REGIONAL ENERGY DEMAND RESPONSES TO CLIMATE CHANGE: METHODOLOGY AND APPLICATION TO THE COMMONWEALTH OF MASSACHUSETTS

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Abstract. Climate is a major determinant of energy demand. Changes in climate may alter energy demand as well as energy demand patterns. This study investigates the implications of climate change for energy demand under the hypothesis that impacts are scale dependent due to region-specific climatic variables, infrastructure, socioeconomic, and energy use profiles.

In this analysis we explore regional energy demand responses to climate change by assessing temperature-sensitive energy demand in the Commonwealth of Massachusetts. The study employs a two-step estimation and modeling procedure. The first step evaluates the historic temperature 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. 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 several methodological issues relevant to the development of climate change impact assessments of energy demand.

1. Introduction

Although the majority of climate change assessments have concentrated on contributions of the energy sector to climate change, few have explored the reverse – implications of climate change for the energy sector. We argue that the results of such an exploration will fundamentally depend on region-specific climatic variables, infrastructure, socioeconomic, and energy use profiles. In the present research, we assess potential energy demand responses to climate change 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

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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 monthly residential and commercial energy demand to climatic variables controlling for energy prices, socioeconomic factors, and hours of daylight. 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 and 4 address, respectively, the data and methodology used in our study. Section 5 presents empirical results of historic demand sensitivities and the modeling results of potential demand responses to various future climate scenarios. The paper closes with a policy discussion and set of recommendations for future research in Section 6.

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% (EIA, 1999), commercial buildings 40% (EIA, 1995), and industrial facilities 6% (EIA, 2001) of energy consumption to space-conditioning requirements, not including water heating. As these sectors account for 20, 16, and 38% of total US end-use energy demand, respectively, roughly 22% 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" (Sailor, 1997, p. 313).

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; Downton et al., 1988; Badri, 1992; Lehman, 1994; Lam, 1998; Yan, 1998; Morris, 1999; Pardo et al., 2002). However, to date few analyses address the longer-term implications of climate change for energy use patterns and investment decisions. The results of the few studies that have examined the effects of climate change on the energy sector suggest, in general, 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. (1992) estimate an increase in temperature of 4 °C is associated with a 10% increase in average summer peak loads. In Greece, a 1 °C temperature increase is projected to decrease energy consumption for heating by 10% and increase energy used for cooling by 28%, assuming a business-as-usual scenario (Cartalis et al., 2001). A study examining potential changes in US commercial energy use due to climate change finds a 4 °C increase in average annual temperature results in a 0–5% reduction in total energy use by the commercial sector in 2030, after accounting for changes in the building stock (Belzer et al., 1996). Rosenthal et al. (1995) estimate that a 1 °C warming in the US would reduce energy expenditures by \$5.5 billion and primary energy use by 0.70% in 2010 relative to a non-warming scenario. In contrast, a study examining the impacts of climate change on total US energy use finds a 2 °C 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 course 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" (IPCC, 2001, p. 25).

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 due to 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, end use technologies, and characteristics of end users. 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 (Pressman, 1995). 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% of households have central air-conditioning units whereas the average is 47% 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 (2001) observes significantly different variation in sectoral demand sensitivities between states. He finds a temperature increase of 2 °C is associated with an 11.6% *increase* in residential per capita electricity used 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 colleagues estimate the sensitivity of state-level electricity and natural gas consumption to temperature variables and find considerable variation (Sailor and Munoz, 1997; Sailor et al., 1998). Warren and LeDuc (1981) statistically relate natural gas consumption to prices and heating degree-days in a nine-region model of the US and find noticeable regional differences. Scott et al. (1994) 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). 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 at least two reasons. First, compared to the national average, Massachusetts has a large share of energy consumed by end users whose demand is relatively temperature-sensitive such as residential and commercial end users. In fact, in 1999 Massachusetts' residential and commercial sectors represented 73% of the total non-mobile end use energy, whereas for the nation as a whole these sectors accounted for only 49%. 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 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 because 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 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 is from the U.S. Energy Information Administration (EIA). Monthly electricity sales and price to residential and commercial end users are from the *Electric Power Monthly* (EIA, various years). The electricity sales data span from January 1977 to December 2001 while monthly electricity price data is limited to the January 1990 to December 2001 period (Figure 1). The overall upward trends for both the residential and commercial sectors' electricity use 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. Prices of electricity demonstrate intra-annual oscillation but, in general, no inter-annual trend. To adjust for inflation, the electricity price data is deflated with the Bureau of Labor Statistics' consumer price index for electricity in the New England region (BLS, 2003).

Monthly natural gas sales to residential and commercial end users are from the *Natural Gas Monthly* (EIA, various years). Natural gas sales and price data for the residential and commercial sectors span from January 1984 to December 2001 are shown in Figure 2. Monthly sales of heating oil (distillate fuel oil No. 2) to all end users are published in the *Petroleum Marketing Monthly* (EIA, various years). Because sales to end use sector are not available and the majority of heating oil is consumed by the residential sector, we assume that all heating fuel sales are to

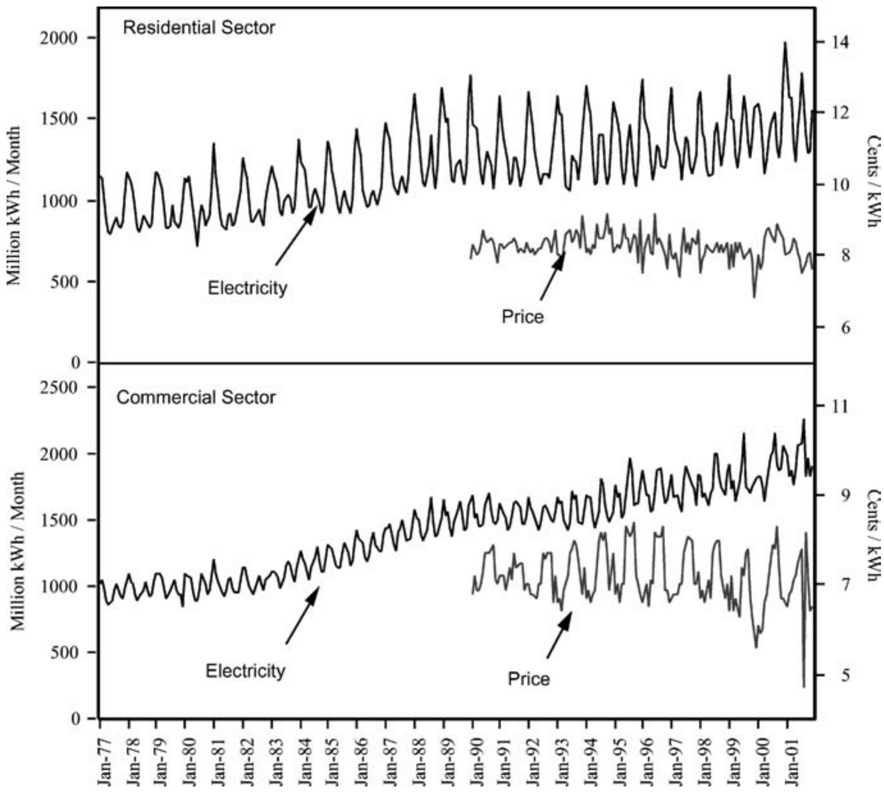

Figure 1. Massachusetts' residential and commercial monthly electricity consumption and price, 1977–2001.

residential end users. The heating oil sales and price data cover the January 1983 to December 2001 period (see Figure 3). The prices of both natural gas and heating oil are adjusted for inflation using the Bureau of Labor Statistics' consumer price index for fuels in the New England region (BLS, 2003).

