DOE/ER/ 61917--T1-P4.1

**The Impacts of Climate Change on Energy:
An Aggregate Expenditure Model for the US**

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Proposed running head:
The Impacts of Climate Change on Energy

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This research was funded by the US Department of Energy, DE SG02 94ER 61917. Special thanks to John Houghton for his support and to the Energy Information Administration for sharing their data.

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ABSTRACT

This paper develops a theoretical model to measure the climate change impacts to the energy sector. Welfare effects are approximately equal to the resulting change in expenditures on energy and buildings. Using micro data on individuals and firms across the United States, energy expenditures are regressed on climate and other control variables to estimate both short-run and long-run climate response functions. The analysis suggests that energy expenditures have a quadratic U-shaped relationship with respect to temperature. Future warming of 2C is predicted to cause annual damages of about \$6 billion but increases of 5C would increase damages to almost \$30 billion.

The energy sector plays a dual role in the climate change debate -- it both generates greenhouse gases that lead to climate change and it is impacted when climate actually does change. Although a substantial literature has focused on evaluating the costs of controlling greenhouse gas emissions from the energy sector [15], much less has been done to measure energy impacts. In order to justify expensive controls, it is important to identify and quantify the resulting benefits (damages avoided) from stopping or slowing climate change. A few sectors of the economy have been carefully studied: agriculture, forestry, and coastal property [15]. However, the few studies that examine energy impacts rely on expert opinion, engineering models, or case studies [5, 6, 7, 16, 19, 20, 21, 22, 23]. This paper seeks to supplement this literature by providing a theoretical model to measure the welfare impacts of climate change on energy demand. The study then conducts a comprehensive empirical study of the climate sensitivity of the energy sector in the US using micro-data for individuals and firms across all fuels.

The demand for energy derives from the demand for many residential and commercial services including lighting, hot water, refrigeration, and appliance use. However, the part of the energy sector most sensitive to climate change is space conditioning (heating and cooling). Further, this is a large part of at least the US residential energy sector. In 1990, 36% of electricity demand and 70% of natural gas demand went to space conditioning [19]. Climate change is expected to increase the cost of cooling and decrease the cost of heating by altering expenditures on energy and building structure necessary to maintain desirable interior temperatures. These changes are likely to vary by region. In 1990, approximately 66% of total space heating demand in the US residential energy sector came from the Northeast and Midwest regions while 79% of total air

conditioning demand came from the South and West [19]. Areas dominated by heating will likely benefit from warming whereas areas dominated by cooling are expected to be harmed.

Previous studies of climate and energy emphasize electricity impacts. Surprisingly, Crocker [17] finds little correlation between electricity usage and degree-days. However, Linder et al [16], in an industry case study of specific utilities, estimates that climate change will induce increases in electricity peak demands, especially in southern states. On the basis of the Linder study, Smith and Tirpak [23] argue that climate will cause electricity demand to increase by 4-6% with larger increases during peak hours. While detailed electricity studies are informative, they are not representative of the energy sector since electricity is the primary fuel used for cooling but only one of several fuels used for heating.

Studies of other fuels have relied on either expert opinion or engineering models. Nordhaus [20] and Cline [6] review the Smith and Tirpak study and use their expert opinion to conclude that climate change from doubling CO₂ would increase US electricity demand between \$2.4 billion and \$11.2 billion and reduce non-electric heating between \$1.7 billion and \$1.2 billion, respectively.¹ Nelson [19] finds that degree-days are the key explanatory variables in predicting the demand for oil, natural gas and coal, highlighting the importance of incorporating these fuels into a study of climate change impacts. A fuel-wide analysis by Rosenthal et al [21] using a degree-day based engineering methodology predicts that a 1°C increase in temperature in 2010 would yield net benefits on the order of \$5.3 billion, in contrast with the net damages found in previous studies.² Baxter and Calandri [5] and Scott et al [22] use an alternative engineering

¹ Figures are in 1990 dollars for a CO₂ doubling scenario. Nordhaus's estimates were converted from 1981 dollars to 1990 dollars using the GDP deflator.

² This figure was converted from 1991 to 1990 dollars using the GDP deflator.

methodology to estimate climate-induced changes in energy for a prototypical building based on detailed building simulation models.

A significant deficiency in the literature is that these early studies did not anticipate adaptation. The literature treats energy impacts as though only energy demand would change. It is likely, however, that consumers would also make adjustments in building characteristics to either conserve energy or to increase air conditioning capacity. This paper builds a theoretical model to take into account such adaptations. Section 1 presents a model, which explains how climate could impact both energy and building choices. At least during the heating season, surveys show that people in all climates across the US try to maintain the same interior temperature [19]. The model shows that as long as people try to maintain interior temperatures while climate changes, changes in energy and building expenditures are a good proxy for welfare. Increases (decreases) in energy and building expenditures measure the decrease (increase) in welfare.

The empirical methodology and data are described in Section 2. Due to unobservable building expenditure data, an empirical model of short and long run behavior is developed in order to estimate a total welfare measure from energy expenditures alone. The difference between the short and long run estimates (whether building characteristics are controlled or endogenous) should reflect the importance of missing building expenditures. Section 3 reports the estimation results based on a representative sample of residential and commercial buildings across the US. Section 4 summarizes the results of sensitivity analysis based on a range of climate and economic scenarios that are used to simulate global warming impacts and Section 5 discusses the policy implications of this analysis.

