Regional Energy Demand Responses to Climate Change: Methodology and Application to the Commonwealth of Massachusetts

Matthias Ruth and Anthony D. Amato

Environmental Policy Program
School of Public Affairs
University of Maryland,
3139 Van Munching Hall, College Park, MD 20742, USA

Abstract:

While the majority of climate impact assessments have concentrated on contributions of the energy sector to climate change, few have explored the reverse – implications of climate change on the energy sector. The results of such an exploration will fundamentally depend on region-specific climatic variables, infrastructure, socioeconomic, and energy use profiles.

The purpose of our analysis is to explore regional energy demand responses to climate change. Specifically, we focus on climate sensitive energy demand by the residential and commercial sectors in the Commonwealth of Massachusetts. The assessment employs a two step estimation and modeling procedure. The first step evaluates the historic climate sensitivity of residential and commercial demand for electricity and heating fuels, using a degree-day methodology. We find that when controlling for socioeconomic factors, degree-day variables have significant explanatory power in describing historic changes in residential and commercial energy demands. In the second step, we assess potential future energy demand responses to scenarios of climate change using dynamic modeling. Model results are based on alternative climate scenarios that were specifically derived for the region on the basis of local climatological data, coupled with regional information from available global climate models. We find notable changes with respect to overall energy consumption by, and energy mix of the residential and commercial sectors in the region. On the basis of our findings we identify effective response strategies to climate change for the energy sector.

Keywords:
Climate change, global warming, adaptation, regional analysis, energy demand, energy forecasting, energy policy, climate change policy

Acknowledgments:
The research described in this article has been funded in part by the United States Environmental Protection Agency through grant number R827450-0, but has not been subjected to the Agency's peer and policy review and does not, therefore, necessarily reflect the views of the Agency. No endorsements should be inferred.

1. Introduction

Consensus has yet to be established in the research community as to whether the effects of climate change on the energy sector will be “perceptible but modest” {p.376} (IPCC 1996a) or “profound” {p.11-1} (UNEP 1998). Nevertheless, as the IPCC’s Third Assessment Report notes “{o}nly a handful of studies since the SAR (Second Assessment Report, 1996) have looked at the effects of climate change on overall energy demand” {7.3.1} (IPCC 2001a). The present research provides an initial step towards understanding the potential impacts of climate change on the energy sector and towards identifying effective adaptation policies by assessing the sensitivity of demand to climatic variables in the Commonwealth of Massachusetts. The study is part of a larger assessment of “Climate’s Long-term Impacts on Metro Boston” (CLIMB) which explores potential impacts on a variety of local infrastructure systems and services, including, among others, energy, transportation, communication, coastal and riverine flooding, water quality and supply, and public health (Ruth and Kirshen 2001).

The study employs a two-step procedure to assess energy demand responses to climate change. The first step quantifies the historic sensitivity of residential and commercial energy demand to climatic variables controlling for socioeconomic factors. We then use, in step two, the sensitivities to estimate energy demand responses to climate change scenarios. The outline of this paper closely follows these two steps. The next section provides background on the sensitivity of energy demand to climate and climate change. Sections 3 describes the data used in our study. Section 4 presents our methodology and empirical results for historic demand sensitivities, while Section 5 shows potential demand responses to various future climate scenarios. The paper closes with a policy discussion and set of recommendations.

2. Energy Demand Sensitivity to Climate and Climate Change

Much of society’s use of energy is to satisfy heating and cooling preferences. In the United States (US), residential households devote 58 percent (EIA 1999), commercial buildings 40 percent (EIA 1995), and industrial facilities 6 percent (EIA 2001) of energy consumption to space-conditioning requirements, not including water heating. As these sectors account for 20, 16, and 38 percent of total US end-use energy demand, respectively, roughly 22 percent of all end-use energy is directly utilized for space-conditioning purposes. Such a large share of energy devoted to heating and cooling suggests climatic change may have real and measurable effects on energy consumption and, subsequently, emissions from the combustion of fossil fuels. Clearly, while emphasis has been placed on the influence of energy consumption in altering climate "it is equally important to realize that climate variability and climatic change can itself impact both energy supply and demand" {p.313}(Sailor 1997).

Although the link between climatic variables and energy use has been widely documented and utilized 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; Badri 1992; Lehman 1994; Lam 1998; Yan 1998; Morris 1999; Considine 2000; Pardo, Meneu et al. 2002), to date few analyses address the longer-term implications of climate change for energy use patterns and investment decisions. In studies that do examine the effects of climate change on the energy sector the results, in general, suggest noticeable impacts on energy demand, capital requirements or expenditures. Linder's national assessment of climate change impacts on the electricity sector finds that between 2010 and 2055 climate change could increase capacity addition requirements by 14-23% relative to non-climate change scenarios, requiring investments of $200-300 billion ($1990) (Linder 1990). In a national assessment of Israel, Segal et al. estimate an increase in temperature of 4℃ is associated with a 10% increase in average summer peak loads (Segal, Shafir et al. 1992). In Greece, a 1℃ temperature increase is projected to decrease energy consumption for heating by 10% and increase energy used for cooling by 28.4%, assuming a business-as-usual scenario (Cartalis, Synodinou et al. 2001). Belzer et al. examine potential changes in commercial energy use due to climate change at the national level for the US in 2030 (Belzer, Scott et al. 1996). After accounting for change in the building stock the study finds a 4℃ increase in average annual temperature results in a 0-5% reduction in total energy use by the commercial sector. Rosenthal et al. estimate that a 1℃ warming in the US would reduce energy expenditures by $5.5 billion and primary energy use by 0.70 percent in 2010 relative to a non-warming scenario (Rosenthal, Gruenspecht et al. 1995). In contrast, a study examining the impacts of climate change on total US energy use finds a 2℃ increase in average temperature would increase energy expenditures by $6 billion in 2060 (Morrison and Mendelsohn 1998).

The majority of studies examining the consequences of climate change for the energy sector typically quantify the impacts at a relatively coarse spatial resolution. As a consequence, they capture only an average response for a large geographic area. However, average responses have little value in guiding place-specific adaptation response (Wilbanks and Kates 1999) and may result in the prescription of inappropriate policy recommendations. Therefore, if the objective of a study is not only to quantify impacts but also identify policy solutions it must be conducted at a scale where, as the IPCC notes, “the impacts of climate change are felt and responses are implemented” {p.25}(IPCC 2001a).

2.1 Regional Energy Demand Sensitivities

We argue that for policy analyses, energy demand sensitivities to climate and climate change should be performed at the regional scale for a number of reasons. First, global climate change is anticipated to have geographically distinct impacts. For example, global climate models predict that the Northeast region of the US will experience among the lowest rates of warming relative to other regions of the country (Barron 2002). As a consequence, analyses that apply a uniform temperature increase over entire continents or nations may miss important geographic impacts on energy use. The ability to capture and interpret geographical variations in climate change impacts on energy systems is particularly important for the US given its large geographic extent and heterogeneous climate.