3.2. SOCIO-ECONOMIC DATA

Annual population estimates for the Commonwealth of Massachusetts are from the Census Bureau (U.S. Census Bureau, 2002). Massachusetts' employment data are from the Bureau of Economic Analysis (U.S. Bureau of Economic Analysis, 2002). Commercial employment data were 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 and commercial employment data are held constant throughout each month of the year.

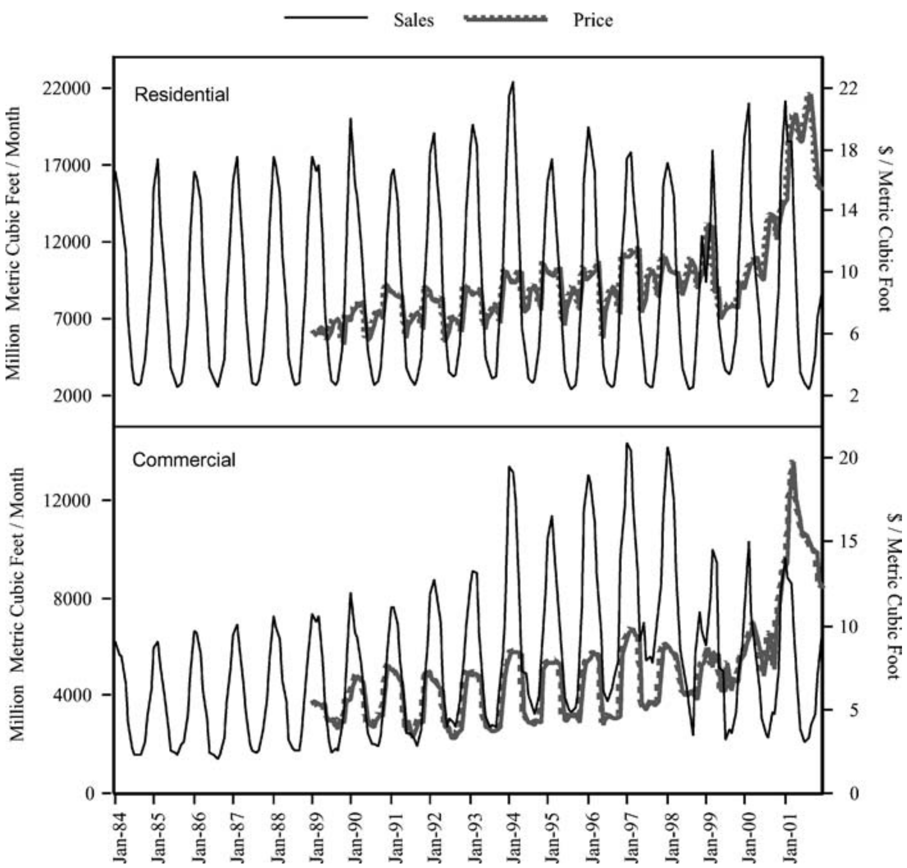

Figure 2. Massachusetts' residential and commercial monthly natural gas sales and price, 1984–2001.

3.3. CLIMATE DATA

The historic climate data consist of daily average temperature for Logan Airport in Boston generated by the National Weather Service (NWS) of the National Oceanic and Atmospheric Administration (NOAA, 2001). We use temperature in Boston as a proxy for temperature in the entire state of Massachusetts for three main reasons. First, the temperature data from Boston closely tracks population-weighted historical temperature for the state and thus is a good proxy for intra-annual and inter-annual climate variation. Second, the study presented in this paper is an integral component of a larger research project, part of which developed an innovative methodology for simulating future weather patterns based on Boston's past daily weather and regional projections of climate change from global change models. We wanted to use these scenarios because they offer a unique representation of climate change for the region and because we wanted to have consistent input data with the other studies in our project. Additionally, the available climate change data for

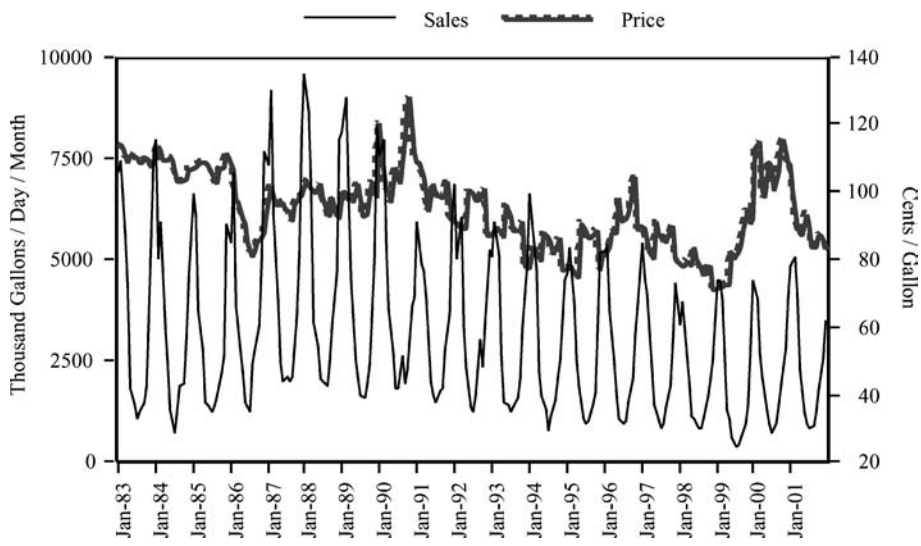

Figure 3. Massachusetts' monthly heating oil sales and price, 1983–2001.

Boston allowed us to directly calculate degree-days from future daily weather data rather than estimate them from projections of monthly temperature as would be the case if we used a population-weighted temperature.

Monthly heating degree-days (HDD) and cooling degree-days (CDD) are derived from the daily temperature data for numerous base temperatures to coincide with the time-step of the energy data. Each degree deviation from a predefined balance point temperature is counted as a degree-day. For example, if a balance point temperature of 65 °F is chosen and the day's average temperature is 70 °F this would result in 5 CDD for that day. Cooling and heating degree-days can be accumulated over time to give monthly or annual degree-day totals.

In addition to the climatological variables, we calculated daylight hours in each month of the year. Information on daylight hours helps us reduce bias in the econometric estimates of demand sensitivity to temperature variables because daylight hours are correlated with temperature and because they affect energy use. Daylight hours influence energy use for lighting needs as well as other energy use that may change as individuals are more likely to be indoors. The length of daylight effect may be especially pronounced in higher latitude regions such as Massachusetts where winter darkness sets in at around 4 in the afternoon. We use the hours of daylight on the 15th day of each month, calculated as the time elapsing between sunset and sunrise, as a proxy for the number of daylight hours per month in Boston (NOAA, 2003).

The historical weather data was used as the basis for regional forecasts of weather conditions. To generate future weather patterns that are consistent with past patterns, we applied a moving block bootstrapping approach (Vogel and Shallcross, 1996;

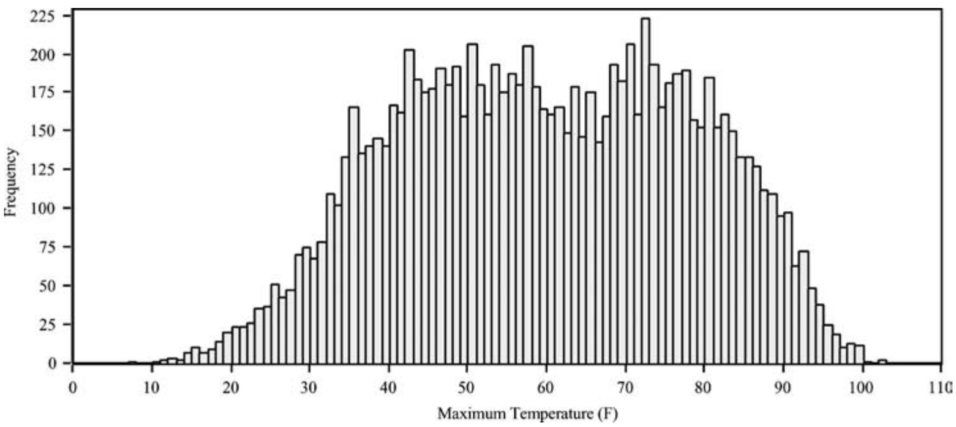

Figure 4. Maximum temperature frequency in Boston, 1970–1998.

