CHAPTER 2. EFFECTS OF CLIMATE CHANGE ON ENERGY USE IN THE UNITED STATES

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2.1 INTRODUCTION

As the climate of the world warms, the consumption of energy in climate-sensitive sectors is likely to change. Possible effects include (1) decreases in the amount of energy consumed in residential, commercial, and industrial buildings for space heating and increases for space cooling; (2) decreases in energy used directly in certain processes such as residential, commercial, and industrial water heating, and increases in energy used for residential and commercial refrigeration and industrial process cooling (e.g., in thermal power plants or steel mills); (3) increases in energy used to supply other resources for climate-sensitive processes, such as pumping water for irrigated agriculture and municipal uses; (4) changes in the balance of energy use among delivery forms and fuel types, as between electricity used for air conditioning and natural gas used for heating; and (5) changes in energy consumption in key climate-sensitive sectors of the economy, such as transportation, construction, agriculture, and others.

In the United States, some of these effects of climate change on energy consumption have been studied enough to produce a body of literature with empirical results. This is especially the case for energy demand in residential and commercial buildings, where studies of the effects of climate change have been under way for about 20 years. There is very little literature on the other effects mentioned above.

This chapter summarizes current knowledge about potential effects of climate change on energy demand in the United States. The chapter mainly focuses on the effects of climate change on energy consumption in buildings (emphasizing space heating and space cooling, but also addressing net energy use, peak loads, and adaptation), because studies of these effects account for most of the available knowledge. The chapter more briefly addresses impacts of climate change on energy use in other sectors, including transportation, construction, and agriculture, where studies are far less available. The final section summarizes the chapter's conclusions.

2.2 ENERGY CONSUMPTION IN BUILDINGS

2.2.1 Overview

U.S. residential and commercial buildings currently use about 20 quadrillion Btus (quads) of delivered energy per year (equivalent to about 38 quads of primary energy, allowing for electricity production-related losses). This energy consumption accounts directly or indirectly for 0.6 GT of carbon emitted to the atmosphere (38% of U.S. total emissions of 1.6 GT and approximately 9% of the world fossil-fuel related anthropogenic emissions of 6.7 GT (EIA, 2006). The U.S. Energy Information Administration (EIA) has projected that residential and commercial consumption of delivered energy would increase to 26 quads (53 quads primary energy) and corresponding carbon emissions to 0.9 GT by the year 2030 (EIA, 2006). However, these routine EIA projections do not account for the effects any temperature increases on building energy use that may occur as a result of global warming, nor do they account for consumer reactions to a warmer climate, such as an increase in the adoption of air conditioning.

To perform an assessment of the impact of climate change on energy demand, it is helpful to have as context a set of climate scenarios. The Intergovernmental Panel on Climate Change (IPCC) projected in 2001 that climate could warm relative to 1990 by 0.4˚C to 1.2˚C by the year 2030 and by 1.4˚C to 5.8˚C by the end of the 21st century Cubasch et al.(2001) and Ruosteenoja et al. (2003) performed a reanalysis of the seventeen 2001 IPCC climate simulations by seven different climate models at the regional level. Their results for the United States are reported for three subregions, four seasons, and three major time steps, as summarized in Table 2.1. This is not the only set

Table 2.1. Seasonal Temperature Increases For Three U.S. Regions (˚C) In Winter (DJF), Spring (MAM), Summer (JJA), And Fall (SON). Derived From Ruosteenoja et al., 2003.

Region and Season	Time Step					
	2010-2039 (2020)		2040-2069 (2050)		2070-2099 (2080)	
	Median	Range	Median	Range	Median	Range
Western U.S.						
DJF	1.6	0.5-2.4	2.3	1.0-4.2	4.1	2.0-7.6
MAM	1.4	0.5-1.9	2.5	1.1-4.1	3.8	1.0-7.6
JJA	1.8	0.8-2.6	2.8	1.7-5.2	4.2	2.8-9.1
SON	1.3	0.5-2.1	2.8	1.4-4.6	3.9	1.6-8.0
Central U.S						
DJF	1.6	0.0-2.6	3.0	1.2-4.5	4.2	1.9-7.9
MAM	1.8	0.5-2.8	2.9	1.2-5.1	4.4	1.9-8.0
JJA	1.8	0.9-2.2	3.0	1.5-5.4	4.4	1.9-8.5
SON	1.3	0.4-2.3	2.8	1.2-5.0	4.1	1.8-8.8
Eastern U.S.						
DJF	1.8	0.4-2.6	2.6	1.4-5.8	4.6	2.2-10.2
MAM	1.7	0.6-3.2	2.7	1.4-6.0	4.4	1.9-9.6
JJA	1.6	0.8-1.9	2.8	1.4-5.5	4.2	1.8-8.6
SON	1.5	0.6-2.3	2.8	1.4-5.4	4.0	1.8-9.0

of climate scenarios available, and the energy studies cited in this chapter often use other scenarios; but the table broadly characterizes the range of average temperature changes that might occur in the United States in the 21st century and can provide context for the various energy impact analyses that have been done.

Approximately 20 studies have been done since about 1990 concerning the effect of projected climate change on energy consumption in residential and commercial buildings in the United States. Some of these studies concern particular states or regions, and the impacts estimated depend crucially on local conditions.

Some of the studies analyze only electricity. Almost all show both an increase in electricity consumption and an increase in the consumption of primary fuels used to generate it, except in the few regions that provide space heating with electricity (for example, the Pacific Northwest). The few studies that examine effects on peak electricity demand emphasize that increases in peak demand would cause disproportionate increases in energy infrastructure investment.

Some studies provide demand estimates for heating fuels such as natural gas and distillate fuel oil in addition to electricity. These all-fuels studies provide support for the idea that climate warming causes significant decreases in space heating; however, whether energy savings in heating fuels offset increases in energy demand for cooling depends on the initial balance of energy consumption between heating and cooling, which in turn depends upon geography. Empirical studies show that the overall effect is more likely to be a significant net savings in delivered energy consumption in northern parts of the country (those with more than 4,000 heating degree-days per year) and a significant net increase in energy consumption in the south for both residential and commercial buildings, with the national balance slightly favoring net savings of delivered energy.

Studies vary in their treatment of the expected demographic shifts in the United States, expected evolution of building stock, and consumer reaction to warmer temperatures. Roughly half of the studies use building energy simulation models and account explicitly for the current trend in U.S. population moving toward the south and west, as well as increases in square footage per capita in newer buildings and increases in market penetration of air conditioning in newer buildings (See Annex A for a summary of methods). They do not, however, include consumer reactions to warming itself. For example, the market penetration of air conditioning is not directly influenced by warming in these studies. The other studies use econometric modeling of energy consumption choices. Many of these studies emphasize that the responsiveness of climate change of energy use to climate change is greater in the long-run than in short run; for example, consumers not only run their air conditioners more often in response to higher temperatures, but may also adopt air conditioning for the first time in regions such as New England, which still feature relatively low market penetration of air conditioning. Commercial building designs may evolve to reduce the need for heating by making better use of internal energy gains and warmer weather. Rising costs of space conditioning could modify the current trend in floor space per capita. Most econometric studies of building energy consumption estimate effects like this statistically from databases on existing buildings such as the Energy Information Administration's (EIA's) Residential Energy Consumption Survey (RECS) (EIA, 2001b) and Commercial Building Energy Consumption Survey (CBECS) (EIA, 2003).

When losses in energy conversion and delivery of electricity are taken into account, primary energy consumption (source energy) at the national level increases in some studies and decreases in others, with the balance of studies projecting a net increase in primary energy consumption. When the higher costs per delivered Btu of electricity are taken into account, the national-level consumer expenditures on energy increase in some studies and decrease in others, with the balance of studies favoring an increase in expenditures.

Various studies include a range of climate warming scenarios as well as different time frames and methods. Table 2.2 summarizes the main qualitative conclusions that can be drawn from an overview of this literature concerning the marginal effect of climate warming on energy use in buildings. These effects are discussed further in Sections 2.3 through 2.5.