A second justification for carrying out a regional assessment lies in the regional differences of energy infrastructures (Boustead and Yaros 1994). Regional energy systems differ in terms of energy sources, efficiencies and characteristics of supply and conversion infrastructure, age of transmission and distribution systems, and end use technologies. In part, structural differences between regional energy systems have arisen as the built end use infrastructure and housing stock have evolved to service a unique mix of heating and cooling requirements under relatively stationary historic regional climate regimes. To illustrate the point, apartment buildings in metropolitan Boston are commonly constructed of heat-retaining red brick and few offer central air-conditioning. Similarly, in New England only 8 percent of households have central air-conditioning units whereas the average is 47 percent nationwide (EIA 1999).

A third justification for energy demand sensitivity analysis to be carried out at regional scales is that residential, commercial, and industrial sectors exhibit distinct demand sensitivities to climate. Since sectoral compositions vary across regions, the structure of a region's economy significantly influences the sensitivity of regional energy demand to climate (Lakshmanan and Anderson 1980; Sailor and Munoz 1997).

Several empirical studies support these arguments for regional assessments of climate impacts on the energy sector. For example, in a state-level analysis of residential and commercial electricity Sailor observes significantly different variation in demand sensitivities among states (Sailor 2001). He finds a temperature increase of 2°C is associated with an 11.6% *increase* in residential per capita electricity use in Florida, but a 7.2% *decrease* in Washington. Even in neighboring states, such as Florida and Louisiana, residential and commercial demand sensitivities are noticeably different. Similarly, Sailor and Munoz estimate the sensitivity of electricity and natural gas consumption in eight states and find considerable variation (Sailor and Munoz 1997). Sailor et al. correlate natural gas consumption in the residential and commercial sectors for each of the 50 US states to climatic variables and observe a wide range of sensitivities (Sailor and Munoz 1997). Warren and LeDuc statistically estimate natural gas consumption to prices and heating degree-days in a nine-region model of the US and find noticeable regional differences (Warren and LeDuc 1981). Linder and Inglis (quoted in (Smith and Tirpak 1990)) project a 1°C temperature change would alter US utility area peak demands by between –1.35 to 5.4 percent. Scott et al. use a building energy simulation model to assess the impacts of climate change on commercial building energy demand in four US cities (Seattle, Minneapolis, Phoenix, and Shreveport) (Scott, Wrench et al. 1994). Each city was found to have a unique demand response to climatic changes with, for instance, a 7°F increase in daily temperature increasing cooling energy use 36.6% in Phoenix and 93.3% in Seattle.

2.2 The Massachusetts Energy Sector

This analysis examines energy demand sensitivities to climatic variables for Massachusetts. The implications of climate change for the Massachusetts' energy sector may be particularly noteworthy and as a consequence important for energy planners to recognize early for a least two reasons. First, compared to the national average, Massachusetts has a large share of energy consumed by end users whose demand is relatively weather-sensitive such as residential and commercial end users. In fact, in 1999 Massachusetts' residential and commercial sectors represented 73 percent of the total non-mobile end use energy, whereas for the nation as a whole these sectors accounted for only 49 percent. Thus, a changing climate may alter energy demand patterns in Massachusetts significantly differently from those in other states or the nation as a whole. Second, Massachusetts has a high dependence on a few sources of energy. Consequently, understanding future energy demand dynamics is especially critical for the region's energy planners.

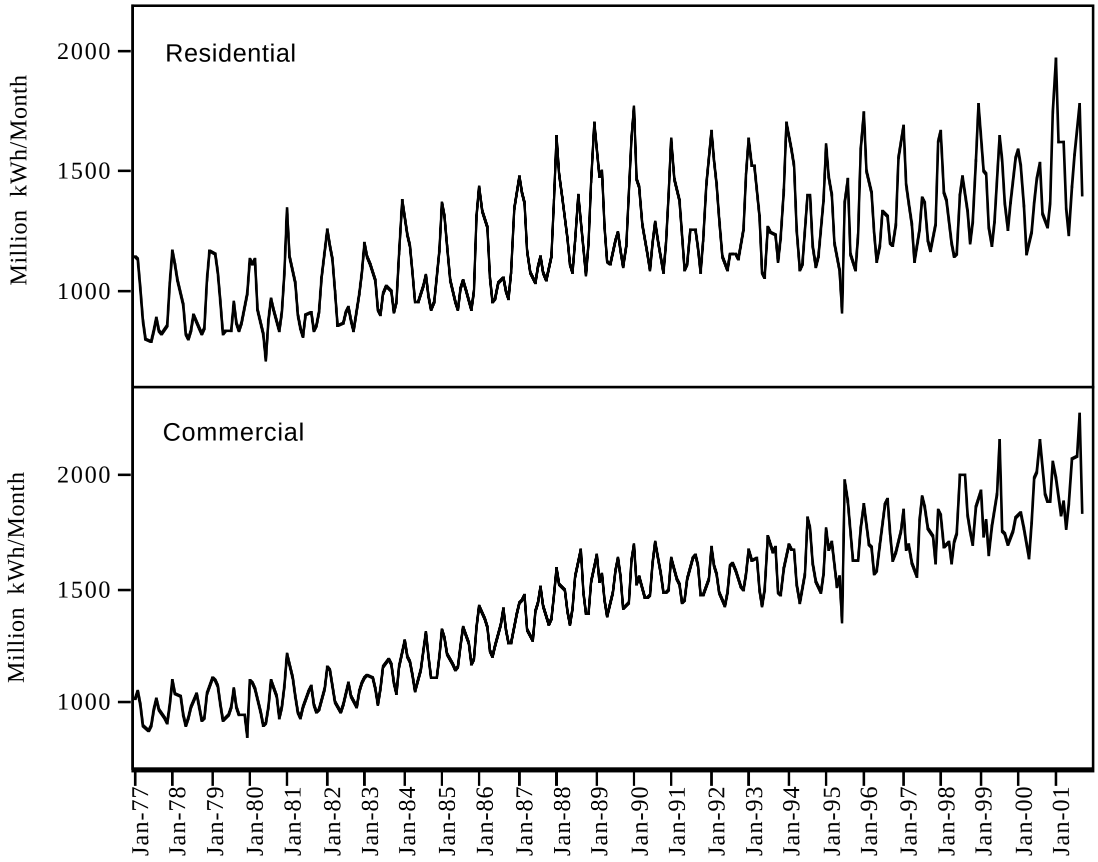
3. Data Sources

Our analysis uses monthly energy consumption and degree-day data. Time-series data on a monthly interval may produce more robust estimates of the energy-climate relationship than annual time-series data since there are more observations and variability between observations. Additionally, the use of monthly data allows for the assessment of non-uniform seasonal climatic changes, such as the more pronounced warming during the winter season than in other seasons of the year for higher latitude regions, as predicted by global climate models (Greco, Moss et al. 1994). As a consequence, analyses that apply a uniform temperature increase over the entire year may miss important seasonal impacts on energy use. The following sections describe the data used in our energy demand sensitivity analysis.