1. THEORETICAL MODEL

Climate change is expected to alter the choices among energy and building characteristics that are derived from the demand for interior temperature. To illustrate this decision process in the residential and commercial energy sectors, separate models are developed for households and firms. We take a partial equilibrium approach to this problem and build a model of energy demand independent of other sectors of the economy. Although a general equilibrium approach would be able to capture interactions between the energy sector and other climate sensitive parts of the economy, these interactions are expected to be small, suggesting such an effort would not be warranted. There is an important interaction that should be considered in future studies between energy impacts and carbon abatement programs, but this is beyond the scope of this paper.

Residential Model

In the long-run, individuals are assumed to choose expenditures on energy, building characteristics and all other goods in order to maximize utility subject to a budget constraint. Utility is assumed to be dependent upon interior temperature, T , and upon an index of all other goods, R . Interior temperature, T , is assumed to be a function of climate, C , energy use, Q , and building characteristics, Z . The budget constraint exhausts income, Y , upon purchases of all other goods, energy, and building characteristics where the price of all other goods is normalized to 1 and P_Q and P_Z are the prices of energy and building attributes, respectively. The household problem is to choose the level of Q , Z , and R given climate:

$$\begin{array}{ll} 1) & \max_{Q, Z, R} U(T, R) \\ & \text{s.t. } R + P_Q \cdot Q + P_Z \cdot Z = Y \\ & T = f(C, Q, Z) \end{array}$$

$$\begin{array}{ll}
\text{where: } C < T^* (\text{heating}) \Rightarrow T_Q > 0, T_{QQ} < 0 & C > T^* (\text{cooling}) \Rightarrow T_Q < 0, T_{QQ} > 0 \\
T_Z > 0, T_{ZZ} < 0 & T_Z < 0, T_{ZZ} > 0 \\
T_{QZ} ? 0, T_C > 0 & T_{QZ} ? 0, T_C > 0
\end{array}$$

with T^* representing optimal interior temperature and subscripts representing first and second partial derivatives. We assume that people must cope with both a heating and cooling season during a year. During the heating season, the desired interior temperature is assumed to be higher than the outside temperature so that expenditures on both energy (Q) and buildings (Z) increase interior temperatures. During the cooling season, expenditures are needed to reduce interior temperature. An increase in ambient temperature (C) during the heating season consequently reduces expenditures needed to achieve a given interior temperature. An increase in ambient temperature during the cooling season, in contrast, requires more expenditure by the household to maintain initial interior temperatures. We assume that there exists a minimum cost climate that minimizes heating and cooling. If warming moves a household towards this minimum cost point, warming will be a net benefit and if it moves a household away from this point, warming will be a net damage.

The relationship between energy and building expenditures is expected to be different during the heating and cooling seasons. Building characteristics such as insulation and storm windows tend to reduce the energy expenditures required during the heating season. Building and energy expenditures are substitutes. If warming reduces the energy expenditures required to keep a home warm, the homeowner may well decide to spend less on building expenditures in the long run. Some of the long run benefits from warming during the heating season will be taken as lower expenditures on building insulation. During the cooling season, expenditures on buildings often involve adding cooling capacity. During the cooling season, building and energy expenditures are

complements. Warming at first will encourage households to spend more on energy given their existing buildings. In the long run, households will add additional capacity and spend even more on energy.

Maximizing (1) will lead to an optimal bundle of interior temperature, T^* , and all other goods, R^* given initial conditions. With climate change, individuals can respond by changing: 1) expenditures on energy, 2) expenditures on building characteristics, or 3) interior comfort levels. Despite the wide range of outside winter temperatures across the US, households keep interior temperatures almost identical across the entire US.³ This implies that households will respond to climate change by adjusting expenditures to hold onto their desired interior temperature. In this case, the expenditure required to compensate a household for a climate change is equal to the change in building and energy expenditures they will need to maintain their current interior temperature.

If people maintain interior temperature regardless of climate, then they will respond to warming by adjusting energy expenditures alone in the short run and building and energy expenditures in the long run. Fully differentiating the interior temperature production function and setting the sum to zero:

$$2) \quad T_C dC + T_Q dQ + T_Z dZ = 0$$

Equation (2) describes the change in building and energy expenditures required to compensate for a change in climate. The welfare impacts of climate change on energy can be described as the change in income necessary to pay for the change in energy expenditures:

$$3) \quad dY/dC = P_Q dQ + P_Z dZ$$

If people maintain their desired interior temperature regardless of climate, a precise measure of welfare, is the change in expenditures on energy and building characteristics necessary to maintain interior temperature. An increase in energy expenditures thus implies a welfare loss and a decrease a welfare gain. Note that this expression is not a traditional welfare expenditure function. An increase in expenditures in this model is a welfare loss because it entails a necessary expenditure to maintain a current level of services.

The constant winter interior temperatures support the assumption that interior temperatures will remain constant as climate changes across the US today. However, it is not clear whether summer interior temperatures are also the same across the US. If people accepted a slight loss of comfort rather than spending what it would take to maintain interior temperatures at optimal levels, the proposed welfare measure (3) would be biased. It would understate damages during the cooling season since part of the response by people to warmer summer temperatures is likely to be a reduction in desired interior comfort. Further research needs to explore the extent of this bias by measuring interior temperatures across the US during summer time and including this factor in the analysis.