2.2.2 The Literature in Greater Detail

The general finding about the net impact of climate warming on the consumption of delivered heating fuel and electricity is that for regions with more than about 4000 heating degree-days Fahrenheit (EIA Climate Zones 1-3, roughly the dividing line between "north" and "south" in most national studies—see Figure 2.1) climate warming tends to reduce consumption of heating fuel more than it increases the consumption of electricity (e.g., Hadley et al., 2004, 2006). The reverse is true south of that line. By

Table 2.2. Summary of Qualitative Effects of Global Warming on Energy Consumption in the United States

Sector	National Effects	Regional Effects	Other Effects	Comments
Residential and Commercial Buildings Annual Energy Use	Slight decrease or increase in net annual delivered energy; Likely net increase in primary energy	Space heating savings dominate in North; space cooling increases dominate in South	Overall increase in carbon emissions	Studies agree on the direction of regional effects; national direction varies with the study
Peak Electricity Consumption	Probable increase	Increase in summer peaking regions; probable decline in winter peaking regions	Increase in carbon emissions	Most regions are summer-peaking due to air conditioning
Market Penetration of Energy-Using Equipment	Increase in market penetration of air conditioning	Air conditioning market share increases primarily in North	--	Very few studies. Strength of the effect is not clear.

coincidence, the national gains and losses in delivered energy approximately balance. Existing studies do not agree on whether there is small increase or decrease. The picture is different for primary energy and carbon dioxide. Because the generation, transmission, and distribution of electricity is subject to significant energy losses, national primary energy demand tends to increase with warmer temperatures. Finally, because electricity is about 50% generated with coal, which is a high-carbon fuel, and about 3.2 Btu of primary energy are consumed for every Btu of delivered electricity (EIA, 2006), carbon dioxide emissions also tend to increase. The extent of this national shift in energy use is expected to depend in part on the strength of residential adoption of air conditioning as the length of the air conditioning season and the warmth of summer increases in the north, where the market penetration of air conditioning is still relatively low. The potential reaction of consumers to a longer and more intense cooling season in the future has been addressed in only a handful of studies (e.g., Sailor and Pavlova, 2003) and must be considered highly uncertain. There is even less information available on the

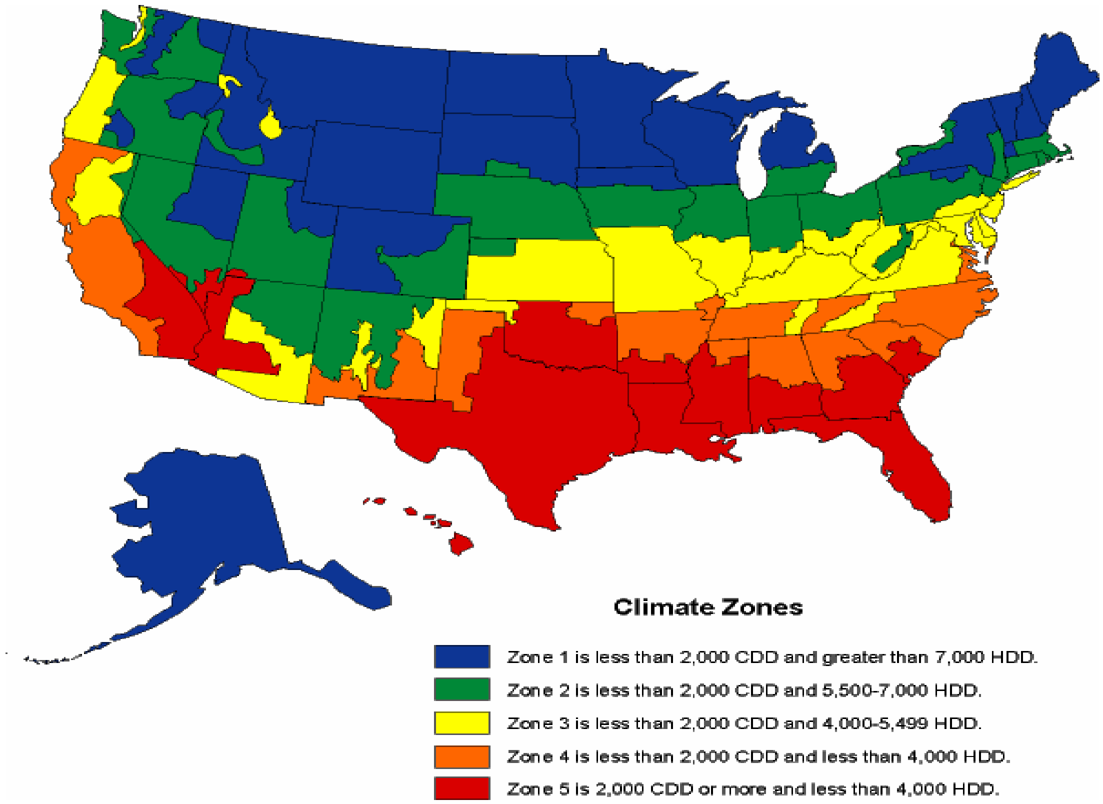
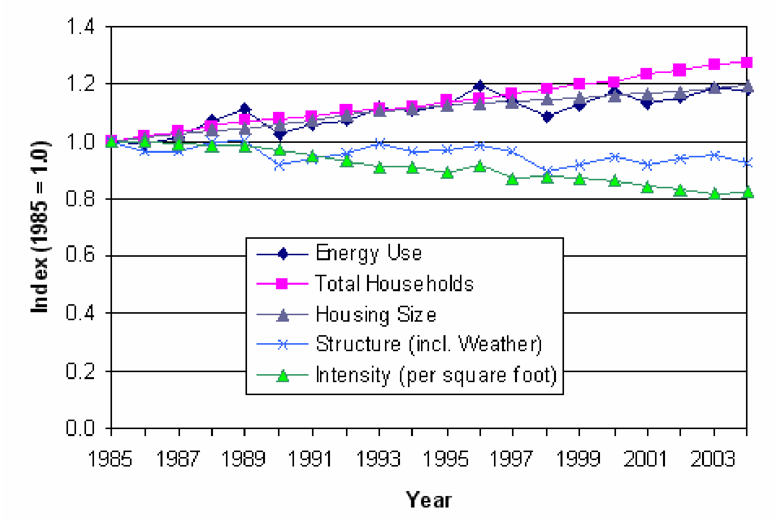


Figure 2.1. U.S. Climate Zones (Zones 1-3 are "North," Zones 4-5 are "South"). Source: Energy Information Administration, *Residential Energy Consumption Survey* (EIA, 2001c).

offsetting effects of adaptations such as improved energy efficiency or changes in urban form that might reduce exacerbating factors such as urban heat island effects.

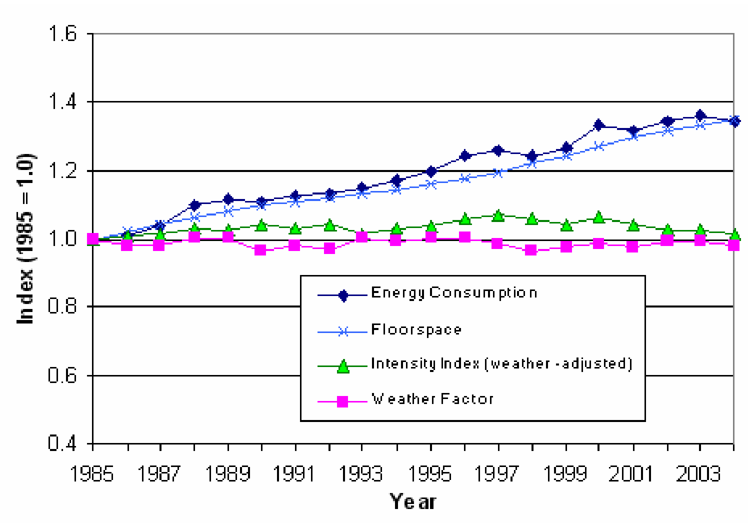
Box 2.1 provides insight into the recent trends in the intensity of energy consumption in residential and commercial buildings in the United States. There are a number of underlying trends, such as an ongoing population shift to the South and West, increases in the floor space per building occupant in both the residential and commercial sectors, and improvements in building shell performance, the balance of which have led to overall reductions in the intensity in the use of fuels for heating. Climate warming could be

Box 2.1. Trends in the Energy Intensity of Residential and Commercial Buildings.



Box Figure 2.1. Energy Use, Activity, Intensity and Other Factors in the Residential Sector - Delivered Energy, 1985-2004

Total energy use of delivered energy in households increased from 1985 to 2004. While both the number of households and housing size has increased over the period, the weather-adjusted intensity of energy use has fallen. Heating and cooling energy use declined, while appliance energy use increased enough to offset the declines in other end-uses. EIA (2006) projects an increase in building residential floor space per household of 14% during the period 2003-2030.



Box Figure 2.2. Commercial Energy Use, Activity, Weather, and Intensity - Delivered Energy

Estimated total floor space in commercial buildings grew 35% during the 1985-2004 period, while weather-adjusted energy intensity remained about constant. Declines in 1991 and since 2001 resulted from recessions, during which commercial vacancies increased and the utilization of occupied space fell. EIA (2006) projects the ratio of commercial floor space per member of the U.S. labor force to increase by 23% in the period 2003-2030.

(Data from the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, "Indicators of Energy Intensity in the United States," http://intensityindicators.pnl.gov/index.stm) and from EIA's Annual Energy Outlook (EIA, 2006).

expected to reinforce this trend. At the same time, the demographic shifts to the South and West, increases in floor space per capita, and electrification of the residential and commercial sectors all have increased the use of electricity, especially for space cooling. This trend also would be reinforced by climate warming.