3.1 Energy Data

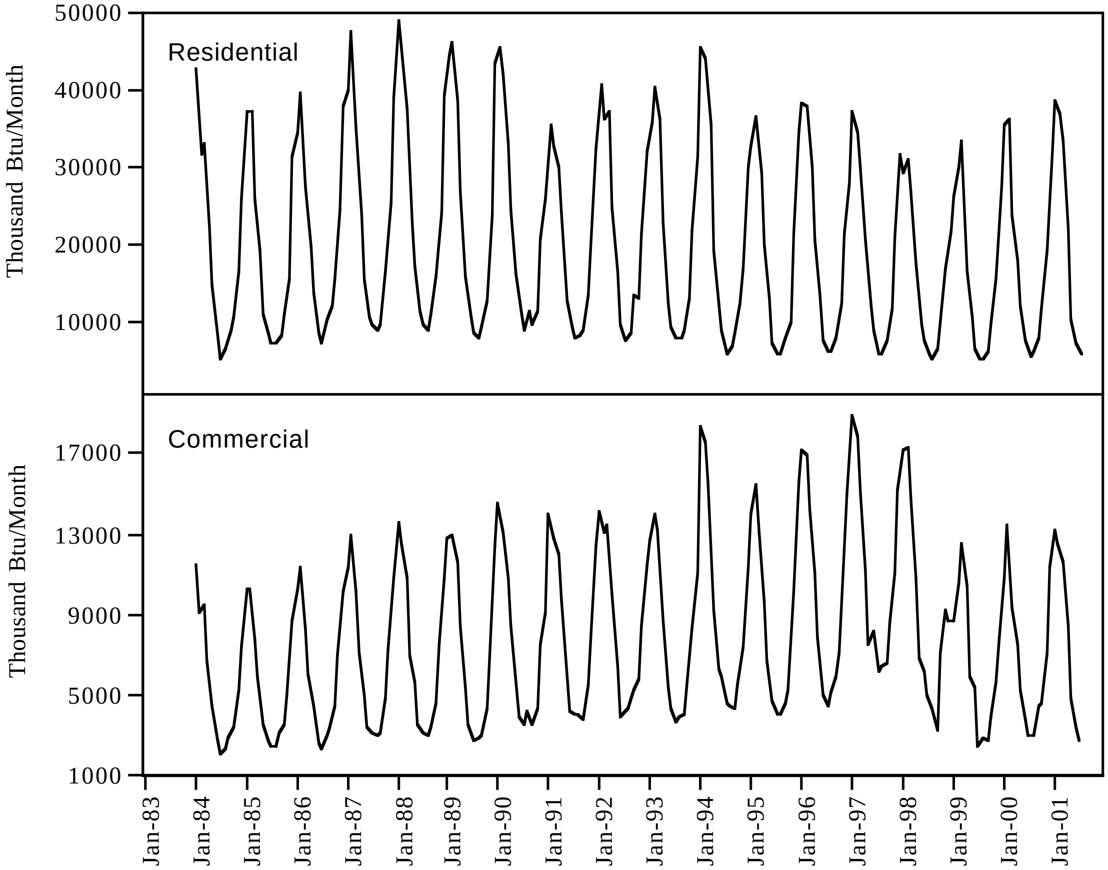
The Massachusetts' energy data was obtained from the U.S. Energy Information Administration (EIA). Residential, commercial and industrial monthly electricity consumption are from the *Electric Power Monthly* (EIA, various years). The electricity data contain observations from January 1977 to August 2001 (see Figure 2). The overall upward trends for both the residential and commercial sectors are due to changes in the size of the local population combined with changes in household sizes, building stock and increased proliferation of electric heating and air-conditioning, as well as increases in overall economic activity in the region.

Figure 2. Massachusetts' Residential and Commercial Monthly Electricity Use, 1977-2001.



Monthly natural gas sales to residential, commercial and industrial end users are from the *Natural Gas Monthly* (EIA, various years). The natural gas data span from January 1984 to July 2001. Sales of heating oil (distillate fuel oil No. 2) in Massachusetts only to all end users on a monthly basis are published in the *Petroleum Marketing Monthly* (EIA, various years). Therefore, we estimate monthly consumption by end use sector by weighing the monthly total sales figures by the annual sectoral sales ratios of heating oil as published in *Fuel Oil and Kerosene Sales Annual* (EIA, various years). The derived monthly heating oil data span from January 1983 to December 2001.

Figure 3. Massachusetts' Residential and Commercial Monthly Heating Fuels Sales, 1984-2001.



Natural gas and heating oil are the two primary heating fuels in Massachusetts. There is some possibility for fuel switching between these two energy carriers. But because only limited data are available to infer the extent of fuel switching under different scenarios and because we are not concerned here with carbon emissions from using either fuel, we aggregate natural gas and heating oil consumption to better capture their combined demand sensitivity to climate. Here, natural gas and heating oil are aggregated based on British thermal unit (Btu) equivalents and categorized as 'heating fuels'. The heating fuel data span from January 1984 to July 2000 and are shown in Figure 3.

3.2 Socio-economic Data

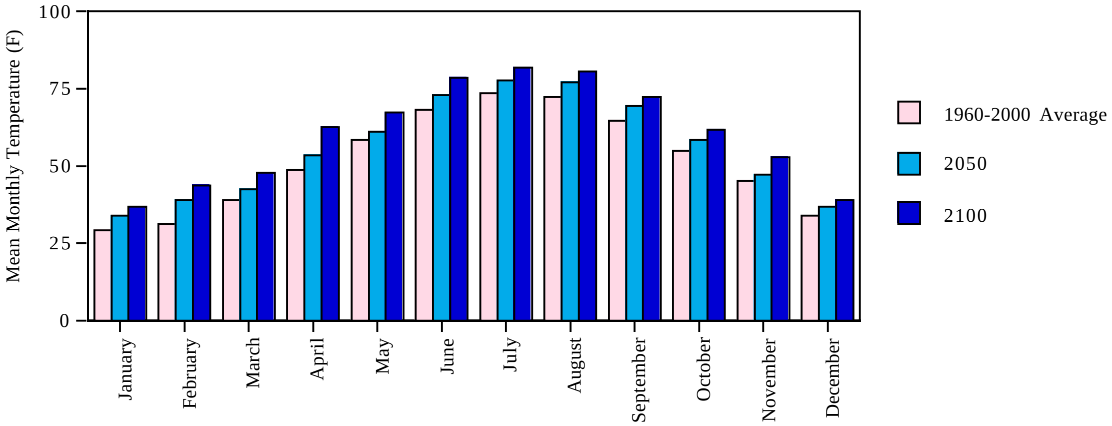
Annual population estimates for the Commonwealth of Massachusetts are from the Census Bureau (Census 2001). Massachusetts' annual personal income data are from the Bureau of Economic Analysis (Bureau of Economic Analysis 2001). Income figures are deflated using a consumer price index constructed by the Bureau of Labor Statistics (Bureau of Labor Statistics 2001). Massachusetts' employment data are from the (Bureau of Economic Analysis 2001). Commercial employment was disaggregated from the overall Massachusetts' employment data based on commercial enterprises that compose commercial energy use as defined in the *State Energy Report 1999* (EIA 2001). To coincide with the time-step of the monthly energy data the annual population, income and commercial employment data are held constant throughout each month of the year.