Firm Model

A parallel model to the household can be constructed for the firm. Instead of maximizing utility, however, the firm maximizes profit. Rather than being constrained by income, the firm is

³ Energy Information Administration [9].

constrained by its production possibility set. This represents the combination of inputs and outputs that are feasible given the production technology. Assuming firms take prices as given exogenously in factor markets, the firm chooses the combination of energy, Q , building characteristics, Z , and all other inputs, X , that minimizes costs subject to its possible production:

$$4) \quad \min_{Q, Z, X} P_Q \cdot Q + P_Z \cdot Z + P_X \cdot X \quad \text{s.t.} \quad g(Q, Z, X) = y$$

where Q and Z are interior temperature inputs, P_Q , P_Z and P_X are respective prices and y is output. The firm must choose the optimal level of interior temperature and all other inputs in order to minimize costs while ensuring production of chosen output W . Solving (4) for the optimal combinations of Q , Z and X yields the well-known economic principle that firms will equate the technical rate of substitution with the economic rate of substitution:

$$5) \quad \frac{P_Q}{P_Z} = \frac{g'(Q)}{g'(Z)}$$

Interior temperature measurements suggest that many firms maintain the same interior temperature in both summer and winter across the entire US. The expenditure necessary to maintain firm profits at their original level is consequently equal to the change in building and energy expenditures needed to maintain interior temperature:

$$6) \quad dY/dC = P_Q dQ + P_Z dZ \quad \text{s.t.} \quad T_C dC + T_Q dQ + T_Z dZ = 0$$

If interior temperatures are held constant, changes in energy and building expenditures provide an accurate estimate of welfare change for both households and firms.

2. SOURCES AND METHODS

Data

This study relies on data from the Department of Energy's 1989 Commercial Buildings Energy Consumption Survey [18] and 1990 Residential Energy Consumption Survey [19]. These surveys provide detailed data on annual energy expenditures and consumption as well as demographics, building characteristics and climate. The data are for several thousand buildings distributed in random clusters across the continental US and are weighted to represent the true population of buildings. These weights make it possible later in the analysis to extrapolate from the sample to the population as a whole.

Only limited annual weather data is available in these surveys. Because this study is more interested in drawing the connection between climate and energy rather than weather and energy, the surveys were supplemented with county estimates of climate from [17]. The climate data involved long term (30 year) measurements of temperature and precipitation in each of 4 months: January, April, July and October. This data was combined with the survey information permitting an analysis of climate and energy.

Feasible Climate Change Measure

The welfare measure derived in the previous section suggests that the energy impacts from climate change can be captured by the change in energy and building expenditures. Unfortunately, only energy expenditures and detailed building characteristics are available. Therefore, an alternative welfare measure must be developed to account for the missing building expenditure data. Short and long run models are used to evaluate the importance of unobserved building expenditures. In the short run, individuals and firms adjust only energy expenditures. A model of

energy expenditures, holding building characteristics constant, reflects these short run adjustments. In the long run, individuals and firms can adapt buildings as well as energy. The long run measure of energy expenditures assumes building characteristics are endogenous. The long run measure, therefore, allows for flexibility of building characteristics. The difference between the short run and long run measures provides an indication of how important building adjustments are likely to be. If short run and long run measures are similar, building adjustments are likely to be small. If the disparity between short and long run adjustments using energy alone is large, however, building adjustments are likely to be important.

The short and long run climate response functions are expected to be different for buildings dominated by heating versus cooling. Because energy and building expenditures are substitutes on the heating side, in the long run, people will reduce building expenditures for heating dominated buildings. Short run heating expenditures are expected to fall more than long run heating expenditures with warming. Because energy and building expenditures are expected to be complements on the cooling side, people will increase building expenditures (cooling capacity) with warming. Long run increases in energy for cooling are expected to be higher than short run increases from warming.

If the climate warms from A to A^* , heating energy expenditures will decline sharply in the short run (see Figure 1). In the long run, people can make themselves even better off by reducing thermal enhancing building capital. This increases energy expenditures in the long run but it results in greater overall savings. Because the shift from short run to long run reflects further savings, the true welfare gain is expected to be larger than the short run gain which is expected to be larger than the long run gain in energy alone. The difference between the short run and long run energy expenditures provides a measure of the importance of these savings in building costs.

If the differences between short and long run are small, the bias from omitting building expenditures is likely to be small.

FIG. 1. Climate Elasticity of Long and Short Run Heating Expenditures

Capital in the form of space conditioning capacity may complement energy used for cooling. With cooling, there is significant potential for greater saturation of cooling equipment as a result of climate change. This cooling case is illustrated in Figure 2, for a building experiencing ambient temperature B at a given point in time. If the climate warms to B*, in the short run, only expenditures on cooling energy can increase. In the long run, cooling capacity can be increased, increasing the possibility of spending more energy on cooling. Long run energy expenditures on cooling are consequently expected to be greater than short run expenditures. Both energy measures underestimate total expenditures and thus welfare effects. Again, the difference between the long and short run measures indicates the importance of building adjustments.

FIG. 2. Climate Elasticity of Long and Short Run Cooling Expenditures

Because heating expenditures decrease as ambient temperature rises while cooling expenditures increase, the overall relationship between energy expenditures and climate should be a quadratic function with the minimum indicating the temperature at which total energy expenditures are lowest. Our energy-only measures of welfare underestimate the benefits of heating reductions and underestimate the damages from increased cooling costs. Since the overall bias depends upon these two offsetting factors, the direction of the bias from using energy-only measures of welfare is indeterminate. However, the magnitude of the bias is reflected in some degree by comparing the short and long run responses. If these two responses are similar, the magnitude of the bias from omitting building expenditures is likely to be small.

Econometric Specification

An empirical model is estimated to measure how energy expenditures in residential and commercial buildings vary with climate. The expenditure equation is assumed to be separable in energy and all other goods. Ordinary least squares regression analysis is used to estimate total expenditures on electricity, natural gas, fuel oil, and district heat on the commercial side and

electricity, natural gas, fuel oil, liquid petroleum gas, and kerosene on the residential side.

Independent variables include climate, demographic and firmographic information and building characteristics. The building characteristics are divided into climate sensitive and non-sensitive categories to draw the distinction between the short and long run models. Non-climate sensitive building characteristics such as building size, type of occupancy, and building age are included in all model runs to control for exogenous non-climatic factors that affect energy consumption.

