technologies. Little energy efficiency improvement is assumed in bus, rail, or ship technologies, as in the Annual Energy Outlook (EIA 2007). Hybrid electric vehicles (HEVs) are included in the reference scenario, though non-fuel costs are approximately 20% higher than non-fuel costs of internal combustion engine (ICE) vehicles, as in Lipman and Delucchi (2006).

Table 3.2. Historical, reference, and advanced assumptions for average fleet vehicle miles per gallon of selected transportation technologies. LDV = light duty vehicle.

	Historical		**Reference**		**Advanced**	
	1990	**2005**	**2050**	**2095**	**2050**	**2095**
Passenger LDV						
ICE Automobile	20.3	22.8	27.1	30.8	38.7	50.7
HEV Automobile	na	29.5	35.1	39.9	58.3	76.4
ICE Light Truck	16.1	18.1	24.4	30.4	30.8	40.3
HEV Light Truck	na	23.0	30.9	38.5	39.0	51.1
Freight Trucking						
Diesel Truck	6.1	5.9	7.0	7.8	9.9	12.4

In the advanced technology scenarios, the rates of improvement of several key technologies are enhanced, particularly in the passenger light duty vehicle stock, the freight trucking fleet, and aviation. For example, freight truck fuel economy reaches 12 mpg in 2095, and the passenger HEV automobile average reaches 75 mpg (Table 3.2). No large-scale infrastructural changes are assumed in the advanced scenarios, but several rail technologies that are currently deployed in other countries are introduced: high speed rail and electric freight rail. Their deployment is limited by a low share weight parameter, reflecting development of systems only in specific areas.

The present study does not model the entry of technologies that could potentially revolutionize the transportation energy infrastructure, such as plug-in hybrid electric vehicles or fuel cell vehicles. These technologies are not addressed because the aim of this study is to investigate the value of end-use energy efficiency. Electrification of transportation or a shift to a hydrogen-fueled automobile fleet would require energy supply infrastructural changes that are beyond the scope of this study.

3.2.4. Scenario Results: No Emissions Constraint

In all scenarios presented in this study, population in the U.S. is projected to grow to 574 million persons in 2095, and economic growth during the upcoming century results in per-capita GDP of $123,000 (2005 USD). Both of these factors put substantial upward pressure on service demands, leading to increases in final energy consumption in both reference and advanced scenarios, despite technological improvement. The links between service demands, technological change, technology choice, and ultimately fuel consumption and emissions constitute the focus of this section. Service demands and technology switching in each end-use sector are inter-related with changes in future U.S. fuel prices. Figure 3.8 shows the reference scenario prices of the five major end-use fuels in the industrial sector (biomass, coal, natural gas, refined fuels, and electricity). While the buildings and transportation sectors pay different prices for each fuel, the prices across all sectors generally follow similar trends over time. Coal and electricity remain stable or decrease in price, whereas the other three increase, especially refined liquid fuels.

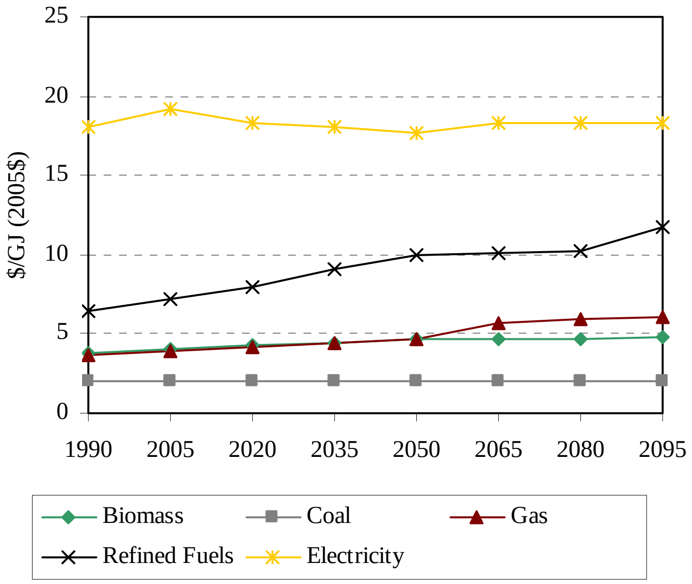

Figure 3.8. Energy prices paid by the industrial sector in the reference technology scenario.

The U.S. Buildings Sector

In all three end-use technology scenarios (reference, advanced, and no technological improvement after 2005), floorspace grows by about 150% total and 30% per-capita from 2005 to 2095, and service demands generally scale commensurately. Fuel consumption by the residential sector in the reference and advanced technology scenarios is shown in Figure 3.9. The advanced scenario shows a general flattening of fuel consumption, as technological advancement roughly counter-balances increasing building service demands. In contrast, energy consumption in the scenario with no technological advancement increases by 28% relative to the reference technology scenario in 2095, and by 150% relative to 2005 energy consumption. In all three technology scenarios, demands are supplied increasingly by electricity, continuing a historical trend that has been evident for the past three decades (EIA 2006).

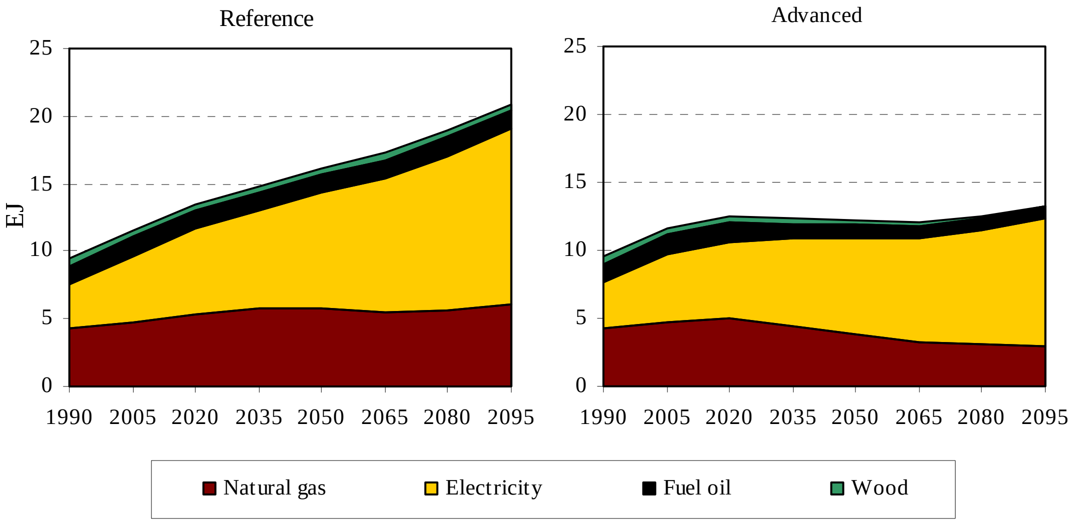

Figure 3.9. Fuel consumption by U.S. residential buildings in the reference and advanced technology scenarios.

This trend towards electricity use is due to a number of interesting developments in the building sector. As shown in Figure 3.10, the fastest growing service demands are the “other” services and commercial office equipment; these are supplied almost entirely by electricity. Furthermore, these services contribute to internal gain energy, reducing heating demands, which are supplied mostly by natural gas (Table 3.3). Space heating demands are further reduced by assumed improvements in building shell efficiency, which aside from directly reducing heating demands (Equation 4), have the effect of enhancing the retention of internal gain energy. Internal gain energy increases cooling demands (Equation 5), an effect which can be seen in Figure 3.10: cooling service demands grow more than heating. A final driver of electrification is that the share of electricity in supplying heating and water heating services increases as natural gas prices increase (Figure 3.8), and as heat pump technologies become more efficient and cost-effective, particularly in the advanced scenario (Table 3.1; Appendix**).**

Heating demands differ between the advanced and reference scenarios (Figure 3.10) due to the assumed building shell efficiency improvements. This reduction in service demand in the advanced scenario is not seen for cooling services, however, because of the internal gain effects discussed above. Lighting service demands increase in the advanced scenario relative to the reference, due to improvements in solid-state lighting costs and performance (Table 3.1; Appendix). Many of the service demands, including lighting, water heating, and residential appliances, increase substantially from 2005 to 2095 in both the reference and advanced scenarios, due to assumed improvements in the technologies.

Table 3.3. Percentage of services provided by natural gas and electricity in 2005 and in 2095, for reference and advanced technology scenarios. Services that are only fueled by electricity (cooling, lighting, and commercial office equipment) are not shown.

	2005		**2095 Reference**		**2095 Advanced**	
	Gas	Electricity	Gas	Electricity	Gas	Electricity
Residential						
Heating	64%	8%	56%	22%	47%	30%
Water Heating	66%	24%	81%	18%	76%	22%
Appliances	7%	93%	5%	95%	6%	94%
Other	11%	75%	7%	84%	9%	80%
Total	41%	42%	29%	62%	22%	71%
Commercial						
Heating	79%	11%	66%	32%	31%	20%
Water Heating	69%	24%	52%	44%	57%	39%
Other	33%	52%	32%	61%	34%	57%
Total	36%	55%	26%	70%	28%	67%

In these scenarios, service consumption increases in response to new, advanced technologies that decrease costs of service provision. While the amount of additional services demanded per unit of cost decrease is generally not certain (the “rebound” effect; see Greening et al. 2000), the direction of the effect is. This effect of low-cost advanced technologies increasing service demands is important to consider in assessing the potential for efficiency-driven reductions in energy consumption.

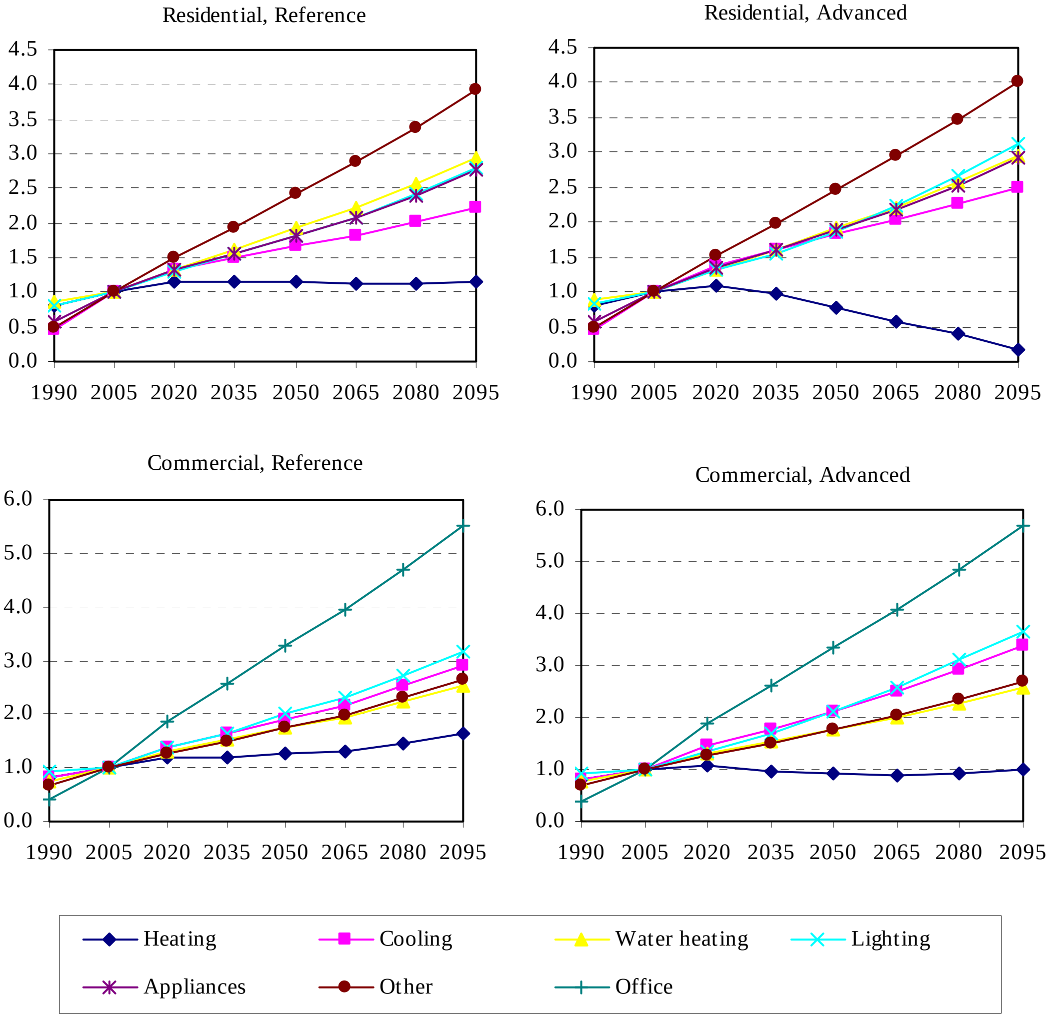

Figure 3.10. Building service demand in the residential and commercial sectors, in the reference and advanced technology scenarios. Values are unitless, indexed to 2005.

The U.S. Industrial Sector

Total industrial output during the upcoming century is shown in Figure 3.11; the industry groups with the most future growth are petroleum and chemicals, the groups with the highest income elasticities. Industry groups with population-based demand (pulp paper and wood, and food processing) also grow faster than the remaining industries. Industrial output in the advanced scenario exceeds that of the reference by 20% in every industry group, due to the reduced services required for each unit of output.

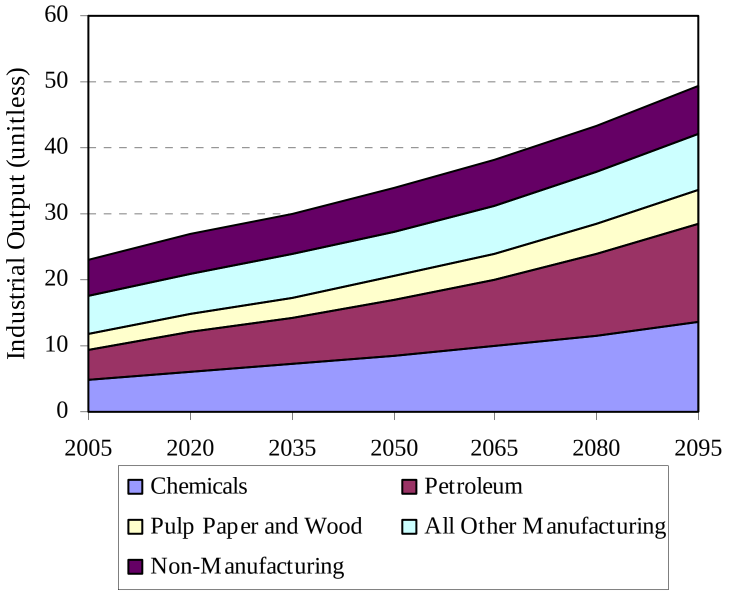

Figure 3.11. Industrial output in the reference technology scenario, 2005-2095.

Energy delivered to industry in the reference scenario is shown in Figure 3.12; the total in 2095 in the reference scenario is 18% less than the scenario with no future technological development, and advanced technology further reduces energy consumption by 15%. The composition of the fuel mixture consumed by the end-use sectors changes somewhat over time; in aggregate, industries shift from natural gas towards biomass and coal starting in 2050, in response to increasing gas prices (Figure 3.8). Prices of refined liquid fuels prices also increase, but as a feedstock these fuels often have few substitutes. The chemicals and petroleum industry groups combined consume 11.9 EJ of refined liquid fuels as feedstocks in 2095. As a result, the sector-wide share of refined liquid fuels among all industrial fuel sources remains stable over time. Electricity, which also has no substitutes for many end uses (e.g. electro-chemical), also retains a relatively constant share of total industrial delivered energy. Trends in future energy use and technology choice are similar between the three technology scenarios, as the future process improvement rates that define the differences between scenarios are applied equally to all industry groups, and to all services within each industry group.

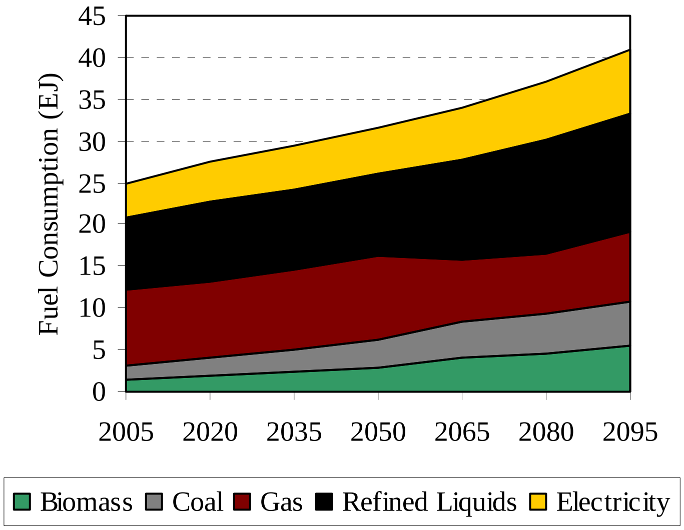

Figure 3.12. Fuel consumption by the U.S. industrial sector in the reference technology scenario.

Figure 3.13 shows the evolution of boiler technologies in the chemicals industry group, and in the pulp, paper, and wood industry group. In the chemicals group, more than half of the energy delivered to boilers was consumed by cogeneration (CHP) systems in 2005; by 2095, CHP only accounts for less than one third of boiler fuel consumption. In this year, total boiler fuel consumption exceeds the 2005 output by 93%, and coal is the most common boiler fuel, accounting for 64% of the fuel consumed. The pulp, paper, and wood industry group follows a different trajectory. Biomass was the dominant boiler fuel in 2005, with about a quarter of the biomass energy consumed by CHP systems. The high preference for biomass fuel by this industry group, combined with assumed enhancements in future efficiency from use of biomass gasification, results in biomass supplying greater than 80% of boiler fuel, with 70% of this as CHP. This result highlights the importance of addressing each industry group separately, as each has its own blend of service demands, preferences for technologies, expected future growth, and opportunities for emissions reductions.

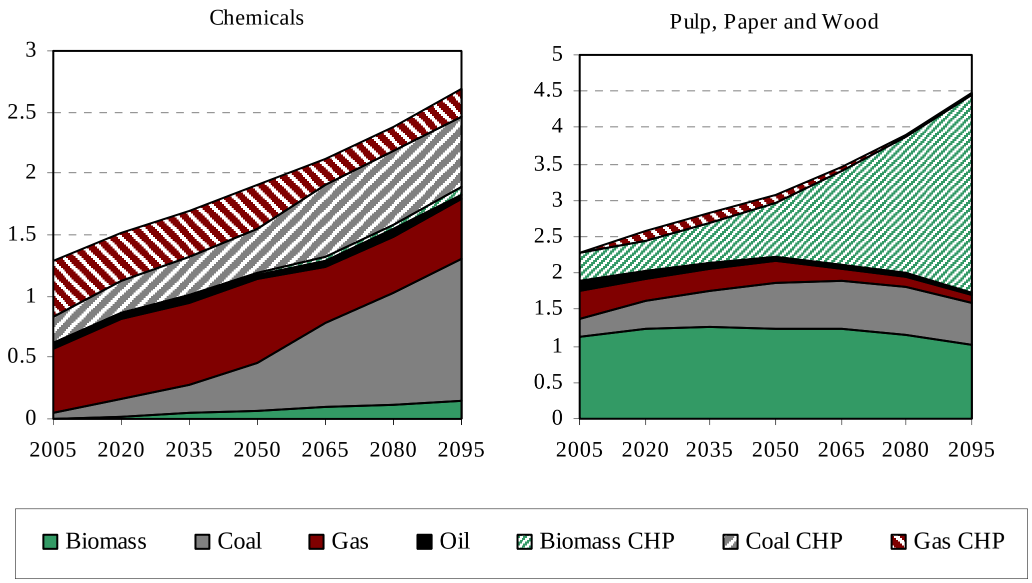

Figure 3.13. Fuel consumption by boilers in the chemicals and pulp, paper, and wood industry groups.

The U.S. Transportation Sector

Service provision by the different modes in the passenger and freight sectors in the reference technology scenario are shown in Figure 3.14. Total passenger miles increase by about 300% between 2005 and 2095, whereas freight ton miles increase by 120%. This difference is due in large part to income elasticity assumptions: passenger income elasticity is assumed equal to 1, whereas freight is 0.5, reflecting an assumed shift towards service-based income, and saturation of demand for heavy goods such as food grains and metals.