Amato et al. (2005) observe that many studies worldwide have analyzed the climate sensitivity of energy use in residential, commercial, and industrial buildings and have used these estimated relationships to explain energy consumption and to assist energy suppliers with short-term planning (Quayle and Diaz, 1979; Le Comte and Warren, 1981; Warren and LeDuc, 1981; Downton et al., 1988; Badri, 1992; Lehman, 1994; Lam, 1998; Yan, 1998; Morris, 1999; Considine, 2000; Pardo, et al., 2002). The number of studies in the U.S. analyzing the effects of climate *change* on energy demand, however, is much more limited. One of the very early national-level studies was of the electricity sector, projecting that between 2010 and 2055 climate change could increase capacity addition requirements by 14–23% relative to nonclimate change scenarios, requiring investments of $200–300 billion ($1990) (Linder and Inglis, 1989). The Linder-Inglis results are similar to electricity findings in most of the studies that followed. Subsequently, a number of studies have attempted an "all fuels" approach and have focused on whether net national energy demand (decreases in heating balanced against increases in cooling) would increase or decrease in residential and commercial buildings as a result of climate change (e.g., Loveland and Brown, 1990; Rosenthal et al., 1995; Belzer et al., 1996; Hadley et al., 2004, 2006; Mansur et al., 2005; Scott et al., 2005; Huang, 2006). The picture here is more clouded. While the direction of regional projections in these studies are reasonably similar, the net impacts at the national level differ among studies and depend on the relative balance of several effects, including scenarios used, assumptions about demographic trends and building stock, market penetration of equipment (especially air conditioning), and consumer behavior.

In the sections that follow, this chapter discusses the impacts of climate warming on space heating in buildings (divided between residential and commercial), space cooling (again divided between residential and commercial buildings), net energy demand, market penetration of air conditioning, and possible effects of adaptation actions such as increased energy efficiency and changes to urban form, which could reduce the impacts of some compounding effects such as urban heat islands.

2.3 EFFECTS OF CLIMATE WARMING ON ENERGY USE FOR SPACE HEATING

2.3.1 Residential Space Heating

Temperature increases resulting from global warming are almost certain to reduce the amount of energy needed for space heating in residential buildings in the United States. The amount of the reduction projected by a number of U.S. studies has varied, depending mainly on the amount of temperature change in the climate scenario, the calculated sensitivity of the building stock to warming, and the adjustments allowed in the building stock over time (Table 2.3).

In most areas where it is available, the fuel of choice for residential and commercial space heating is natural gas, which is burned directly in a furnace in the building in question. There are some exceptions. In the Northeast, some of these savings will be in fuel oil, since fuel oil still provides about 36 % of residential space heating in that region, according to the 2001 RECS. In some other parts of the country with relatively short, mild winters or relatively inexpensive electricity or both, electricity has a significant share of the space heating market. For example, electricity accounted for 15% of residential heating energy in the Pacific Census Division and 19% in the South Atlantic Census Division in 2001 (EIA, 2001).

In Mansur et al., the impact of climate change on the consumption of energy in residential heating is relatively modest. When natural gas is available, the marginal impact of a 1°C increase in January temperatures in their model is predicted to reduce residential electricity consumption by 2.8% for electricity-only consumers and 2% for natural gas customers.

Table 2.3. Effects of Climate Change on Residential Space Heating in U.S. Energy Studies

Study: Author(s) and Date	Change in Energy Consumption (%)	Temperature Change (˚C) and Date for Change
National Studies		
Rosenthal et al., 1995	-14%	+1°C (2010)
Scott et al., 2005	-4% to -20%	+About 1.7°C median (varies from 0.4° to 3.2°C regionally and seasonally) (2020)
Mansur et al., 2005	-2.8% for electricity-only customers; -2% for gas customers; -5.7% for fuel oil customers	+1° C January temperatures (2050)
Huang, 2006	Varies by location and building. vintage average HVAC changes: -12% heating in 2020 -24% heating in 2050 -34% heating in 2080	18 US locations, (varies by location, month, and time of day) Average winter temperature increases 1.3° C in 2020 2.6° C in 2050 4.1° C in 2080
Regional Studies		
Loveland and Brown, 1990	-44 to -73%	3.7°C to 4.7°C (Individual Cities) (No Date Given)
Amato et al., 2005 (Massachusetts)	-7 to -14% , natural gas -15 to 20%, fuel oil -15 to -25%, natural gas -15 to -33%, fuel oil	-8.7% in HDD (2020) -11.5% in HDD (2030)
Ruth and Lin, 2006 (Maryland)	-2.5% natural gas -2.7% fuel oil	1.7°C-2.2°C (2025)

Scott et al. (2005), working directly with residential end uses in a building energy simulation model, projected about a 4% to 20% reduction in the demand for residential space heating energy by 2020, given no change in the housing stock and with winter temperature increases ranging from 0.4° to 3.2° C, or roughly 6% to 10% decrease in space heating per degree C increase. This is roughly twice the model sensitivity of Mansur et al., 2005. The Scott et al. analysis utilized the projected seasonal ranges of temperatures in Table 2.1 (Ruosteenoja et al,. 2003). Huang, 2006 also found decreases in average energy use for space heating. While these varied considerably by location and building vintage as well, the overall average was about a 12% average site energy reduction for space heating in 2020, or 9.2% per 1°C.

Regional level studies show similar effects, with a sensitivity of about 6% to 10% per 1°C in temperature change among the studies using building models and only about 1% per degree 1°C in studies using econometrics, in part possibly due to reactive increases in energy consumption (energy consumption "take-backs") as heating energy costs decline with warmer weather in this type of model, but also due to choice of region. In two studies with many of the same researchers and using very similar methodologies, Amato et al. 2005 projected about a 7% to 33% decline in space heating in the 2020s in Massachusetts, which has a long heating season, while Ruth and Lin, 2006 projected only a 2%-3% decline space heating energy during the same time frame in Maryland, which has a much milder heating season and many days where warmer weather would have no impact on heating degree-days or heating demand.

2.3.2 Commercial Space Heating

Although historically the intensity of energy consumption in the commercial sector has not followed a declining trend in the residential sector (Box 2.1), the effects of climate warming on space heating in the commercial sector (Table 2.4) are projected in most studies to be similar to those in the residential sector.

Belzer et al. (1996) used the detailed CBECS data set on U.S. commercial buildings, and calculated the effect of building characteristics and temperature on energy consumption in all U.S. commercial buildings. With building equipment and shell efficiencies frozen at 1990 baseline levels and a 3.9°C temperature change, the Belzer model predicted a decrease in annual space heating energy requirements of 29% to 35%, or about 7.4% to 9.0% per 1°C. Mansur et al. 2005 projected that a 1°C increase in January temperatures would produce a reduction in electricity consumption of about 3% for electricity for all-electric customers. The warmer temperatures also would reduce

Table 2.4. Effects of Climate Change on Commercial Space Heating in U.S. Energy Studies

Study: Author(s) and Date	Change in Energy Consumption (%)	Temperature Change (˚C) and Date for Change
Rosenthal et al., 1995	-16%	+1°C (2010)
Belzer et al., 1996	-29.0% to -35.0%	+3.9°C (2030)
Scott et al., 2005	-5% to -24%	About 1.7°C median (varies from 0.4° to 3.2°C regionally and seasonally) (2020)
Mansur et al., 2005	-2.6% electricity, -3% natural gas, -11.8% fuel oil	+1°C January temperature (2050)
Huang, 2006	Varies by location and building vintage; Average heating savings: -12% in 2020 -22% in 2050 -33% in 2080	5 US locations, (varies by location, month, and time of day) Average winter temperature increases 1.3° C in 2020 2.6° C in 2050 4.1° C in 2080
Regional Studies		
Loveland and Brown. 1990	-37.3% to -58.8%	3.7°C to 4.7°C (Individual cities) (no date given)
Scott et al.. 1994 (Minneapolis and Phoenix)	-26.0% (Minneapolis); -43.1% (Phoenix)	3.9ºC (no date)
Amato et al., 2005 (Massachusetts)	-7 to -8% -8 to -13%	-8.7% in HDD (2020) -11.5% in HDD (2030)
Ruth and Lin, 2006 (Maryland)	-2.7% natural gas	1.7°C-2.2°C (2025)

natural gas consumption by 3% and fuel oil demand by a sizeable 12% per 1°C. This larger impact on fuel oil consumption likely occurs because warming has its largest impacts on heating degree days in the Northeast and in some other northern tier states where fuel oil is most prevalent. Another factor may be the fact that commercial buildings that use fuel oil may be older vintage buildings whose energy consumption is more sensitive to outdoor temperatures. Similar to its residential findings, Hung, 2006 showed that the impact of climate change on commercial building energy use varies greatly depending on climate and building type. For the entire U.S. commercial sector, the simulations showed 12% decrease in energy use for space heating or 9.2% per 1°C.