Climate sensitive characteristics affecting thermal efficiency such as building material, conservation, the choice of heating and cooling equipment, and some aspects of the household structure are included in the short run models but not the long run models since they are assumed endogenous in the long run.

A log-log functional form is used for the estimation as it provides the highest predictive power based on F-tests of the overall significance of the regression, it is commonly used in the energy demand literature, and it provides the expected proportional relationship between the continuous variables and energy expenditures. The climate variables, however, are included in linear and quadratic form to reflect the hypothesized quadratic climate-expenditure relationship. Tests of various combinations of climate variables indicate that including only the January and July variables provides a better fit than including all four seasons. We explored using degree-days as a measure of climate but degree-days are defined in terms of an arbitrary target (for example, 60 degrees F). The resulting analysis was highly sensitive to the target temperature chosen. The hypothesized expenditure equations for the short and long run, respectively, are:

$$7) \ln \sum_{i=1}^F E_i = \alpha + \beta_0 C + \beta_1 C^2 + \beta_2 \ln P + \beta_3 \ln S + \beta_4 \ln Z_{nc} + \beta_5 D_{nc} + \beta_6 \ln Z_c + \beta_7 D_c$$

$$8) \ln \sum_{i=1}^F E_i = \alpha + \beta_0 C + \beta_1 C^2 + \beta_2 \ln P + \beta_3 \ln S + \beta_4 \ln Z_{nc} + \beta_5 D_{nc}$$

where $i=1, F$ represents the total number of fuels, E_i is energy expenditures, C is a vector of climate variables, P is a vector of average fuel prices, S is a vector of demographic (firmographic) characteristics, Z is a vector of building characteristics and D is a vector of dummy variables. Subscripts c and nc represent portions of the vectors Z and D that are climate sensitive and non-climate sensitive, respectively.

These equations are estimated using micro-data for individuals and firms. Not that the identification of demand is not expected to be a problem in this study. This contrasts with many energy studies which rely on aggregate data where prices would be endogenous. With disaggregate data, one can reasonably assume that prices are exogenous and predict expenditures taking prices as given for the relevant sectors. However, prices are a problem in the analysis in that we have no observed marginal prices. The prices used in this study are average prices calculated by dividing energy expenditures by quantities consumed. Given that consumers often face declining block prices, this could introduce a bias in the analysis because the measurement error on prices could be correlated with the error in the dependent variable. In order to test whether the analysis is sensitive to errors in prices, we explore a two-stage regression where we first predict prices and then use the predicted prices in the expenditure regression.

3. RESULTS

Tables 1 and 2 present the regression results for the residential and commercial models. The climate variables have been de-meanned to allow for easier interpretation. The linear term represents the marginal effect of climate on energy expenditures evaluated at the US mean. The quadratic term shows how the marginal effect changes in movements away from the mean.

Control Variables

The control variables in the residential sector are well behaved. Because the dependent variable is expenditures, not quantity demanded, price elasticity must be calculated from the estimated coefficients.⁴ The estimated price elasticities fall within the predicted range of the literature from -0.5 to -2.0.⁵ The specific estimates are -0.6 for electricity, -0.6 for natural gas, -1.0 for fuel oil, -1.2 for LPG and -1.2 for kerosene. Demographic characteristics that positively influence energy expenditures include income, family size, metropolitan location, age of household head, a tenant controlling the heat, race (Black or White), and receipt of heating vouchers. Expenditures are less if the head is Hispanic, receives cash aid for heating, participates in an energy discount program or burns wood as an alternative fuel. Structural characteristics that positively influence expenditures include square footage, the number of rooms, the number of doors and windows, and inadequate insulation. The presence of a basement or more than one unit cause expenditures to be lower as does the year the home was built and the number of floors, controlling for square feet. Appliances and electrical equipment such as a TV, computer, dishwasher, clothes washer and clothes dryer positively influence energy expenditures. Similarly, space conditioning equipment including central AC, wall or window AC units, electric wall or radiator units and portable kerosene heat positively influence expenditures. Only some households have access to natural gas. If this option is available to the household, expenditures are less.

⁴ Predicted elasticities based on average rates are expected to be biased [42], however, Halvorsen [20] demonstrates that with a double-log form, elasticity estimates for marginal and average rates are quite comparable.

⁵ See Anderson [1], Baker et al [2], Barnes et al [3], Halvorsen [10] and Wilson [26].

The commercial price elasticity estimates fall within the range most commonly cited in the literature of -1.0 to -3.0.⁶ The specific price elasticities predicted in this study are -3.0 for electricity, -0.9 for natural gas and -1.0 for both fuel oil and district heat. Characteristics of the commercial operation that positively influence expenditures include the number of months open per year, the year built, metropolitan location, various building activities and the presence of appliances such as ice, water or vending machines and commercial refrigerators and freezers. If an alternative fuel is used, there is a large percentage of non-refrigerated warehouse or vacancy, or the tenant controls the heat, expenditures are less. Building characteristics that have a positive effect on expenditures include square footage, number of floors, and built-up roof material. Glass and metal surfacing are roof materials that lower expenditures as do wall materials such as masonry, siding and shingles. All space conditioning equipment cause expenditures to be higher except heat pumps for cooling which lower expenditures.

Climate-Expenditure Relationship

In the residential sector, the marginal effects of increases in January temperature are negative and increases in July temperature are positive. These two effects reflect heating saving in winter and cooling damages in summer. Both January and July precipitation positively influence expenditures at the mean reflecting increased expenditures in more humid locations. The squared terms in the climate response functions are generally significant indicating the response function is quadratic.