Harmel et al., 2002). This is a nonparametric statistical method that maintains probability relationships of time-series values both within years and over years and consists of sampling with replacement from the existing time series of annual climate events until a time series of desired length is obtained. The technique retains the region's non-normal temperature distribution (Figure 4). To represent a range of possible future climate conditions, 100 bootstrapped data series have been generated from historical data. Each of these alternative climate runs extends from the year 2001 until 2100 and represents a base case assumption of no climate change.

To model time series of climate change scenarios, trends of climate changes are applied to the set of bootstrapped time series. These trends have been derived from the same Canadian Climate Centre (CCC) and Hadley Center (HC) scenarios that were used in New England during the recent US national assessment of climate change (New England Regional Assessment Group, 2001). The atmosphere – ocean general circulation models used for the scenarios are the Canadian CGCM1 and the Hadley HadCM2. The greenhouse gas emission scenario assumed a 1% annual increase in equivalent CO_2 and included the direct effects of sulphate aerosols in the atmosphere (IS92a scenario). Scenario data were obtained for the inland grid cell closest to our study area for 2030 and 2100 climate scenarios.

By bootstrapping local weather data and superimposing trends from more aggregate global climate models, we have created a set of time-series data for potential future weather conditions that are consistent with past patterns *and* global warming trends. In retaining past weather patterns, we also retain the standard deviation associated with past weather, which could change with climate change. This set of time-series data is used in the second step of our analysis to simulate potential impacts of climate change on temperature-related energy demand in metropolitan Boston. A comparison of model results against the base case then helps discern climate-induced changes in energy demand in the region.

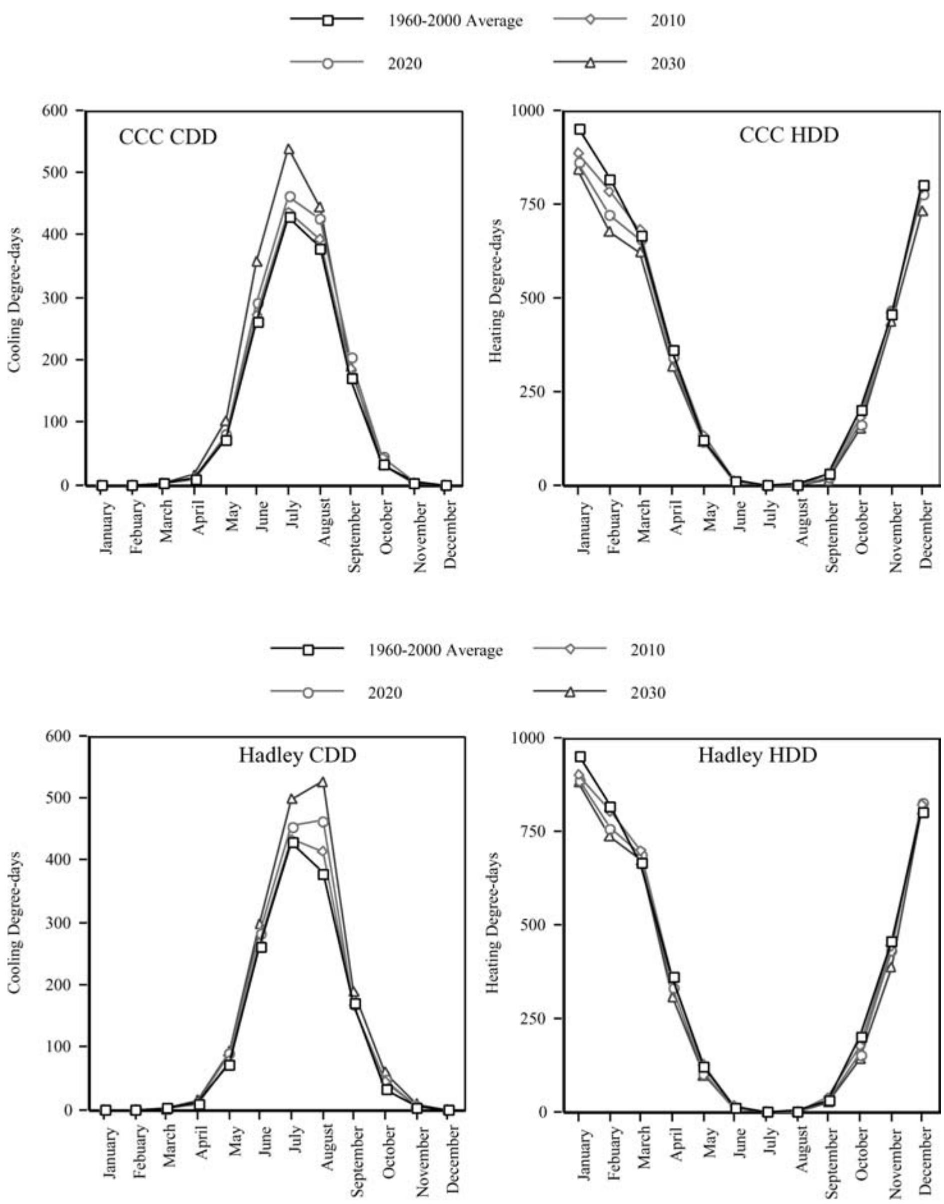

Figure 5. Projected changes in degree-days for Boston.

Monthly degree-days are derived from the projections of future daily temperatures for both the Canadian Climate Centre model and the Hadley model (see Figure 5). An appreciable increase in cooling-degree-days (for a base temperature of 60 °F) occurs in the summer with, for instance, July totals increasing under the assumptions of the Canadian Climate Centre model from the historic average of

428–436 in the 2010 scenario, 461 in the 2020 scenario, and 538 in the 2030 scenario. The annual cooling degree-day changes relative to the historic 1960–2000 average represent increases of 4.2, 12.1 and 24.1%, respectively, under the assumptions of the Canadian Climate Centre model. During the winter months heating degree-day totals (for a base temperature of 60 °F) are projected to decrease. For instance, January heating degree-days are projected to decrease from the historic average of 951–885 in 2010, 859 in 2020, and 840 in 2030. Annually, heating degree-day decreases of 2.2, 8.7 and 11.5%, respectively, relative to the historic 1960–2000 average are projected.

4. Methodology

Our methodology is a two-step modeling and estimation procedure. First, we use monthly time-series data to quantify the historic sensitivity of end use energy demand to temperature variables while controlling for socioeconomic factors such as population size and energy prices as well as daylight hours.

We independently estimate Massachusetts' residential and commercial energy demand sensitivities to temperature 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-temperature-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. 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. While the implications may not be significant in physical energy terms, the implications may be significant in terms of 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 the first step of our analysis. While this study focuses on the temperature effects of climate change, other weather variables not modeled here – such as humidity, precipitation, and wind – may have a significant impact on energy demand if they change as climate changes.