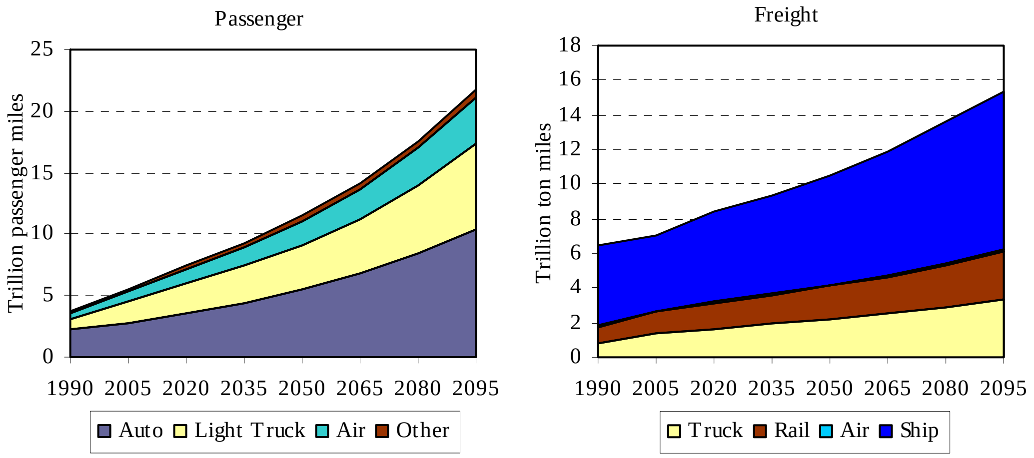

Figure 3.14. Passenger and freight service by transportation mode in the reference technology scenario.

In these scenarios, advanced technologies in transportation improve fuel efficiency, decreasing service costs. This decrease in service costs from enhanced fuel efficiency is generally thought to lead to increased service demand (the “rebound” effect; Greening et al. 2000), reducing the overall fuel-saving effect of enhanced efficiency. In this study, this “rebound” effect is small, as fuel costs account for a relatively small part of the transportation service costs. This is especially the case in the passenger sector, as the time value of transportation is added to the vehicle costs. In 2095, for example, operating an ICE automobile costs $0.53 in non-fuel costs, $0.06 in fuel costs, and $2.06 in time value (2005 USD). In the freight sector, advanced scenario efficiency improvements apply mostly to aviation and trucking, the two most expensive freight modes. The effect of advanced technology is to increase the output of these two modes by about 10% in 2050 and 2095, but overall freight shipments differ by less than 1% between the two scenarios.

In the advanced technology scenario, final energy consumption by the U.S. transportation sector is 34% lower in 2095 than in the reference technology scenario. The scenario with no technological improvement has 43% higher energy consumption than the reference scenario in 2095. Passenger and freight fuel consumption by mode for the reference and advanced technology scenarios is shown in Figure 3.15. The passenger light duty vehicle modes show the greatest divergence between the technology scenarios, consuming 43% less final energy in 2095 in the advanced technology scenario than the reference. However, transportation uses almost entirely refined liquid fuels, and as such, final energy only accounts for a portion of the emissions associated with supplying the transportation service.

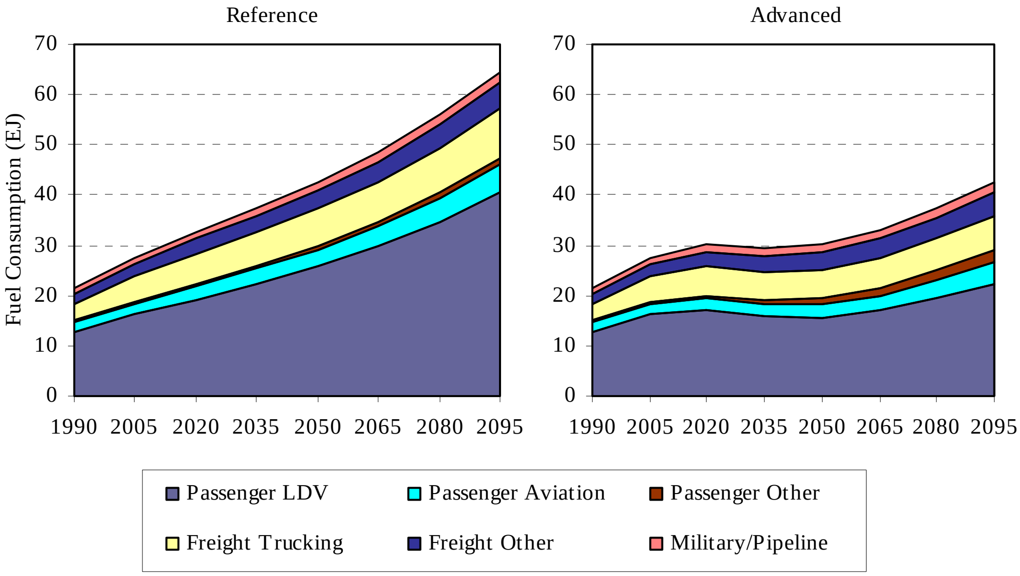

Figure 3.15. Passenger and freight final energy consumption by mode. LDV = light duty vehicle.

U.S. Carbon Emissions by End-Use Sector

U.S. carbon emissions in the reference technology scenario is shown in Figure 3.16, broken down into direct and indirect emissions from the buildings, industry, and transportation sectors. Indirect emissions consist of emissions from the production of secondary fuels consumed by the end-use sectors, electricity and refined liquid fuels in these scenarios.[2] The end-use technological improvements assumed in the reference scenario result in a 26% reduction in carbon emissions in 2095, compared to the scenario in which 2005 end-use technology does not improve in energy efficiency. Advanced technology accounts for a further 31% reduction in emissions from the reference technology scenario (Figure 3.16). Still, advanced end-use technology does not ultimately limit the growth of carbon emissions, as 2095 emissions exceed the 2005 levels by 39%.

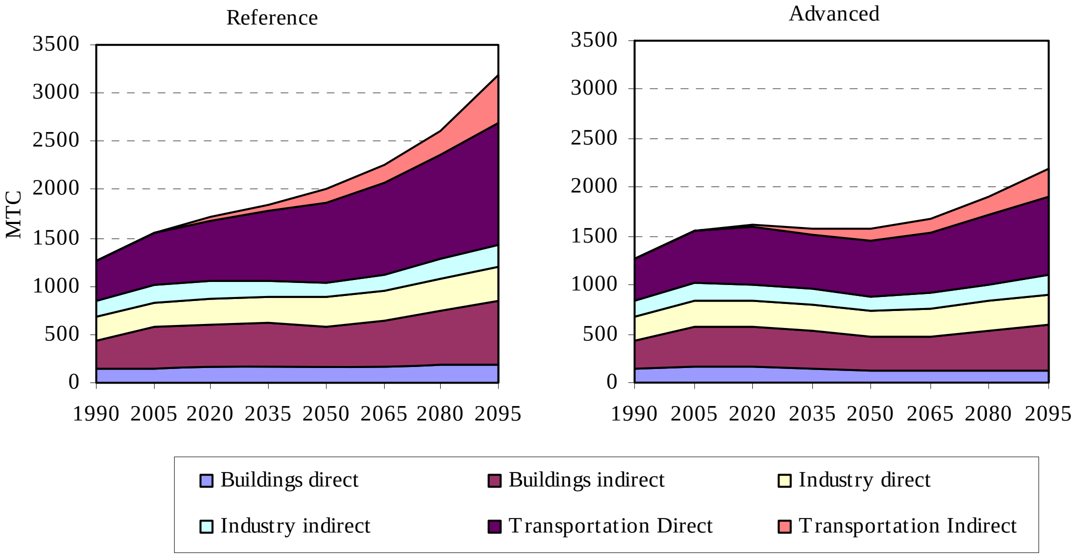

Figure 3.16. Indirect and direct emissions from buildings, industry, and transportation in the reference and advanced technology scenarios. Indirect emissions are from fuel refining and electricity generation; figures do not show emissions from electricity system own use and transmission and distribution losses (< 5% of total).

3.2.5. Scenario Results: 450 ppmv CO_2 Stabilization

For the following analysis, global carbon emissions are constrained such that atmospheric CO_2 concentrations are ultimately stabilized at 450 ppmv. The global emissions pathway,

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[2] Electricity emissions for each end-use sector are estimated using the average U.S. carbon intensity of electricity generation in each time period, multiplied by the amount of electricity delivered to the given sector. Liquid fuel refining emissions are calculated similarly, using the average carbon intensity of fuel refining. Biomass converted to refined liquid fuels is given an emissions credit at this stage, whereas non-crude oil feedstocks (shale oil, coal, and natural gas) entail emissions.

shown in Figure 3.1, is characterized by increasing emissions reductions over time, starting in the first future model time period, 2020. Emissions reductions are obtained by carbon taxes that increase over time, until the equilibrium level of emissions of the stabilization target is approached (shown for the reference technology scenario in Figure 3.2). The consequent fuel prices in the industrial sector are shown in Figure 3.17. Fuels are taxed in proportion to their carbon content, and coal and natural gas have fixed carbon intensities, so the tax directly increases their prices. In contrast, the tax induces responses in the technologies used to produce electricity and refined liquid fuels (see Figure 3.3); these technological responses lower the average carbon intensities of the fuels, and therefore mitigate the price increases of these fuels. Biomass is not taxed, but nevertheless increases in price over time due to increased demand. Overall, the price increases for electricity and biomass are much less than the increases for fossil fuels, leading to increased use of technologies that use these fuels.

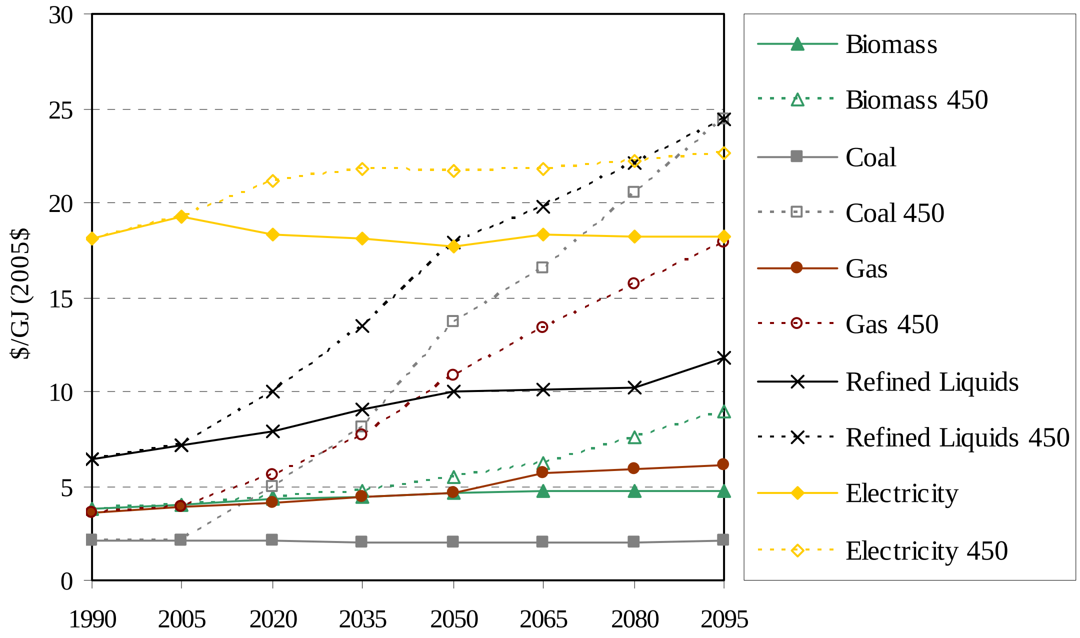

Figure 3.17. Fuel prices in the industrial sector in the reference technology scenario, with and without a 450 ppmv CO_2 stabilization policy.

The advanced technology scenario is characterized by lower emissions absent a CO_2 stabilization policy (see Figure 3.16), and as such, the taxes necessary to reach stabilization targets are lower than the taxes in reference technology. This is shown in Figure 3.18. Note that the emissions trajectory prescribed by the policy, outlined in Clarke et al. (2007a), does not differ between technology scenarios for the 450 ppmv stabilization policy. The responses of the technology scenarios to the climate policy do differ in service demands and technology choices; these responses are addressed individually for each sector.

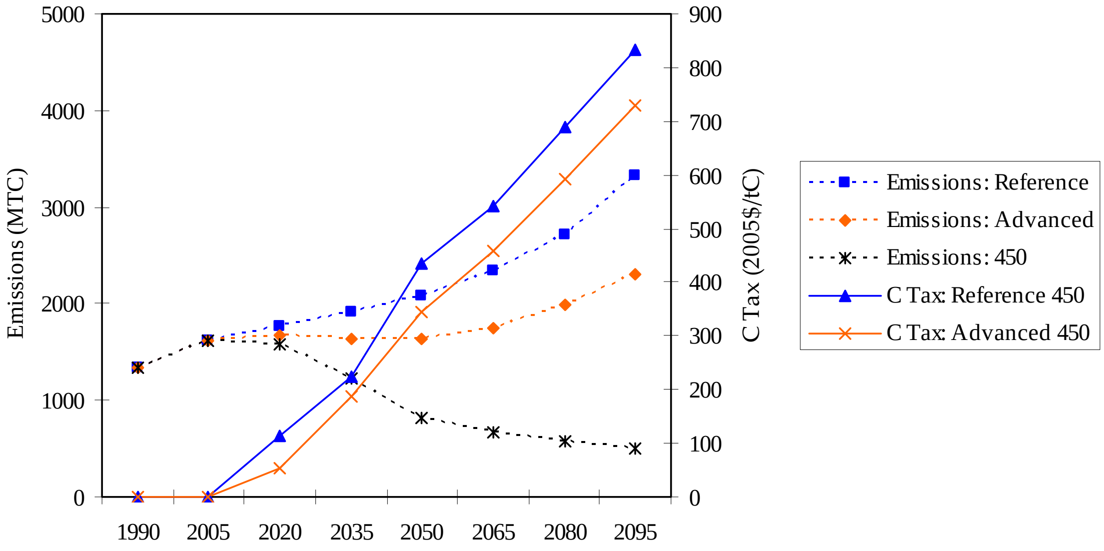

Figure 3.18. Carbon prices and emissions in the reference and advanced technology scenarios, with a 450 ppmv CO_2 stabilization policy. Also shown are the emissions in the reference and advanced technology scenarios without a climate policy.

U.S. Buildings

Even without the carbon policy, the share of electricity relative to other fuels increases substantially in the buildings sector, both in the reference and advanced technology scenarios (Figure 3.9; Table 3.3). The climate policy furthers this trend, as electricity prices increase less than natural gas (Figure 3.17). In reference technology, for instance, the climate policy induces the electricity share of building final energy consumption to increase from 58% to 68% in 2050. Figure 3.19 shows a representative response at the technology level for the residential heating service in the reference technology scenario: the policy induces a technology switch from gas furnaces to electric heat pumps. However, the response to the policy also entails a 13% reduction in total heating service demand in 2050, in both the reference and advanced scenarios. In contrast, cooling service demand only decreases by less than 3% in the reference and advanced technology scenarios in 2050. In fact, the policy-induced service demand decreases of all services that are fueled primarily by electricity—cooling, lighting, residential appliances, commercial office equipment, and electric others—are less than 5% in 2050, in both technology scenarios. This result is due to the policy-induced technology switching in the electricity generation sector, which mitigates the electricity price increases to consumers.

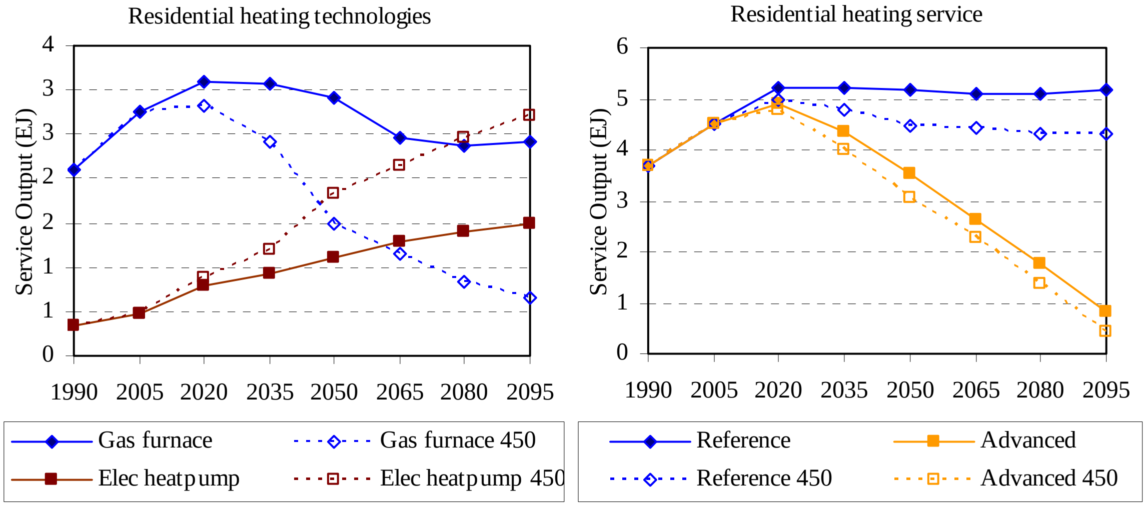

Figure 3.19. Residential sector responses to a 450 ppmv stabilization policy. Technology responses in heating services in reference technology scenario shown on left; total heating service demand responses for reference and advanced technology scenarios shown on right.

While the role of the electricity sector is critical in the buildings sector's response to emissions constraints, advanced end-use technology in the buildings sector is also important for minimizing electricity generation requirements. All of the electricity generation technologies shown in Figure 3.3 become more expensive with increasing electricity generation, because least-cost resources are used first. As electricity generation increases, so do marginal generation costs. Advanced end-use technologies can therefore reduce the marginal costs of electric generation, a point which will be re-visited in Section 3.3.

U.S. Industry

Because the reference and advanced assumptions do not differ at the technology level for these scenarios, climate policy effects on industrial technology switching and fuel choices are only examined for the reference technology scenario. Boiler fuel consumption by fuel type across all industry groups is shown in Figure 3.20. Climate policy induces a shift away from coal and gas, and towards biomass and electricity. The share of CHP (40%) is not affected by the policy, but nearly all CHP in the policy scenario is fueled by biomass (assumed to be emissions-free in this study). This is interesting, as CHP presently entails less carbon emissions than separate heat and power systems (Kaarsberg and Roop 1998). However, when the carbon intensity of the electricity sector is reduced, so are the emissions associated with purchased electricity, which has a negative effect on the relative emissions savings of fossil fuel-powered cogeneration.

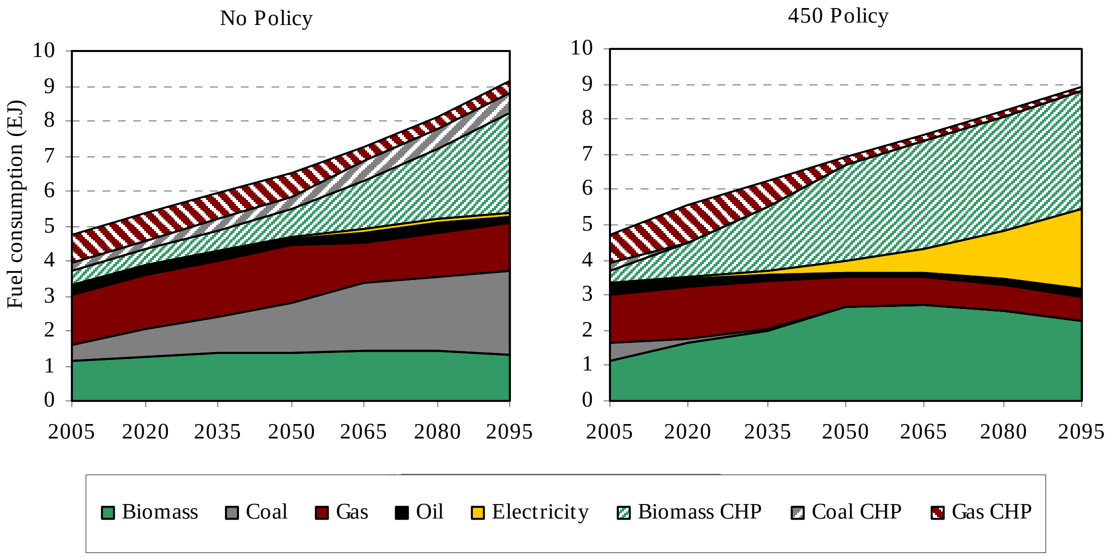

Figure 3.20. Fuel consumption by boilers for all of U.S. industry, reference technology scenario, with and without 450 stabilization policy.