⁶ See Baughman & Joskow [4] and Mount et al [18].

TABLE I

Residential Model Results - Aggregate Expenditure Analysis

Variables included in all model runs

Variable	Short Run	Long Run	Variable	Short Run	Long Run
Constant	39.81 (7.58)	18.70 (3.86)	log income	5.27e-2 (7.35)	0.10 (14.17)
Jan. temp	-7.61e-3 (-4.40)	-6.16e-3 (-3.41)	log home area	0.18 (12.28)	0.28 (26.34)
Jan. temp ²	-2.06e-4 (-1.73)	-1.23e-4 (-0.98)	log # floors	-0.10 (-7.86)	-0.13 (-9.60)
Jan. precip	2.00e-2 (3.51)	2.23e-2 (3.70)	log year built	-4.61 (-6.66)	-1.93 (-3.02)
Jan. precip ²	-1.68e-3 (-2.44)	-1.13e-3 (-1.55)	log family size	0.23 (23.71)	0.26 (25.69)
July temp	1.34e-2 (4.13)	2.34e-2 (7.00)	log age of head	7.35e-2 (4.22)	0.11 (5.89)
July temp ²	2.39e-3 (4.68)	1.50e-3 (2.81)	multiple units	-9.77e-2 (-5.84)	-0.11 (-6.89)
July precip	1.75e-2 (3.93)	2.01e-2 (4.31)	tenant controls heat	0.18 (4.39)	0.23 (5.39)
July precip ²	-4.56e-3 (-2.81)	-5.29e-3 (-3.09)	black/white	0.10 (3.43)	0.11 (3.62)
log elec. price	0.33 (17.86)	0.29 (15.12)	hispanic	-4.76e-2 (-2.54)	-6.75e-2 (-3.41)
log nat. gas price	0.17 (8.43)	0.19 (9.24)	over 65	-2.54e-2 (-1.57)	-4.07e-2 (-2.40)
log fuel oil price	-3.82e-2 (-1.26)	-1.74e-2 (-0.55)	cash aid	-0.19 (-3.86)	-0.18 (-3.40)
log lpg price	-8.29e-2 (-3.45)	-6.57e-2 (-2.61)	heat aid	7.13e-2 (2.76)	6.75e-2 (2.48)
log kero. price	1.52e-2 (0.27)	-3.50e-2 (-0.60)	wood burning	-5.20e-2 (-4.43)	-4.27e-2 (-3.49)
Metropolitan	2.00e-2 (1.90)	1.97e-2 (1.77)			

*(t-statistics in parentheses)

TABLE I (continued)

Residential Model Results - Aggregate Expenditure Analysis

Variables included in short run model only

Variable	Short Run	Variable	Short Run
log # rooms	0.12 (4.97)	dish/cloth wash/dry	0.10 (7.10)
log # doors/ windows	8.56e-2 (6.16)	central AC	0.16 (11.34)
basement	-9.21e-2 (-6.92)	wall/window AC	4.47e-2 (3.80)
poor insulation	3.96e-2 (3.36)	elec. Wall heat	9.15e-2 (6.87)
elec. Discount	-6.71e-2 (-2.44)	portable kerosene.	0.20 (3.05)
color TV	5.95e-2 (10.82)	nat. gas avail.	-5.20e-2 (-4.54)
computer	3.71e-2 (2.81)		
Adjusted R ²		0.97	0.96
Number of Obs.		5030	5030

*(t-statistics in parentheses)

TABLE II

Commercial Model Results - Aggregate Expenditure Analysis

Variables included in all model runs

Variable	Short Run	Long Run	Variable	Short Run	Long Run
Constant	-58.00 (-8.05)	-64.83 (-8.45)	% outpatient	2.95e-3 (3.61)	3.99e-3 (4.50)
Jan. temp	-1.31e-2 (-2.90)	-1.79e-2 (-3.64)	% lab/ref whs	9.65e-3 (6.57)	1.11e-2 (6.93)
Jan. temp ²	4.20e-4 (1.37)	6.85e-4 (2.06)	% industry	1.36e-2 (4.00)	1.96e-2 (5.30)
Jan. precip	2.98e-2 (2.32)	4.73e-2 (3.40)	% office	4.21e-3 (9.62)	5.36e-3 (11.71)
Jan. precip ²	-1.58e-2 (-8.45)	-1.94e-2 (-9.54)	% retail/service	2.81e-3 (7.54)	3.50e-3 (8.84)
July temp	-2.62e-2 (-3.11)	-5.80e-3 (-0.64)	% education	2.97e-3 (5.30)	4.23e-3 (7.00)
July temp ²	-5.22e-3 (3.83)	5.23e-3 (3.53)	metropolitan	0.38 (13.69)	0.47 (15.79)
July precip	2.67e-3 (0.25)	-6.81e-4 (-0.06)	log sqft	0.52 (39.06)	0.69 (52.44)
July precip ²	5.66e-3 (1.45)	5.05e-3 (1.19)	log # floors	0.13 (4.14)	0.21 (6.27)
log elec. price	-0.53 (-16.91)	-0.65 (-19.35)	log year built	7.83 (8.22)	8.55 (8.43)
log nat. gas price	-9.73e-2 (-3.21)	-0.10 (-3.05)	months open/year	2.67e-2 (4.87)	2.91e-2 (4.87)
log fuel oil price	9.01e-2 (0.45)	-0.17 (-0.79)	alt. fuel used	-0.53 (-11.90)	-0.61 (-12.51)
log dist.heat price	-1.03e-2 (-0.07)	-9.78e-2 (-0.66)	% food sale/serve	8.15e-3 (13.45)	1.46e-2 (25.71)
% health	7.09e-3 (5.87)	1.09e-2 (8.33)	% nonref wh/vac	-3.45e-3 (-7.68)	-5.90e-3 (-12.52)