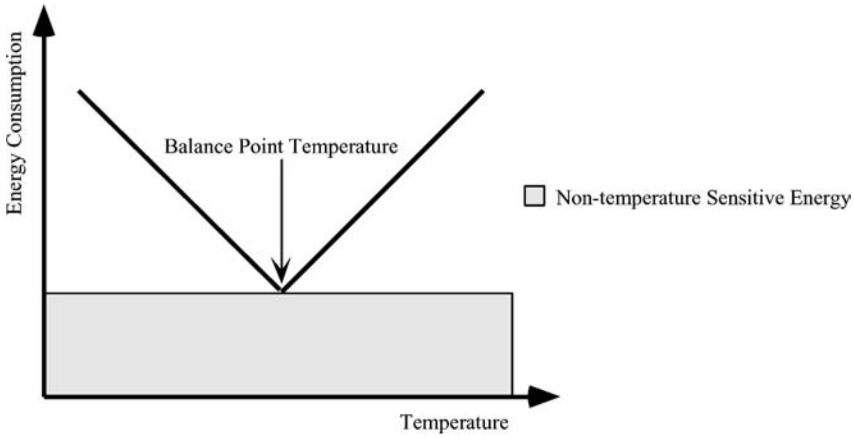

Figure 6. Theoretical relationship between temperature and energy use.

4.1. IDENTIFICATION OF BALANCE POINT TEMPERATURES

For the demand sensitivity analysis, we use a degree-day methodology to estimate energy demand under various climate scenarios. Degree-days are a common energy accounting practice for forecasting energy demand as a function of heating degree-days (HDD) and cooling degree-days (CDD). The degree-day methodology presumes a V-shaped temperature – energy consumption relationship as shown in Figure 6 (Jager, 1983). At the balance point temperature (the bottom of the V-shaped temperature–energy consumption function), energy demand is at a minimum since outside climatic conditions produce the desired indoor temperature. The amount of energy demanded at the balance point temperature is the non-temperature-sensitive energy load. As outdoor temperatures deviate above or below the balance point temperature, energy demand increases proportionally. Energy demanded in excess of the level at the balance point temperature is the temperature-sensitive energy load.

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 because of the ease of data collection since degree-days are commonly calculated with 65 °F as the base.

In this study we use a quantitative approach to objectively tailor the balance point to the attributes of the Massachusetts energy infrastructure such that the

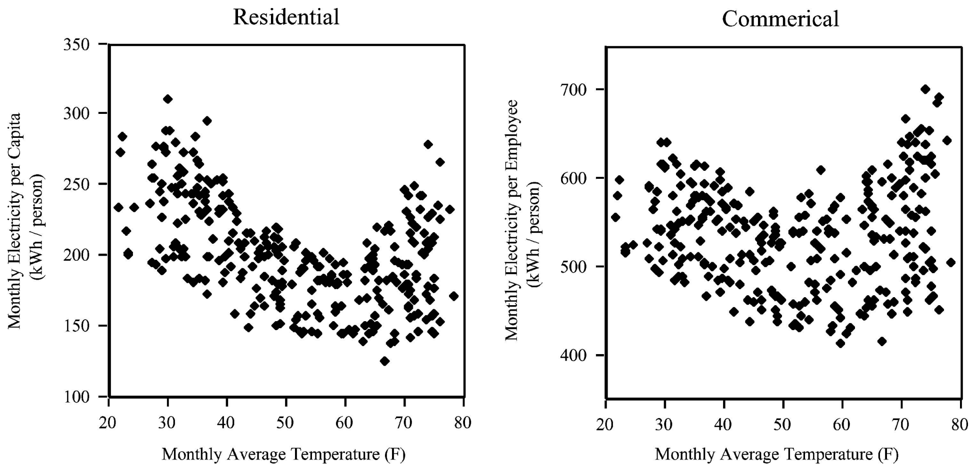

Figure 7. Monthly average temperature and sectoral electricity consumption, 1977–2001.

functional relationship is optimally specified. Similar to the methodology used by Belzer et al. (1996), we iteratively regressed the statistical models with base temperatures at 5 °F choosing the base temperature producing the highest R^2 as the balance point temperature. In this way the temperature explaining the largest share of changes in energy use is objectively designated as the balance point temperature. A simplifying assumption we make is that heating degree-days and cooling degree-days are derived from the same balance point temperature. Consequently, the energy use–temperature function is V-shaped and any temperature difference from the balance point results in some temperature-sensitive energy use. Although not modeled here, it is possible that there exists a zone of non-temperature-sensitive energy use. We find a balance point temperature for electricity of 60 °F in the residential sector and 55 °F for commercial sector. The balance point temperature for fuels used for heating is 65 °F in the residential sector and 60 °F in the commercial sector.

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 65 °F threshold customarily used in energy demand analysis. The lower threshold for Massachusetts is expected 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 approximately 70 °F (21 °C) (Sailor, 2001).

Commercial buildings typically have a lower balance point temperature due to higher internal heat gains from office machinery, lighting and occupants. Not

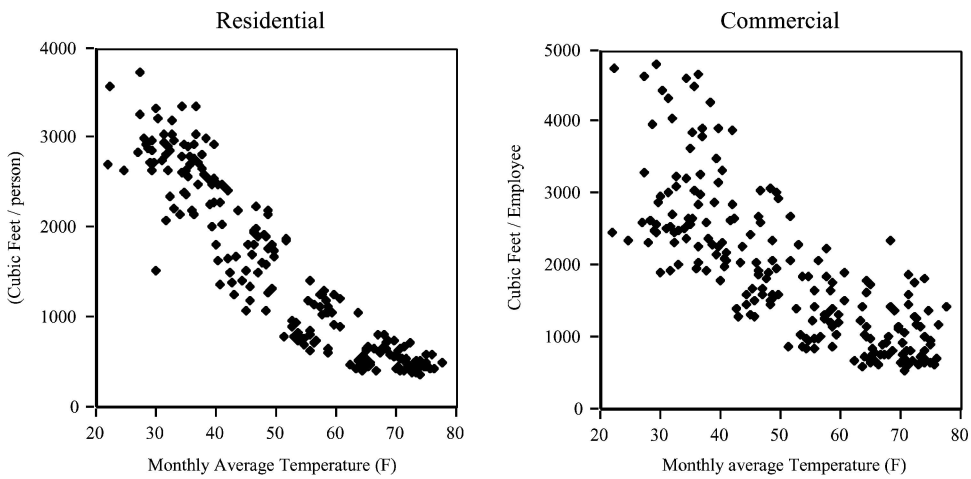

Figure 8. Average monthly temperature and sectoral natural gas sales, 1984–2001.

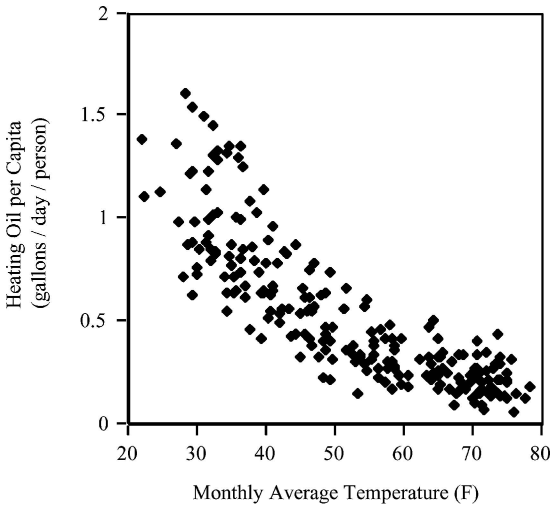

Figure 9. Average monthly temperature and heating fuel sales, 1983–2001.

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.

The relationship between monthly sectoral natural gas sales and temperature and monthly residential heating oil sales and temperature are shown in Figures 8 and 9, respectively. Since natural gas and heating oil are predominantly used for heating purposes, the relationship with temperature is a downward sloping function.