While the policy induces a shift in the relative shares of the fuels consumed by industry, total final energy consumption (and therefore service output) is not heavily influenced by the policy. Averaged across all industries, service output in 2095 is reduced by less than 5%. Therefore, the presence of low-cost, low-carbon fuels (biomass, refined liquids, and electricity) enables the industrial sector to adapt to the climate constraints with minimal loss in output.

U.S. Transportation

Unlike the industrial sector, the transportation sector relies almost entirely on one fuel type, refined liquid fuels, for all service provision. While future switches to different fuels such as electricity or hydrogen have been proposed, this study does not investigate such a scenario. However, in this analysis, no end-use distinction is drawn between the different refined liquid fuels (e.g. diesel, gasoline, ethanol, or biodiesel). Refined liquid fuels produced from biomass or coal feedstocks are assumed functionally equivalent to those produced from crude oil.

Because of the lack of fuel options at the end-use level, the relevant fuel switching induced by the policy takes place in the liquid fuel refining sector (see Figure 3.3). End-use consumers do have technology options, however, with implications for fuel use. Figure 3.21 shows the number of passenger miles driven by hybrid-electric and ICE light-duty vehicles in the advanced technology scenario, with and without the climate policy. As shown, in the passenger sector, the policy induces little technology switching, or change in the levels of service demand. The reason is that fuel costs account for a small portion of the cost of passenger transportation, particularly as high incomes increase the time value of transportation near the end of the century.

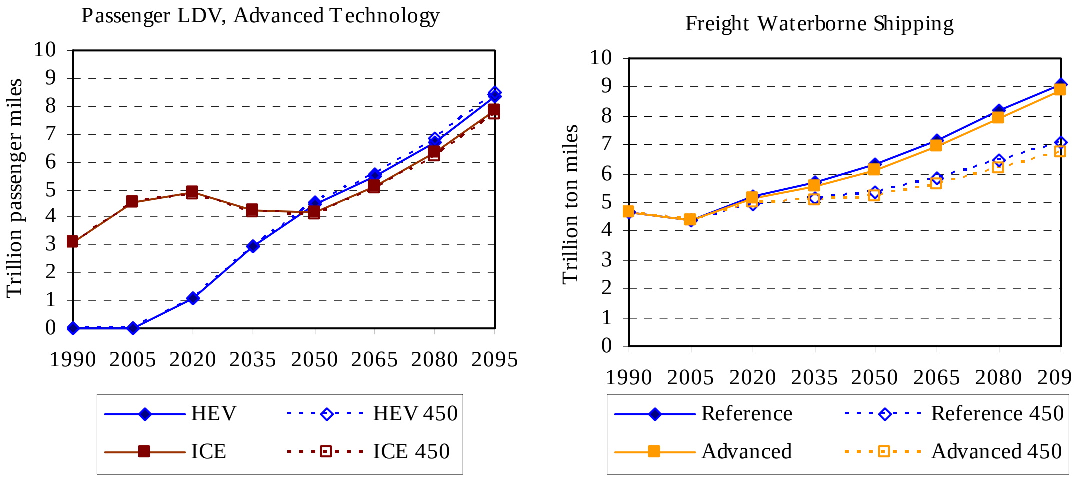

Figure 3.21. Passenger miles by transportation technology for light duty vehicles, and freight waterborne shipping in both advanced and reference technology. Note that the policy induces larger changes in freight shipping than passenger transportation.

In contrast, the freight sector shows more responsiveness to climate policy (Figure 3.21), as fuel prices account for a larger proportion of the service costs in freight shipping than in passenger transportation. Whereas passengers are limited by 24 hours in the day, with time in transit incurring opportunity costs, no such opportunity cost is assessed for freight shipments. Moreover, the fuel cost relative to the vehicle capital and operating costs are relatively high in the freight sector. In 2005, fuel costs accounted for 17% of costs for freight trucking and rail, 30% of waterborne shipping costs, and 40% of air freight costs. In the passenger sector, for comparison, fuel costs accounted for 10% of the vehicle costs per vehicle mile, and only 3% of the service costs when the time value is also considered.

U.S. Carbon Emissions by End-Use Sector: 450 and 550 ppmv

Figure 3.22 presents the total (direct + indirect) emissions from each end-use sector in reference and advanced technology, with no policy, a 450 ppmv policy, and a 550 ppmv policy. The global emissions trajectory and carbon taxes of the 550 ppmv policy are shown in Figure 3.1 and Figure 3.2; the policy is characterized by having lower taxes than the 450 ppmv policy.

Note that in the advanced end-use technology scenario, U.S. emissions absent any policy are actually lower than the emissions targets of the 550 ppmv reference technology scenario policy between 2020 and 2050. A new pathway was, therefore, used for the 550 stabilization scenario with advanced end-use technology. Emissions in this advanced-550 scenario are allowed to be higher than emissions in the reference-550 scenario, keeping long-term cumulative emissions roughly constant.

In both the 450 and 550 ppmv scenarios, about 70% of the total emissions in 2095 are from the transportation sector. This is because emissions mitigation from transportation is relatively expensive. Almost all transportation technologies consume refined liquid fuels, limiting the range of technological responses, and the fuel costs account for a small portion of service costs, limiting the effect of increased fuel prices on consumer behavior. While transportation technologies can be de-carbonized by refining fuels from biomass feedstocks, this process is costly, more so than de-carbonization of electricity. Because of this, the buildings and industrial sectors show a larger response in terms of decarbonization than the transportation sector. Note that the carbon taxes in the advanced-550 scenario have very little effect on the transportation sector emissions, indicating that the switch towards biomass in liquid fuel refining (shown for a 450 ppmv policy in Figure 3.3) is not induced by low carbon prices.

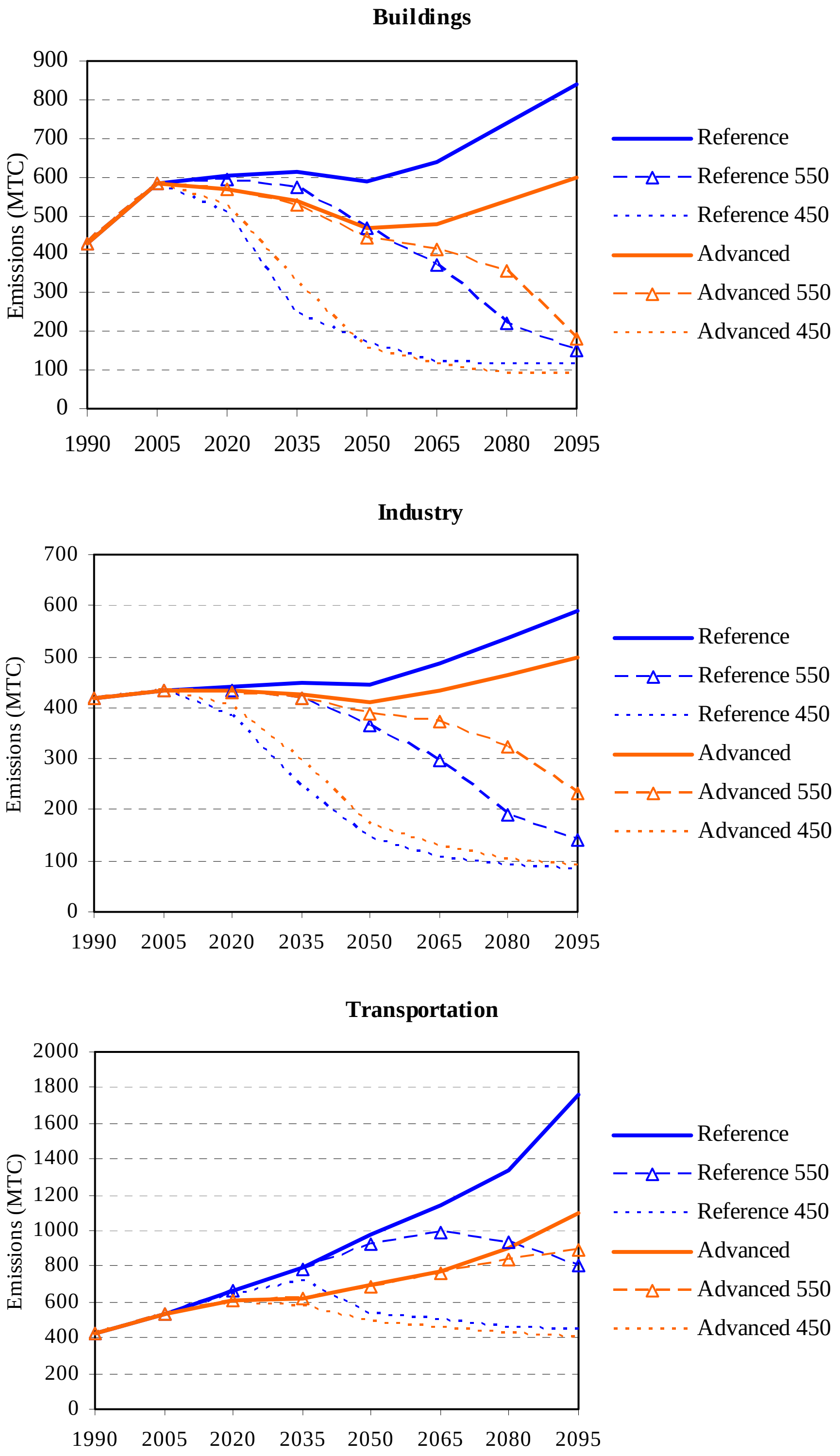

Figure 3.22. Total (direct + indirect) emissions from the buildings, industry, and transportation sectors, advanced and reference technology, with no policy, a 450 ppmv stabilization policy, and a 550 ppmv stabilization policy. Indirect emissions are from electricity generation and liquid fuel refining.

3.3. The Value of Energy Efficiency

3.3.1. Aggregate U.S. Carbon Emissions

Future U.S. carbon emissions in the reference and advanced technology scenarios are shown in Figure 3.23, along with the emissions pathways to CO_2 stabilization in the reference and advanced scenarios. Also shown is the "no tech change" scenario, in which future end-use efficiencies are maintained at their 2005 levels. While this is not a realistic scenario, it does allow quantification of the effect of technological improvement in the reference scenario. The technological improvement assumed in the reference technology scenario results in a 27% reduction in carbon emissions in 2095, relative to the scenario with no technological change. Advanced end-use technology accounts for a further 31% reduction in carbon emissions in 2095, relative to the reference technology scenario. The reduced emissions due to enhanced energy efficiency do not lead to emissions stabilization, however. Carbon emissions must decrease further to follow the global stabilization paths outlined in Figure 3.1.

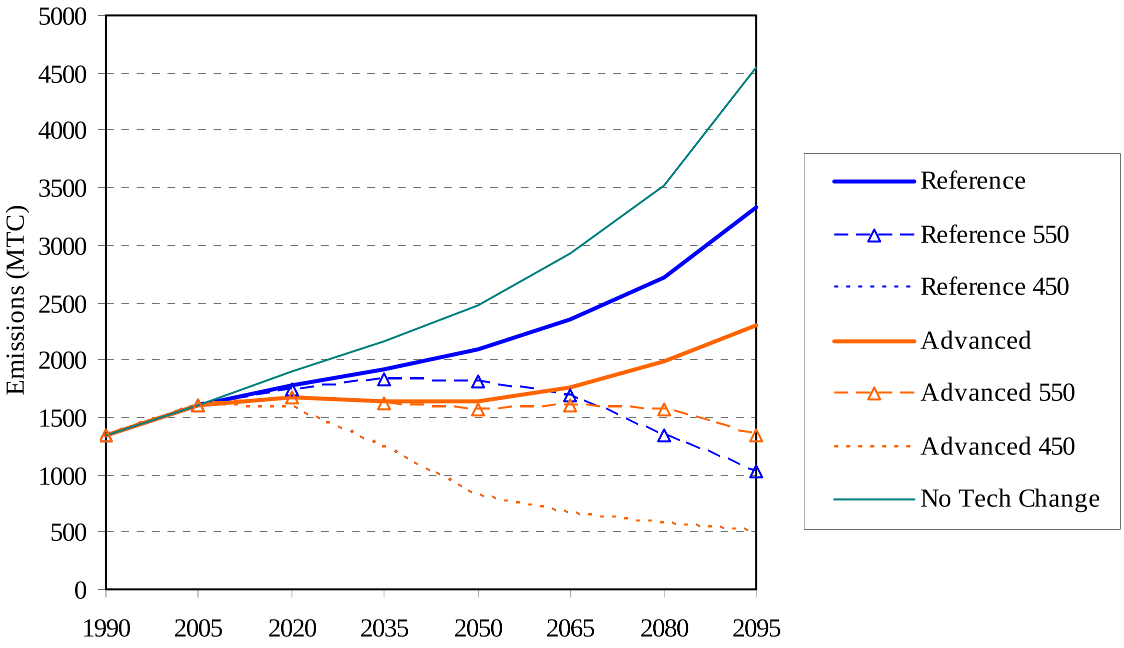

Figure 3.23. Total U.S. carbon emissions in the three technology scenarios, and with the two CO_2 stabilization policy constraints.

Both technology scenarios follow the same emissions path in the 450 ppmv stabilization policy (also shown in Figure 3.18), as the emissions targets of this relatively stringent emissions pathway (from Clarke et al. 2007) are less than the emissions without a policy. However, the advanced technology scenario with no climate policy has lower emissions between 2020 and 2050 than the U.S. portion of the global emissions path for the 550 ppmv stabilization pathway. A new emissions path for the 550 stabilization scenario was therefore constructed such that cumulative U.S. emissions were approximately equal by the early 22nd century. This results in the emissions trajectory for the advanced-550 scenario shown in Figure 3.23. For the time frame of this study, the advanced technology scenario has far less emissions reductions necessary to meet the 550 ppmv policy emissions targets in all time periods than the reference technology scenario, due to emissions reductions resulting from the adoption of energy-saving technologies.

3.3.2. Costs of CO_2 stabilization

The total discounted costs of meeting emissions constraints for the 450 ppmv and 550 ppmv stabilization targets are shown for the reference and advanced technology scenarios in Figure 3.24. The implementation of advanced end-use technologies substantially reduces the costs of meeting a climate policy. The discounted policy costs with advanced end-use technology are 50% and 86% lower than with reference technology for the 450 ppmv and 550 ppmv policies, respectively.

Note that the relative benefit of energy efficiency is larger for the 550 ppmv policy as compared to the 450 ppmv policy. This because in the advanced technology scenario, additional emissions reductions due to a climate policy are shifted to later time periods, which substantially lowers the discounted policy costs. The absolute reduction in policy costs from advanced end-use technology is, however, still much larger for the 450 policy than the 550 policy, due to the higher overall costs of the more stringent stabilization policy.

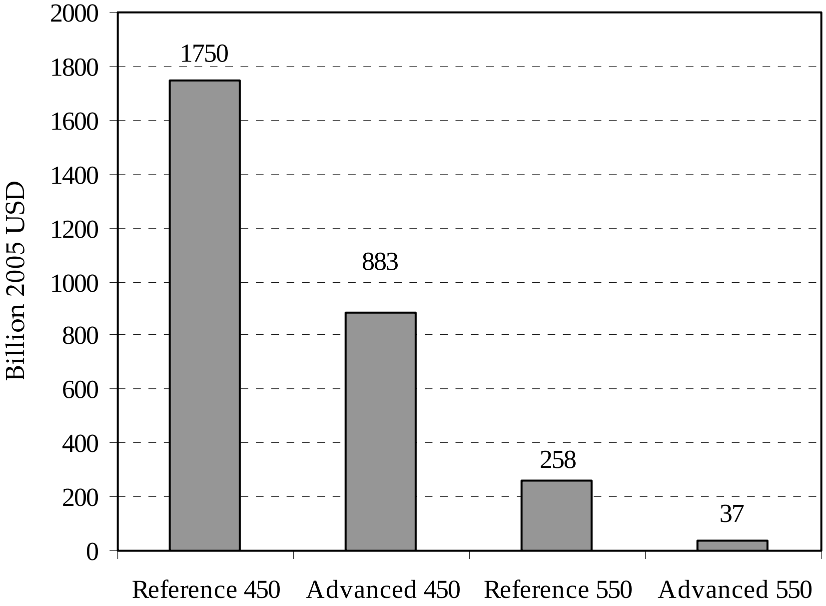

Figure 3.24. Total discounted costs for the U.S. to meet 450 and 550 ppmv CO_2 stabilization policy emissions targets, in 2005 USD, with reference and advanced end-use technologies.

3.3.3. The Importance of Each Sector

In order to investigate the contribution of advanced technology in each end-use sector towards reducing costs of carbon mitigation, Figure 3.25 presents discounted policy costs for scenarios in which only one end-use sector has advanced technology, while the other two have reference technology. The relative reduction in cost for each individual sector is 14% for buildings, 4% for industry, and 35% for transportation. The sector with the largest technology-induced reduction in policy cost is transportation. The cost reduction from advanced technologies in the buildings sector is only 40% of that in the transportation sector, and the contribution from the industrial sector is even smaller.

Advanced transportation technologies have such a large effect on policy costs in part because the transportation sector accounts for an increasing proportion of future emissions in this scenario (see Figure 3.22). Transportation accounted for 35% of total U.S. carbon emissions in 2005; this grows to about 50% in 2095 absent any climate policy. In the policy scenarios transportation accounts for 70% of emissions, reflecting the relative difficulty of reducing emissions in this sector. One reason for the difficulty of reducing transportation emissions is the reliance almost entirely on refined liquid fuels in these scenarios (plug-in hybrid or hydrogen vehicles were not included as options in this study). In these scenarios, refined liquid fuel emissions are partly offset by the policy-induced switch in the fuel refining sector from shale oil refining and coal-to-liquids to biomass liquids. However, emissions from refined liquid fuels are ultimately more difficult and costly to mitigate than emissions from electricity (Clarke et al. 2007a). With the 450 ppmv policy, the average carbon intensity of refined liquid fuel consumption is 6 kg C per GJ in the reference technology scenario, and 10 kg C per GJ in the advanced scenario, in contrast to electricity, which emits 1.1 kg C per GJ in both the reference and advanced technology scenarios.

The buildings sector relies increasingly over time on electricity, regardless of the presence of a climate policy (see Table 3.3). Therefore, advanced, energy-efficient end-use technologies in the buildings sector serve mostly to reduce electricity generation requirements. Because the marginal costs of each electricity generation technology increases with the amount of carbon-neutral electricity supplied, these electricity demand reductions can reduce the costs of electricity generation. However, in this study, the electricity generating costs do not appear to be sensitive to deployment levels. With the 450 ppmv policy, in 2095, generation requirements in the advanced technology scenario are reduced by 30% relative to reference technology, but electricity costs do not differ between the advanced and reference technology scenarios (<1%). Therefore, while the energy savings of advanced buildings technologies are substantial (see Figure 3.9), their value in carbon mitigation is limited by the relative cost-effectiveness of low-carbon electricity generation technologies (see Figure 3.3a).

The effect of advanced technology on carbon mitigation costs in industry is relatively small, for several reasons. Perhaps the most important reason is that the assumed change from the reference to advanced technology in terms of carbon emissions reduction is relatively small for this sector. Larger assumed efficiency improvements (if possible) would produce a larger effect. Further, many of the industrial end-uses can be met by several of the five final energy fuels, allowing fuel switching towards biomass and electricity in response to a climate policy (see Figure 3.20). This fuel switching reduces the carbon intensity of industry, minimizing the policy cost-reducing effects of energy-efficient industrial technologies. Future industrial emissions also grow the least of the three end-use sectors (Figure 3.22), due mostly to assumptions of relatively low income elasticities. As a result, service demands in industry do not increase as fast as demands in the buildings or transportation sectors.