*(t-statistics in parentheses)

TABLE II (continued)

Commercial Model Results - Aggregate Expenditure Analysis

Variables included in short run model only

Variable	Short Run	Variable	Short Run
ice/vending/wtr	0.47 (17.05)	ht. Pump-heat	0.14 (2.06)
refrigerator	0.45 (12.62)	tenant controls	-0.15 (-5.57)
air duct-cool	0.12 (3.64)	heat	0.14 (4.87)
air duct-heat	0.08 (2.47)	roof: built up	-1.79 (-5.69)
boilers	0.22 (6.16)	roof: glass	-0.15 (-4.32)
AC in computer rm	0.59 (11.00)	roof: metal surf.	-0.80 (-4.23)
ht. pump-cool	-0.12 (-1.74)	wall: masonry	-0.14 (-4.33)
		wall: shingle	
Adjusted R ²		0.96	0.95
Number of Obs.		5611	5611

*(t-statistics in parentheses)

In the commercial sector, an increase in both January and July temperature reduces energy expenditures at the margin. While January precipitation positively influences expenditures at the mean, July precipitation is not a significant predictor of expenditures. The squared terms are again generally significant indicating the response function is quadratic.

The climate-expenditure relationships for the residential and commercial models are pictured in Figures 3 and 4 for a 1990 economy. The overall relationship between total energy expenditures and climate has the expected U-shape. At lower temperatures, heating effects dominate and warming would result in net benefits. At high temperatures, cooling effects dominate and warming would result in net damages. Given the current US mean temperatures of 12°C, the US is close to the minimum cost temperature. Small changes in temperature could have either small positive or negative impacts on the US depending on exactly where the model picks the minimum cost temperature to be. The minimum residential expenditure occurs at approximately 11°C in the short run model and 6°C in the long run model. The minimum commercial energy expenditure occurs at 17°C in the short run model and 15°C in the long run. The higher minimum cost temperature for commercial rather than residential buildings was not expected. Commercial buildings use more energy than residential buildings and have purchased more cooling capacity. Both facts should have led commercial buildings to have a cooler minimum cost temperature than residential buildings. It is not clear what is causing this result.

Examining Figure 3 and 4 confirms our hypotheses about energy and building substitution. In colder climates, long run expenditures are below short run expenditures reflecting substitution where heating dominates. In warmer climates, long run exceed short run expenditures, confirming our hypothesis that building and energy expenditures are complements on the cooling side. Note also that short run and long run expenditures are reasonably close across a broad

range of climates. This suggests that building expenditures are only small part of the climate response function.

FIG. 3. Residential Model

Climate-Expenditure Relationship

FIG.4. Commercial Model

Climate Expenditure Relationship

3. CLIMATE CHANGE SIMULATIONS

Climate Simulation

A series of simulations are explored to understand the magnitude of effects that climate change might cause on the US energy sector. We examine changes to a 1990 and a 2060 economy. The 1990 example is used so that the results can be compared to past studies and to provide a benchmark from current conditions. The 2060 example is used because climate change will occur largely in the end of the next century and it is helpful to measure the impact of climate change on the economy that will be in place at that time.

It is beyond the scope of this paper to predict what climate changes will actually occur as greenhouse gases accumulate. The paper relies on predictions made by climate scientists to

determine a range of possible changes. The most recent climate prediction by the International Panel on Climate Change (IPCC) suggests global temperatures will vary from 1- 3.5 C by 2100 [14]. In this paper, we examine a range of climate scenarios with temperature changes of 1.5, 2.5 and 5° Celsius and precipitation changes of 0, 7%, and 15% for a total of nine scenarios. These nine scenarios are not equally likely. The best guess scenario by the IPCC is a 2C increase by 2100 [14]. We assume that this climate change is uniform across the entire US and across every season. Individual General Circulation Models (GCMs) predict that changes in climate are not likely to be uniform, but would vary by region and season. However, for the United States, these models do not make consistent predictions so that the uniform scenarios examined here are reasonable predictions of the expected effect [25]. To get a complete picture of the range of possible outcomes, one would have to extend these simulations to include variations in regional and seasonal changes.

For each climate prediction, the estimated regression equations are used to predict how each firm and household would alter its behavior. The sample results are then extrapolated to the population of buildings in the US using sample weights.

A series of adjustments are made to predict expenditures in a 2060 economy in order to reflect population and economic growth as well as changes in fuel prices. The model results are obviously sensitive to these assumptions. US population is projected to grow by approximately 19% over the period from 1990 to 2060 [13]. A uniform population increase across the country is applied. GDP per capita is projected to grow by 223% over the same period [13]. And every region is predicted to grow uniformly. Energy expenditures are assumed to increase proportionately to the income elasticity of energy expenditures predicted in the residential model (0.10). This implies that energy expenditures will grow 22%. An additional adjustment is made

to reflect the 2060 age of building stock. In 2060 the average building age is assumed to be 20 years.

In addition to accounting for major demand drivers such as GDP and population growth there is likely to be price-induced substitution away from particular types of energy over the next century as fossil fuel supplies begin to decline and prices rise. A Hotelling-type model is used to predict changes in fuel prices over the period. The Hotelling Rule states the net prices for depletable resources will rise at the rate of interest to compensate resource owners for holding onto stock [12]:

$$(9) \quad \frac{\dot{P}}{P} = r \left(1 - \frac{c}{P} \right)$$

where P is fuel price, c is extraction costs and r is the discount rate. For example, assuming that the discount rate is 4%, and that extraction costs are approximately half of gross prices, the Hotelling Rule implies that fuel prices would be expected to rise at an annual rate of about 2% on average. Electricity prices are expected to increase at a slower rate than other fuel prices because of utilities can rely on more plentiful coal resources. Hence, electricity prices are assumed to increase at a rate of 1% annually while all other prices increase at an annual rate of 2%. This future scenario is highly uncertain. However, by contrasting the future scenario and the 1990 scenario, one can get a sense how important the baseline conditions are likely to be.