4.2. ENERGY DEMAND SENSITIVITY ANALYSIS

The dependent variable (energy use) in each energy model is specified in natural log format. The output coefficients on the independent variables, therefore, represent the percent change in energy use associated with a unit change in the independent variable. The constant terms indicate the level of non-temperature-sensitive energy use. The trend variable in each model represents the average annual percent change in non-temperature-sensitive energy use over the period of analysis. The coefficients on the HDD and CDD variables indicate percent changes, respectively, in heating and cooling energy use associated with changes in heating degree-days and cooling degree-days. The annual trend HDD and CDD variables capture potential time-varying components of energy demand sensitivities to changes in degree-days over the period of analysis. For example, with the increasing penetration of air-conditioning into buildings, it is expected that the sensitivity of electricity to cooling degree-days would increase. The light variable indicates the percent change in energy use associated with a 1 h change in daylight. The price of energy variable, which itself is expressed in the natural log format, represents the percent change in energy use associated with a percent change in the price of energy (i.e., price elasticity of energy demand).

4.2.1. *Residential Sector*

The regression results for monthly residential per capita electricity consumption in Massachusetts are shown in Table I. The analysis is restricted to the 1990–2001 period due to the data limitation of monthly sectoral electricity prices. Heating and cooling degree-days used in the residential electricity model are derived from a 60 °F base temperature.

TABLE I
Regression results for residential sector

	Log monthly electricity per capita (kWh/person/month)
Constant	5.971958***
Annual trend	0.0030124
Monthly HDD (base 60 °F)	0.0004722***
Annual trend HDD (base 60 °F)	−0.00000545
Monthly CDD (base 60 °F)	0.0003818***
Annual trend CDD (base 60 °F)	0.0000456***
Hours of daylight	−0.0101859***
Log electricity price	−0.3340608***
R^2	0.8931
Durbin–Watson statistic	1.8561
N	144

***Significant at the 1% level.

The constant term in the regression model is representative of non-temperature-sensitive electricity demand or the amount of energy demanded at the balance point temperature, which has been relatively stable over the period of analysis as indicated by the annual trend variable. The coefficient on the heating degree-day variables indicates a 100 unit increase in monthly heating degree-days is associated with a 4.7% increase in monthly per capita electricity consumption. During the period of analysis, the sensitivity of electricity use to changes in heating degree-days demonstrated no statistically significant change as suggested by the trend variable for the heating degree-days. At the beginning of the period of analysis (i.e., 1990) a 100 unit increase in cooling degree-days is associated with a 3.8% increase in per capita electricity consumption. However, the cooling degree-day annual trend variable indicates the sensitivity of electricity consumption to a 100 unit increase cooling degree-days more than doubled over the period of analysis to 8.8% in 2001, possibly a result of a higher air conditioning penetration rate. Residential electricity consumption is inversely and statistically associated with daylight hours. An additional hour of daylight is associated with a 1% decrease in per capita electricity demand. Electricity use is also inversely related to electricity prices – a 10% price increase is associated with a 3.3% consumption decrease. The regression model explains 89% of the historic variation in per capita electricity consumption.

Table II contains the natural gas and heating oil regression models for the residential sector, which both use degree-days derived from a 65 °F temperature base. The natural gas regression indicates natural gas is consumed irrespective of the presence of heating degree-days, which is expected since one of its primary uses is for cooking purposes. The annual trend variable suggests consumption increases of 1% per year, however, the increase is not statistically significant. The heating degree-day variable indicates natural gas consumption is highly sensitive to changes in heating degree-days. A 100 unit increase in heating degree-days is associated with

TABLE II
Regression results for residential sector

	Log natural gas per capita (cubic ft/person/month)	Log heating oil per capita (gallons/person/month)
Constant	7.064334***	4.194367***
Annual trend	0.0111487	−0.0789409***
Monthly HDD (base 65 °F)	0.0017359***	0.001334***
Annual trend HDD (base 65 °F)	0.00000884	0.000033***
Log natural gas price	−0.3956136***	
Log heating oil price		0.352137***
R^2	0.8831	0.9223
N	156	156

***Significant at the 1% level.

a 17% increase in natural gas consumption. The demand sensitivity of consumption to changes in heating degree-days has been relatively stable over the analysis period as suggested by the heating degree-day annual trend variable. Consumption of natural gas is inversely related to the price of natural gas – a 10% price increase is associated with a 4% consumption decrease.

The constant indicates heating oil is purchased even in months with no heating degree-days. The annual variable coefficient indicates that heating oil sales have been decreasing with time, which in part could be explained by the increasing use of natural gas or electric heaters in the region. Monthly heating degree-days are positively and significantly correlated with increases in heating oil sales. A 100 unit increase in heating degree-days is associated with a 13% increase in heating oil sales. A small, but statistically significant, increase in the sensitivity of heating oil sales to heating degree-days is present.

The regression models for natural gas and heating oil explain 88 and 92%, respectively, of the historical variation in per capita heating fuels sales. A Breusch–Pagan test of independence between the residuals of the two models indicates no correlation.

4.2.2. *Commercial Sector*

Results of regression analyses for electricity and natural gas use per employee are presented, respectively, in columns 2 and 3 of Table III. Monthly electricity consumption per employee is modeled as a function of a constant, an annual trend

TABLE III
Regression results for commercial sectors

	Log electricity per employee (kWh/employee/month)	Log natural gas per employee (cubic feet/employee/month)
Constant	6.543654***	6.7899***
Annual trend	0.038953	0.0081153
Monthly HDD (base 55 °F)	0.000195***	
Annual trend HDD (base 55 °F)	−0.00000821	
Monthly CDD (base 55 °F)	0.0003468***	
Annual trend CDD (base 55 °F)	0.0000861	
Monthly HDD (base 60 °F)		0.00097***
Annual trend HDD (base 60 °F)		0.00000118
Hours of daylight	−0.012406***	
Log electricity price	−0.0841782**	
Log natural gas price		0.14944
R^2	0.9039	0.7491
Durbin–Watson statistic	2.0088	2.0082
N	144	156

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

and heating and cooling degree-days derived from a 55 °F temperature base. The constant term denotes non-temperature-sensitive electricity load, which the annual trend variable suggests has no significant increase over time. The heating degree-day variable implies that a 100 unit increase is associated with a 1.9% increase in per employee monthly electricity consumption whereas a 100 unit increase in monthly cooling degree-days is associated with a 3.4% increase in per employee electricity consumption. Electricity for cooling is used more intensively than that for heating as suggested by the larger coefficient of the cooling degree-day variable. Both the heating degree-day and cooling degree-day annual trend variables indicate no changes in the sensitivity of electricity use to degree-days. Commercial electricity consumption is inversely related to hours of daylight. In months with 1 h more daylight on the 15th day on average employees use 1.2% less electricity per capita. Electricity consumption is inversely related to the price of electricity for commercial establishments. An electricity price increase of 10% is associated with a 0.8% consumption decrease. The regression model explains 90% of the historical variation in per employee electricity consumption.

Commercial natural gas sales are positively correlated with heating degree-days. A 100-unit increase in monthly heating degree-days is associated with a 9.7% increase in monthly natural gas sales per employee. As the heating degree-day annual trend variable indicates, the sensitivity of natural gas sales to changes in heating degree-days has had no statistically significant modification over the period of analysis. No relation is present between the price of natural gas and sales. The regression model explains 75% 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, natural gas and heating oil demand in conjunction with various climate change scenarios to project future energy use. Price parameters are held constant at 2000 levels since future prices are unknown. Not all of the future changes in the region's energy consumption is due to climate change; part is driven by trends in proliferation and efficiencies of energy using technologies, changes in household structure and size, as well as changes in income in the region. We assume these factors continue to change as they have over the analysis period.