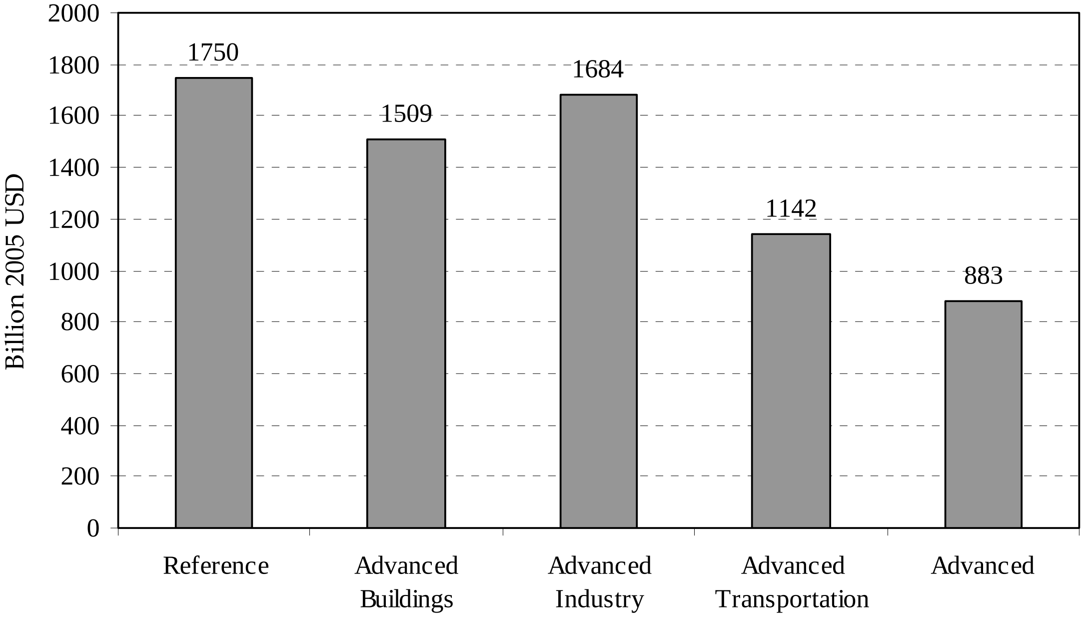

Figure 3.25. Discounted 450 ppmv stabilization policy costs for the advanced and reference technology scenarios, and scenarios in which advanced end-use technologies are applied to a single sector at a time.

The sum of the cost reductions relative to the reference technology scenario for each single-sector scenario is larger than the cost reduction from the combined scenario—that is, the scenario that includes advanced end-use technologies in all three sectors. The difference between these two measures of cost reduction is an indication of the substitution between benefits in individual sectors. The degree of substitution decreases over time as carbon prices increase. For example, in the 450 ppmv stabilization scenario, the sum of the cost reductions from the three single-sector policy scenarios exceed the cost reductions of the combined (advanced) scenario by 19% in 2020, and 12% in 2035. By 2050 (and thereafter), this difference is only 1%. This means that there is some degree of substitution between sectoral end-use technology improvements when carbon prices are low, whereas at high carbon prices end-use technology improvements are almost completely complementary. Therefore, adding up impacts from separate sectoral efficiency initiatives will overstate the net effect of energy efficiency at lower carbon prices. In higher carbon price regimes, however, there is very little overlap: efficiency increases anywhere in the economy translate to cost reductions.

3.3.4. The Importance of Timing of Advanced Technology

In order to investigate the role of the timing of the switch to advanced technology, this section presents discounted 450 ppmv stabilization policy costs of three scenarios in which advanced end-use technologies are deployed with time lags of 5, 10, and 15 years. While the model operates in 15-year timesteps, future technology assumptions are adjusted accounting for a time lag in deployment of advanced technology. It is assumed that during the time lag intervals, all end-use technologies in these scenarios have rates of improvement that are identical to the reference technology scenario assumptions. Thereafter, rates of improvement of technological efficiencies and non-energy costs follow the annual improvement rates of the advanced technology scenario assumptions, starting in 2005, until convergence with the advanced scenario assumptions. An example of this procedure is shown for the fuel economy of ICE automobiles in Figure 3.26.

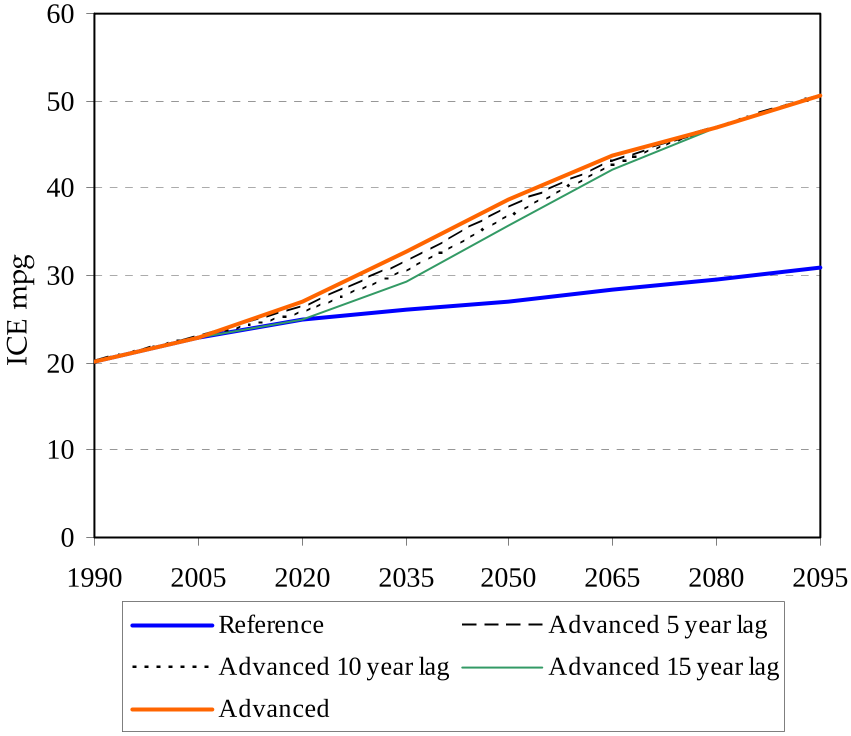

Figure 3.26. Fuel economy of ICE automobiles for advanced, reference, and time-lag-advanced technology scenarios. In the time lag scenarios, technological improvement matches the reference scenario for the given number of years, and the advanced scenario thereafter.

The discounted policy costs of the time lag scenarios are shown in Figure 3.27, along with the costs of the reference and advanced scenarios for comparison. Costs in all three time lag scenarios are closer to costs of the advanced scenario than the reference scenario. This highlights the importance of deployment of advanced technologies, even if the implementation takes a decade or two. However, the discounted policy costs are still higher than costs of the advanced technology scenario—the 15-year time lag increases the policy cost of the advanced technology scenario by more than 20%. This highlights the value of early deployment of advanced end-use technologies.

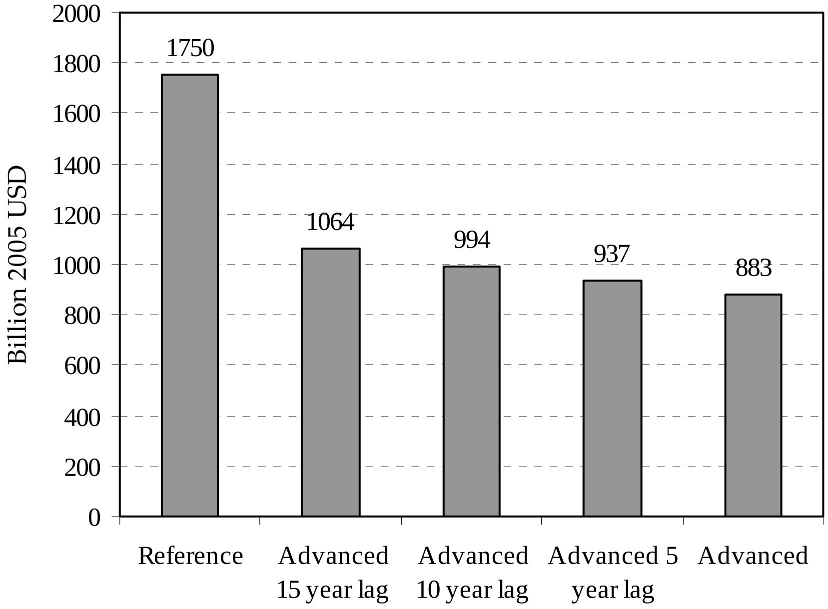

Figure 3.27. Total discounted costs, in billion 2005 USD, of meeting 450 ppmv emissions targets with reference end-use technology, advanced end-use technology, and advanced technology with given time lag intervals.

4. Conclusions

This study used detailed modules of U.S. building, industry, and transportation energy demand to examine the impact of improved end-use technologies over a 100-year time period. Using a global integrated assessment model, it was shown that advanced end-use technologies can substantially reduce the costs of meeting U.S. emissions targets by reducing the magnitude of the required emissions reductions.

Without a policy that places a price on carbon, however, advanced end-use technology alone is not sufficient to stabilize greenhouse gas concentrations. During the upcoming century, a number of factors put upward pressure on emissions even in the advanced technology scenario. Service demands increase as population and per-capita GDP increase. Also, in this reference, no-policy, case the electricity sector continues rely predominantly on coal and natural gas, and in the liquid fuel refining sector, declining crude oil stocks lead to a shift towards unconventional sources such as shale oil and coal-to-liquids that entail substantial emissions.

In policy cases, the advanced technologies reduced costs of meeting emissions targets by 50% under a 450 ppmv policy, and by 86% under a 550 ppmv policy. Increased efficiency within the transportation sector accounted for the largest portion of these cost reductions with the buildings sector next in importance, followed by industry. There is some overlap in terms of the impact on policy costs for efficiency improvements in different sectors, such that the impact of individual-sector efficiency improvements is slightly reduced. This effect nearly disappears at high carbon prices, however, where the full effect of efficiency improvements anywhere in the economy contributes fully to policy cost reductions.

The importance of improved efficiency in the transportation sector is due to both the high growth rate of transportation service demands and the assumption of limited alternatives to consumption of refined liquid fuels. While the policy does induce a shift in the liquid-fuel refining sector towards biomass feedstocks, reducing the average "well-to-wheel" emissions, this transition is costly, and liquid fuels in aggregate remain more carbon intensive than electricity. In the analysis, a number of cost-effective emissions-reduced electricity generation technologies were available; and as a consequence, the electricity sector showed a large shift in generation technologies in response to a policy. This was particularly important for the buildings sector, which showed a continuation of its historical trend towards electrification even absent a carbon policy.

The timing of the entry of advanced end-use technologies is also important in reducing costs. For the 450 ppmv policy, a time lag of 15 years resulted in a 22% increase in the total cost of meeting the emissions targets. However, even with a time lag, this is still 39% lower than the policy cost in the reference technology scenario.

This analysis did not consider induced technological change. While it would be expected that increasing carbon prices would spur the development and deployment of more efficient end-use technologies, determining the magnitude of this effect is extremely difficult (Clarke and Weyant 2002; Clarke et al. 2006b; Clarke et al. 2007c). This is particularly true for end-use technologies, where a multitude of barriers to adoption exist and explicit policy programs such as efficiency standards are often a key factor that shapes the aggregate efficiency of the deployed technology suite. The analysis here has exogenously specified two technology development pathways. The actual path, particularly under a carbon policy, could lie in between the two scenarios sketched here.

Dramatic changes in end-use technologies were not considered in this analysis. The technological improvements assumed in the advanced scenario focused primarily on reducing energy requirements of existing technologies, and reducing costs of energy-saving technologies currently in use or in development. Even with this limitation, however, the potential policy cost savings of improved energy efficiency for the U.S. alone is very large, both in relative and absolute terms.

This work could be extended in a number of ways. While we have identified the key role of improvements in the transportation and building sectors, more focused work to identify the role of individual suites of technologies could be conducted. This would allow comparison between different technological strategies at the end-use level.

There are a number of potentially important technologies that could also be examined. In light of the importance of the transportation sector, technologies that allow the use of non-liquid fuels to provide transportation services would be potentially quite valuable. Plug-in hybrid electric vehicle in particular are of particular interest, as these would allow some portion of passenger service demand to be met by electricity without requiring a substantial new infrastructure or sacrificing the amenity value of a long driving range. Technologies such as solar hot water in the buildings sector might also be important, given the high fraction of this service that is provided by the direct use of fossil fuels.

It may also be worthwhile to address the service demand drivers in more detail than has been done in this study. For instance, recreational passenger transportation can be expected to have a different time value than commuting, which will have implications for future demand increases. In addition, demands now considered separately in the model could be linked so that the full impact of efficiency improvements would be measured. For example, end-use fuel consumption requires transportation of the fuels to be consumed, implying a demand for freight and pipeline transportation services. It may be useful to link freight service demands more closely to levels of fuel consumption.

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Appendix: Data and Assumptions

The purpose of this appendix is to present data sources and calculations used in the analysis presented in the body of the report, including historical calibration (in 1990 and 2005), and derivation of the future reference and advanced technology scenarios in the buildings, industry, and transportation sectors. The appendix does not explicitly address the no-technology scenario, which simply applies 2005 end-use energy efficiency and non-energy cost assumptions in all time periods through 2095.

A.1. U.S. Buildings Module

Historical calibration of the U.S. buildings sector is based on 1990 and 2005 estimates of floorspace, building shell thermal characteristics, and the following characteristics for each building technology: energy consumption, efficiency, and non-energy cost. Future floorspace growth is influenced by supply and demand elasticities; the values assumed are shown in Table A.1, and do not differ between the advanced and reference technology scenarios. Service demand evolution is influenced by price elasticities, saturation percentages, and internal gain fractions, which also do not vary between technology scenarios and are shown in Table A.2. In the scenarios presented, no climate change-induced warming is assumed; HDD and CDD are assumed equal to the average climate from 1971 to 2000 (EIA 2005, Tables 1.7 and 1.8).

Table A.1. Supply and demand floorspace elasticities in all scenarios presented.

Price Elasticity of Floorspace Supply	β_S	0.5
Price Elasticity of Floorspace Demand	β_D	0.5
Income Elasticity of Floorspace Demand	λ	1.0

Table A.2. Parameters influencing service demand evolution in all scenarios presented.

Residential	**Internal gain fraction**	**Saturation (2005)**	**Price elasticity of service demand**
Heating	0%	100%	-0.4
Cooling	0%	93%	-0.4
Water Heating	10%	100%	-0.4
Lighting	74%	100%	-0.4
Appliances	50%	98%	-0.4
Other	50%	60%	-0.4
Commercial			
Heating	0%	100%	-0.4
Cooling	0%	93%	-0.4
Water Heating	10%	100%	-0.4
Lighting	80%	100%	-0.4
Office Equipment	80%	70%	-0.4
Other	17%	60%	-0.4

The market share of each technology competing to provide a service depends on costs, and "share weights" assigned to each technology. Costs consist of a non-energy cost and an energy cost; the energy cost of a technology in a given time period is determined by the cost of the fuel consumed and the efficiency of the technology. The share weight of a technology represents consumer preferences and availability and is a calibration parameter for historical years. In all scenarios presented, share weights of technologies on the market in 2005 are assumed constant through 2095. This means that consumers will retain the same cost-independent preferences for, e.g., incandescent lighting as compared to fluorescent lighting in all future time periods.

A.1.1. Technology Efficiencies

Each technology in the buildings module is assigned a stock average efficiency in each period, representative of the average efficiency of all operating units of the given technology. Efficiencies in the buildings module are unitless, expressed as service output divided by energy consumption. For space heating, space cooling, and water heating, interpretation of the efficiency measure is straightforward because the services consist of energy transfer. For example, a gas furnace with 82% efficiency produces 82 GJ of heating service for every 100 GJ of energy consumption. Lighting service is generally represented in lumens, so a conversion of 683 lumens per watt is used in this study, in order to represent the lighting service in terms of energy. For appliances, office equipment, and the "other" services—services that can not be readily represented in terms of energy—efficiencies are indexed to 2005.

Efficiency estimates between 1990 and 2035 are informed, where possible, by NEMS stock models, EIA (2007), TIAX (2006), and NCI (2004a). Some efficiencies are limited by physical or thermodynamic constraints, and these constraints will be noted where applied. Long-term future efficiency improvements are generally assumed to follow one of the five prescribed trajectories shown in Table A.3. The trajectories refer to different stages of maturity of technologies; each technology is assigned to one trajectory based on its present rates of efficiency improvement, as well as opportunities for improvement in stock averages with present-day technology.

Table A.3. Trajectories of annual technological improvement rates used in buildings scenarios; letters (A-E) refer to different trajectories, based on maturity and opportunities for improvement of technologies.

Period	A	B	C	D	E
1990-2005	0.60%	0.80%	1.00%	1.00%	1.00%
2005-2020	0.50%	0.60%	0.80%	1.00%	1.00%
2020-2035	0.25%	0.50%	0.60%	0.80%	1.00%
2035-2050	0.10%	0.25%	0.50%	0.60%	0.80%
2050-2065	0.10%	0.10%	0.25%	0.50%	0.60%
2065-2080	0.05%	0.10%	0.10%	0.25%	0.50%
2080-2095	0.05%	0.05%	0.10%	0.10%	0.25%

A.1.2. Technology Non-Energy Costs

Non-energy costs in MiniCAM are expressed in terms of dollars per service provided. Non-energy costs are calculated accordingly for technology *i* in year *t*:

$$NonEnergyCost_{i,t} = \frac{LevelizedCapitalCost_{i,t} + O\&MCost}{ServiceOutput_{i,t}}$$

$$LevelizedCapitalCost_{i,t} = CapitalCost_{i,t} * \frac{DiscountRate}{1-(1+DiscountRate)^{EquipmentLifetime_{i,t}}}$$

$$CapitalCost_{i,t} = \frac{InstalledEquipmentCost_{i,t}}{MaximumPowerOutput_{i,t}}$$

$$ServiceOutput_{i,t} = MaximumServiceOutput_{i,t} * CapacityFactor_{i,t}$$

$$MaximumServiceOutput_{i,t} = MaximumPowerOutput_{i,t} * SecondsInYear$$

$$CapacityFactor_{i,2005} = \frac{EnergyConsumption_{i,2005} * Efficiency_{i,2005}}{EquipmentStock_{i,2005} * MaximumServiceOutput_{i,2005}}$$

Non-energy costs, shown in Table A.5, are calculated assuming constant future capital costs per unit output (installed cost per maximum power output), equipment lifetimes, O&M costs, and capacity factors. The discount rate is assumed to be 10% for all technologies. Efficiency improvements reduce non-energy costs by increasing maximum power output and therefore maximum service output. Data sources for all technologies are addressed individually in Sections A.1.4 and A.1.5.

A.1.3. Energy Consumption by Technology

Energy consumption by each technology is calculated based on the energy consumption by service and fuel in 1993 and 2005, from EIA (1996 and 2007, Table A.4 and Table A.5). Estimates for 1993 are scaled to 1990 based on residential and commercial final energy consumption by fuel in 1990 as compared to 1993 (EIA 2005, Tables 2.1b and 2.1c). This disaggregation is adequate for estimating energy consumption by most technologies in the buildings module. However, some technologies, such as incandescent and fluorescent lighting, each consume the same fuel, and require additional calculations from other data sources. Sections A.1.4 and A.1.5 address the data sources used for each individual technology in the U.S. buildings module.

A.1.4. Technological Specifications in the Residential Sector

Efficiency and non-energy cost assumptions for all residential building technologies are shown in Table A.4 and Table A.5.

Table A.4. Technological efficiency assumptions in the residential sector. All efficiencies are represented as energy out divided by energy in, except where noted.

	Historical		**Reference**		**Advanced**	
	1990	**2005**	**2050**	**2095**	**2050**	**2095**
Shell efficiency (indexed to 2005)	0.92	1.00	1.34	1.70	1.50	2.45
Heating						
Gas furnace	0.70	0.82	0.88	0.91	0.88	0.91
Gas heatpump	na	na	na	na	1.94	2.37
Electric furnace	0.98	0.98	0.99	0.99	0.99	0.99
Electric heatpump	1.61	2.14	2.49	2.58	2.81	3.00
Fuel oil furnace	0.76	0.82	0.85	0.87	0.85	0.87
Wood furnace	0.52	0.58	0.66	0.68	0.66	0.68
Cooling						
Air conditioning	2.16	2.81	3.76	3.90	4.18	4.47
Water heating						
Gas water heater	0.52	0.56	0.80	0.91	0.80	0.91
Gas heatpump water heater	na	na	na	na	1.73	1.96
Electric resistance water heater	0.84	0.88	0.95	0.96	0.95	0.96
Electric heatpump water heater	na	na	na	na	2.69	2.80
Fuel oil water heater	0.51	0.55	0.56	0.58	0.56	0.58
Lighting (lumens per watt)						
Incandescent lighting	14	14	16	17	16	17
Fluorescent lighting	76	76	101	108	101	108
Solid-state lighting	na	na	122	127	152	186
Appliances and other (indexed to 2005)						
Gas appliances	0.96	1.00	1.66	1.72	1.66	1.72
Electric appliances	0.67	1.00	1.41	1.47	1.59	1.80
Gas other	0.99	1.00	1.12	1.25	1.12	1.25
Electric other	1.00	1.00	1.02	1.05	1.41	1.47
Fuel oil other	0.99	1.00	1.05	1.09	1.05	1.09

Table A.5. Technological non-energy cost assumptions in the residential sector. All costs are represented in 2005 $ per GJ of output

	Historical		**Reference**		**Advanced**	
	1990	**2005**	**2050**	**2095**	**2050**	**2095**
Aggregate building	12.89	20.99	55.51	134.64	55.51	134.64
Heating						
Gas furnace	6.24	5.38	5.00	4.85	5.00	4.85
Gas heatpump	na	na	na	na	14.42	11.79
Electric furnace	7.24	7.15	7.08	7.08	7.08	7.08
Electric heatpump	20.93	15.75	13.56	13.07	12.03	11.24
Fuel oil furnace	6.93	6.45	6.23	6.04	6.23	6.04
Wood furnace	5.98	5.36	4.72	4.58	4.72	4.58
Cooling						
Air conditioning	19.16	14.73	11.04	10.63	9.92	9.27
Water Heating						
Gas water heater	13.25	11.46	6.90	5.83	6.90	5.83

Gas heatpump water heater	na	na	na	na	15.19	13.37
Electric resistance water heater	13.39	12.76	11.86	11.74	11.86	11.74
Electric heatpump water heater	na	na	na	na	21.01	20.24
Fuel oil water heater	12.54	12.32	11.99	11.63	11.99	11.63
Lighting[1]						
Incandescent lighting	803	803	707	686	707	686
Fluorescent lighting	1012	1012	761	712	761	712
Solid-state lighting	na	na	1630	1531	1033	721
Appliances and Other						
Gas appliances	16.59	16.34	15.62	14.94	15.62	14.94
Electric appliances	31.83	31.36	29.98	28.66	29.98	28.66
Gas other	76.05	76.05	76.05	76.05	76.05	76.05
Electric other	145.93	145.93	145.93	145.93	145.93	145.93
Fuel oil other	76.05	76.05	76.05	76.05	76.05	76.05

1 Lighting output converted to GJ assuming 683 lumens per watt; 1 GJ = 190 million lumen-hours

Aggregate Residential Building Shell Efficiency

The residential sector is commonly disaggregated into single-family homes, multi-family apartment buildings, and mobile homes (e.g. U.S. Census Bureau, EIA 2007). Each of these building types can be expected to have different thermal properties. The scenarios detailed in this report represent the sector as one aggregate building, with characteristics representative of all residential building types.