3.3 Climate Data

The historic climate data consist of daily and monthly average temperature from the National Weather Station of the National Oceanic and Atmospheric Administration (NWS NOAA 2001). We derived annual and monthly heating degree-days (HDD) and cooling degree-days (CDD) for numerous base temperatures to coincide with the time-step at which our energy data is reported. Additionally, we created scenarios of future monthly temperatures and degree-days for Boston using regional outputs from the Canadian Centre for Modeling and Analysis's Canadian Global Coupled Model (CGCM2 model) along with historic Boston weather by employing a statistical 'bootstrapping' technique. Because temperature is not normally distributed (Harmel, Richardson et al. 2002) this technique retains the region's temperature distribution while at the same time accounting for projected climatic changes from the CCC model.

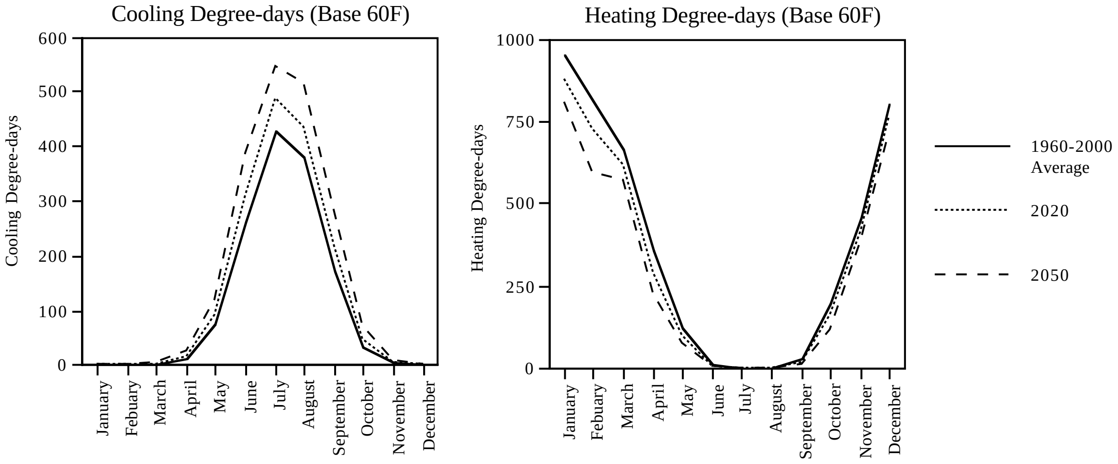
All monthly climatological data used in this study are derived from the average daily projections of 100 Monte Carlo simulations of future daily weather, bootstrapped using data from the 1951-2000 period. For instance, as shown in Figure 4, scenarios of mean monthly temperature as produced from the CCC mid-range outputs.

Figure 4. Historic and projected mean monthly temperatures at Logan Airport, Boston.



Monthly degree-days are derived from the projections of future daily temperatures (see Figure 5). An appreciable increase in cooling-degree days occurs in the summer with, for instance, July totals increasing from the historic average of 428 to 487 with the 2020 climate scenario and 545 with the 2050 climate scenario. The annual cooling degree-day changes relative to the historic 1960-2000 average represent increases of 19% and 44%, respectively for 2020 and 2050. During the winter months heating degree-day totals are projected to decrease. For instance, January heating degree-days are projected to decrease from the historic average of 951 to 878 in 2020 and 810 in 2050. Annually, heating degree-day decreases of 10% and 21%, respectively, relative to the historic 1960-2000 average are projected.

Figure 5. Projected Changes in Massachusetts' Degree-days.



4. Methodology

We assess potential energy demand responses to climatic change in two-steps. First, we use monthly time-series data to quantify the historic sensitivity of end use energy demand to climatic variables while controlling for socioeconomic factors such as population size and economic activity. We independently estimate Massachusetts' residential and commercial energy demand sensitivities to climatic variables because potentially different energy use-temperature relations exist between economic sectors (Sailor and Munoz 1997; Sailor 2001). Industrial energy demand is not estimated since previous investigations (Elkhafif 1996; Sailor and Munoz 1997) and our own findings indicate that it is non-weather sensitive.

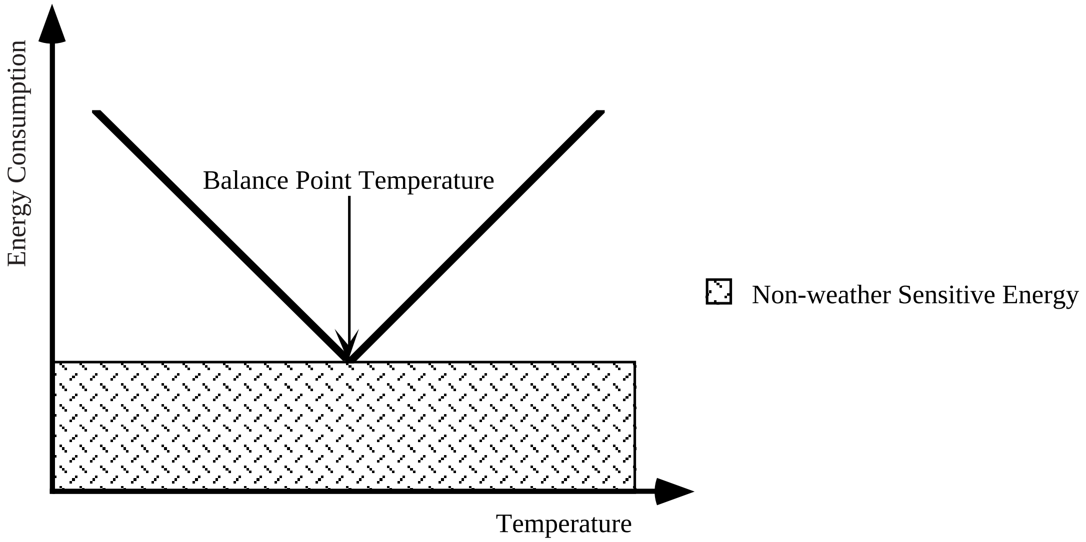
Furthermore, for each sector the demand for electricity and heating fuels is separately estimated. We assume the separation of energy forms used predominantly for heating (i.e. natural gas, fuel oil) and those for cooling (i.e. electricity) is important because climate change is anticipated to have unique impacts on the use of each form of energy and, subsequently, on the different energy delivery systems. Therefore, while analyses focusing on total energy use may find only negligible changes in energy use or expenditure given the potential for changes in cooling and heating energy to offset one another, we believe they under-appreciate the large capital costs associated with cooling energy system expansion and heating energy system contraction.