The projections for residential monthly electricity under the assumption of climate trends from the Canadian Climate Centre model are shown in Figure 10. The results presented in that figure, as well as those of Figures 11–19, are averages of model results from 100 bootstrapped climate series. To the right of each figure is a bar chart of the percent change in monthly energy use attributable to climate change – the difference between the amount projected for a year under a climate change scenario and the amount for the same year under a non-climate change scenario. The climate change scenario for 2020 produces a 2.1% increase in per

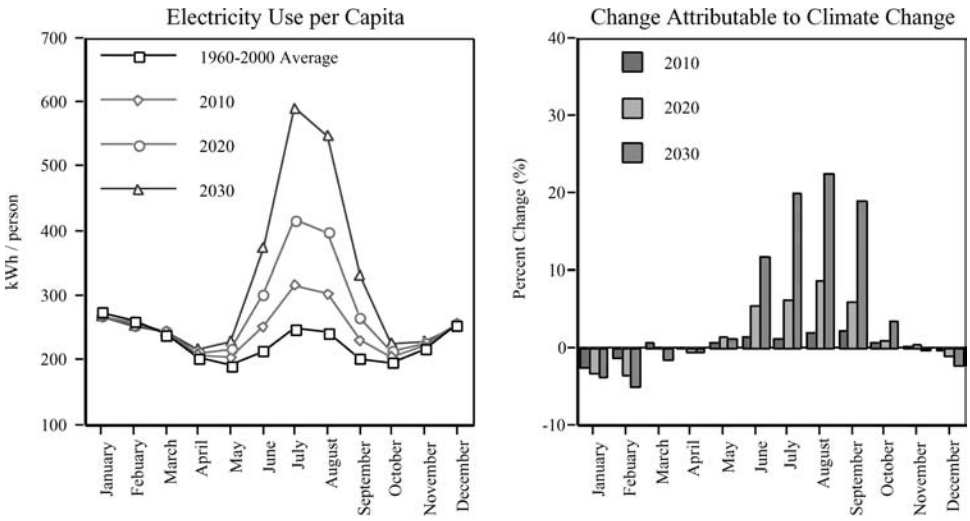

Figure 10. Residential electricity per capita under Canadian Climate Centre climate scenarios (results are averages across 100 bootstrapped climate scenarios).

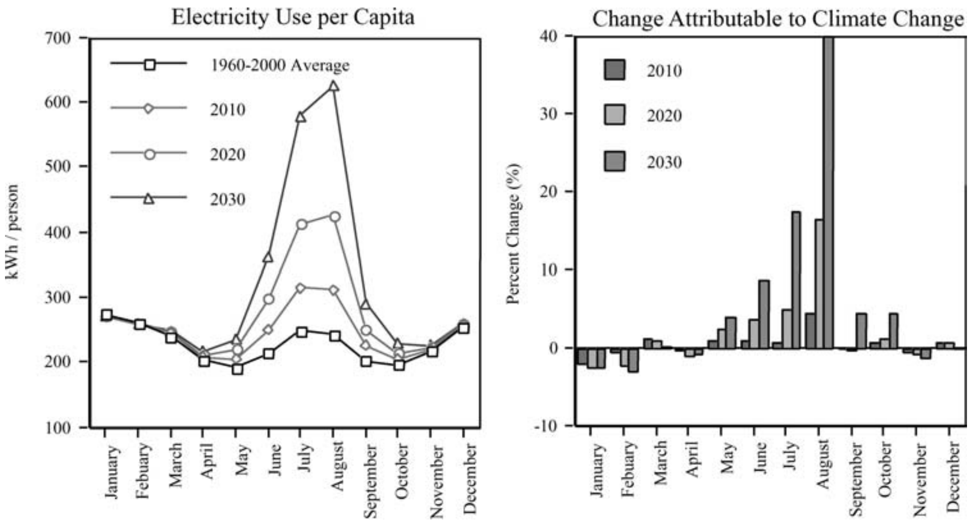

Figure 11. Residential electricity per capita under Hadley climate scenarios (results are averages across 100 bootstrapped climate scenarios).

capita residential electricity consumption relative to the 2020 non-climate change scenario. Most of the annual increase results from the 6.8% increase during the summer months (June–August) which outweigh declines of 2.7% in per capita electricity use in winter months (December–February). Similar, though more pronounced, changes in per capita electricity consumption are observed for Hadley climate scenarios (Figure 11).

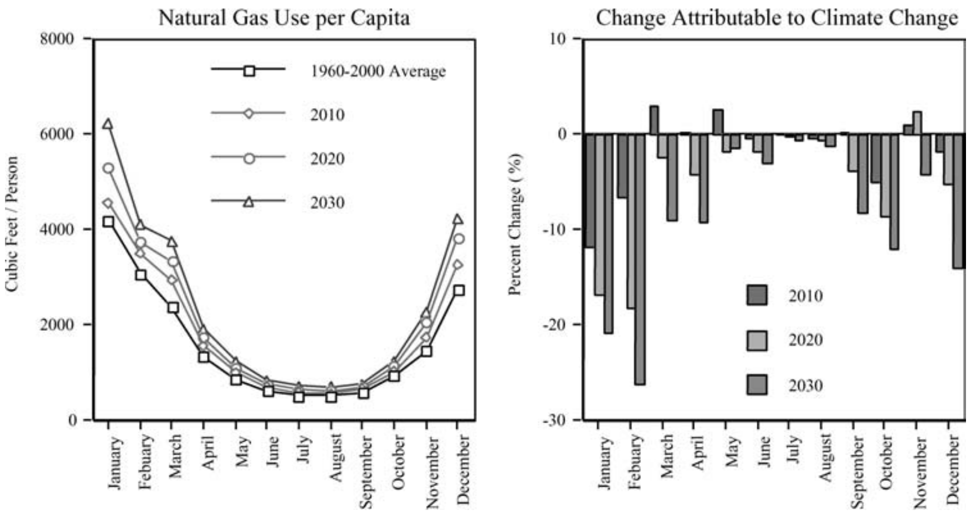

Figure 12. Residential natural gas per capita under Candian Climate Centre climate scenarios (results are averages across 100 bootstrapped climate scenarios).

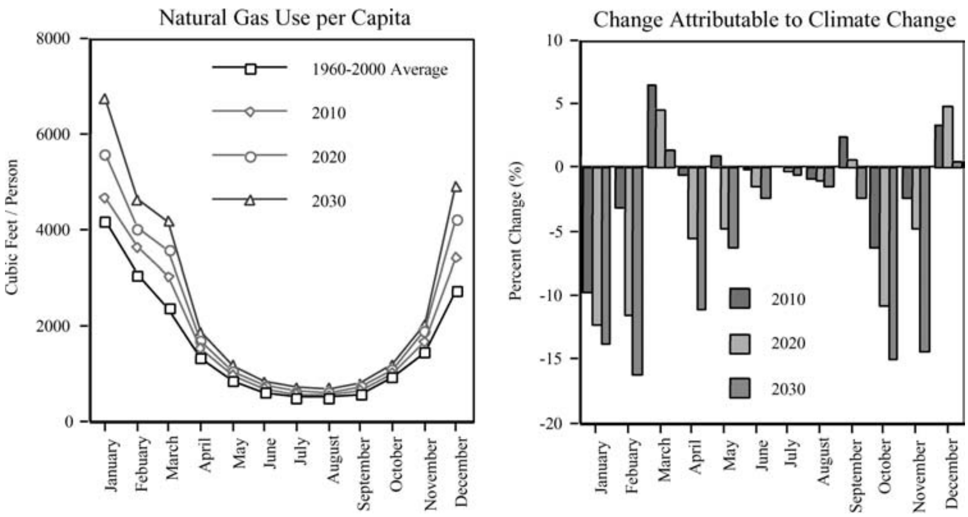

Figure 13. Residential natural gas per capita under Hadley climate scenarios (results are averages across 100 bootstrapped climate scenarios).