Simulation Results

Table 3 summarizes the predicted net impacts across climate scenarios for the residential sector in the 1990 and 2060 economies and Table 4 shows effects in the commercial sector. Positive values imply the welfare change is beneficial (reduced costs) and negative values reflect damages (increased costs). Warming results in damages across the board for the residential sector.

This result was expected since the mean US temperature is already slightly above the minimum expenditure temperature pictured in Figure 3. As Table 3 illustrates, damages increase with greater changes in both temperature and precipitation. Since cooling dominates heating effects in the residential model, the long run climate response function is a more accurate measure of welfare. A 1.5C increase is expected to cost \$7 billion while a 5C increase would cost \$27 billion to the residential sector. Note that welfare effects are more sensitive to temperature than precipitation.

The response by the commercial sector is more complicated because small amounts of warming are beneficial and large amounts of warming are harmful. At first, the heating benefits dominate cooling damages leading to a net beneficial effect. When heating dominates the energy equation, the short run effects are a better welfare measure. With a 1.5C temperature increase, the short run benefits are in the neighborhood of \$2.7 billion. These benefits increase slightly as temperatures rise to 2.5C. However, above 2.5C, cooling damages begin to dominate heating benefits and overall welfare declines. Examining long run responses, damages reach \$2.1 billion with a 5°C increase. That is, going from 2.5C to 5C results in marginal damages of almost \$6 billion. Increased precipitation has a negligible impact on the commercial energy sector.

The impacts are sensitive to the baseline assumptions. The damages from warming in 2060 are almost double the damages in 1990 in the residential sector. The commercial sector impacts are less sensitive because that sector is not predicted to grow. However, the welfare effects, measured as a percent of the sector size, remain the same. That is, the damages as a fraction of energy expenditures are approximately the same in both 1990 and 2060.

TABLE III

Residential Model

Total Welfare Impacts of Climate Change on Energy (billion \$)

		1.5 C TEMP Δ	2.5 C TEMP Δ	5 C TEMP Δ
<i>1990</i>				
0%	short run	-1.3	-2.8	-9.0
PRECIP Δ	long run	-3.1	-5.6	-13.7
7%	short run	-1.9	-3.4	-9.6
PRECIP Δ	long run	-3.8	-6.3	-14.4
15%	short run	-2.4	-3.9	-10.2
PRECIP Δ	long run	-4.5	-7.0	-15.2
<i>2060</i>				
0%	short run	-2.4	-5.1	-16.5
PRECIP Δ	long run	-5.6	-10.2	-25.0
7%	short run	-3.4	-6.2	-17.6
PRECIP Δ	long run	-7.0	-11.6	-26.4
15%	short run	-4.4	-7.2	-18.6
PRECIP Δ	long run	-8.2	-12.9	-27.8

TABLE IV

Commercial Model

Total Welfare Impacts of Climate Change on Energy (billion \$)		1.5 C	2.5 C	5 C
		TEMP Δ	TEMP Δ	TEMP Δ
<i>1990</i>				
0%	short run	3.5	4.6	3.7
PRECIP Δ	long run	1.7	1.6	-2.9
7%	short run	3.4	4.5	3.6
PRECIP Δ	long run	1.6	1.5	-3.0
15%	short run	3.4	4.5	3.5
PRECIP Δ	long run	1.5	1.4	-3.2
<i>2060</i>				
0%	short run	2.7	3.7	3.1
PRECIP Δ	long run	1.4	1.4	-2.0
7%	short run	2.7	3.6	3.0
PRECIP Δ	long run	1.3	1.3	-2.0
15%	short run	2.7	3.6	2.9
PRECIP Δ	long run	1.3	1.3	-2.1

Table V details the impacts in 2060 by climate zone for the residential and commercial sectors in order to show the regional differentiation implied by the various models.⁷ The middle climate and precipitation scenario is presented. In general for the residential sector, the magnitude of predicted short and long run impacts by climate zone follow a reasonable pattern. The coldest regions experience the lowest damages because of offsetting heating benefits and the warmer regions experience the greatest damages. In the commercial sector, warming damages regions that are already hot, but warming benefits regions that are currently cool.

Tables 8 and 9 present the results of the two-stage least squares analysis. In a first stage, average prices were regressed on a set of independent variables that can explain demand. The predicted prices from the first stage regression was then entered in the second stage expenditure equation. Note that the price coefficients behave poorly in these models. The price elasticities are xxx in the residential model and xxx in the commercial model. The temperature coefficients become xxx.

⁷ The following definition of climate zones is assumed: Zone 1: cdd65<2000, hdd65>7000, Zone 2: cdd65<2000, hdd65=5500-7000, Zone 3: cdd65<2000, hdd65=4000-5499, Zone 4: cdd65<2000, hdd65<4000, Zone 5: cdd65>2000, hdd65<4000. On the residential side there are 20 observations that have cdd65>2000 and hdd65 slightly more than 4000 which are included in Zone 5.