Shell thermal efficiency is estimated using a building shell stock model, which takes into account the long lifetimes of buildings. In this way we can investigate historical shell efficiency improvement, and how the future aggregate building stock shell efficiency might respond to changes in characteristics of new construction. The building shell stock model is based on the following equations. The aggregate building stock efficiency at any time is calculated as:

$$StockEfficiency_{total} = \sum_{i}^{n} Efficiency_{i} * \frac{Floorspace_{i}}{Floorspace_{total}}$$

Where *i* refers to the building type (single-family, multi-family, and mobile), and *n* is the number of different building types (in this case, three). Floorspace by building type in each year is computed from the number of units in each building type (U.S. Census Bureau 1990 for 1950-1990, and the base years of the Annual Energy Outlook for 1993 to 2005; EIA 1996-2007, http://www.eia.doe.gov/oiaf/archive.html#aeo) multiplied by the average floorspace of each housing type (U.S. Census Bureau 2004; AEO 1996-2007). The stock average efficiency of building type *i* in year *t* is calculated accordingly:

$$StockEfficiency_{i,t} = \sum_{t}^{N} Efficiency_{t,i} * \frac{Stock_{t,i}}{Stock_{total,i}}$$

Where *N* refers to each year in the database (going back to 1950), $Efficiency_t$ stands for the average efficiency of buildings of vintage *t*, and $Stock_t$ stands for the number of buildings of vintage *t* that are still in use. Eff_t is estimated using the Residential Energy Consumption Survey database (RECS; EIA 2001). Values are indexed to 2005, and shell efficiency is calculated according to per-floorspace heating service consumption by building age in each RECS climate zone (RECS database). Heating service consumption is assumed to be equal to fuel input times equipment efficiency, using stock efficiency estimates for equipment from EIA (2007, Table 21). For simplicity, buildings of all ages (in a given year) are assumed to have equal heating equipment efficiency.

The stock of buildings of vintage *t* in a given year is calculated according to the following equations:

$$Stock_{t,i} = Stock(1950)_{t,i} + \sum_{t}^{N} (construction_{t,i} - retirement_{t,i})$$

$$Stock(1950)_{t,i} = Stock(1950)_{t-1,i} - retirement(1950)_{t,i}$$

$$retirement(1950)_{t,i} = \frac{Stock_{1950,t-1,i}}{AverageBuildingLifetime(1950\,stock)_i}$$

$$construction_{t,i} = Stock_{t,i} - Stock_{t-1,i} + retirement_{t,i} + retirement(1950)_{t,i}$$

$$retirement_{t,i} = \sum_{t}^{N} Stock_{t-1,i} * (1 - SurvivalRate_{t,i})$$

$$SurvivalRate_{t,i} = 1 \qquad \text{if } t < MinimumBuildingLifetime_i$$

$$SurvivalRate_{t,i} = \frac{1}{TurnoverRate_i} \quad \text{if } t > MinimumBuildingLifetime_i$$

The stock in each year is specified, retirements are calculated given lifetime assumptions, and the amount of new construction is then determined. This results in a set of building vintages by year. The model is initialized in 1950, so by the present-day the impact of uncertain building lifetimes for early years is small.

The stock efficiency for each building type in historical years is therefore calculated for each building type, given assumptions of the following parameters: minimum building lifetime, turnover rate, and average lifetime of the buildings from the 1950 stock. This model is similar to building equipment stock models used by NEMS (U.S. DOE 2004), with the exception that retirement is assumed to be exponential rather than linear; therefore, no maximum building lifetime is assigned. Parameters are set such that the model roughly replicates the age distribution of all structures in 2005; this is shown in Figure A.1.

The different housing types are assumed to have different relative shell efficiencies in 2005, with mobile homes 20% less efficient than single family homes (due to less insulation), and multi-family homes 30% more efficient than single family homes (due to shared walls between units). Future improvement in shell efficiency is informed by analysis in heating and cooling service demands for houses on the path to zero net energy in five U.S. cities using BEopt (Christensen et al. 2005).

For each of these cities (Atlanta, Chicago, Houston, Phoenix, and San Francisco), two points on the path to zero net energy were analyzed: the point at which total costs (which include utility bills plus amortized capital costs on energy efficient equipment) are minimized, and the point at which costs of energy-saving equipment plus utility bills are equal to the "benchmark" utility bills. At each of these points, the heating and cooling service demands were computed as the product of energy consumption for the service and the energy efficiency of the equipment providing the service. Service demands were averaged between all cities, and then heating and cooling service demand reductions were averaged to compute a factor by which thermal improvements reduced space conditioning needs. In the advanced technology scenario, the cost-minimizing point was used as the basis for the estimate of average shell efficiency new construction in 2050, and the cost-neutral point was used for the estimate of the efficiency of new construction in 2095. This results in 100% improvement from 2005 to 2050 in shell efficiency of new construction, and 240% improvement from 2005 to 2095. In the reference scenario, shell efficiency of new construction of single family homes is assumed to be 40% higher than the 2005 average in 2050, and 80% higher in 2095 (Table A.4).

While the model explicitly incorporates efficiency improvements in new construction, the results could also be interpreted as a lesser improvement in new construction combined with improvements in existing building stock (e.g. through retrofits). In order to present a straightforward scenario, only improvements in new construction were considered because a well-documented residential building energy model (BEopt) was available to guide the selection of parameter values.

Aggregate Residential Building Cost

Aggregate building cost is based on the median value of owner-occupied housing in 2005 ($165,344; U.S. Census Bureau 2005), divided by the median number of square feet per house (1790 ft^2), levelized assuming a 5% discount rate and a 30 year term. An annual maintenance cost of $1843 per house (U.S. Census Bureau 2005, American Housing Survey, Table 2-13) is added to the aggregate building cost, and also converted to annual cost per square foot of floorspace.

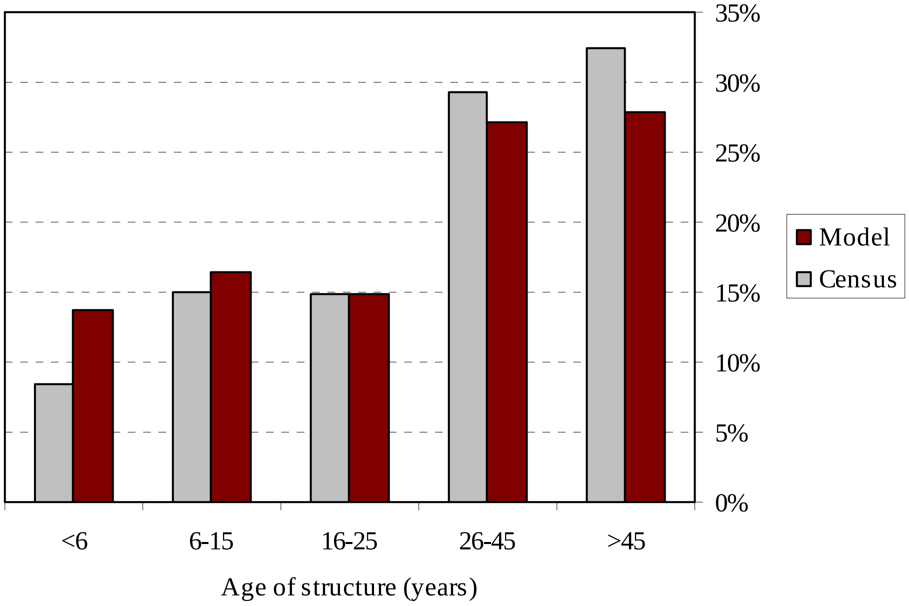

Figure A.1. Age distribution of residential structures in 2005, building shell stock model and U.S. Census data (U.S. Census Bureau 2005).

Residential Heating Service

The residential heating service is assumed to be fully saturated in 2005. This is consistent with EIA (2007, Table 21), in which the number of heating units relative to the number of housing units remains constant between 2005 and 2030 (2007, Table 21).

Gas Furnace

The reference and advanced scenarios do not differ in assumptions for gas furnaces.

Efficiency: In 2005, efficiency is from EIA (2007, Table 21) and the 1990 estimate is back-calculated from this 2005 estimate using the 1990-2005 annual rate of improvement for gas furnaces in the residential NEMS stock model. The reference scenario assumes that efficiency in 2020 and 2035 follows projected rates of improvement for these time periods (EIA 2007, Table 21), and thereafter efficiency improvement follows trajectory A.

Non-energy cost: Equipment lifetime, installed capital cost, and operating cost are from NCI (2004a), and capacity factor is calculated from the service output in 2005 divided by the maximum capacity. The service output is equal to the fuel consumption (EIA 2007, Table A4) multiplied by equipment efficiency (EIA 2007, Table 21). Maximum output is equal to the number of units (EIA 2007, Table 21) times the maximum hourly capacity of each unit in NCI (2004a) times the number of hours in a year. These values do not change over time in either scenario.

Gas Heatpump

Because gas heatpumps currently have no market share (nor does the EIA project their entry by 2035; EIA 2007, Table 21), they are not included in the reference scenario. In the advanced scenario, they enter in 2020, but have a low share weight, reflecting a limited range of applications (i.e. large apartment buildings).

Efficiency: The 2020 estimate is equal to the EIA (2007, Table 21) estimate for 2030. Trajectory E is used for all years thereafter.

Non-energy cost: Installed capital cost, maintenance cost, and lifetime are from NCI (2004a). Capacity factor is assumed equal to that of the electric heatpump.

Electric Resistance Furnace

The reference and advanced scenarios do not differ in assumptions for electric resistance furnaces.

Efficiency: Efficiency reaches its physical limit of 0.99 in 2020.

Non-energy cost: Capital and operating costs are assumed equal to those of gas furnaces, multiplied by an electric-gas cost conversion factor from Sezgen et al. (1995, Table 6.10). Capacity factor is equal to that of the electric heatpump.

Base year energy consumption: Because electric resistance furnaces share the electricity-fueled space heating category with electric heatpumps, the residential NEMS stock model is used to estimate the relative market share of each technology in 1990 and 2005, according to the following equation:

$$Energy_{ElectricFurnace} = \frac{Energy_{HeatingElectric} * \frac{Stock_{ElectricFurnace}}{Efficiency_{ElectricFurnace}}}{\frac{Stock_{ElectricFurnace}}{Efficiency_{ElectricFurnace}} + \frac{Stock_{ElectricHeatpump}}{Efficiency_{ElectricHeatpump}}}$$

Stock = number of units of the specified technology in use at the specified time period

Efficiency = stock average efficiency of the specified technology at the specified period

Energy = energy consumption by the specified fuel or technology at the specified period

Electric Heatpump

Efficiency: The EIA (2007, Table 21) estimate is used in 2005, and the 1990 value is back-calculated assuming the annual rate of improvement between 1990 and 2005 in the residential NEMS stock model. In the reference scenario, 2005-2020 and 2020-2035 rates of improvement are from EIA (2007, Table 21). Thereafter, improvement takes place according to Trajectory B. In the advanced scenario, the 2030 stock average in EIA

(2007, Table 21) is reached in 2020, and thereafter, efficiency improvement follows Trajectory C.

Non-energy cost: Equipment lifetime, installed capital cost, and operating cost are from NCI (2004a), and capacity factor is calculated as the actual service output in 2005 divided by the maximum possible output. The service output is equal to the fuel consumption (EIA 2007, Table A4) multiplied by equipment efficiency (EIA 2007, Table 21). Maximum output is equal to the number of units (EIA 2007, Table 21) times the maximum hourly capacity of each unit in NCI (2004a) times the number of hours in a year.

Base year energy consumption: Energy consumption is calculated as the electricity consumption for space heating minus the electricity consumption by electric furnaces.

Oil furnace

The reference and advanced scenarios do not differ in assumptions for oil furnaces.

Efficiency: The 2005 estimate is from EIA (2007, Table 21), and the 1990 value is back-calculated from this estimate using the average 1990-2005 rate of efficiency improvement in the residential NEMS stock model. Efficiency in 2020 and 2035 is estimated from projected rates of improvement in EIA (2007, Table 21), and thereafter efficiency improves according to Trajectory A.

Non-energy cost: Equipment lifetime, installed capital cost, and operating cost are from NCI (2004a), and capacity factor is calculated as the actual service output in 2005 divided by the maximum possible output. The service output is equal to the fuel consumption (EIA 2007, Table A4) multiplied by equipment efficiency (EIA 2007, Table 21). Maximum output is equal to the number of units (EIA 2007, Table 21) times the maximum hourly capacity of each unit in NCI (2004a) times the number of hours in a year.

Wood furnace

The reference and advanced scenarios do not differ in assumptions for wood furnaces.

Efficiency: Data on the stock average efficiency of U.S. wood furnaces is not available; thermal efficiencies of equipment currently on the market are estimated to be approximately 70% (Wood stove heating capacity comparison chart, http://www.chimneysweeponline.com/wscompha.htm). In this study, efficiency in 2005 is assumed to be 58%, with future improving taking place according to Trajectory A.

Non-energy costs: Capital costs are estimated to be between $1000 and $3000 (EPA 2007). This study assumes a capital cost of $2000 for a stove with a lifetime of 30 years, of moderate capacity (30,000 BTU/hr). Capacity factor is calculated based on EIA (2007; Tables A4 and 21) estimates of energy consumption and the number of units.

Residential Cooling Service

The saturation parameter for residential cooling service in 2005, 93%, is computed from future projections of the number of air conditioning units relative to the number of housing units in EIA (2007, Table 21). It is assumed that the market reaches full saturation in 2035.

Air Conditioning

Efficiency: The 2005 estimate is from EIA (2007; Table 21), and the 1990 value is estimated from average annual rates of improvement for central air conditioners in the NEMS stock model. In the reference technology scenario, efficiency in 2020 is equal to the EIA projection, and the 2035 estimate is calculated assuming the rate of improvement between 2020 and 2030 in EIA (2007, Table 21). Future improvement takes place according to Trajectory B. In the advanced technology scenario, the EIA projection for 2030 is reached in 2020, and thereafter, improvement takes place according to Trajectory C.

Non-energy cost: Equipment lifetime, installed capital cost, and operating cost are from NCI (2004a), and capacity factor is calculated as the actual service output in 2005 divided by the maximum possible output. The service output is equal to the fuel consumption (EIA 2007, Table A4) multiplied by equipment efficiency (EIA 2007, Table 21). Maximum output is equal to the number of units (EIA 2007, Table 21) times the maximum hourly capacity of each unit in NCI (2004a) times the number of hours in a year.

Residential Water Heating Service

The residential water heating service is assumed to be fully saturated in 2005. This is consistent with EIA (2007, Table 21), in which the number of water heating units relative to the number of housing units remains constant between 2005 and 2030 (2007, Table 21).

Gas Water Heater

Reference and advanced scenario assumptions for gas water heaters do not differ.

Efficiency: The 2005 estimate is from EIA (2007, Table 21), and the 1990 value is back-calculated from this estimate using the average 1990-2005 rate of efficiency improvement in the residential NEMS stock model. Efficiency in 2020 and 2035 is estimated from projected rates of improvement in EIA (2007, Table 21), and thereafter efficiency improves according to Trajectory D, reflecting a general switch towards condensing gas water heaters.

Non-energy cost: Equipment lifetime, installed capital cost, and operating cost are from NCI (2004a), and capacity factor is calculated as the actual service output in 2005 divided by the maximum possible output. The service output is equal to the fuel consumption (EIA 2007, Table A4) multiplied by equipment efficiency (EIA 2007, Table 21). Maximum output is equal to the number of units (EIA 2007, Table 21) times the maximum hourly capacity of each unit in NCI (2004a) times the number of hours in a year.

Gas Heatpump Water Heater

The technology is not used in 1990 or 2005, and does not enter the market in the reference scenario.

Efficiency: In 2020, efficiency is based on EIA (2007, Table 21), and thereafter, efficiency improvement takes place according to Trajectory D.

Non-energy cost: Capital cost is assumed 20% higher than the capital cost of electric heatpump water heaters. Operating cost, lifetime, and capacity factor are the same between these two technologies.

Electric Resistance Water Heater

Reference and advanced scenario assumptions for electric resistance water heaters do not differ.

Efficiency: The 2005 estimate is from EIA (2007, Table 21), and the 1990 value is back-calculated from this estimate using the average 1990-2005 rate of efficiency improvement in the residential NEMS stock model. Efficiency in 2020 and 2035 is estimated from projected rates of improvement in EIA (2007, Table 21), and thereafter efficiency improves until the maximum assumed limit, 0.96, is reached in 2050.

Non-energy cost: Equipment lifetime, installed capital cost, and operating cost are from NCI (2004a), and capacity factor is calculated as the actual service output in 2005 divided by the maximum possible output. The service output is equal to the fuel consumption (EIA 2007, Table A4) multiplied by equipment efficiency (EIA 2007, Table 21). Maximum output is equal to the number of units (EIA 2007, Table 21) times the maximum hourly capacity of each unit in NCI (2004a) times the number of hours in a year.

Electric Heatpump Water Heater

The technology is not used in 1990 or 2005, and does not enter the market in the reference scenario.

Efficiency: Efficiency in 2020 is based on the typical equipment efficiency in NCI (2004a), and improves according to Trajectory C.

Non-energy cost: Equipment lifetime, installed capital cost, and operating cost are from NCI (2004a), and capacity factor is calculated as the actual service output in 2005 divided by the maximum possible output. The service output is equal to the fuel consumption (EIA 2007, Table A4) multiplied by equipment efficiency (EIA 2007, Table

21). Maximum output is equal to the number of units (EIA 2007, Table 21) times the maximum hourly capacity of each unit in NCI (2004a) times the number of hours in a year.

Oil Water Heater

Efficiency: The 2005 estimate is from EIA (2007, Table 21), and the 1990 value is back-calculated from this estimate using the average 1990-2005 rate of efficiency improvement in the residential NEMS stock model. Efficiency in 2020 and 2035 is estimated from projected rates of improvement in EIA (2007, Table 21), and thereafter efficiency improves according to Trajectory A.

Non-energy cost: Equipment lifetime, installed capital cost, and operating cost are from NCI (2004a), and capacity factor is calculated as the actual service output in 2005 divided by the maximum possible output. The service output is equal to the fuel consumption (EIA 2007, Table A4) multiplied by equipment efficiency (EIA 2007, Table 21). Maximum output is equal to the number of units (EIA 2007, Table 21) times the maximum hourly capacity of each unit in NCI (2004a) times the number of hours in a year.