Figures 12 and 13 show residential per capita gas consumption for the Canadian Climate Centre and Hadley model trends. Similarly, Figures 14 and 15 show the results for heating oil consumption. Natural gas consumption is expected to increase with the climate change scenarios as it is increasingly used as a heating fuel, however, the increase is reduced under the climate change scenarios relative to the non-climate change scenario. In 2020 the Canadian Climate Centre and Hadley climate scenarios reduce winter natural gas consumption of 14 and 7%, respectively, relative

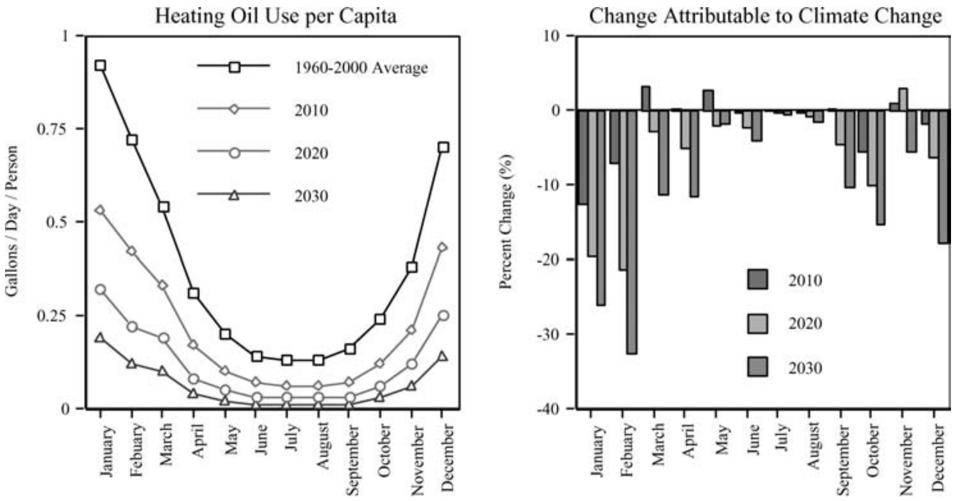

Figure 14. Residential heating oil per capita under Canadian Climate Centre climate scenarios (results are averages across 100 bootstrapped climate scenarios).

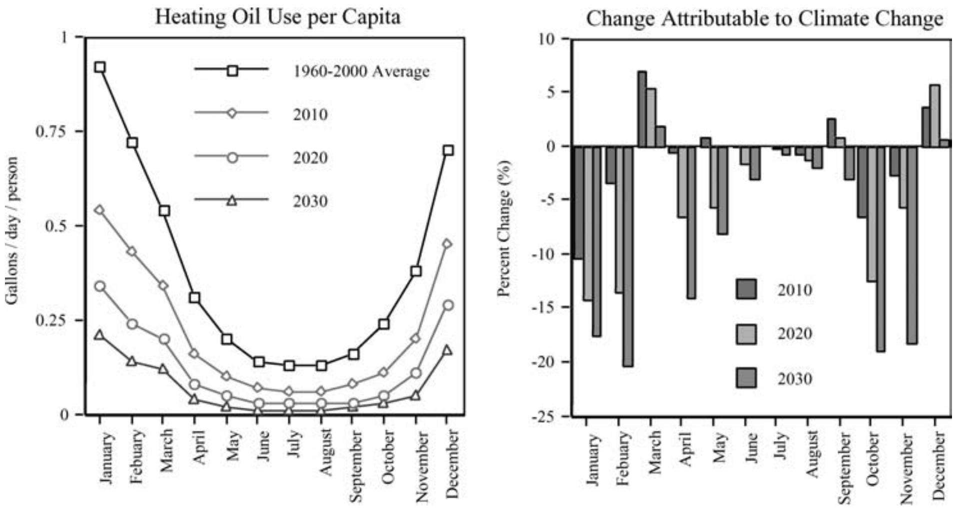

Figure 15. Residential heating oil capita under Hadley climate scenarios (results are averages across 100 bootstrapped climate scenarios).

to the 2020 non-climate change scenario. Heating oil consumption is expected to decline with the most pronounced decreases expected during the winter months. Small, though notable, discrepancies among the scenarios are due to different temporal patterns in changes of winter temperatures across different climate models. For example, the Hadley model predicts that at least until Decembers 2030 will be getting cooler; the Canadian Climate Centre model suggests some slight cooling during March and November during the first decade of the 21st century, resulting in more heating degree-days and in turn higher gas and oil consumption.

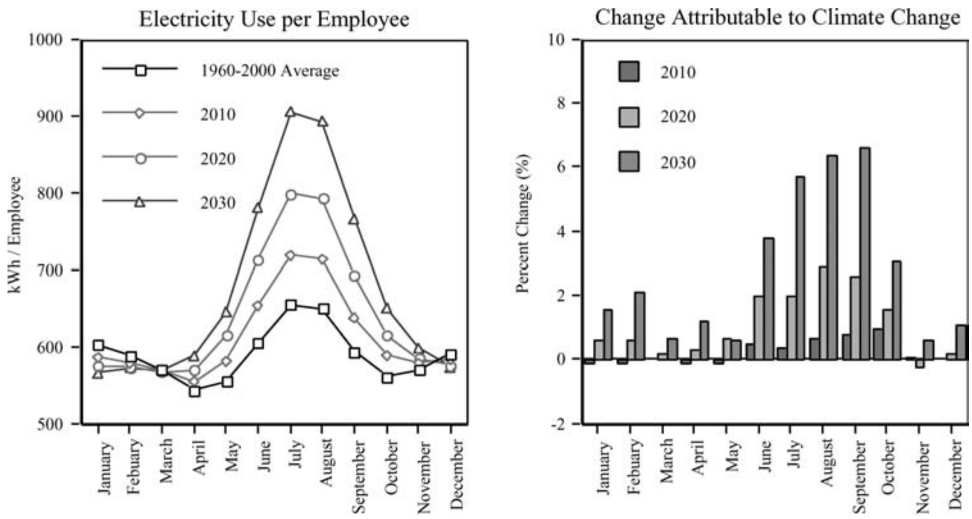

Figure 16. Commercial electricity use per employee under Canadian Climate Centre climate scenarios (results are averages across 100 bootstrapped climate scenarios).

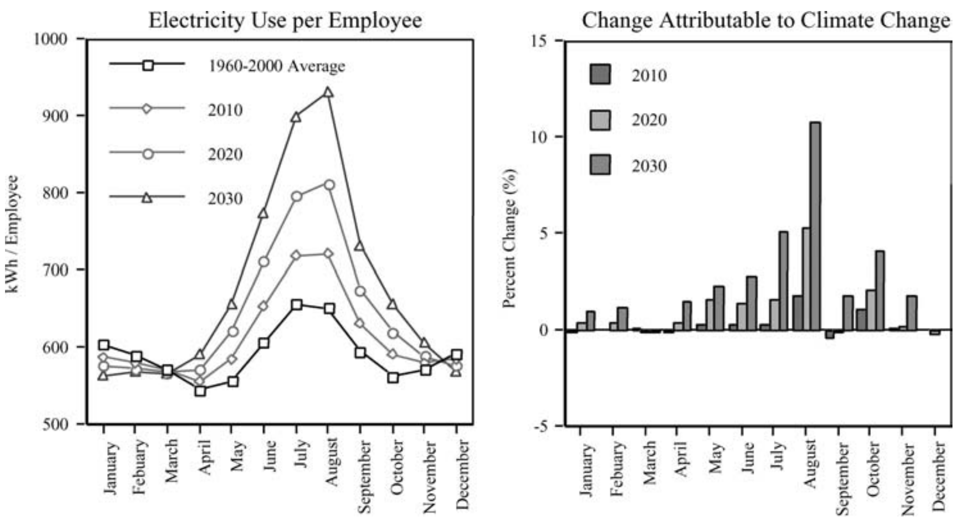

Figure 17. Commercial electricity use per employee under Hadley climate scenarios (results are averages across 100 bootstrapped climate scenarios).