In order to better isolate the influence of climate on energy use from socioeconomic factors we modify the raw electricity and heating fuels data by accounting for consumption on a per capita level in the residential sector and a per employee level in the commercial sector. In the second part of the analysis we estimate future energy consumption under various climate change scenarios by employing the energy sensitivity relationships developed in step one.

4.1 Methodology for Demand Sensitivity Analysis

For the demand sensitivity analysis we use a degree-day methodology to estimate energy consumption under various climate scenarios. Degree-days are a common energy accounting practice for forecasting energy demand as a function of either heating degree-days (HDD) or cooling degree-days (CDD). The degree-day methodology presumes a V-shaped temperature-energy consumption relationship as shown in Figure 6 (Jager 1983). The temperature at the bottom of the V-shaped temperature-energy consumption function is referred to as the balance point temperature. At the balance point, energy demand is at a minimum since outside climatic conditions produce the desired indoor temperature. As outdoor temperatures deviate above or below the balance point temperature, energy demand increases. Each degree deviation from the balance point temperature is counted as a degree-day. For example, if a balance point temperature of 65°F is designated and the day's average temperature is 70°F this would result in 5 cooling degree-days for that day. Cooling and heating degree-days can be accumulated over time to give monthly or annual degree-day totals.

Figure 6. Theoretical Relationship Between Temperature and Energy Use.

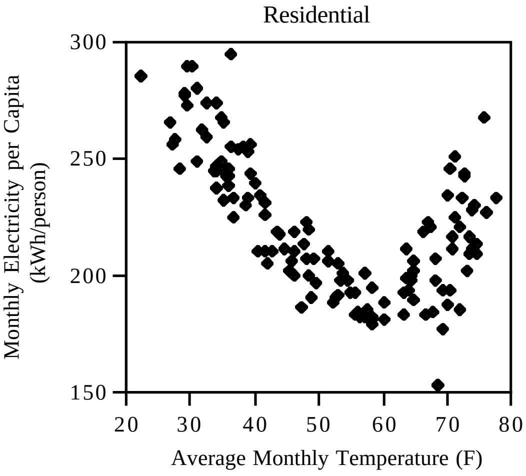


The amount of energy consumed at the balance point temperature is the non-weather sensitive energy load, which is projected to increase with the increasing proliferation of electronic devices. Within the residential sector estimates of future electricity use indicate that 90 percent of future electricity growth will be due to increases in miscellaneous electricity uses, which are comprised mostly of demand to operate consumer electronics (Sanchez, Koomey et al. 1998). Energy consumed in excess of the energy demanded at the balance point temperature is weather-sensitive energy use. Large deviations in temperature from the balance point temperature result in large increases in energy consumption.

Energy analyses commonly use a base temperature of 65°F as the balance point threshold in the space-conditioning temperature relationship. However, the actual balance point temperature of an energy system varies depending on the place-specific characteristics of the building stock, non-temperature weather conditions (e.g. humidity, precipitation, wind), and cultural preferences (Nall and Arens 1979; de Dear and Brager 2001). For example, a region with a housing stock comprised of well-insulated homes will have a relatively low balance point temperature. Nonetheless, while place-specific variations in base temperatures exist, most assessments continue to use the 65°F base either because of the ease of data collection since degree-days are commonly calculated with 65°F as the base or to allow for comparison with other assessments performed with the 65°F base. In this assessment we tailor the balance point to the attributes of the Massachusetts energy infrastructure and behavioral characteristics, using a quantitative approach such that the functional relationship is optimally specified. Similar to the methodology used by Belzer and colleagues (Belzer, Scott et al. 1996), we iteratively performed regressions with numerous base temperatures and then chose the balance point temperature producing the highest R-square. We found a balance point temperature of 60°F in the residential sector, 55°F for commercial electricity, and 60°F for commercial heating fuel use.

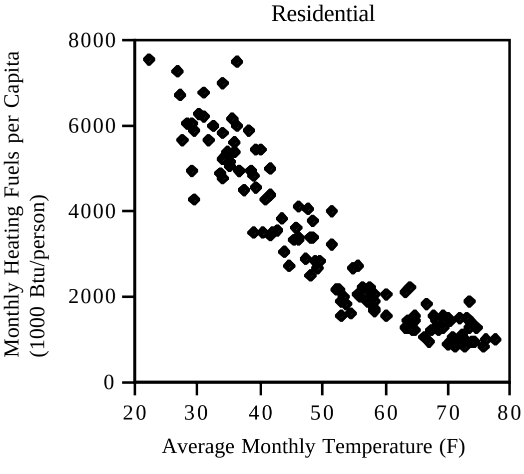
The relationship between monthly sectoral electricity consumption and mean monthly temperatures in Massachusetts is shown in Figure 7. For the residential sector the balance point temperature is approximately 60°F, which is slightly below the customary 65°F threshold. The lower threshold for Massachusetts is not surprising given the adaptation to the regional climate characteristics by the population. For example, Massachusetts' housing stock is comprised of homes with sufficient insulation for the historically cold winter months. In contrast to our findings for Massachusetts, a previous analysis of state-level energy use finds Florida has a balance point temperature of 70°F (21°C) (Sailor 2001).

Figure 7. Average Monthly Temperature and Sectoral Electricity Consumption, 1990-2000.



Commercial buildings typically have a lower balance point temperature due to higher internal heat gains from office machinery, lighting and occupants. Not surprisingly, as is evident in Figure 7, the balance point temperature for the Massachusetts commercial sector electricity consumption is 55°F, which is significantly below the balance point for the residential sector.

Figure 8. Average Monthly Temperature and Sectoral Heating Fuel Sales, 1990-2000.



The relationship between monthly sectoral heating fuels sales and mean monthly temperatures in Massachusetts are shown in Figure 8. Due to the fact that heating fuels are predominantly used for heating purposes the relationship with temperature is a downward sloping function.

4.2 Energy Demand Sensitivity Analysis

4.2.1 Residential Sector

The regression results for monthly residential per capita electricity consumption in Massachusetts are shown in the first column of Table 1. The constant term together with the annual income per capita variable are representative of non-weather sensitive electricity demand or the amount of energy demanded at the balance point temperature. The coefficient on the annual income per capita variable indicates that increases in real annual income levels of $1000 have been associated with increases in annual non-weather sensitive electricity demands of 2.2%. The results suggest that future increases in per capita income may be accompanied by increases in non-weather sensitive electricity demand.

The heating and cooling degree-days used in the residential electricity model are derived from a 60°F base temperature. The coefficients on the heating and cooling degree-day variables suggest that residential per capita electricity demand exhibits a similar sensitivity to changes in heating and cooling degree-days. To illustrate, a 100 unit increase in monthly heating degree-days is associated with a 4.3% increase in monthly per capita electricity consumption. Similarly, a 100 unit increase in cooling degree-days is associated with a 4.4% increase in per capita electricity consumption. The regression model accounts for 86% of the historic variation in per capita electricity consumption.