Residential Lighting Service

Saturation is assumed to be 100% in 2005 (and all future years) for residential lighting service. The lighting technologies are all fueled by electricity, and as such energy consumption by each technology is not separated in the Annual Energy Outlook (EIA 1996 and 2007). The share of total lighting energy by incandescent and fluorescent/HID is therefore assigned according to the 2001 estimates in NCI (2002). The same proportion—90% incandescent and 10% fluorescent/HID—is used for 1990 and 2005 because no historical trend data is available. A second point should be noted: the lighting energy consumption by the residential sector in the Annual Energy Outlook differed between the two issues used due to a methodological difference in the energy estimation (J. Cymbalski, EIA, pers. comm.). As such, the 1990 energy consumption estimate is multiplied a factor, 2.1, designed to correct for this methodological difference. The factor was estimated using the 2000 lighting energy consumption estimate from the Annual Energy Outlook in 2002 and 2003, the years in which the methodological switch occurred. The amount of energy added to lighting was then subtracted from the “other” category.

Incandescent

Efficiency: 2005 efficiency is assumed to be 14.4 lumens per watt, calculated as the output (teralumen-hours; NCI 2002, Table 5-8) divided by the energy input (terawatt-hours; NCI 2002, Table 8-2). Future improvement takes place according to Trajectory A.

Non-energy cost: Incandescent non-energy cost is estimated as the sum of the fixture cost and the light bulb cost. Fixtures are assumed to last 12 years and cost $17.04 each (PNNL estimates); light bulbs are assumed to cost $1.20 each and to last for 1,500 hours. The capacity factor, 0.08, is calculated as the average number of hours per day that lights are on (NCI 2002, Table 8-6), and is assumed equal between the two technologies.

Fluorescent

Efficiency: 2005 efficiency is assumed to be 60 lumens per watt, calculated as the output (teralumen-hours; NCI 2002, Table 5-8) divided by the energy input (terawatt-hours; NCI 2002, Table 8-2). Future improvement takes place according to Trajectory C, reflecting the improvements with present-day technology.

Non-energy cost: Fluorescent non-energy cost is estimated as the sum of the fixture cost and the light bulb cost. Fixtures are assumed to last 14 years and cost $72.00 each (PNNL estimates); light bulbs are assumed to cost $3.60 and to last for 18,000 hours. The capacity factor is assumed to be 0.08.

Solid-state

Efficiency: This technology is not available in 2005. Improvement from an assumed 2005 value of 100 lumens per watt improves according to Trajectory B, to 127 lumens per watt in 2095, in the reference technology scenario. In the advanced scenario, Trajectory E is used, reaching 186 lumens per watt in 2095. This is within the range of future scenario assumptions for solid-state lighting in NCI (2006).

Non-energy cost: Capital cost of solid-state lighting remains constant in the future in the reference scenario ($50; PNNL estimate), and decreases according to technological improvement Trajectory E in the advanced scenario. Operating cost is $1.00 per year, and the lifetime is assumed to be 20 years (PNNL estimates).

Residential Appliances Service

Residential appliances consist of the following: refrigerators, freezers, washing machines, clothes dryers, and dishwashers. The saturation percentage in 2005, 98%, is determined from projections of the number of total appliance units relative to the number of housing units between 2005 and 2030 in EIA (2007, Table 21), and it is assumed that 100% saturation is reached in 2035. Gas clothes dryers are considered separately from the electric-fueled appliances; there is no efficiency or cost difference for gas dryers between the two technology scenarios. The electric-fueled appliances are treated in aggregate fashion in the model, using energy consumption-weighted averages for equipment efficiencies and non-energy costs.

Efficiency: Appliances are characterized by having high rates of improvement in recent times (residential NEMS stock model), and high projected rates of improvement through 2020 (EIA 2007, Table 21), after which efficiency improvements reach a plateau. In the scenarios presented, efficiency estimates are indexed to 2005. 1990 estimates are based on historical rates of improvement in each of the five appliance types (from the residential NEMS stock model), weighted by energy consumption in 2005 (EIA 2007, Table 21). The future efficiency improvement in 2020 and 2035 is calculated in similar fashion, using projected rates of improvement in EIA (2007, Table 21). For following periods, Trajectory D is used. In the advanced scenario, Trajectory D is used starting in 2035.

Non-energy cost: Capital costs and lifetimes for the different appliances are identical to those used in the BEopt program (Christensen et al. 2005). Because the efficiency is set to 1 across all appliances in 2005, the service output is assumed equal to the fuel consumption. Unit fuel consumption is calculated as total energy consumption by each appliance, divided by the number of appliances in the residential stock in 2005 (NEMS stock model). The cost per unit of service output is then averaged between the five appliances, weighted by energy consumption in 2005. Future costs are assumed to decrease at 0.1% per year through 2095.

Residential Other Services

Other services can be disaggregated into many sources, many of which do not have service outputs that can be measured in terms of energy. As with appliances, efficiency estimates are indexed to 2005, and therefore in 2005, energy consumption is assumed equal to service output. Saturation in 2005 is assumed to be 60%, as the category represents future services that do not currently exist. The category reaches full saturation in 2080.

Gas and Fuel Oil Other

No data were available on gas and fuel oil other technologies, so these are modeled in aggregate form, assuming 0.25% efficiency improvement per year. Non-energy costs are calculated by multiplying the electric other average non-energy costs by the non-energy cost ratio of gas appliances to electric appliances. Note that in historical years, the fuel oil category also includes the EIA category “other fuels,” which are specified as kerosene, coal, and other minor fuels (2007, Table A4).

Electric Other

The residential electric other services category consists of three categories from the Annual Energy Outlook (furnace fans, computers, and cooking equipment; EIA 2007), and another 13 from TIAX (2006). Each of these technologies is analyzed separately, and average efficiencies and non-energy costs are weighted by estimated energy consumption in 2005. These identified technologies account for 62% of the energy consumption by the other services category; the features of the identified technologies are assumed to represent the entire category.

Efficiency: Table A.6 shows each of the 16 technologies addressed explicitly, along with expected near-term future improvement rates, which are used to calculate an average “other” efficiency improvement rate for the near future in the reference scenario. No improvement is assumed to take place through 2035, after which the improvement rate is assumed to be 0.1% through 2095. In the advanced scenario, the other efficiency improvement rate matches that of residential appliances in the reference technology scenario, reflecting standards on the miscellaneous electric household equipment.

Table A.6. Residential other equipment total electricity consumption, and assumed annual improvement in unit energy consumption (UEC) between 2005 and 2025, reference technology scenario. Note: 1TWh = 0.0036 EJ. Sources: TIAX (2006), EIA (2007, Table A4).

	Electricity consumption TWh/yr	UEC improvement (2005-2025) % per year
TVs	73	-0.8%
Cooking equipment	31	0.0%
Set-top boxes	30	-1.3%
Furnace Fans	25	0.0%
Personal computers	23	0.0%
Ceiling fans	20	0.0%
Microwave ovens	16	0.0%
Audio equipment	13	0.4%
VCRs	12	2.0%
Portable electric spas	9.5	0.2%
Coffee machines	4.7	-0.2%
Cordless phones	4.16	0.6%
Power tools	3.63	0.9%
Security systems	1.8	2.1%
Cell phones	0.78	0.0%
Vacuum cleaners	0.48	0.7%
Total	**231**	**-0.07%**

Non-energy cost: The non-energy costs are calculated as a capital cost, levelized according to the equipment lifetime, divided by expected energy consumption per unit. Costs and lifetimes assumed for equipment are estimated from many sources, and are shown in Table A.7. The sources used include the BEopt computer program (Christensen et al. 2005), the Buildings Energy Data Book (D&R 2006), and the U.S. EPA EnergyStar Program, among others.

Table A.7. Non-energy costs of residential appliance and other categories, 2005. Costs are input to the model in 2005 $ per GJ of output. Because efficiency is indexed to 2005, energy input is equal to service output in this year.

	Capital cost $/unit	**Lifetime** years	**Annual cost** $/unit	**UEC** GJ/unit	**Non-energy cost** $/GJ	**Energy consumption** EJ
Refrigerators	1052	14	$142.81	3.79	$37.66	0.41
Freezers	500	12	$73.38	6.47	$11.34	0.13
Clothes washers	516	11	$79.44	0.46	$173.68	0.04
Electric clothes dryers	319	12	$46.82	3.67	$12.74	0.26
Dishwashers	293	13	$41.25	1.66	$24.80	0.03
Electric Appliances					**$31.36**	
Gas clothes dryers	363	12	$53.28	3.259872	$16.34	0.07

Gas Appliances					**$16.34**	
Cooking ranges	350	17	$43.63	2.17	$20.07	0.32
Computers	1800	3	$723.81	1.53	$474.42	0.08
Audio equipment	500	5	$131.90	0.43	$307.89	0.04
Ceiling fans	135	10	$21.97	0.29	$75.35	0.06
Coffee machines	150	8	$28.12	0.21	$134.66	0.01
Microwave ovens	300	9	$52.09	0.61	$86.03	0.05
Electric spas	4000	10	$650.98	9.09	$71.62	0.03
Rechargeable electronics	100	3	$40.21	0.10	$401.79	0.03
Security systems	1000	10	$162.75	0.27	$610.91	0.01
Set-top boxes	40	4	$12.62	0.64	$19.69	0.06
Televisions	600	7	$123.24	0.69	$177.38	0.30
VCRs/DVDs	300	7	$61.62	0.28	$219.45	0.05
Electric Other					**$145.93**	

A.1.5. Technological Specifications in the Commercial Sector

Efficiency and non-energy cost assumptions for all commercial building technologies are shown in Table A.8 and Table A.9. Except where noted, the saturation assumptions of each service in the commercial sector are equal to those used for the respective service in the residential sector.

Table A.8. Technological efficiency assumptions in the commercial sector. Unless otherwise noted, values are presented in terms of energy out divided by energy in.

	Historical		**Reference**		**Advanced**	
	1990	**2005**	**2050**	**2095**	**2050**	**2095**
Shell efficiency (indexed to 2005)	0.97	1.00	1.18	1.22	1.34	1.43
Heating						
Gas furnace/boiler	0.69	0.76	0.85	0.89	0.85	0.89
Gas heatpump	na	na	na	na	1.94	2.37
Electric furnace	0.98	0.98	0.99	0.99	0.99	0.99
Electric heatpump	2.67	3.10	3.69	3.83	3.95	4.10
Fuel oil furnace	0.73	0.77	0.81	0.84	0.81	0.84
Cooling						
Air conditioning	2.44	2.80	3.72	3.87	4.29	4.87
Water heating						
Gas water heater	0.72	0.82	0.93	0.93	0.93	0.93
Gas heatpump water heater	na	na	na	na	1.73	1.96
Electric resistance water heater	0.96	0.97	0.98	0.98	0.98	0.98
Electric heatpump water heater	na	na	na	na	2.69	2.80
Fuel oil water heater	0.74	0.76	0.80	0.82	0.80	0.82
Lighting (lumens per watt)						
Incandescent lighting	14	14	16	17	16	17
Fluorescent lighting	76	76	101	108	101	108
Solid-state lighting	na	na	122	127	152	186
Office equipment and other (indexed to 2005)						

Office equipment	1.00	1.00	1.12	1.15	1.56	1.61
Gas other	1.00	1.00	1.12	1.15	1.33	1.51
Electric other	1.00	1.00	1.12	1.15	1.33	1.51
Fuel oil other	1.00	1.00	1.12	1.15	1.12	1.15

Table A.9. Technology non-energy cost assumptions in the commercial sector. All values are presented in terms of 2005 $ per GJ of service output.

	Historical		**Reference**		**Advanced**	
	1990	**2005**	**2050**	**2095**	**2050**	**2095**
Aggregate building	13.20	22.92	67.83	172.43	67.83	172.43
Heating						
Gas furnace/boiler	1.95	1.77	1.58	1.52	1.58	1.52
Gas heatpump	na	na	na	na	14.42	11.78
Electric furnace	2.13	2.13	2.11	2.11	2.11	2.11
Electric heatpump	14.97	12.87	10.81	10.41	10.12	9.74
Fuel oil furnace	2.17	1.72	1.94	1.88	1.94	1.88
Cooling						
Air conditioning	13.23	11.54	8.66	8.34	7.52	6.62
Water heating						
Gas water heater	5.35	4.67	4.12	4.12	4.12	4.12
Gas heatpump water heater	na	na	na	na	41.15	30.89
Electric resistance water heater	3.31	3.26	3.21	3.21	3.21	3.21
Electric heatpump water heater	na	na	na	na	39.79	33.32
Fuel oil water heater	6.20	6.07	5.77	5.60	5.77	5.60
Lighting[1]						
Incandescent lighting	251	251	221	214	221	214
Fluorescent lighting	165	142	107	100	107	100
Solid-state lighting	na	na	304	293	209	162
Office equipment and other						
Office equipment	249.94	246.22	235.38	225.02	235.38	225.02
Gas other	80.67	80.67	80.67	80.67	80.67	80.67
Electric other	80.67	80.67	80.67	80.67	80.67	80.67
Fuel oil other	80.67	80.67	80.67	80.67	80.67	80.67

1 Lighting output converted to GJ assuming 683 lumens per watt; 1 GJ = 190 million lumen-hours

Aggregate Building Shell Efficiency and Cost

The commercial sector consists of office buildings, retail establishments, hotels, hospitals, schools, churches, restaurants, warehouses, and municipal buildings, among others. In this study, the commercial sector is modeled as a single, aggregate building with features representative of all types.

The thermal shell efficiency of commercial buildings is not estimated using a stock model due to the wide diversity of building types and lack of data from which to build a model. Instead, commercial shell efficiency improvement is estimated with a technology trajectory, informed by the insulation properties of stock compared to new building materials for 12 commercial building types in Sezgen et al. (1995, Table 6.2), and the building stock turnover time implied by the age distribution of commercial buildings (CBECS: EIA 2003). In the reference scenario, building shell efficiency in 2095 exceeds that of 2005 by 18%; this improvement is 30% in the advanced scenario.

Building non-energy costs in historical years are calculated as the per-business revenue from the commercial sector, multiplied by an assumed fixed charge rate of 10% to estimate the capital cost (10%), plus the revenue times as assumed fixed charge rate of 5% to estimate the operating costs. This is then divided by the total number of square feet of floorspace in the commercial sector. As in the residential sector, the future increase in floorspace non-energy costs is determined by matching exogenous supply and demand curves calculated using scenario assumptions of elasticities and future GDP and population growth.

Commercial Heating Service

The capacity factors of all heating equipment in the commercial sector is assumed to be 0.10, as data on the total number of units are not available.

Gas Furnace/Boiler

The reference and advanced scenarios do not differ in assumptions for gas furnaces.

Efficiency: In 2005, efficiency is from EIA (2007, Table 22) and the 1990 value is back-calculated from this estimate using the average 2003-2010 rate of efficiency improvement in EIA (2007, Table 22). The reference scenario assumes that efficiency in 2020 and 2035 follows projected rates of improvement for these time periods (EIA 2007, Table 22), and thereafter efficiency improvement follows trajectory A.

Non-energy cost: Equipment lifetime, installed capital cost, and operating cost are from NCI (2004a). No changes are assumed for the future.

Gas Heatpump

Because gas heatpumps currently have no market share (nor does the EIA project their entry by 2035; EIA 2007, Table 21), they are not included in the reference scenario. In the advanced scenario, they enter in 2020, but have a low share weight, reflecting limited applicability (e.g. in warmer climate zones only).

Efficiency: The 2020 estimate is equal to the EIA (2007, Table 21) residential gas heatpump estimate for 2030. Trajectory E is used for all years thereafter.

Non-energy cost: Capital and operating costs are calculated as compared to the costs of gas furnaces in the NEMS technological inputs module. Equipment lifetime is assumed equal to that of electric heatpumps.

Electric Furnace/Boiler

The reference and advanced scenarios do not differ in assumptions for this technology.

Efficiency: Efficiency reaches its theoretical maximum of 0.99 in 2020.

Non-energy cost: Capital and operating costs are calculated as compared to the costs of gas furnaces in the NEMS technological inputs module. Equipment lifetime is from NCI (2004a).

Base year energy consumption: Because electric furnaces share the electricity-fueled space heating category with electric heatpumps, a commercial NEMS stock model is used to estimate the relative energy consumption of each technology in 1990 and 2005.

Electric Heatpump

Efficiency: The 2005 estimate is from NCI (2004a), and the 1990 estimate is back-calculated from this value assuming 1% per year improvement. In the reference scenario, the 2020 stock efficiency is equal to the typical stock heatpump in NCI (2004a), and thereafter, improvement follows Trajectory B. In the advanced scenario, the 2020 efficiency is equal to the NCI (2004a) estimate for a high-efficiency heatpump in 2010, and the 2035 estimate is based on the similar NCI (2004a) estimate for 2020. Thereafter, improvement follows Trajectory B.

Non-energy cost: Capital and operating costs are calculated as compared to the costs of gas furnaces in the NEMS technological inputs module. Equipment lifetime is from NCI (2004a).

Oil furnace

The reference and advanced scenarios do not differ in assumptions for oil furnaces.

Efficiency: The 2005 estimate is from EIA (2007, Table 22), and the 1990 value is back-calculated from this estimate using the average 2003-2010 rate of efficiency improvement in EIA (2007, Table 22). Efficiency in 2020 and 2035 is estimated from projected rates of improvement in EIA (2007, Table 22), and thereafter efficiency improves according to Trajectory A.

Non-energy cost: Capital and operating costs are calculated as compared to the costs of gas furnaces in the NEMS technological inputs module. Equipment lifetime is from NCI (2004a).

Commercial Cooling Service

Air Conditioning

Efficiency: The 2005 estimate is from EIA (2007; Table 22), and the 1990 value is back-calculated from this estimate using the average annual rate of efficiency improvement between 2003 and 2010 in EIA (2007, Table 22). In the reference technology scenario, efficiency in 2020 is equal to the EIA projection, and the 2035 estimate is calculated assuming the rate of improvement between 2020 and 2030 in EIA (2007, Table 21). Future improvement takes place according to Trajectory B. In the advanced technology scenario, the EIA projection for 2030 is reached in 2020, and thereafter, improvement takes place according to Trajectory D.

Non-energy cost: Equipment lifetime, installed capital cost, and operating cost are from NCI (2004a), and capacity factor is assumed to be 0.10.

Commercial Water Heating Service

The capacity factors of all water heating equipment in the commercial sector is assumed to be 0.05, as data on the total number of units are not available.

Gas Water Heater

The reference and advanced scenarios do not differ in assumptions for gas water heaters.

Efficiency: In 2005, efficiency is from EIA (2007, Table 22) and the 1990 value is back-calculated from this estimate using the average 2003-2010 rate of efficiency improvement in EIA (2007, Table 22). The reference scenario assumes that efficiency in 2020 and 2035 follows projected rates of improvement for these time periods (EIA 2007, Table 22), and reaches the assumed maximum possible efficiency for gas water heaters (0.93) in 2050.

Non-energy cost: Equipment lifetime, installed capital cost, and operating cost are from NCI (2004a). No changes are assumed for the future.

Gas Heatpump Water Heater

The technology is not used in 1990 or 2005, and does not enter the market in the reference scenario.

Efficiency: Efficiency is assumed equal to the residential sector average efficiency.

Non-energy cost: Capital and operating costs are estimated using the cost factors between gas heatpumps and gas furnaces in the commercial NEMS technical input module. The lifetime is assumed equal to that of electric heatpump water heaters.

Electric Resistance Water Heater

Reference and advanced scenario assumptions for electric resistance water heaters do not differ.

Efficiency: Efficiency reaches its theoretical maximum of 0.98 in 2020.

Non-energy cost: Equipment lifetime, installed capital cost, and operating cost are from NCI (2004a), and capacity factor is calculated as the actual service output in 2005 divided by the maximum possible output. The service output is equal to the fuel consumption (EIA 2007, Table A4) multiplied by equipment efficiency (EIA 2007, Table 21). Maximum output is equal to the number of units (EIA 2007, Table 21) times the maximum hourly capacity of each unit in NCI (2004a) times the number of hours in a year.

Electric Heatpump Water Heater

The technology is not used in 1990 or 2005, and does not enter the market in the reference scenario.

Efficiency: Efficiency in 2020 is based on the typical equipment efficiency in NCI (2004a), and improves according to Trajectory C.

Non-energy cost: Capital and operating costs are calculated as compared to the costs of gas water heaters in the NEMS technological inputs module. Equipment lifetime is from NCI (2004a).

Oil Water Heater

Efficiency: The 2005 estimate is from EIA (2007, Table 22), and the 1990 value is back-calculated from this estimate using the average 2003-2010 rate of efficiency improvement in EIA (2007, Table 22). Efficiency in 2020 and 2035 is estimated from projected rates of improvement in EIA (2007, Table 22), and thereafter efficiency improves according to Trajectory A.