Again, the regional level studies produce more dramatic decreases in energy demand in colder regions than in warmer ones; however, the differences are less between cold regions and warm regions than in residential buildings because commercial buildings are more dominated by internal loads such as lighting and equipment than are residential buildings.

2. 4 EFFECTS OF CLIMATE WARMING ON ENERGY USE FOR SPACE COOLING

2.4.1 Residential Space Cooling

According to all studies surveyed for this chapter, climate warming is expected to significantly increase the energy demand in all regions for space cooling, which is provided almost entirely by electricity. The effect in most studies is nonlinear with respect to temperature and humidity, such that the *percentage* impact increases more than proportionately with increases in temperature (Sailor, 2001). Some researchers have projected that increases in cooling eventually could dominate decreases in heating as temperatures continue to rise (Rosenthal et al., 1995), although that effect is not necessarily observed in empirical studies for the temperature increases projected in the United States during the 21st century (Table 2.5).

Electricity demand for cooling was projected to increase by roughly 5% to 20% per 1ºC for the temperature increases in the national studies surveyed. This can differ by location and customer class. For example, Mansur et al., 2005 projected that when July temperatures were increased by 1ºC, electricity-only customers increased their electricity consumption by 5%, natural gas customers increased their demand for electricity by 6%, and fuel oil customers bought 15% more electricity. The impact on all electricity consumption is somewhat lower because electricity also is used for a variety of non-climate-sensitive loads in all regions and for space heating and water heating in some regions. Looking specifically at residential sector cooling demand (rather than all electricity) with a projected 2020 building stock, Scott et al. 2005 projected nationally that an increase of 0.4° to 3.2°C summer temperatures (Table 2.5) results in a corresponding 8% to 39% increase in national annual cooling energy consumption, or roughly a 12% to 20% increase per 1°C. Huang's (2006) projections show an even

Table 2.5. Effects of Climate Change on Residential Space Cooling in U.S. Energy Studies

Study: Author(s) and Date	Change in Energy Consumption (%)	Temperature Change (˚C) and Date for Change
National Studies		
Rosenthal et al., 1995	+20%	+1°C (2010)
Scott et al., 2005	+8% to +39%	About 1.7°C median (varies from 0.4° to 3.2°C regionally and seasonally) (2020)
Mansur et al., 2005	+4% (electricity only customers); +6% (natural gas customers); +15.3% (Fuel oil customers)	+1° C July Temperature (2050)
Huang, 2006	Varies by location and building vintage Average HVAC changes: +38% elec 2020 +89% elec 2050 +158% elec 2080	18 U.S. locations (varies by location, month, and time of day) Average summer temperature increases: 1.7° C in 2020 3.4° C in 2050 5.3° C in 2080
Regional Studies		
Loveland and Brown, 1990	+55.7% to 146.7%	3.7°C to 4.7°C (Individual cities) (No date given)
Sailor, 2001	+0.9% (New York) to +11.6% (Florida) per capita	2°C (no date given)
Sailor and Pavlova, 2003 (Four states)	+13% to +29%	1ºC (no date given)
Amato et al., 2005 (Massachusetts)	+6.8% in summer, +10% to +40% (summer)	+12.1% CDD (2020) +24.1% CDD (2030)
Ruth and Lin, 2006 (Maryland)	+2.5% in May-Sep, (high energy prices); +24% (low energy prices)	1.7°C-2.2°C (2025)

stronger increase of about a 38% increase in 2020 for a 1.7°C increase in temperature, or 22.4% per 1°C, perhaps in part because of differences in the in the details of locations and types of new buildings in particular, which tend to have more cooling load and less heating load.

Among the state studies, Loveland and Brown, 1990 found very high residential cooling sensitivities in a number of different locations across the country. Cooling energy consumption increased by 55.7% (Fort Worth, from a relatively high base) up to 146% (Seattle, from a very low base) for a temperature increase of 3.7°C to 4.7°C. This implies about a 17% to 31% increase in cooling energy consumption per degree C. Using a similar model in the special case of California, where space heating is already dominated by space cooling, Mendelsohn, 2003 projected that total energy expenditures for electricity used for space cooling would increase nonlinearly and that net overall energy expenditures would increase with warming in the range of 1.5°C, more for higher temperatures. In such mild cooling climates, relatively small increases in temperature can have a large impact on air-conditioning energy use by reducing the potentials for natural ventilation or night cooling. The residential electricity results in Sailor 2001, Sailor and Pavlova 2003; for several locations, and Amato et al., 2005 for Massachusetts are consistent with the national studies, with the expected direction of climate effects and about the expected magnitude, but the Ruth et al., 2006 results for the more southerly state of Maryland turn out to be very sensitive to electricity prices, ranging from +2.5% at high prices (about 8 cents per kWh, 1990$) prices to +24% if prices were low (about 6 cents per kWh, 1990$).

2.4.2 Commercial Space Cooling

U.S. studies also have projected a significant increase in energy demanded for space cooling in commercial buildings as a result of climate warming, as summarized in Table 2.6.

Commercial sector studies show that the percentage increases in space cooling energy consumption tend to be less sensitive to temperature than are the corresponding energy increases in the residential sector for the same temperature increase. For example, Rosenthal et al. 1995 found residential cooling increased 20% but commercial sector cooling only 15% for a 1°C temperature increase. The increase in Scott et al. 2005 had a

Table 2.6. Effects of Climate Change on Commercial Space Cooling in U.S. Energy Studies

Study: Author(s) and Date	Change in Energy Consumption (%)	Temperature Change (˚C) and Date for Change	Comments
National Studies			
Rosenthal et al., 1995	+15%	+1°C (2010)	Energy-weighted national averages of census division-level data
Belzer et al., 1996	+53.9%	+3.9°C (2030)	
Scott et al., 2005	+6% to +30%	About 1.7°C median (varies from 0.4° to 3.2°C regionally and seasonally) (2020)	Varies by region
Mansur et al., 2005	+4.6% (electric-only customers); -2% (natural gas customers); +13.8% (fuel oil customers)	+1° C July temperature (2050)	A negative effect on electricity use for natural gas customers is statistically significant at the 10% level, but unexplained
Huang. 2006	Varies by location, building type and vintage average HVAC changes: +17% in 2020 +36% in 2050 +53% in 2080	5 U.S. locations (varies by location, month, and time of day) Average summer temperature increases: 1.7° C in 2020 3.4° C in 2050 5.3° C in 2080	
Regional Studies			
Loveland and Brown, 1990 (General office building in 6 individual cities)	+34.9% in Chicago; +75.0% in Seattle	3.7°C to 4.7°C (Individual cities) (no date given)	
Scott et al,. 1994 (small office bldgs in specific cities)	+58.4% in Minneapolis; +36.3% in Phoenix	3.9ºC (no date)	
Sailor, 2001 (7 out of 8 energy-intensive states; one state - Washington - used electricity for space heating)	+1.6% in New York; +5.0% in Florida (per capita)	2°C (No date given)	
Amato et al., 2005 (Massachusetts)	+2% to +5% summer +4% to +10% summer	+12.1% CDD (2020) +24.1% CDD (2030)	Monthly per employee
Ruth and Lin, 2006 (Maryland)	+10% per employee in Apr-Oct,	+ 2.2° (2025)	

range of 9.4% to 15% per 1°C for commercial and 12% to 20% per 1°C for residential customers. As with heating, in both cases this is likely to be in part because of the relatively greater sensitivity of space conditioning to internal loads in commercial buildings. Mansur et al. 2005 econometric results were less clear in this regard, possibly because geographic and behavioral differences among customer classes tend to obscure the overall effects of the buildings themselves. With building equipment and shell efficiencies frozen at 1990 baseline levels, Belzer et al. 1996 found impacts in the same range as the other studies. A 3.9°C temperature change increased annual space cooling energy requirements by 53.9% or about 9.0% to 13.8% per 1°C. Huang, 2006 also showed strong increases in cooling energy consumption at the national level. In 2020, his average increase was 17% for a 1.7°C temperature increase, or +10% per 1°C.

State-level studies generally show impacts that are in the same range as their national counterparts. Analyses performed with building energy models generally indicate a 10% to 15% electric energy increase for cooling per 1°C. The econometric studies also show increases, but because the numerator is generally the change in consumption of all electricity (including lighting and plug loads, for example) rather than just that used for space cooling, the percentage increases are much smaller.