Table 1. Regression Results for Residential Sector.

	Log monthly electricity per capita (kWh / month)	Heating fuels per capita (1000 Btu / month)
Constant	4.492798***	3506.188***
Annual Income per capita ($/person)	0.0000229***	-0.073002***
Monthly heating degree-days (Base 60°F)	0.0004266***	5.198097***
Monthly cooling degree-days (Base 60°F)	0.0004419***	
R^2	0.8613	0.8487
Durbin-Watson statistic	1.8819	2.0372

*Significant at the 10% level **Significant at the 5% level ***Significant at the 1% level

The second column of Table 1 contains the heating fuel regression model for the residential sector, which also uses degree-days derived from a 60℉ temperature base. The constant variable indicates heating fuels are purchased even in months with no heating degree-days. The annual income per capita coefficient indicates that rising incomes are associated with decreases in heating fuel sales. A host of factors could explain the inverse relation between income and heating fuel sales including more efficient furnaces, better insulated homes, stricter building codes, urbanization or increasing use of electric heaters. Monthly heating degree-days are positively and significantly correlated with increases in heating fuels sales. A 100 unit increase in heating degree-days is associated with a rise in heating fuels sales of 520,000 Btu per person per month. The regression model explains 85% of the historical variation in per capita heating fuels sales.

4.2.2 Commercial Sector

Electricity and heating fuel per employee results are presented in columns one and two, respectively, of Table 2. Monthly electricity consumption per employee is modeled as a function of a constant, an annual trend and heating and cooling degree-days derived from a 55°F temperature base. The constant term denotes non-weather sensitive electricity load, which as indicated by the annual trend variable is increasing at 1.2% per year. The heating degree-day variable implies that a 100 unit increase is associated with a 1.9% increase in per employee monthly electricity consumption.

Table 2. Regression Results for Commercial Sectors.

	Log monthly electricity per employee (kWh / employee)	Log monthly heating fuels per employee (1000 Btu / employee)
Constant	6.017787***	7.367029***
Annual trend	0.0120644***	
Monthly heating degree-days (Base 55℉)	0.0001941***	
Monthly cooling degree-days (Base 55℉)	0.0002767***	
Monthly heating degree-days (Base 60℉)		0.0011474***
R^2	0.9185	0.8057
Durbin-Watson statistic	2.1298	1.9624

*Significant at the 10% level **Significant at the 5% level ***Significant at the 1% level

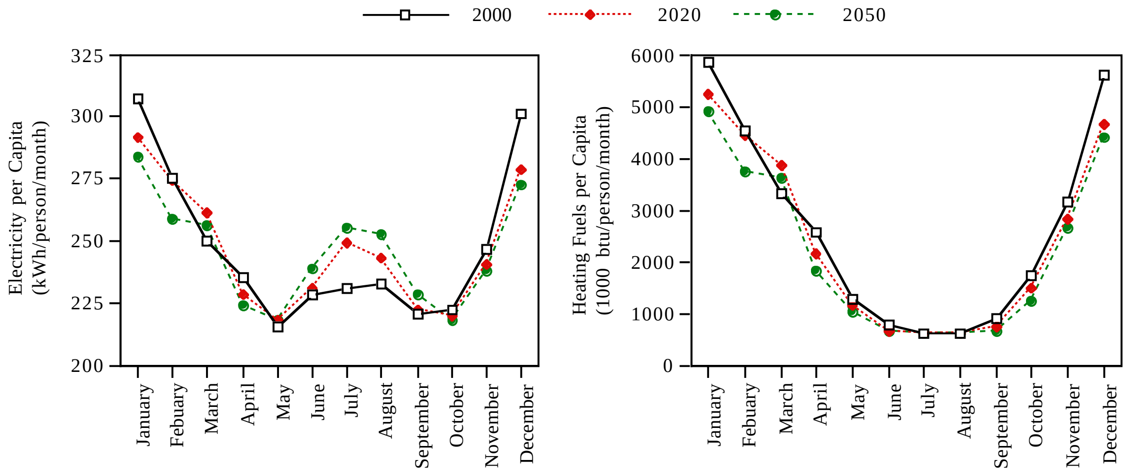
Electricity for cooling is used more intensively than that for heating as suggested by the larger coefficient of the cooling degree-day variable. A 100 unit increase in monthly cooling degree-days is associated with a 2.8% increase in per employee electricity consumption. The regression model explains 91% of the historical variation in per employee electricity consumption.

Commercial heating fuel use is a function of a constant variable and heating degree-days. Initial runs indicated that a trend variable and cooling degree-days are insignificant. A 100-unit increase in monthly heating degree-days is associated with a 1.1% increase in monthly heating fuel sales per employee. The regression model explains 81% of the historical variation in per employee heating fuels sales.

5. Projections of Energy Use Under Future Climate Scenarios

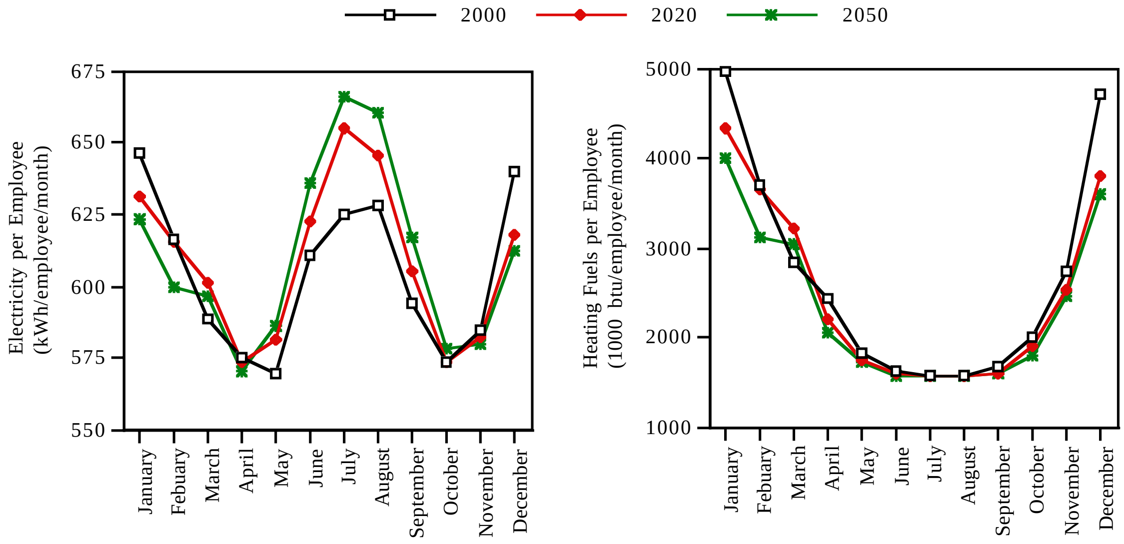
In the second part of our analysis we use the regression results for electricity and heating fuels demand in conjunction with various climate change scenarios. All parameters except degree-days are held constant to better illustrate the effects of changes in climatic variables on energy demand. The projections for residential monthly electricity and heating fuels are shown in Figure 9. The climate scenarios of 2020 and 2050 are projected to decrease residential electricity demands during the winter months and increase in the summer months. With the average climate of 1960-2000 the regression model indicates that monthly per capita electricity is highest in January at 301 kilowatt-hours a person. The climate scenarios of 2020 and 2050 are estimated to reduce January electricity consumption to 292 and 284 kilowatt-hours a person, respectively. Summertime monthly electricity demand per capita is highest in July at 243 kilowatt-hours a person, which would increase to 249 and 255 under the projected climates of 2020 and 2050, respectively. The seasonal effect on electricity use is a 2.8% and 6.2% decrease in winter (December-February) under the climates of 2020 and 2050, respectively. Summer (June-August) electricity use is projected to increase 2.4% and 5.6% under the respective scenarios.