Non-energy cost: Capital and operating costs are calculated as compared to the costs of gas water heaters in the NEMS technological inputs module. Equipment lifetime is from NCI (2004a).

Commercial Lighting Service

As in the residential sector, no distinction is made in the Annual Energy Outlook (EIA 1996, 2007) between incandescent and fluorescent energy consumption. Therefore, the fraction of energy consumption by each of these technologies is assigned according to NCI (2002): fluorescent/HID lighting consumes 68%, and incandescent the remaining 32%. This share is assumed for both 1990 and 2005 because no historical trend data is available. The capacity factor, 0.41, is calculated as the average number of hours per day that lights are on (NCI 2002, Table 8-6), and is assumed equal between the two technologies. Note that it is far higher than the capacity factor in the residential sector, which has the effect of decreasing the per-output service costs. Lighting capital costs in the commercial sector are also assumed to be 20% lower than in the residential sector due to bulk purchasing.

Incandescent

Efficiency: 2005 efficiency is assumed to be 14.3 lumens per watt, calculated as the output (teralumen-hours; NCI 2002, Table 5-8) divided by the energy input (terawatt-hours; NCI 2002, Table 8-2). Future improvement takes place according to Trajectory A.

Non-energy cost: Incandescent non-energy cost is estimated as the sum of the fixture cost and the light bulb cost. Fixtures are assumed to last 12 years and cost $14.00 each (PNNL estimates); light bulbs are assumed to cost $1.00 each and to last for 1,500 hours.

Fluorescent

Efficiency: 2005 efficiency is assumed to be 76 lumens per watt, calculated as the output (teralumen-hours; NCI 2002, Table 5-8) divided by the energy input (terawatt-hours; NCI 2002, Table 8-2). Future improvement takes place according to Trajectory C, reflecting the improvements possible with present-day technology.

Non-energy cost: Fluorescent non-energy cost is estimated as the sum of the fixture cost and the light bulb cost. Fixtures are assumed to last 14 years and cost $60.00 each (PNNL estimates); light bulbs are assumed to cost $3.00 and to last for 18,000 hours. The capacity factor is assumed to be 0.08.

Solid-state

Assumptions for solid-state lighting are identical to the assumptions in the residential sector, with the 20% cost reduction to account for bulk purchasing, and the higher capacity factor which has the effect of reducing per-output service costs. The efficiencies are equal to those assumed for the residential sector; in the reference scenario, the 2095 stock average efficiency is 127 lumens per watt, whereas in the advanced scenario it is 186 lumens per watt in 2095.

Commercial Office Equipment

Commercial office equipment is assumed to be 70% saturated in 2005, and to reach full saturation in 2050. Office equipment is a fast-growing energy consumer, and little historical efficiency improvement has been evident for these technologies. Development for these technologies has focused on improving qualitative function (e.g. speed, cost) rather than unit energy consumption. In this study, individual technologies (computers, copies, fax machines and copiers) are modeled in aggregate form, but accessed individually in order to estimate efficiency and non-energy cost changes over time.

Efficiency: Efficiency is indexed to the 2005 value, due to the lack of any simple method to convert energy consumption into actual service. No efficiency improvement is assumed in the reference scenario between 2005 and 2020; thereafter Trajectory A is used. In the advanced scenario, it is assumed that the stock average of commercial office equipment reaches the savings possible by switching to EnergyStar equipment, as outlined in NCI (2004a). The energy savings possible for computers, printers, fax machines, and copiers are weighted by the energy consumption of each in 2005 (assuming equal numbers of each, and the unit energy consumption shown in Table A.10) in order to compute an average efficiency improvement for all office equipment.

Non-energy cost: Cost estimates in historical years are shown in Table A.10; these estimates are based on a variety of sources, including Kawamoto et al. (2001) and the Building Energy Data Book (D&R 2005). Estimates for these individual technologies are weighted by energy consumption in order to compute the average cost; the energy consumption estimates are from EIA (2007, Table A5), and assume equal numbers of copiers, fax machines, and printers.

Table A.10. Assumptions used to calculate non-energy costs of commercial office equipment, 2005. Costs are represented in 2005 $ per GJ of service output, assumed equal to energy consumption in 2005.

	Capital cost	**Lifetime**	**Annual cost**	**UEC**	**Non-energy cost**	**Energy consumption**
	$/unit	years	$/unit	GJ/unit	$/GJ	TWh
Computers	1800	4	$567.85	3.18	$178.84	50.0
Printers	700	5	$184.66	1.14	$161.30	19.4
Copiers	1616	6	$371.05	3.80	$97.69	61.1
Fax Machines	200	5	$52.76	1.11	$47.74	16.7
Office Equipment					**$127.28**	

Commercial Other Services

Commercial other services are assumed to be 70% saturated in 2005, and to reach full saturation in 2080. As in the residential sector, other services can be disaggregated into many sources, many of which do not have service outputs that can be measured in terms of energy. Efficiency is therefore indexed to 2005, and in 2005, energy consumption is equal to service output. As a side note, approximately two thirds of the commercial other energy consumption that is addressed explicitly in this study represents energy expended exterior to the building shell. As such, this end-use category contributes relatively little to internal gains (see Table A.2).

Gas and Fuel Oil Other

No data were available on gas and fuel oil other, so these are modeled in aggregate, assuming 0% improvement between 2005 and 2020, and Trajectory A thereafter. Non-energy costs are equal to the electric other costs. Note that in historical years, the fuel oil category also includes the EIA category “other fuels,” which are specified as LPG, kerosene, coal, and other minor fuels (2007, Table A4).

Electric Other

The residential electric other services category consists of fourteen aggregated services, shown in Table A.11. Three of these services are from the Annual Energy Outlook (furnace fans, computers, and cooking equipment; EIA 2007), and the other 11 are from

TIAX (2006). Each of these technologies is analyzed separately, and average efficiencies and non-energy costs are weighted by estimated energy consumption in 2005. These identified technologies account for 53% of the total other service category; the features of the identified technologies are assumed to represent the entire category.

Efficiency: Table A.11 shows each of the 14 technologies addressed explicitly, along with near-term future improvement rates, which are used to calculate an average “other” efficiency improvement rate for the near future in the reference scenario. In the advanced scenario, the other efficiency improvement rate is 0.5% between 2005 and 2020, and thereafter, it is assigned to Trajectory D. The commercial other category represents technologies with long lifetimes (e.g. water treatment and distribution infrastructure), and as such will be slower to improve in efficiency than residential appliances, for example.

Table A.11. Commercial other technologies, by energy consumption, and projected unit energy consumption improvement (2005-2025) for the reference technology scenario. Note: 1TWh = 0.0036 EJ. Sources: TIAX (2006), EIA (2007, Table A5).

	Energy consumption TWh/yr	UEC improvement (2005-2025) % per year
Refrigeration	64.6	0.26%
Distribution transformers	53.8	1.06%
Ventilation	52.2	0.00%
Water distribution	44.0	0.15%
Water treatment	26.0	-0.16%
Cooking	10.7	0.00%
X-Ray	8.9	-2.69%
Non-road electric vehicles	5.8	0%
Elevators	4.9	0.71%
Coffee makers	3.2	0.09%
Magnetic Resonance Imaging	2.9	-2.06%
Computed Tomography	2.2	0%
Water purification	1.2	0%
Escalators	0.9	0%
Total	264.9	**0.39%**

Non-energy cost: Cost data for commercial other equipment are not available, and therefore non-energy costs for all fuels are assumed equal to 60% of the cost of the other electric equipment in the residential sector. No change is assumed in commercial other cost in the future in either scenario.

A.2. U.S. Transportation Module

The U.S. transportation module consists of four sectors: passenger, freight, military, and pipeline. Military and pipeline transportation are modeled in aggregate; efficiency does not change in the future in either technology scenario, and future energy consumption is determined by income elasticities and fuel price elasticities. All elasticities are shown in Table A.12. Historical calibration of the passenger and freight sectors is based on the following input parameters for each transportation technology: energy consumption, vehicle miles traveled, load factor, and non-energy cost. Vehicle fuel intensity in historical years is calculated as total energy consumption divided by total vehicle miles traveled. In future years, load factors remain constant. The distinction between future reference and advanced technology scenarios lies mostly in assumptions about vehicle fuel intensities, non-energy costs of several key technologies, and availability of advanced transportation technologies (e.g. high-speed rail).

Table A.12. Income elasticity and fuel price elasticity assumptions for the four sectors of the U.S. transportation module.

	Income	Price
Passenger	1.0	-0.4
Freight	0.5	-0.5
Military	0.25	-0.2
Pipeline	0.5	-0.5

The market share of technologies competing within a mode (e.g. HEV and ICE automobiles) depends on the relative costs of service provision, and the “share weight” (availability) of each technology. Costs consist of the sum of the non-energy cost, which is an exogenous model input, and the energy cost. The energy cost is equal to the service intensity (an exogenous model input) times the fuel price in a given period, which is an endogenous output of the model.

In addition to the technological competition, there is competition that takes place at the modal level (e.g. between rail and air). This modal competition also depends on relative costs and share weights. Relative costs at the modal level consist of the weighted average cost (non-energy cost plus energy cost) of all technologies competing within the mode, plus a time value of transportation cost, which in this study is only assessed in the passenger sector. The time value of transportation (per mile) is assumed equal to the wage rate divided by the average vehicle speed; faster vehicles therefore incur lower time value costs. In this study, vehicle speeds are not assumed to vary over time, and are shown in Table A.13.

Table A.13. Assumed average speed and load factor for each passenger and freight transportation mode. Note that no time value of freight transportation is assessed in this study, so the speeds shown for freight transportation do not influence the costs of service provision.

	Speed	Load factor
Passenger mode	mph	passengers / vehicle
Auto	30	1.57
Truck	30	1.72
Bus	25	17.1
Rail	35	23.5
Air	120	143
High-Speed Rail	100	310
Ship	5	4
Motorcycle	35	1.22

Freight mode		tons / vehicle
Truck	30	5.85
Rail	24	43.6
Air	120	15.4
Ship	5	16732

A.2.1. Fuel Intensity

Transportation costs in the passenger and freight sectors are influenced by service fuel intensity; in the passenger sector, this refers to energy consumption per passenger-mile, and in the freight sector this refers to the energy consumption per ton-mile. This *service* fuel intensity is equal to the *vehicle* fuel intensity divided by the load factor. Load factors in this study do not vary between technologies within any given mode, or over time, and are shown in Table A.13.

Future fuel intensity improvements for the reference and advanced technology scenarios are informed by projections and studies, and are addressed for each individual technology in Sections A.2.3 and A.2.4. Service fuel intensities for all transportation technologies are shown in terms of Btu per service mile in Table A.14. Note that these values refer to final energy, and do not account for electricity-related losses.

Table A.14. Service fuel intensities for technologies in the passenger and freight sectors.

	Historical		**Reference**		**Advanced**	
	1990	**2005**	**2050**	**2095**	**2050**	**2095**
Passenger service fuel intensity (Btu per passenger-mile)						
Hybrid Auto	na	2491	2095	1844	1261	962
ICE Auto	3560	3222	2710	2386	1900	1449
Hybrid Truck	na	2918	2171	1741	1721	1312
ICE Truck	4469	3698	2752	2207	2181	1663
Diesel bus	1304	1341	1282	1226	1282	1226
Hybrid bus	1029	1058	1012	967	1012	967
CNG bus	1799	1850	1769	1691	1769	1691
Trolleybus	440	453	433	414	433	414
Diesel rail	1798	1719	1644	1571	1644	1571
Electric rail	1035	1052	1005	961	1005	961
High speed rail	na	na	na	na	660	631
Air	3624	2357	1698	1461	1316	1133
Motorcycle	2093	2048	1958	1871	1958	1871
Freight service fuel intensity (Btu per ton-mile)						
Truck	3601	3717	3146	2811	2225	1776
Diesel rail	420	338	324	309	324	309
Electric rail	na	na	na	na	109	104
Air	34440	21944	18630	17283	16415	15228

Ship	237	212	202	193	202	193

A.2.2. Transportation costs

Transportation costs consist of energy costs, non-energy costs, and in the passenger sector, time value costs. The energy costs are determined by fuel prices and service fuel intensities, non-energy costs are model inputs, and time value costs are determined by the wage rate. The wage rate is calculated as the per-capita GDP divided by 2000 working hours in a year, and therefore increases substantially during the time frame of this analysis.

The non-energy costs of automobile ownership are summarized in Table 10.12 of the 2006 Transportation Energy Data Book (TEDB; Davis and Diegel 2006), and consist of depreciation of capital costs, insurance, registration fees, and taxes, as well as operating (maintenance) costs. Such components of transportation non-energy costs are not separated in the transportation module; non-energy costs are modeled in aggregate form. For other transportation modes, the following equation was generally used to calculate non-energy cost of technology *i* in 2005:

$$NonEnergyCost_i = Revenue_i * LoadFactor_i - VehicleIntensity_i * FuelCost$$

Revenue refers to the revenue per revenue passenger (or ton) mile. Each transportation technology is assigned a vehicle cost per mile, which can be converted to a service cost by dividing by the load factor(this allows comparison between modes). All transportation technology service costs are shown in Table A.15. Note that, in contrast to vehicle fuel intensity, there is not widespread improvement assumed in costs of transportation technologies, even in the advanced scenario. This is because costs of transportation have not decreased historically (e.g. Davis and Diegel 2006, Table 10.11), as technological change has been focused on design improvements that do not necessarily reduce costs.

Table A.15. Passenger and freight service non-energy costs. Note that these costs do not account for the time value of transportation.

	Historical		**Reference**		**Advanced**	
	1990	**2005**	**2050**	**2095**	**2050**	**2095**
Passenger service non-energy cost (2005 $ per passenger-mile)						
Hybrid Auto	na	0.294	0.294	0.294	0.243	0.243
ICE Auto	0.200	0.243	0.243	0.243	0.243	0.243
Hybrid Truck	na	0.296	0.296	0.296	0.245	0.245
ICE Truck	0.221	0.245	0.245	0.245	0.245	0.245
Diesel bus	0.072	0.077	0.077	0.077	0.077	0.077
Hybrid bus	0.087	0.093	0.093	0.093	0.077	0.077
CNG bus	0.087	0.092	0.092	0.092	0.092	0.092
Trolleybus	0.082	0.087	0.087	0.087	0.087	0.087

Diesel rail	0.085	0.128	0.128	0.128	0.128	0.128
Electric rail	0.102	0.090	0.090	0.090	0.090	0.090
High speed rail	na	na	na	na	0.156	0.156
Air	0.076	0.067	0.051	0.051	0.051	0.051
Motorcycle	0.187	0.184	0.184	0.184	0.184	0.184
Freight service non-energy cost (2005 $ per ton-mile)						
Truck	0.154	0.158	0.158	0.158	0.158	0.158
Diesel rail	0.017	0.014	0.014	0.014	0.014	0.014
Electric rail	na	na	na	na	0.016	0.016
Air	0.297	0.271	0.208	0.208	0.208	0.208
Ship	0.004	0.004	0.004	0.004	0.004	0.004

A.2.3. Technological Specifications in the Passenger Sector

Auto and Light Truck

Internal Combustion Engine (ICE) Vehicle

Load factor: Davis and Diegel (2006, Table A17) is used for 1990; for 2003, Davis and Diegel (2006, Table 2.10) is used.

Non-energy cost: Non-fuel costs for both 1990 and 2005 are from Davis and Diegel (2006, Table 10.11). The 2003 estimate is assumed for 2005, and all periods thereafter.

Vehicle fuel intensity: Davis and Diegel (2006, Table 2.11) is used for both 1990 and 2005. The 2005 estimate is calculated by linear extrapolation from 1990–2003 trend. In the reference scenario, improvement rates are assumed equal to EIA (2007, Table A7) from 2005 to 2020 (0.59% per year for auto, 0.99% for light truck), with the 2020–2030 annual rates of improvement (0.28% per year for auto, 0.49% for truck) extrapolated to 2095. In the advanced scenario, improvement rates are greater than 1% per year from 2005 to 2050, and decline to 0.5% per year thereafter. Auto stock average fuel economy is 33 mpg in 2035, and 50 mpg in 2095 (DeCicco et al. 2001, NRC 2002).

Energy consumption: Davis and Diegel (2006, Table 2.6) is used for 1990; EIA (2007, Table 35) is used for 2005. Hybrid energy consumption is subtracted from the total.

Hybrid Electric Vehicle (HEV)

Load factor: HEV load factor is assumed equal to ICE vehicle.

Non-energy cost: Hybrids are assumed 21% more expensive than ICE (as in Lipman and Delucchi 2006). In the reference scenario, this cost premium is assumed to remain constant in future time periods. In the advanced scenario, HEV costs converge with ICE costs in 2050.

Vehicle fuel intensity: HEV intensity is assumed to be 23% less than ICE auto fuel intensity, and 21% less than ICE light truck fuel intensity, based on EPA estimates for fuel economy of HEV and ICE versions of similar makes of vehicles in 2007. Auto models used consisted of the Honda Accord, Toyota Prius/Yaris, Honda Civic, Toyota Camry, Lexus 450, and Nissan Altima. Truck models consisted of the Ford Escape, Lexus RX, Saturn Vue, Mercury Mariner, and Toyota Highlander.

Energy consumption: The HEV share in mileage is assumed proportional to the share in registrations (R.L. Polk & Co.; http://usa.polk.com); the energy consumption share was assumed equal to vehicle fuel intensity multiplied by registration share (hybrid registrations compared to total car registrations).

Future intensity improvement: Future intensity improves at the same rate as ICE in the reference technology scenario. In the advanced scenario, it is assumed to be 2% per year in 2005–2020, declining over time, such that HEV stock averages reach 75 mpg for auto and 50 mpg for light trucks by 2095.

Bus

Load factor: Load factors are assumed equal across all four technologies. In 1990, this is assumed to be 17.1 persons per vehicle (Davis and Strang 1993), and in 2005, it is assumed to be 16.6 persons per vehicle from Davis (2000, Table 2.11).

Diesel

Non-energy cost: Revenue per revenue passenger mile is from BTS (2005, Table 7.5A and 7.6A), with fuel cost from Table 14.4A (BTS 2005).

Vehicle fuel intensity: Intensity is calculated as energy use (1990: Table 2.6 in Davis 1995) divided by total vehicle miles (1990: Table 3.2 in Davis 1995), with transit buses, inter-city buses, and school buses calculated separately, weighted by energy consumption. Vehicle fuel intensities for inter-city buses and school buses could only be calculated for 1990; 2005 intensities for each bus type are assumed equal to the 1990 values. Future vehicle intensities in both technology scenarios are assumed to improve at 0.1% per year.

Energy consumption: For 1990, Davis and Diegel (1995, Table 2.6) is used; total bus energy consumption was assumed equal to the sum of transit, intercity, and school buses. Electric and CNG transit bus energy use is subtracted (see below). For 2005 energy consumption, EIA (2007, Table 35) is used.

Total vehicle miles: Estimates for transit buses in 1990 and 2003 are from Davis and Diegel (2006, Table 5.12). Intercity and school buses in 1990 come from Davis (1995, Table 3.27). Intercity and school bus vehicle miles in 2000 are used for 2005 due to lack of more recent data; Davis (1995) Table 5.13.

Electric and CNG

Non-energy cost: CNG is assumed to be 20% more expensive than diesel; electric is assumed to be 13% more expensive (based on National Transit Database operating costs per passenger mile).

Vehicle fuel intensity: Conversion factors are calculated for electric-diesel and CNG-diesel. Electric intensity is assumed to be approximately one third of diesel intensity, and CNG intensity is assumed to be 37% higher than diesel intensity, based on NREL (Chandler et al. 2006). Future intensity improves at 0.1% per year for both technologies, in both scenarios.

Energy consumption: The 1990 values were calculated from Davis and Diegel (2006), Table A3, using 3324 British thermal units per kilowatthour (Btu/kWh) for electric buses. The 2003 electric and CNG shares of bus fuel use were assumed to remain equal in 2005.

Hybrid

Non-energy cost: Hybrid buses are assumed to be 21% more expensive than diesel; this was the same cost premium as was used for light truck and auto. In the reference technology scenario, this cost premium remains through 2095, and in the advanced, it converges with diesel bus costs in 2050.

Vehicle fuel intensity: Hybrid buses are assumed 27% more efficient than diesel buses, similar to HEV to ICE vehicle fuel intensity ratio for light duty vehicles (auto and truck).

Energy consumption: No calibration data was entered.

Rail

Diesel and Electric

Due to the level of data overlap between diesel and electric rail, the two technologies are addressed together in this section, with the distinguishing features highlighted.

Load factor: This was calculated from Davis and Diegel (2006) data on total service output and vehicle miles traveled (Tables 9.13–9.15; sum of Amtrak, commuter, and transit rail).