2.4.3 Other Considerations: Market Penetration of Air Conditioning and Heat Pumps (All-Electric Heating and Cooling), and Changes in Humidity

Although effects of air conditioning market penetration were not explicitly identified, the late-1990s econometrically based cross-sectional studies of Mendelsohn and colleagues might be interpreted as accounting for increased long run market saturations of air conditioning because warmer locations in the cross-sectional studies have higher market saturations of air conditioning as well as higher usage rates. However, more recent studies have examined the effects directly. In one example, Sailor and Pavlova 2003 have projected that potential increases in market penetration of air conditioning in the residential sector in response to warming might have an effect on electricity consumption larger than the warming itself. They projected that although the temperature-induced increases in market penetration of air conditioning had little or no effect on residential energy consumption in cities such as Houston (93.6% market saturation), in cooler cities such as Buffalo (25.1% market saturation) and San Francisco (20.9% market saturation), the extra market penetration of air conditioning induced by a 20% increase in CDD more than doubled the energy use due to temperature alone. Using cross-sectional data and econometric techniques Mendelsohn 2003 and Mansur et al. 2005 also have estimated the effects of the market penetration of space cooling into the energy market. Mansur et al. found that warmer winter temperatures were associated with higher likelihood of all-electric space conditioning systems in the sample survey of buildings in EIA's RECS and CBECS datasets. In warmer regions they noted that electricity has a high marginal cost but a low fixed cost, making it desirable in moderate winters. Electric heating is currently more prevalent in the South than in the North (EIA 2001a). In general, however, the effects of adaptive market response of air conditioning to climate change have not been studied thoroughly in the United States.

High atmospheric humidity is known to have an adverse effect on the efficiency of cooling systems in buildings in the context of climate change because of the energy penalty associated with condensing water. This was demonstrated for a small commercial building modeled with the DOE-2 building energy simulation model in Scott et al. (1994), where the impact of an identical temperature increase created a much greater energy challenge for two relatively humid locations (Minneapolis and Shreveport), compared with two drier locations (Seattle and Phoenix). A humidity effect does not always show up in empirical studies (Belzer et al. 1996), but Mansur et al. 2005 modeled the effect of high humidity by introducing a rainfall as a proxy variable for humidity into their cross-sectional equations. In their residential sector, a one-inch increase in monthly precipitation resulted in more consumption by natural gas users of both electricity (7%) and of natural gas (2%). In their commercial sector, a one-inch increase in July precipitation resulted in more consumption of natural gas (6%) and of fuel oil (40%).

2.5 OVERALL EFFECTS OF CLIMATE CHANGE ON ENERGY USE IN BUILDINGS

2.5.1 Annual Energy Consumption

Many of the U.S. studies of the impact of climate change on energy use in buildings deal with both heating and cooling and attempt to come to a "bottom line" net result for either total energy site consumed or total primary energy consumed (that is, both the amount of natural gas and fuel oil consumed directly in buildings and the amount of natural gas, fuel oil, and coal consumed indirectly to produce the electricity consumed in buildings.) Some studies only deal with total energy consumption or total electricity consumption and do not decompose end uses as has been done in this chapter. Recent studies show similar net effects. Both net delivered energy and net primary energy consumption increase or decrease only a few percent; however, there is a robust result that, in the absence of an energy efficiency policy directed at space cooling, climate change would cause a significant increase in the demand for electricity in the United States, which would require the building of additional electricity generation (and probably transmission facilities) worth many billions of dollars.

In much of the United States, annual energy used for space heating is far greater than space cooling; so net use of delivered energy would be reduced by global warming. Table 2.7 summarizes the results from a number of U.S. studies of the effects of climate change on net energy demand in U.S. residential and commercial buildings. The studies shown in Table 2.7 do not entirely agree with each other because of differences in methods, time frame, scenario, and geography. However, they are all broadly consistent with a finding that, at the national level, expected temperature increases through the first third of 21st Century (Table 2.1) would not significantly increase or decrease net energy use in buildings. The Linder and Inglis 1989 projections concerning increases in electricity consumption have been generally confirmed by later studies, but there are geographical differences. For example, Sailor's state level econometric analyses (Sailor and Muñoz 1997, Sailor 2001, Sailor and Pavlova 2003) projected a range of effects. A

Table 2.7. Climate Change Effects in Combined Residential-Commercial Studies and Combined Results from Sector Studies

Study: Author(s) and Date	Change in Energy Consumption (%)	Temperature Change (˚C) and Date for Change	Comments
National Studies			
Linder-Inglis, 1989	+0.8 to +1.6% Annual electricity consumption; +3.4 to +5.1% annual electricity consumption.	+0.8°C to +1.5°C (2010) +3.5°C to +5.0°C (2050)	Results available for 47 state and substate service areas
Rosenthal, et al., 1995	-11% Annual energy load; balance of heating and cooling nationally.	1ºC (2010)	Space heating and air conditioning combined
Mendelsohn, 2001	+1% to +22% Residential expenditures -11% to +47% Commercial Expenditures	+1.5°C to +5°C (2060)	Takes into account energy price fore-casts, market penetration of air conditioning. Precipitation increases 7%.
Scott et al., 2005	-2% to -7% (Residential and commercial heating and cooling consumption combined (site energy). Energy used for cooling increases, heating energy decreases.	About +1.7°C median (varies from +0.4° to +3.2°C regionally and seasonally) (2020)	Varies by region. Allows for growth in residential and commercial building stock, but not increased adoption of air conditioning in response to warming
Mansur et al., 2005	+2% Residential expenditures , 0% commercial expenditures	+1°C Annual temperature (2050)	Takes into account energy price forecasts, market penetration of air conditioning. Precipitation increases 7%.
Hadley et al., 2004, 2006	Heating -6%, cooling +10% +2% primary energy Heating -11% cooling +22% -1.5% primary energy	+1.2°C (2025) +3.4°C (2025)	Primary energy, residential and commercial combined. Allows for growth in residential and commercial building stock.
Huang. 2006	Varies by location, building type and vintage average HVAC changes: -8% site, +1% primary in 2020 -13% site, +0% primary in 2050 -15% site, +4% primary in 2080	18 U.S. locations (varies by city, month, and time of day); average summer temperature increases: 1.7° C in 2020 3.4° C in 2050 5.3° C in 2080	
Regional Studies			
Loveland and Brown, 1990	+10% to +35% HVAC load in general offices; -22.0% to +48.1% HVAC load in single-family houses	+3.2ºC to +4.0ºC ($2xCO_2$, no date)	Multiple state study: results are for individual areas
Sailor, 2001 (8 energy-intensive states; electricity only)	Residential: -7.2% in Washington to +11.6 in Florida Commercial: -0.3% (Washington) to +5% in Florida	+2°C (Derived from IPCC; but no date given)	

temperature increase of 2°C would be associated with an 11.6% increase in residential per capita electricity used in Florida (a summer-peaking state dominated by air conditioning demand), a 5% increase per 1ºC warming. On the other hand, a 7.2% decrease in Washington state (which uses electricity extensively for heating and is a winter-peaking system), had about a 3% decrease per 1ºC warming.

The Rosenthal et al. 1995 projections of reduced net total delivered energy consumption and energy expenditure reductions have not been confirmed. Results of more recent studies follow a temperature increase of 2°C that would be associated with an 11.6% increase in residential per capita electricity used in Florida (a summer-peaking state dominated by air conditioning demand)and a 5% increase per 1ºC warming. On the other hand, a 7.2% decrease in Washington state (which uses electricity extensively for heating and is a winter-peaking system), had about a 3% decrease per 1ºC warming.

Scott et al. 2005 projected that overall site energy consumption in U.S. residential and commercial buildings is likely to decrease by about 2% to 7% in 2020 (0.4°C to 3.2°C warming). This amounts to about 2% per 1ºC warming, which is in the same direction of the Rosenthal et al. results, but smaller. This effect takes into account expected changes in the building stock, but not increased market penetration of air conditioning that specifically results from climate change. For a 1°C increase in year-round temperatures, Mansur et al. 2005 provide only projections of net energy expenditures—a 2% increase in total residential energy expenditures -- and no net change in commercial energy demand for the year 2060. In residences, electricity expenditures (presumably mainly for cooling) generally increase, while use of other fuels generally decreases. Projected commercial sector expenditures show increases in electricity expenditures that are almost exactly offset by declines in the expenditures for natural gas and fuel oil. Since the Mansur et al. analysis claims to estimate long-term climate elasticities that include fuel choices and comfort choices as well as the direct effect of warmer temperatures on building energy loads, its results likely reflect at least some of the increased adoption of air conditioning that would be expected in residences in currently cooler climates as temperatures increase; residential sector electricity use is projected to grow faster than electricity use in the commercial sector, where air conditioning is more common and internal loads such as lighting dominate electricity use. Hadley et al. 2004, 2006 also project cooling energy consumption increasing and heating energy consumption decreasing. The projected national net effect on delivered energy consumption is slightly negative; but the impact on primary energy consumption is a slight increase. For all three studies, the impact of 1°C to 2°C warming is small. At the individual city level, Loveland and Brown 1990 projected lower residential energy load in northern cities such as Chicago, Minneapolis, and Seattle and increased energy loads in southern cities such as Charleston, Ft. Worth, and Knoxville. A general office building increase showed increased overall energy loads in all six cities.