Figure 9. Residential Electricity and Heating Fuel Use per Capita.



The climate scenarios for 2020 and 2050 are projected to significantly decrease annual heating fuel sales by 6.6% and 13.9%, respectively, relative to the sales projected using the 1960-2000 average degree-day variables. Intra-annual variations are also significant with, for instance, winter (December-February) sales down 6.3% with the climate scenario for 2020 and down 14.5% with the climate scenario for 2050.

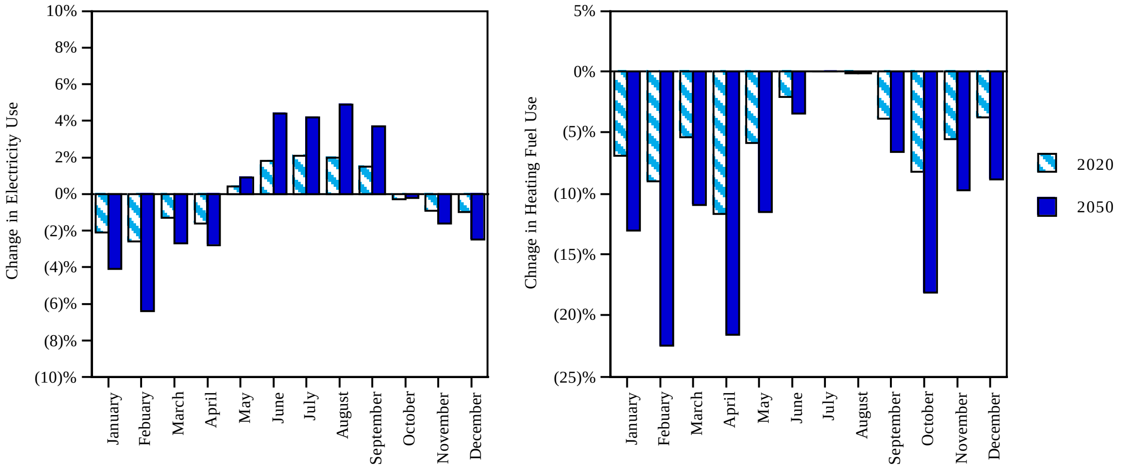
Figure 10. Commercial Electricity and Heating Fuel Use per Employee.



Monthly electricity and heating fuels projections for the commercial sector are shown in Figure 10. The econometric model for electricity demand by the commercial sector indicates that under the climate change scenarios for 2020 and 2050 electricity demand per employee in January would decrease from 640 kWh per employee of the historic climate to 631 in 2020 and 623 in 2050. July's electricity demand would increase to 655 in 2020 and 666 in 2050 from the predicted 644 of the historic climate. Commercial heating fuel use under our climate change scenarios for 2020 and 2050 is projected to decrease for all months, with the largest decreases occurring in January and February.

Changes in total residential and commercial electricity use are shown in Figure 11. Assuming a constant population and income levels, annual electricity use changes by less than 1 % in the 2020 and 2050 climate scenarios. However, notable changes appear in monthly electricity consumption with, for example, July consumption increasing 2.1% and 4.2%, respectively, relative to the historic climate. In contrast, January's electricity consumption is projected to decrease by 2.2% and 4.2%, respectively.

Figure 11. Change in Total Residential and Commercial Electricity and Heating Fuel Use in Response to Climate Scenarios of 2020 and 2050 Relative to Historic Climate.



Annual and monthly consumption of heating fuel by the residential and commercial sectors is also projected to decrease with projected decreases in heating degree-days (Figure 11). Annual heating fuel sales are projected to decrease 6.1% with the 2020 climate change scenario and 12.7% with the 2050 climate change scenario relative to the historic climate. Intra-annual variations are even more significant with, for instance, January sales down 6.9% with the climate scenario for 2020 and 13.1% with the climate scenario for 2050.

Discussion

In this study we have developed a methodology for assessing energy demand responses to climate change at a spatial resolution fine enough to capture place-specific responses. Results indicate that residential and commercial energy demand in Massachusetts are sensitive to climate and that a range of scenarios of climate change may noticeably decrease winter heating fuel consumption and increase summer electricity demands. Our results indicate heating fuel consumption during the winter months (December-February) would decrease by 6.6 percent with the climate scenario of 2020 and 14.6 percent with the climate scenario of 2050. Conversely, electricity demand during the summer months (June-August) would increase by 1.9 percent and 4.5 percent, respectively.

Such increases alone may prove significant enough to warrant changes in peak load capacity planning for the region. However, by using monthly information on changes in climate and energy we may even have under-appreciated the larger increases in peak electric demand, which often occur within narrow daily or hourly time intervals. For instance, Boston normally experiences 12.9 days per year with temperatures exceeding 90℉, and our climate change scenarios indicate that by the end of this century the total number of days in Boston exceeding 90℉ will be approximately 50. Such changes in extremely hot days may result in an appreciable increase in high energy consumption days and need for requisite peaking units. Other studies suggest similar findings. For example, an average temperature increase of 3℃ (5.4℉) in Toronto was found to be associated with a 7 percent increase in mean peak electric demand, but a 22 percent increase in the peak electric load standard deviation (Colombo, Etkin et al. 1999). As a consequence, energy sector decision makers need to incorporate the impacts of climate change into regional energy system expansion plans to ensure adequate supply of energy both throughout the year and for periods of peak demand.

Identifying potential impacts for the region now is important because the energy industry is extremely capital intensive and, therefore, the flexibility of policy induced changes in energy trajectories over the short and medium run is limited (Grubler 1990). In the long run, as the capital stock naturally turns over, building codes may be changed to calibrate the thermal attributes of the building stock to expected future climates (Camilleri, Jaques et al. 2001). However, such changes need to be implemented in the relatively near term or the building stock will on aggregate become increasingly maladapted to climate. In the near term, polices such as urban shade tree planting and installation of high albedo roofs can begin to modify the thermal characteristics of the Massachusetts energy infrastructure in order to reduce space-conditioning energy use.

References:

Badri, M. A. (1992). "Analysis of Demand for Electricity in the United States." Energy **17**(7): 725-733.