Non-energy cost: This was based on BTS (2005, Table 7.5a/7.6a) for revenue per passenger mile, and Table 14.4a (BTS 2005) for fuel costs.

Energy consumption: The 1990 estimate is based on Davis and Diegel (2006, Tables A.13 to A.15), with electricity consumption recalculated without primary energy conversion. Fuel mixes for transit rail, intercity rail, and commuter rail came from Tables A.14, A.15, and A.13, respectively. Shares of diesel versus electric from 2003 are assumed for 2005, but the 2005 aggregate energy consumption estimate is from AEO 2007 (EIA 2007).

Vehicle fuel intensities: Diesel intensity was calculated as weighted average of Amtrak (which is about 90% diesel; Davis and Diegel (2006, Table A.15)) intensity and commuter rail intensity (Davis and Diegel 2006, Table A.13), weighted by the number of miles traveled by each (Davis and Diegel 2006, Tables 9.13 and 9.14). Commuter rail number of miles were multiplied by the percent that were fueled by diesel (as calculated by commuter rail consumption of diesel fuel and electricity).

Aggregate commuter rail fuel intensity was adjusted accordingly to calculate diesel-only commuter rail intensity:

$$\mathit{DieselFuelIntensity}_{\mathit{Commuter}} = \mathit{FuelIntensity}_{\mathit{Commuter}} * \frac{\mathit{FuelIntensity}_{\mathit{Amtrak}} + \mathit{FuelIntensity}_{\mathit{transit}}}{2 * \mathit{FuelIntensity}_{\mathit{transit}}}$$

Electric intensity was calculated as weighted average of transit rail (which is 100% electric; Table A.14) and commuter rail (Table A.13), weighted by the number of miles traveled by each (Tables 9.14 and 9.15). Commuter rail number of miles (Table 9.14) were multiplied by the percentage that were fueled by electricity.

Aggregate commuter rail fuel intensity was adjusted accordingly to calculate electric-only commuter rail intensity:

$$\mathit{ElectricFuelIntensity}_{\mathit{Commuter}} = \mathit{FuelIntensity}_{\mathit{Commuter}} * \frac{\mathit{FuelIntensity}_{\mathit{Amtrak}} + \mathit{FuelIntensity}_{\mathit{transit}}}{2 * \mathit{FuelIntensity}_{\mathit{Amtrak}}}$$

Future vehicle intensity is assumed to improve at 0.1% per year for both diesel and electric trains, in the reference and advanced technology scenarios.

High-Speed Rail

High-speed rail is modeled as a mode separate from rail, as the average transit speed is greater than that of regular rail. The technology is only available in the advanced technology scenario, starting in 2020. Even in this case, the share weight remains low through 2095, reflecting limited availability (only a limited number of high-population corridors are likely to be suitable for this mode).

Vehicle fuel intensity and load factor: These are estimated as the average of the four electric-fueled high-speed rail systems worldwide detailed in CCAP & CNT (2006). The systems include the TGV (France), ICE (Germany), MagLev (Japan) and Shinkansen (Japan). Future intensity improvement is assumed to be 0.1% per year.

Non-energy costs: Non-energy costs are estimated based on the costs comparing aviation to high-speed rail development Levinson et al. (1999). High-speed rail costs are assumed to be 1.8 times greater than aviation. Note that this figure includes the costs of building the infrastructure.

Air

Vehicle miles and energy consumption are disaggregated into passenger and freight according to the respective proportion of ton-miles serviced in a given year, assuming a passenger weight of 200 lbs per person (BTS 1995).

Passenger and freight ton-miles, and vehicle miles: 1990 estimates are based on Davis and Diegel (2006, Table 9.2). The 2005 estimates are from BTS (2007a), multiplied by an adjustment factor to match Davis and Diegel (2006) vehicle miles in years 1996 to 2003.

Load factor: This is calculated based on revenue passenger miles traveled (BTS 2007a), divided by number of passenger vehicle miles traveled (the total vehicle miles minus the freight share; BTS 2007a). Because many planes carry both passengers and freight, this method results in a higher load factor (143 persons per plane) than simply dividing total passenger miles by total vehicle miles (96 persons per plane).

Non-fuel cost: Estimates of revenue per revenue passenger are from BTS (2007b, Table 3.16), and fuel costs are from BTS (2007c**)**. The 2002 estimate of revenue per passenger is assumed for 2005. In both reference and advanced technology scenarios, costs decrease roughly matching the trajectory projected for DOC/RPK in Lee et al. (2001).

Energy consumption: This is calculated from airline fuel use (BTS 2007c), corrected for the fraction allocated to passenger transportation.

Vehicle fuel intensity: This is calculated as energy consumption times the load factor, divided by the service output. In reference scenario, improvement rates are set to match EIA (2007, Table A7) through 2035, declining to 0.5% per year through 2065 and 0.25% per year thereafter. In advanced scenarios, improvements in airline fuel use take place more rapidly, reaching the AEO projection for 2030 by 2020. Improvements in both aircraft design and whole-system management continue for the next two time periods, until whole-system airline fuel use approaches present-day fuel intensities of individual aircraft in Lee et al. (2001).

Recreational Boat

While generally not used as a form of transportation, recreational boats are nevertheless significant energy users, accounting for 203 trillion Btu in 2003. Data on fuel intensity and load factor for recreational boats is not available; in this study, fuel intensity is assumed equal to three times that of a freight truck in 2005, and is assumed to improve by 0.1% per year in both the reference and advanced technology scenarios. Load factor is assumed to be four persons per vehicle.

Motorcycle

Fuel intensity, load factor, service output, and energy consumption: 1990 data are from Davis and Strang (1993), and 2005 assumptions are based on the 2003 estimates from Davis and Diegel (2006). Passenger miles and load factor are from Table 2.10, and energy consumption from Table 2.6 (Davis and Diegel 2006). Vehicle fuel intensity is calculated as the product of load factor and fuel consumption divided by the number of passenger miles. Future fuel intensity is assumed to improve by 0.1% per year in both the reference and advanced technology scenarios.

A.2.4. Technological Specifications in the Freight Sector

Truck

Load factor: Load factor is calculated from service (ton-miles, BTS 2005, Table 1-9b) divided by vehicle miles (Davis and Diegel 2006, Tables 5.1–5.2).

Vehicle fuel intensity: Fuel intensity is from heavy single-unit and combination truck fuel intensity, Davis and Diegel (2006), Table 2.14.

Non-fuel cost: Revenue per revenue ton-mile is from BTS (2007d). Fuel costs are from BTS (2005, Table 14.4a**)**.

Energy consumption: Energy consumption is from Davis and Diegel (2006) Table 2.6.

Rail

In the reference technology scenario, all rail is assumed to be powered by diesel. In the advanced scenario, electric freight rail is available as a technology option. However, its deployment is limited by a low share weight, reflecting the assumption that electric freight rail would only be used in several corridors.

Diesel

Load factor: Load factor is calculated as service output (in ton-miles) divided by vehicle miles (per car; Davis and Diegel 2006, Table 9.10).

Energy consumption: This came from Davis and Diegel (2006) Table 9.10.

Fuel intensity: Vehicle fuel intensity (per rail car) is calculated as energy use divided by vehicle miles. Future intensity is assumed to improve at 0.1% per year.

Non-fuel cost: Revenue per revenue ton-mile is from BTS (2007d), and fuel costs are from BTS (2005, Table 14.4a**)** times vehicle fuel intensity.

Electric

Fuel intensity: Applicable data on electric freight rail fuel intensity are not available; this study uses an estimate based on the energy intensity of three electric freight train types in Germany (Jorgensen and Sorenson 1997, Figure 9.7). This estimate is multiplied by 1.3 to account for empty trains and other system losses. Future intensity improves at 0.1% per year.

Non-fuel cost: This is assumed equal to diesel non-fuel cost.

Air

Load factor: This is calculated from freight ton-miles divided by vehicle miles allocated to freight (share of freight ton-miles divided by the sum of freight and passenger ton miles, assuming 200 pounds per passenger; BTS 2007a).

Energy consumption: This is calculated as total fuel consumption by aviation multiplied by freight-to-total service proportion (BTS 2007c).

Vehicle fuel intensity: Fuel intensity is calculated as energy consumption times load factor divided by service output. Future vehicle intensity in the reference scenario is assumed to improve at one half of the rate of passenger air vehicle fuel intensity. Similarly, future freight air fuel intensity in the advanced scenario improves at one half of the rate of improvement in the passenger sector.

Non-fuel cost: Historical revenue per revenue ton-mile is from BTS (2007d), and fuel costs in 1990 and 2005 are from BTS (2007c**)**.

Service output: This is from BTS (2007a) air carrier traffic statistics (freight ton miles by year).

Ship

In this study, international and domestic shipping are modeled as one single mode of transportation. However, the fuel intensities, load factors, service outputs, and energy consumption of international and domestic shipping were calculated separately and aggregated.

Energy consumption by foreign and domestic shipping: This is from Davis and Diegel (2006, Table 9.4).

Domestic shipping service intensity: This is from Davis and Diegel (2006, Table 9.5). Future improvement is assumed to be 0.1% per year for both the reference and advanced technology scenarios.

Domestic shipping load factor: This is assumed to be 900 tons, equivalent to a 1500-ton barge at 60% capacity.

International shipping service intensity: This is assumed equal to average global shipping intensity, calculated as total marine bunker fuel (IEA 2004a and IEA 2004b) divided by total number of ton-miles shipped (UNCTAD 2006).

International shipping load factor: This is calculated based on a breakdown of the U.S. fleet in 1994 and 2004 (UKDFT 2005), estimated cargo capacities of each ship type (Fearnleys 2001), and an assumption of 60% average loading. Ship types considered were tankers, bulk carriers, containerships, general cargo, and merchant trading vessels.

International shipping vehicle fuel intensity: This is calculated as load factor times service intensity (fuel used per ton-mile). Future improvement is assumed to be 0.1% per year for both the reference and advanced technology scenarios.

Non-fuel cost: Average revenue per revenue ton-mile for domestic shipping is from BTS (2007d), and the cost of diesel fuel is from BTS 2005 (Table 14.4a**)**.

A.3. U.S. Industrial Module

Data collected by the EIA formed the basis for determining the categories of industry groups and end-uses for the manufacturing sector. For agriculture, mining, and construction—the non-manufacturing industries—data on end-use energy by fuel is taken from the Annual Energy Outlook (EIA 2007), and for manufacturing industries, the Manufacturing Energy Consumption Survey (MECS) is used. At the time of this analysis, the 1998 MECS (EIA 1999) is thought to be a more internally consistent source of data than the 2002 MECS (EIA 2003). Table A.16 shows the MECS and O^{bj}ECTS disaggregation of industry groups, and Table A.17 shows the total fuel consumption by the most prominent end-uses, by fuel, across all manufacturing industries.

As shown in Table A.17, of the total energy used by the U.S. manufacturing sector, about 26% is electricity, 58% is natural gas, 10% is coal (excluding coal coke and breeze), and the remainder is from liquid fuels. Electricity provides most of the energy for machine drive, electro-chemical, and HVAC (heating, ventilation and air conditioning) services. Process heat tends to be supplied by natural gas, as a clean-burning fuel is required for this service. In contrast, steam can be generated using a number of fuels, and while natural gas is the most common fuel used, the fuel mix for steam production differs by industry. For instance, the pulp, paper, and wood industry group uses mostly biomass, and the petroleum industry uses more oil for this purpose than any other industry.

Table A.16. Mapping of MECS NAICS industry codes into O^{bj}ECTS industry groups.

NAICS Code	**Industry Name**	**O^{bj}ECTS Industry Group**
311	Food	Food Processing
312	Beverage and Tobacco Products	Food Processing
313	Textile Mills	Other Manufacturing
314	Textile Product Mills	Other Manufacturing
315	Apparel	Other Manufacturing
316	Leather and Allied Products	Other Manufacturing
321	Wood Products	Pulp, Paper and Wood
322	Paper	Pulp, Paper and Wood
323	Printing and Related Support	Other Manufacturing
324	Petroleum and Coal Products	Petroleum
325	Chemicals	Chemicals
326	Plastics and Rubber Products	Other Manufacturing
327310	Cement	Cement
327	Nonmetallic Mineral Products (net of cement)	Other Non-Metallic
3313	Alumina and Aluminum	Aluminum
331	Primary Metals	Other Primary Metals

332	Fabricated Metal Products	Other Manufacturing
333	Machinery	Other Manufacturing
334	Computer and Electronic Products	Other Manufacturing
335	Elec. Equip., Appliances, Components	Other Manufacturing
336	Transportation Equipment	Other Manufacturing
337	Furniture and Related Products	Other Manufacturing
339	Miscellaneous	Other Manufacturing

Table A.17. Total fuel consumption by end-use for all manufacturing industries, 1990, trillion Btu.

	Electricity	**Liquid Fuels**	**Natural Gas**	**Coal[1]**	**Total**
Boiler Fuel	29	308	2538	770	3645
Process Heating	363	185	3187	331	4066
Process Cooling and Refrigeration	209	2	22		233
Machine Drive	1881	25	99	7	2012
Electro-Chemical Processes	354				354
Other Process Use	13	5	52		70
Facility HVAC	289	14	403	4	710
Facility Lighting	227				
Other Facility Support	53	7	40		100
On-site Transportation	5	59	5		69
Conventional Electricity Generation		6	210	27	243
Other Nonprocess Use	4	1			5
End Use Not Reported	71	12	72	3	158
Total Fuel Consumption	**3498**	**625**	**6644**	**1143**	**11910**

1 Excluding coke and breeze

A.3.1. Industrial Demand Growth

In addition to the composition of energy demands within industry groups, scale of activity is also important for modeling scenarios of the U.S. industrial sector. Econometric relationships were developed to analyze the historical relationships between U.S. energy consumption, gross domestic product (GDP), and population. Regressions were performed on historical data from 1977 to 2004 for several industry groups, and from 1985 to 2004 for groups in which primary demand sharply decreased in response to the oil shocks of the 1970s. Energy demand was found to be proportional to population in the food processing and pulp, paper, and wood industry groups, while for all others, historical GDP was used to generate income elasticities. These elasticities are shown in Table A.18.

Table A.18. Income elasticities assumed in the industrial sector module.

Industry Group	**Driver**	**Regression Period**	**Income**

			Elasticity
Food Processing	Population and PerCapita Income	1977–2004	0
Pulp Paper and Wood	Population and PerCapita Income	1977–2004	0.05
Chemicals	Total Regional Income (GDP)	1985–2004	0.55
Petroleum	Total Regional Income (GDP)	1985–2004	0.65
Aluminum	Total Regional Income (GDP)	1985–2004	0.15
Total Primary Metals	Total Regional Income (GDP)	1985–2004	0.15
Cement	Total Regional Income (GDP)	1977–2004	0.15
Other NonMetallic Mineral	Total Regional Income (GDP)	1985–2004	0.15
Other Manufacturing	Total Regional Income (GDP)	1977–2004	0.1
Agriculture	Total Regional Income (GDP)	NA	0.1
Mining	Total Regional Income (GDP)	NA	0.1
Construction	Total Regional Income (GDP)	NA	0.1

As shown, the fastest growth is taking place in chemicals and petroleum, whereas all others have elasticities between 0.1 and 0.2. The data for non-manufacturing industries during this time was a residual and was not collected directly. Because the time series does not appear to be reliable, the elasticities of these industries have been set to 0.1, matching the elasticity of other manufacturing.

A.3.2. Consumption of Feedstocks

Approximately 27% of the energy used in the industrial sector is in the form of energy feedstocks (that is, non-fuel uses of energy sources). Distinguishing feedstocks from fuel consumed as energy is critical because much of the total fossil fuel consumed as feedstocks can be assumed to be non-emitting. Instead, some portion of these feedstocks are used in a way that sequesters the carbon content for a significant time. Natural gas, liquefied petroleum gas, asphalt, and coking coal are some examples of fossil fuels that are consumed for non-energy uses. Possible applications include solvents, lubricants, waxes, or as raw materials in the manufacture of plastics, chemicals, rubber, and synthetic fibers. Emissions may arise from non-energy uses during manufacturing processes, or during the product’s lifetime (e.g., solvent use). It is estimated that about 65% of the total carbon content of fuel used in feedstocks is sequestered, a proportion that has remained relatively constant since 1990 (EPA 2005). This proportion was used in the model, and is assumed to remain constant in the future.

Given the large fraction of industrial energy consumption that is actually used as feedstocks, this category has been added as an end-use demand for petroleum, chemicals, primary metals, and construction. These four industry groups together account for greater than 99% of the total industrial consumption of feedstocks. Table A.19 shows the feedstock use of combustible energy in each of these groups in 1998, and the percentage of each industry’s feedstock use accounted for by each fuel.

Table A.19. Consumption of feedstocks in 1998 for the three major manufacturing industry groups that use feedstocks, and the construction industry feedstock use (includes road construction). Also shown are the relative shares of the fuels consumed for feedstocks by each industry.

			Fuel portions (%)		
Industry group	**Fuel (EJ)**	**% of US industrial total**	**Oil**	**Gas**	**Coal**
Petroleum	3.49	44%	99.7%	0%	0.3%
Chemicals	2.56	32%	73.7%	25.4%	0.8%
Primary Metals	0.72	9%	7.0%	5.5%	87.5%
Construction	1.23	15%	100.0%	0.0%	0.0%
Total	8.00		**83.1%**	**8.6%**	**8.3%**

A.3.3. Technological Improvement

Table A.20 shows efficiency assumptions for the end use technologies in the industrial module, in the reference and advanced technology scenarios. Due to the high efficiencies of existing equipment, there are no differences in end-use technological efficiency between the reference and advanced technology scenarios. The efficiencies of boilers and machine drive differ by fuel, based on data compiled by the Coucil of Industrial Boiler Owners (2003). Efficiencies of electric motors were taken from NEMS (DOE 2005), and the efficiencies of all other end uses are not assumed to differ by fuel. A nominal efficiency improvement of 0.1% per year is applied to all end use technologies, except for machine drive, which is closer to its assumed physical efficiency limit.

Table A.20. Assumed efficiencies of technologies providing industrial services, 2005-2095. An improvement rate of 0.1% per year is assumed for all end uses except for machine drive, which is assumed to improve at 0.05% per year.

	2005	2050	2095
Boilers			
Electricity	0.80	0.84	0.88
Oil	0.85	0.89	0.93
Coal	0.88	0.92	0.96
Natural Gas	0.83	0.87	0.91
Biomass	0.73	0.76	0.79
Coal CHP	0.60	0.60	0.60
Natural Gas CHP	0.55	0.55	0.55
Biomass CHP	0.60	0.60	0.60
Machine Drive			
Electricity	0.93	0.95	0.97
Oil	0.85	0.87	0.89
Coal	0.88	0.90	0.92
Natural Gas	0.83	0.85	0.87
Biomass	0.73	0.74	0.76
Process Heat[1]	1.00	1.05	1.09
Natural Gas CHP	0.50	0.50	0.50

HVAC[1]	1.00	1.05	1.09
Electro-chemical[1]	1.00	1.05	1.09
Other[1]	1.00	1.05	1.09
Feedstocks[1]	1.00	1.05	1.09

1 Indicates an index efficiency assumed in 2005

A.3.4. Process Improvements

Due to the unforeseeable nature of technological improvement of industrial processes, generic assumptions for process improvements are applied equally to all industries in each technology scenario. In the reference technology scenario, process efficiencies are assumed to improve at 0.1% per year, with the fuel intensity of each industry's "process" 9% more efficient than present-day processes. In the advanced scenarios, an annual improvement rate of 0.3% is used, resulting in a 31% improvement by 2095 (relative to 2005). These rates are informed by Worrell et al. (2004), which showed that energy-saving industrial process improvements available with current technology have the potential to reduce total industrial energy use in 2025 by 8% with modest adoption rates, and by 24% with complete adoption.

A.3.5. Cogeneration

Efficiency assumptions for cogeneration technologies are adapted from The Institute for Thermal Turbomachinery and Machine Dynamics (2002) for steam, gas turbine, and gas combined cycle technologies. In the model, the investment in cogeneration is based on relative economics as compared with stand-alone boiler or process heat systems. Cogeneration systems are assumed to have 2.5 times higher capital costs and use more fuel than a stand-alone boiler or burner to generate a given quantity of steam or heat. For instance, the stock average efficiency in 2005 for a gas boiler is 83%, but a gas cogeneration system produces steam with an efficiency of 55%, due to the losses from producing electricity (see Table A.20). However, cogeneration systems are compensated for the electricity produced. The calibrated amount of cogenerated electricity in the model base years (1990 and 2005) is based on EIA (1999).