Most recently, Huang 2006 used results from the HADCM3 GCM that project the changes in temperature, daily temperature range, cloud cover, and relative humidity by month for 0.5º grids of the earth's surface to produce future weather files for 18 U.S .locations. under 4 IPCC climate change scenarios (A1FI, A2M, B1, and B2M) for three time periods (2020, 2050, and 2080). These weather files were then used with the DOE-2 building energy simulation program to calculate the changes in space conditioning energy use for a large set of prototypical residential and commercial buildings to represent the U.S. building stock. This study looked in detail at the technical impact of climate change on space conditioning energy use, but did not address socio-economic factors or adaptive strategies to climate change.

These simulations indicate that the overall impact of climate change by 2020 on the U.S. building stock would be a 7% reduction in site energy use, corresponding to a 1% reduction in primary energy, when the generation and transmission losses for electricity are taken into account. The savings were noticeably larger for residential buildings (9% reduction in site and 2% reduction in primary energy use) than for commercial buildings (7% reduction in site, but a 3% increase in primary energy use). The counterbalancing effect of heating savings in the north, however, tends to mask the appreciable impact that climate change can have on cooling-dominant locations in the south. For example, cooling energy use in single-family houses in Miami and New Orleans was expected to increase by about 20%. In the North or West, the percentage increase of cooling was actually much larger, but due to the short cooling season, the savings were more than offset by the reductions in heating energy use. For example, cooling energy use was expected to rise by 100% in San Francisco, 60% in Boston and Chicago, and 50% in New York and Denver.

Because of their larger internal heat gains and less exposure to the outdoors in commercial buildings, these simulations project that commercial buildings would require less heating and more cooling than residential houses. Consequently, some building types such as large hotels and supermarkets showed an increase in site energy use with climate change, and almost all showed increases in primary energy use. In Los Angeles and Houston, commercial building energy use would increase by 2% and 4% in site energy use, and by 15% and 25% in primary energy use.

Huang 2006 also looked at the impact of climate change out to 2050 and 2080, where there are cumulative effects of further temperature increases coupled with newer, tighter buildings that require much less heating and proportionally more cooling than older existing buildings. By 2050, heating loads were expected to be reduced by 28%, and cooling loads increased by 85% due to climate change, averaged across all building types and climates. By 2080, heating loads were expected to be reduced by nearly half (45%), but cooling loads were expected to more than double (165%) due to climate change, averaged across all building types and climates. With falling energy use for heating and rising energy use for cooling, by 2080 the ratio of cooling to heating energy use would be 60% in site energy and close to 180% in primary energy.

There are also a number of specific regional-level studies with similar outcomes. For Massachusetts in 2020, Amato et al., 2005 projected a 6.6% decline in annual heating fuel consumption (8.7% decrease in heating degree days—overall temperature change not given) and a 1.9% increase in summer electricity consumption (12% increase in annual cooling degree-days). Amato et al. noted that per capita residential and commercial energy demands in Massachusetts are sensitive to temperature and that a range of climate warming scenarios may noticeably decrease winter heating fuel and electricity demands and increase summer electricity demands. For 2030, the estimated residential summer monthly electricity demand projected increases averaged about 20% to 40%. Wintertime monthly natural gas demand declined by 10% to 20%. Fuel oil demand was down about 15% to 30%. For the commercial sector, electricity consumption rose about 6% to 10%. Winter natural gas demand declined by 6% to 14%.

The Hadley et al. 2006 study used the DD-NEMS energy model. Two advantages of this approach are that it provides a direct comparison at the regional level to official forecasts and that it provides a fairly complete picture of energy supply, demand, and endogenous price response in a market model. One disadvantage is that the DD-NEMS model only projected to 2025 at the time of that study (now 2030), which is only the earliest part of the period where climate change is expected to substantially affect energy demand. Hadley's regional results were broadly similar to those in Scott et al. 2005. For example, they showed decreases in energy demand for heating, more than offsetting the increased demand for cooling in the north (New England, Mid-Atlantic, West North Central and especially East North Central Census Division). In the rest of the country, the increase in cooling was projected to dominate. Nationally, the site energy savings were shown to be greater than the site energy increases, but because of energy losses in electricity generation, primary energy consumption (primary energy) increased by about 3% by 2025, driving up the demand for coal and driving down the demand for natural gas. Also, because electricity costs more than natural gas per delivered Btu, the increase in total energy cost per year was found to be about $15 billion (2001 dollars).

2.5.2 Peak Electricity Consumption

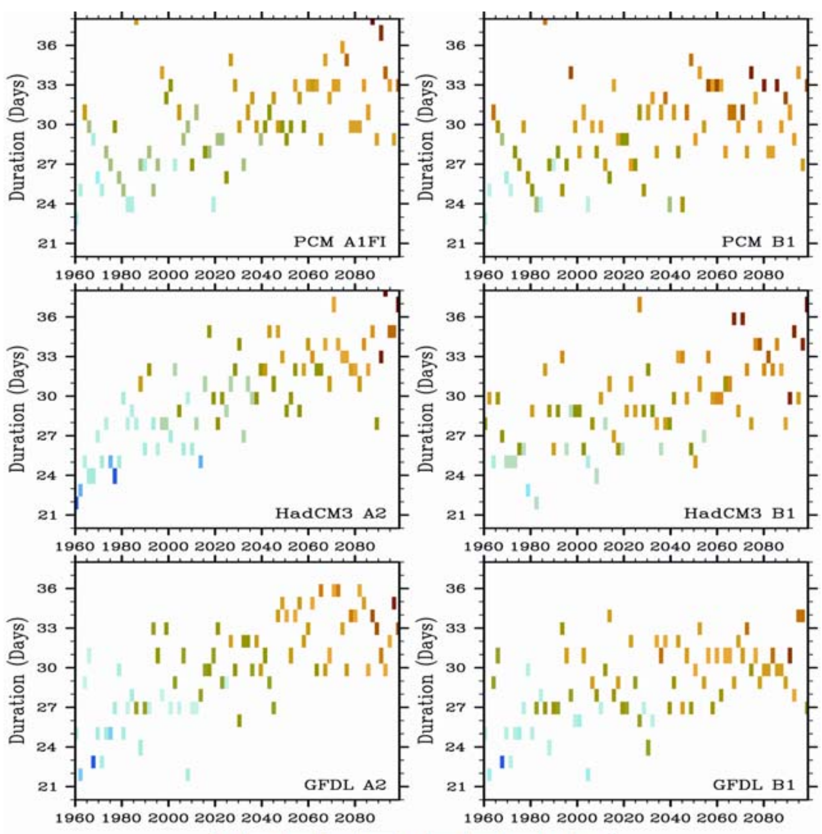
Studies published to date project that temperature increases with global warming would increase peak demand for electricity in most regions of the country. The amount of the increase in peak demand would vary with the region. Study findings vary with the region or regions covered and the study methodology—in particular, whether the study allows for changes in the building stock and increased market penetration of air conditioning in response to warmer conditions. The Pacific Northwest, which has significant market penetration of electric space heat, relatively low market penetration of air conditioning, and a winter-peaking electric system, is likely to be an exception to the general rule of increased peak demand. The Pacific Northwest power system annual and peak demand would likely be lower as a result of climate warming (Northwest Power and Conservation Council 2005).

Concern for peak electricity demand begins with the earliest studies of the climate impacts on building energy demand. Linder and Inglis 1989, in their multiregional study of regional electricity demand, found that although annual electricity consumption increased from +3.4 to +5.1% , peak electricity demand would increase between 8.6% and 13.8% , and capacity requirements between 13.1% and 19.7%, costing tens of billions of dollars.

One of the other few early studies of the effects of climate change on regional electricity was conducted by Baxter and Calandri 1992 in California. The study used degree day changes from General Circulation Model (GCM) projections for 2010 to adjust the baseline heating and cooling energy uses in residential and commercial models that were derived from building energy simulations of prototypical buildings. Two climate change scenarios were considered; a low temperature increase scenario of 0.72°C in the winter, 0.60°C in the spring and fall, and 0.48°C in the summer, and a high temperature increase scenario of 2.28°C in the winter, 1.90°C in the spring and fall, and 1.58°C in the summer. Results were presented for the five major utility districts, and showed a 0.28% decrease in heating coupled with a 0.55% increase in cooling energy use for the low-temperature increase scenario, and a 0.85% decrease in heating coupled with a 2.54% increase in cooling energy use for the high-temperature increase scenario. The state-wide impacts on energy demand were a 0.34-1.51% increase in cooling electricity demand for the low-temperature increase scenario, and a 2.57-2.99% increase in cooling electricity demand for the high-temperature increase scenario.