Figures 16 and 17 show commercial electricity consumption per employee under the two-climate scenarios. Although not as drastic as for the residential sector, the model predominantly suggests increases in consumption, most of which is expected to occur between June and September. Both the Canadian Climate Centre and Hadley climate change scenarios suggest that in 2020 annual commercial electricity consumption per employee will increase 1.2% relative to the non-climate change scenario. Similarly, the changes in natural gas demand are not as pronounced as

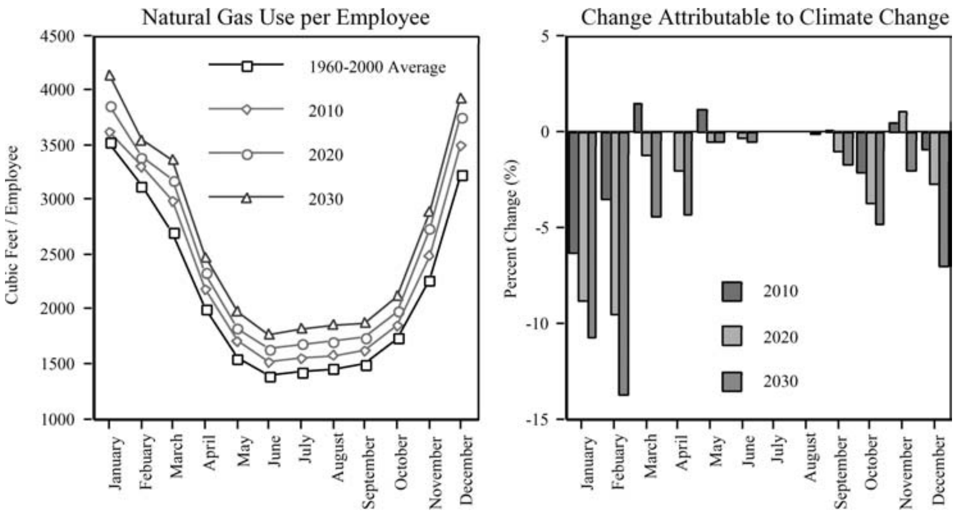

Figure 18. Commercial natural gas use per employee under Canadian Climate Centre climate scenarios (results are averages across 100 bootstrapped climate scenarios).

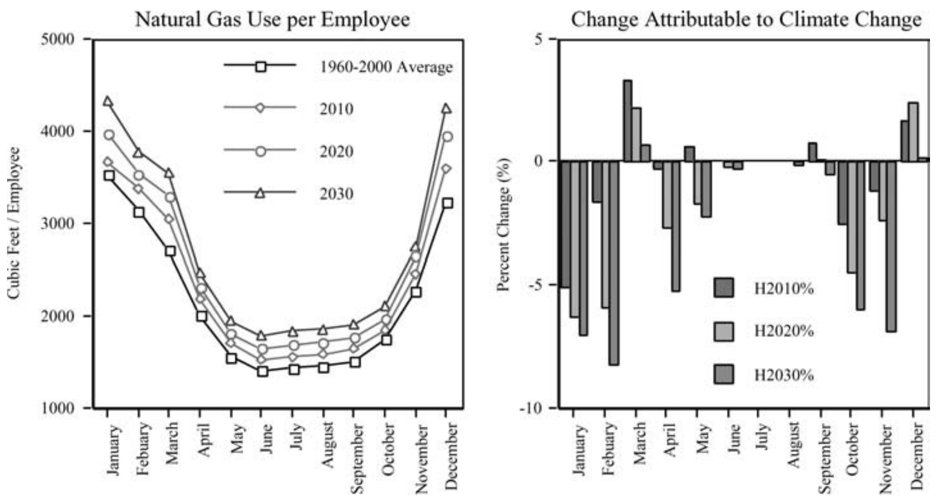

Figure 19. Commercial natural gas use per employee under Hadley climate scenarios (results are averages across 100 bootstrapped climate scenarios).

for the residential sector, but in general show similar changes in demand patterns throughout the year (Figures 18 and 19).

6. 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 region-specific responses. Results indicate that residential and commercial energy demand in Massachusetts are sensitive to temperature and that a range of scenarios of climate change may noticeably decrease winter heating fuel and electricity demands and increase summer electricity demands. These findings suggest a 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.

The present study, as with previous studies of energy demand, formulates energy demand responses to climate change on the basis of past responses to weather variability (temperature, in this case). Since energy users continue to react to temperature variability in the climate change scenarios as if climate has not changed, energy demand responses are modeled as reactive adaptations. The energy demand response function (V-shaped energy use–temperature relation) is assumed to be stable with climate change even though it is, at least in part, a product of energy user's adaptations to the prevailing climate. Hence, energy demand responses modeled with only reactive adaptation provide estimates of the impacts of climate change under a business-as-usual scenario and assist in identifying the need for anticipatory adaptation. Anticipatory adaptation could alter a region's energy demand response function to more effectively correspond with future climatic conditions via planned adjustments in the attributes of temperature-sensitive infrastructure and energy technologies (i.e., building thermal shells, air-conditioners, furnaces).

Identifying potential impacts for the region now is important because the energy industry is extremely capital intensive and as a consequence the flexibility of policy induced changes in energy generation and demand 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 et al., 2001). However, such changes need to be implemented in the relatively near term or the building stock will 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.

Four methodological lessons relevant to the development of policy-orientated analyses of climate change impacts on the energy sector can be drawn from our study. First, potential impacts of climate change are dependent on the spatial scale of the analysis. For example, our findings indicate that Massachusetts' residential and commercial sectors have lower balance point temperatures than the customary 65 °F and likely lower than other parts of the country, given historical adaptation in Massachusetts to the prevailing cooler climate. The ability to capture this place-specific attribute is an integral factor in understanding potential demand responses to climate change.

Second, the time step of the analysis should reflect intra-annual variation in historic energy demand. In this study we use monthly data to infer the seasonal effects of climate change on heating and cooling energy. We find large increases in electricity demand, almost all of which occurs during the summer months. 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 °F, whereas our climate change scenarios indicate that by 2030 the total number of days in Boston exceeding 90 °F will be 23, nearly double the current normal. Such changes in extremely hot days may result in an appreciable increase in high energy consumption days and the need for requisite peaking units. Other studies suggest similar findings. For example, an average temperature increase of 3 °C (5.4 °F) in Toronto was found to be associated with a 7% increase in mean peak electric demand, but a 22% increase in the peak electric load standard deviation (Colombo et al., 1999).

Third, the unique responses by energy type (electricity, natural gas, heating oil) and economic sector (residential, commercial) to climate change scenarios highlight the need for disaggregation in energy analyses. Such a disaggregation also makes the results more relevant to decision makers.

Finally, assessing future energy demand responses requires consideration of the dynamics of historic energy sensitivities. A methodological innovation of this study is the inclusion of degree-day annual trend variables to capture the dynamic characteristics of energy responses rather than using an average response derived from the historical period of analysis. If energy demand sensitivities have a time-varying component, then using an average response could significantly over- or under-account for climate change impacts on energy use. Our findings suggest an increasing sensitivity of residential electricity to cooling degree-days, which in turn produces large future increases in electricity demand in response to hot temperatures. The increasing sensitivity is likely a result of increasing air conditioning use, which could be further exacerbated by climate change if, as some research suggests, a region's air conditioning market saturation is correlated with mean temperature (Sailor and Pavlova, 2003).

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