Barron, E. (2002). Potential Consequences of Climate Variability and Change for the Northeastern United States. Climate Change Impacts on the United States: The Potential Consequences of Climate Variability and Change. National Assessment Synthesis Team.

Belzer, D. B., M. J. Scott, et al. (1996). "Climate Change Impacts on U.S. Commercial Building Energy Consumption: An Analysis Using Sample Survey Data." Energy Sources **18**(2): 177-201.

Boustead, I. and B. R. Yaros (1994). "Electricity Supply Industry in North America." Resources, Conservation and Recycling **12**(3-4): 121-134.

Camilleri, M., R. Jaques, et al. (2001). "Impacts of Climate Change on Building Performance in New Zealand." Building Research & Information **29**(6): 440-450.

Cartalis, C., A. Synodinou, et al. (2001). "Modifications in energy demand in urban areas as a result of climate changes: an assessment for the southeast Mediterranean region." Energy Conversion and Management **42**: 1647-1656.

Colombo, A. F., D. Etkin, et al. (1999). "Climate Variability and the Frequency of Extreme Temperature Events for Nine Sites Across Canada: Implications for Power Usage." Journal of Climate **12**(8): 2490-2502.

Considine, T. J. (2000). "The impacts of weather variation on energy demand and carbon emissions." Resource and Energy Economics **22**(4): 295-314.

de Dear, R. and G. S. Brager (2001). "The Adaptive Model of Thermal Comfort and Energy Conservation in the Built Environment." International Journal of Biometeorology **45**: 100-108.

EIA (1995). Measuring Energy Efficiency in the United States' Economy: A Beginning. Washington, D.C., U.S. Department of Energy.

EIA (1999). A Look at Residential Energy Consumption in 1997. Washington, D.C., Energy Information Administration.

EIA (2001). Annual Energy Review 2000. Washington, D.C., Department of Energy.

EIA (2001). State Energy Data Report 1999. Washington, D.C., U.S. Department of Energy.

Elkhafif, M. (1996). "An Iterative Approach for Weather-Correcting Energy Consumption Data." Energy Economics **18**(3): 221-230.

Greco, S., R. H. Moss, et al. (1994). Climate Scenarios and Socioeconomic Projections for IPCC WG II Assessment. Washington, DC, IPCC - WMO and UNEP**:** 67.

Grubler, A. (1990). The Rise and Fall of Infrastructures. Heidelberg, Germany, Physica-Verlag.

Harmel, R. D., C. W. Richardson, et al. (2002). "Evaluating the Adequacy of Simulating Maximum and Minimum Daily Air Temperature with the Normal Distribution." Journal of Applied Meteorology **41**(7): 744-753.

IPCC (1996a). Climate Change 1995: Impacts, Adaptation and Mitigation of Climate Change.

IPCC (2001a). Climate Change 2001: Impacts, Adaptation and Vulnerability. Geneva, Intergovernmental Panel on Climate Change.

Jager, J. (1983). Climate and Energy Systems: A Review of their interactions. New York, NY, John Wiley & Sons.

Lakshmanan, T. R. and W. Anderson (1980). "Residential Energy Demand in the United States: A Regional Econometric Analysis." Regional Science and Urban Economics **10**: 371-386.

Lam, J. C. (1998). "Climatic and Economic Influences on Residential Electricity Consumption." Energy Conversion and Management **39**(7): 623-629.

Le Comte, D. M. and H. E. Warren (1981). "Modeling the Impact of Summer Temperatures on National Electricity Consumption." Journal of Applied Meteorology **20**: 1415-1419.

Lehman, R. L. (1994). "Projecting Monthly Natural Gas Sales for Space Heating Using a Monthly Updated Model and Degree-days from Monthly Outlooks." Journal of Applied Meteorology **33**(1): 96-106.

Linder, K. P. (1990). National Impacts of Climate Change on Electric Utilities. The Potential Effects of Global Warming on the United States. J. B. Smith and D. A. Tirpak. Washington, D.C., Environmental Protection Agency.

Morris, M. (1999). The Impact of Temperature Trends on Short-Term Energy Demand, EIA. **2001**.

Morrison, W. and R. Mendelsohn (1998). The Impacts of Climate Change on Energy: An Aggregate Expenditure Model for the US. Washington, D.C., U.S. Department of Energy.

Nall, D. and E. Arens (1979). "The Influence of degree-day base temperature on residential building energy prediction." ASHRAE Transactions **85**: 1.

Pardo, A., V. Meneu, et al. (2002). "Temperature and Seasonality Influences on the Spanish Electricity Load." Energy Economics **24**(1): 55-70.

Quayle, R. G. and H. F. Diaz (1979). "Heating Degree Day Data Applied to Residential Heating Energy Consumption." Journal of Applied Meteorology **19**: 241-246.

Rosenthal, D. H., H. K. Gruenspecht, et al. (1995). "Effects of Global Warming on Energy Use for Space Heating and Cooling in the United States." The Energy Journal **16**(2).

Ruth, M. and P. Kirshen (2001). "Integrated Impacts of Climate Change upon Infrastructure Systems and Services in the Boston Metropolitan Area." World Resources Review **13**(1): 106-122.

Sailor, D. J. (1997). "Climatic Change Feedback to the Energy Sector: Developing Integrated Assessments." World Resource Review **9**(3): 301-316.

Sailor, D. J. (2001). "Relating residential and commercial sector electricity loads to climate - evaluating state level sensitivities and vulnerabilities." Energy **26**: 645-657.

Sailor, D. J. and J. R. Munoz (1997). "Sensitivity of electricity and natural gas consumption to climate in the USA - Methodology and results for eight states." Energy **22**(10): 987-998.

Sanchez, M. C., J. G. Koomey, et al. (1998). "Miscellaneous electricity use in US homes: Historic decomposition and future trends." Energy Policy **26**(8): 585-593.

Scott, M. J., L. E. Wrench, et al. (1994). "Effects of Climate Change on Commercial Building Energy Demand." Energy Sources **16**: 317-332.

Segal, M., H. Shafir, et al. (1992). "Climatic-related Evaluations of the Summer Peak-Hours' Electric Load in Israel." Journal of Applied Meteorology **31**(12): 1492-1498.

Smith, J. B. and D. A. Tirpak (1990). The Potential Effects of Global Climate Change on the United States. Washington, D.C., Hemisphere Publishing.

UNEP (1998). Handbook on Methods for Climate Change Impact Assessment and Adaptation Strategies, United Nations Environmental Programme.

Warren, H. E. and S. K. LeDuc (1981). "Impact of Climate on Energy Sector in Economic Analysis." Journal of Applied Meteorology **20**: 1431-1439.

Wilbanks, T. J. and R. W. Kates (1999). "Global Change in Local Places: How Scale Matters." Climatic Change **43**: 601-628.

Yan, Y. Y. (1998). "Climate and Residential Electricity Consumption in Hong Kong." Energy **23**(1): 17-20.