Box 2.2. California's Perspective on Climate Change

There has been probably more analysis done in California on impacts of climate change than anywhere else in the U.S. (also see Box 5.1). The reasons for this are: (1) California's relative mild climate has been shown to be highly sensitive to climate change, not only in terms of temperature, but also in water resources, vegetation distribution, and coastal effects, and (2) California is vulnerable to shortfalls in peak electricity demand, as demonstrated by the electricity shortage in 2001 (albeit mostly man-made) and the recent record heat wave in July 2006 that covered the entire state and was of greater intensity and longer duration than previously recorded. The pioneering work by Baxter and Calandri 1992 on global warming and electricity demand in California has already been described elsewhere in this report (see main text, this section). Mendelsohn 2003 investigated the impact of climate change on energy expenditures, while Franco 2005, Franco and Sanstad 2006, and Miller et al. 2006 have all focused on the impact of climate change on electricity demand. Miller et al., 2006 studied the probability of extreme weather phenomena under climate change scenarios for California and other Western U.S. locations. GCMs show that, over time, California heat waves will have earlier onsets, be more numerous, and increase in duration and intensity. "For example, extreme heat days in Los Angeles may increase from 12 to as many as 96 days per year by the end of the century, implying current-day heat wave conditions may extend the entire summer period". Overall, projected increases in extreme heat by 2070-2099 will approximately double the historical number of days for inland California cities, and up to four times for coastal California cities like Los Angeles and San Diego. The following plots show how the duration of extreme periods in California increases based on GCM results (from Miller et al. 2007).



The authors concluded that the impacts of climate change appear moderate on a percentage basis, but because California's electricity system is so large, a moderate percentage increase results in sizeable absolute impacts. For energy use, the 0.6% and 2.6% increases for the two scenarios signify increases of 1741 GWh and 7516 GWh. For electricity demand, the 0.34-1.51% and 2.57-2.99% increases correspond to increased peak demand by 221-967 MW and 1648-1916 MW. To put these impacts in perspective, uncertainties in the state's economic growth rate would have had comparable or larger impacts on electricity demand over this 20-year projected estimation. Actual growth in noncoincident peak demand between 1990 and 2004 was actually 8,650 MW for total end use load and 9,375 MW for gross generation (California Energy Commission, 2006).

Much more recently, using IPCC scenarios of climate change from the Hadley3, PCM, and GFDL climate models downscaled for California, Franco and Sanstad 2006 found a high correlation between the simple average daily temperature and daily peak electricity demand in the California Independent System Operator region, which comprises most of California. They evaluated three different periods: 2005-2034, 2035-2064, and 2070-2099. In the first period, depending on the scenario and model, peak summer demand was projected to increase relative to a 1961-1990 base period before climate change by 1.0%-4.8%; in the second, 2.2%-10.9%; in the third, 5.6%-19.5%.

A few U.S. regions could benefit from lower winter demand for energy in Canada. An example is in the New England-Middle Atlantic-East North Central region of the country, where Ontario and Québec in particular are intertied with the U.S. system, and where demand on either side of the international border could influence the other side. For example, since much of the space heating in Québec is provided by hydro-generated electricity, a decline in energy demand in the province could free up a certain amount of capacity for bordering U.S. regions in the winter. In Québec, the Ouranos organization (Ouranos 2004) has projected that net energy demand for heating and air conditioning across all sectors could fall by 30 trillion Btus, or 9.4 % of 2001 levels by 2100. Seasonality of demand also would change markedly. Residential heating in Québec would fall by 15% and air conditioning (currently a small source of demand) would increase nearly fourfold. Commercial-institutional heating demand was projected to fall by 13% and commercial air conditioning demand to double. Peak (winter) electricity demand in Québec would decline. Unfortunately, Québec's summer increase in air conditioning demand would coincide with an increase of about 7% to 17% in the New York metropolitan region (Ouranos 2004); so winter savings might be only of limited assistance in the summer cooling season, unless the water not used for hydroelectric production in the winter could be stored until summer and the transmission capacity existed to move the power south (Québec's hydroelectric generating capacity is sized for the winter peak and should not be a constraint).

Although they discuss the impacts of climate change on peak electricity demand, Scott et al. 2005 did not directly compute them. However, they performed a sensitivity analysis using nuclear power's 90% average capacity factor for 2004 as an upper-thatbound estimate of base load power plant availability and projected that national climate sensitive demand consumption (1.3 quads per year by 2080) would be equivalent of roughly 48 GW, or 48 base load power plants of 1,000 MW each. At the much lower 2003 average U.S. generation/capacity ratio of 47%, 93 GW of additional generation capacity would be required. This component of demand would be a factor in addition to any increases due to additional climate-related market penetration of air conditioning and any other causes of increased demand for electricity that the national electrical system will be dealing with for the rest of the century.

For further information about methods for estimating energy consumption in buildings, see Annex A.

2.6 ADAPTATION: INCREASED EFFICIENCY AND URBAN FORM

Although improving building energy efficiency should help the nation cope with impacts of climate change, there is relatively little specific information available on the potential impacts of such improvements. Partly this is because it has been thought that warming would already be reducing energy consumption, so that the additional effects of energy efficiency have not been of much interest. Scott et al. 1994 and Belzer et al. 1996 concluded that in the commercial sector, very advanced building designs could increase the savings in heating energy due to climate warming alone. Loveland and Brown 1990, Scott et al. 1994, Belzer et al. 1996, and Scott et al. 2005 all estimated the effects of energy-efficient buildings on energy consumption in the context of climate change and also concluded that much of the increase in cooling energy consumption due to warming could be offset by increased energy efficiency.

Loveland and Brown 1990 projected that changes leading to -50% lighting, +50% insulation, and +75% window shading would reduce total energy use in residential buildings by 31.5% to 44.4% in the context of a 3.2° to 4°C warming. This suggests that advanced building designs are a promising approach to reducing energy consumption impacts of warming, but further verification and follow-up research is needed both to confirm results and design strategies.

Scott et al. 1994 examined the impact of "advanced" building designs for a 48,000-square foot office building in the context of climate change in the DOE-2 building energy simulation model. The building envelope was assumed to reduce heat transfer by about 70% compared to the ASHRAE 90.1 standard. It included extra insulation in the walls and ceiling, reduction in window conductivity by a factor of 6, and window shading devices. The result was that, assuming a 3.9°C increase in annual average temperature, rather than experiencing between an 8% reduction in energy use (Minneapolis) and a 6.3% increase in overall energy use (Phoenix), an advanced design building would show a 57.2% to 59.8% decrease in energy used. In addition, the cooling energy impact was reversed in sign–a 47% to 60% decrease instead of a 35% to 93% increase. Cost, however, was not analyzed (also see SAP 4.6).

Belzer et al. 1996 projected that with a 3.9°C increase in annual average temperature, the use of advanced buildings would increase the overall energy savings in EIA's year 2030 projected commercial building stock from 0.47 quads (20.4%) to 0.63 quads (27%). Use of advanced building designs in the 2030 commercial building stock would increase the overall energy savings by 1.15 quads (40.6%) relative to a 2030 building stock frozen at 1990 efficiency. The cooling component of building energy consumption was only reduced rather than reversed by advanced designs in this study.

Finally, Scott et al. 2005 explicitly considered the savings that might be achieved under the Department of Energy's energy efficiency programs as projected in August 2004 for the EIA building stock in the year 2020 (temperature changes of about 0.4°C at the low end to about 2.8°C at the high end). This is the only study to have estimated the national effects of actual energy efficiency programs in the context of global warming. (The analysis did not count any potential increase in energy demand due to additional climate change-induced market penetration of air conditioning). The efficiency programs, which mainly targeted heating, lighting, and appliances instead of cooling, were less effective if the climate did not change; however, buildings still saved between 2.0 and 2.2 quads. This was a savings of about 4.5%, which would more than offset the growth in temperature-sensitive energy consumption due to increases in cooling and growth in building stock between 2005 and 2020.

Except for Scott et al. 2005, even where studies consider adaptive response (e.g., Loveland and Brown 1990; Belzer et al. 1996; Mendelsohn 2001), they generally do not involve particular combinations of technologies to offset the effects of future climate warming. Regionally, Franco and Sanstad 2006 did note that the very aggressive energy efficiency and demand response targets for California's investor-owned utilities such as those recently enacted by the California Public Utilities Commission could, if extended beyond the current 2013 horizon -- provide substantial "cushioning" of the electric power system against the effects of higher temperatures.

2.7 OTHER POSSIBLE EFFECTS, INCLUDING ENERGY USE IN KEY SECTORS

2.7.1 Industry

Except for energy used to heat and cool buildings, which is thought to be about 6% of energy use in industry (EIA 2001b) and is generally not analyzed for manufacturing activities in existing studies, it is not thought that industrial energy demand is particularly sensitive to climate change. For example, Amato et al. 2005 stated that "industrial energy demand is not estimated since previous investigations (Elkhafif 1996; Sailor and Munoz 1997) and our own findings indicate that it is non-temperature-sensitive." Ruth and Lin 2006 observe that in contrast to residential households, which use about 58% of their energy for space conditioning, and commercial buildings, which use about 40%, industrial facilities devote only about 6% of their energy use to space conditioning. In absolute numbers, this is about a third of what the commercial sector uses and about 8% of what the residential sector uses for this purpose. According to the 2002 Manufacturing Energy Consumption Survey, among the energy uses that could be climate sensitive, U.S. manufacturing uses about 4% of all energy for directly space conditioning, 22% for process heating, and 1.5% for process cooling (EIA, 2002a).

This does not mean, of course, that industry is not sensitive to climate, or even that energy availability as influenced by climate or weather does not affect industry. Much of the energy used in industry is used for water heating; so energy use would likely decline in industry if climate and water temperatures become warmer. Electrical outages (some caused by extreme weather) cause many billions in business interruptions every year, and large events that interrupt energy supplies are also nationally important (see Chapter 3). However, little information exists on the impact of climate change on energy use in industry. Considine 2000 econometrically investigated industrial energy use data from the EIA Short Term Energy Forecasting System based on HDD and CDD and calculated that U.S. energy consumption per unit of industrial production would increase for an increase 0.0127% per increase in one heating degree day (Fahrenheit) or by 0.0032% per increase of one cooling degree day (Fahrenheit). On an annual basis with a 1°C temperature increase (1.8°F), there would be a maximum of 657 fewer HDD per year and 657 more CDD (Fahrenheit basis, and assuming that all industry was located in climates that experienced all of the potential HDD decrease and CDD increase). This would translate into 6.2% less net energy demand in industry or a saving of roughly 0.04 quads.

A few studies have focused on a handful of exceptions where it was assumed that energy consumption would be sensitive to warmer temperatures, such as agricultural crop drying and irrigation pumping (e.g., Darmstadter 1993; Scott et al. 1993). While it seems logical that warmer weather or extended warm seasons should result in warmer water inlet temperatures for industrial processes and higher rates of evaporation, possibly requiring additional industrial water diversions, as well as additional municipal uses for lawns and gardens, the literature review conducted for this chapter did not locate any literature either laying out that logic or calculating any associated increases in energy consumption for water pumping. Industrial pumping increases are likely to be small relative to those in agriculture, which consumes the lion's share (40%) of all fresh water withdrawals in the United States (USGS, 2004). Some observations on energy use in other climate-sensitive economic sectors follow.

2.7.2 Transportation

Running the air conditioning in a car reduces its fuel efficiency by approximately 12% at highway speeds (Parker 2005). A more extended hot season likely would increase the use of automotive air conditioning units, but by how much and with what consequences for fuel economy is not known. Based on preliminary unpublished data, virtually all new light duty vehicles sold (well over 99% in 2005) in the United Sates come with factory-installed air conditioning (up from about 90% in the mid-1990s)[1], but no statistics appear to be available from public sources on the overall numbers or percentage of vehicles in the fleet without air conditioning. No projections appear to be available on the total impact of climate change on energy consumption in automotive air conditioners;

[1] Data supplied by Robert Boundy, Oak Ridge National Laboratory, based on Ward's Automotive Yearbooks.

however, there are some estimates of the response of vehicle air conditioning use to temperature. Based on a modeling of consumer comfort, Johnson (2002) estimates that at ambient temperatures above 30°C (86°F), drivers would have their air conditioning on 100% of the time; at 21°C-30°C (70°F-86°F), 80%; at 13°C-20°C (55°F-70°F), 45%; and at 6°C-12°C (43°F-55°F), 20% of the time.[2] Data from the Environmental Protection Agency's model of vehicular air conditioning operation suggests that U.S. drivers on average currently have their air conditioning systems turned on 23.9% of the time. With an increase in ambient air temperature of 1°C (1.8°F), the model estimates that drivers would have their air conditioning systems turned on 26.9% of the time, an increase of 3.0% of the time. [3]

Much of the food consumed in the United States moves by refrigerated truck or rail. One of the most common methods is via a refrigerated truck-trailer combination. As of the year 2000, there were approximately 225,000 refrigerated trailers registered in the United States, and their Trailer Refrigeration Units (TRUs) used on average 0.7 to 0.9 gallons of fuel per hour to maintain 0°F. On a typical use cycle of 7200 hours per year (6 days per week, 50 weeks per year), the typical TRU would use 5,000 to 6,000 gallons of diesel per year (Shurepower, LLC, 2005), or between 26 and 32 million barrels for the national fleet. Even though diesel electric hybrid and other methods are making market inroads and over time could replace a substantial amount of this diesel use with electricity from the grid when the units are parked, climate warming would add to the energy use in these systems. No data appear to be available on the total impact of climate change on energy consumption in transportation, however (also see SAP 4.7).

[2] Data supplied by Lawrence Chaney, National Renewable Energy Laboratory.
[3] Data supplied by Richard Rykowski, Assessment Standards and Support Division, Environmental Protection Agency. The model used in this analysis is described in Chapter III of the Draft Technical Support Document to the proposed EPA rulemaking to revise EPA's methodology for calculating the city and highway fuel economy values pasted on new vehicles.

2.7.3 Construction

Warming the climate should result in more days when outdoor construction activities are possible. In many parts of the northern states, the construction industry takes advantage of the best construction weather to conduct activities such as some excavation, pouring concrete, framing buildings, roofing, and painting, while sometimes enclosing buildings, partially heating them with portable space heaters, and conducting inside finishing work during "bad" weather. While the construction season may lengthen in the North, there also may be an increasing number of high-temperature heat stress days during which outdoor work may be hindered. The net effects on energy consumption on construction are not clear. The literature survey conducted for this chapter was not able to locate any studies in the United States that have investigated either the lengthening of the construction season in response to global warming or any resulting impacts on energy consumption.

2.7.4 Agriculture

Agricultural energy use generally falls into five main categories: equipment operations, irrigation pumping, embodied energy in fertilizers and chemicals, product transport, and drying and processing. A warmer climate implies increases in the demand for water in irrigated agriculture and use of energy (either natural gas or electricity) for pumping. Though not a factor in many parts of the country, irrigation energy is a significant source of energy demand west of the 100^{th} meridian, especially in the Pacific Southwest and Pacific Northwest. For example, irrigation load in one early climate change impact assessment increased from about 8.7% to about 9.8% of all Pacific Northwest electricity load in July (Scott et al. 1993), even with no change in acreage irrigated.

In some parts of the country, the current practice is to keep livestock and poultry inside for parts of the year, either because it is too cold or too hot outside. Often these facilities are space-conditioned. In Georgia, for example, there are 11,000 poultry houses, and many of the existing houses are air-conditioned due to the hot summer climate (and all new ones are) (University of Georgia and Fort Valley State University 2005). Poultry producers throughout the South also depend on natural gas and propane as sources of heat to keep their birds warm during the winter (Subcommittee on Conservation, Credit, Rural Development, and Research 2001). The demand for cooling livestock and poultry would be expected to increase in a warmer climate, while that for heating of cattle barns and chicken houses likely would fall. There are no available quantitative estimates of the effects on energy demand.

Food processing needs extensive refrigerated storage, which may take more energy in a warmer climate. However, there seem to be no U.S. studies on this subject.

2.8 SUMMARY OF KNOWLEDGE ABOUT POSSIBLE EFFECTS

Generally speaking, the net effects of climate change in the United States on total energy demand are projected to be modest, amounting to between perhaps a 5% increase and decrease in demand per 1ºC in warming in buildings, about 1.1 Quads in 2020 based on EIA 2006 projections (EIA 2006). Existing studies do not agree on whether there would be a net increase or decrease in energy consumption with changed climate because a variety of methodologies have been used. There are differences in climate sensitivities among models and studies as well as differences in methodological emphasis. For example, econometric models have incorporated some market response to warming and fuel costs but not necessarily differences in building size and technology over time and space, while the opposite is true of building simulation approaches. There are also differences in climate and market scenarios. It appears likely that some of the largest effects of climate change on energy demand are in residential and commercial buildings, however, with other sensitivities in other sectors being of secondary or tertiary importance.

Another robust finding is that most regions of the country can be expected to see significant increases in the demand for electricity, due both to increases in the use of existing space-cooling equipment and also to likely increases in the market penetration of air conditioning in response to longer and hotter summers. This is likely in Northern regions where market penetration of air conditioning is still relatively low.

To some extent, it is possible to control for differences in climate scenarios by comparing percentage changes in energy use per a standardized amount of temperature change, as has been done in this chapter. It is also possible to search for a set of robust results and to compare impacts, for example, that come from models that have fixed technologies and no market responses with those that allow technology to evolve and businesses and individuals to respond to higher or lower energy bills.

Some of the apparently conflicting results are more likely to be correct than others. Because of compensating market and technological responses, impacts of climate change should be less with models that allow technology to evolve and businesses and individuals to respond to higher or lower energy bills. Because they also assess more realistically the factors actually likely to be in play, they are likelier to be closer to correct. None of the models actually does all of this, but Mansur et al. 2005 probably comes the closest on the market side and Scott et al. 2005 or Huang 2006 on the technology side. Using the results from these two approaches, together with Sailor and Pavlova 2003 to inform and modify the Hadley et al. 2006 special version of NEMS, probably has the best chance of being correct for buildings.