TABLE IV

Results by Climate Zone: 2060 Economy, 2.5 C, 7%P

Predicted Net Change in Welfare (billion \$)

Sector/Year		Residential	Commercial
(coldest)	<u>Climate Zone 1</u>		
	Short Run	-0.02	1.4
	Long Run	-0.4	1.1
	<u>Climate Zone 2</u>		
	Short Run	-0.4	1.8
	Long Run	-1.6	1.2
	<u>Climate Zone 3</u>		
	Short Run	-1.5	0.5
	Long Run	-3.4	0.2
	<u>Climate Zone 4</u>		
(warmest)	Short Run	-1.3	0.6
	Long Run	-2.7	0.1
	<u>Climate Zone 5</u>		
	Short Run	-2.9	-0.7
	Long Run	-3.5	-1.3

5. CONCLUSIONS

This study derives a theoretical model of climate-sensitive energy demand. The paper argues that changes in energy and building expenditures provide a reasonable measure of the welfare impacts from climate change if there are no significant changes in interior temperatures. The theory predicts a U-shaped relationship exist between annual energy expenditures and outside temperature. The theory also implies that both energy and building capital may respond to climate changes. By examining both short run and long run energy responses, one can estimate the importance of these building responses.

The most important contribution of the paper, however, is the empirical analysis of a complete set of residential and commercial buildings for the US. The study provides a comprehensive

empirical analysis of energy and climate. The analysis indicates that energy is sensitive to climate as predicted. Warming is expected to lead to substantial damages in the US residential energy sector. The predicted damages for a 1.5C warming are in the neighborhood of \$7 billion whereas they rise to \$26.6 billion for a warming of 5C (2060). Since the cooling effects dominate on the residential side, actual impacts could be slightly higher since the costs of building adjustments are not included in the analysis. Predicted impacts for the US commercial sector are expected to be beneficial for mild warming scenarios. Benefits reach approximately \$2.7 billion for a 1.5C warming and \$3.6 billion for a 2.5C warming (2060). These effects turn to damages above 2.5C reaching a net damage of \$2.1 billion for a 5C warming. The residential and commercial results imply that the US energy sector is likely to experience net damages from a 2C warming in the neighborhood of \$6 billion (.03% of 2060 GDP).

The analysis indicates that regions in the US which are currently cool are likely to benefit from mild warming whereas areas which are currently warm are expected to be more severely damaged. These results probably apply to other developed countries with similar incomes and technologies. Developed countries which are currently cooler than the US are likely to find warming more beneficial to their energy sectors while countries which are already warmer are likely to find warming more harmful. Extrapolation to developing countries is more difficult because of large differences in income and capital between these countries and the US. Extending climate impact research to developing countries is clearly a high priority.

This study estimates the climate sensitivity of the energy sector using an energy expenditure model. Further research is underway exploring a fuel specific model. Evaluating the fuel-choice responsiveness to climate change will provide more detail about the climate-energy relationship, including how people might respond to climate change by changing fuels. Research is also

underway exploring more complicated climate forecasts such as those produced by GCM's. As we better understand the impacts of climate change on the economy and our quality of life, it will become clearer what mitigation policy we need to follow both in the near term and the distant future.

APPENDICES

Data Definitions

Definitions of Independent Variables: Residential Regressions

<u>Variable</u>	<u>Definition</u>
age of head	head householder age
basement	1 if home has basement, 0 otherwise
black/white	1 if resident is black or white, 0 otherwise
cash aid	1 if resident receives cash aid for heat, 0 otherwise
central AC	1 if household has central air conditioning, 0 otherwise
color TVs	number of color TVs in household
computer	1 if household has computer, 0 otherwise
dish/cloth wash/dry	1 if household has dishwasher, clothes washer, clothes dryer, 0 otherwise
# doors/windows	number of doors and windows in home
elec. wall - heat	1 if household uses electric wall units or radiators to heat, 0 otherwise
elec. Price	average electricity price
family size	number of household members
# floors	number of floors in home
fuel oil price	average fuel oil price
heat aid	1 if resident receives heating vouchers, 0 otherwise
hispanic	1 if resident is hispanic/non-black, 0 otherwise
home area	home area - square feet
income	average household income for relevant income range
elec. discount	1 if household has discounted or interruptible electricity rates, 0 otherwise
Jan. temp	average January temperature(demeaned) - degrees C
Jan. temp ²	average January temperature(demeaned) squared
Jan. precip	average January precipitation(demeaned) - inches
Jan. precip ²	average January precipitation (demeaned) squared
July temp	average July temperature(demeaned) - degrees C
July temp ²	average July temperature(demeaned) squared
July precip	average July precipitation(demeaned) - inches
July precip ²	average July precipitation(demeaned) squared
kero. Price	average kerosene price
lpg price	average liquid petroleum gas price
metropolitan	1 if metropolitan statistical area, 0 otherwise
multiple units	1 if more than 1 unit, 0 otherwise
nat. gas price	average natural gas price
nat. gas avail.	1 if natural gas is available, 0 otherwise
over 65	1 if age of head householder > 65, 0 otherwise
poor insulation	1 if household has inadequate insulation or window leaks, 0 otherwise
portable kerosene	1 if household uses portable kerosene to heat, 0 otherwise
# rooms	number of rooms in home
tenant controls heat	1 if a tenant also occupies the residence, 0 otherwise
wall/window AC	1 if household has wall or window ac units, 0 otherwise
wood burning	1 if wood is burned as alternative heat source, 0 otherwise
year built	year home constructed

Definitions of Independent Variables: Commercial Regressions

<u>Variable</u>	<u>Definition</u>
AC in computer rm	1 if there is air conditioning in computer room, 0 otherwise
air duct-cool	1 if air ducts used for cooling, 0 otherwise
air duct-heat	1 if air ducts used for heating, 0 otherwise
alt. fuel used	1 if alternative fuel used, 0 otherwise
boilers	1 if boilers used for heating, 0 otherwise
refrigerator	1 if commercial freezer or refrigerator used, 0 otherwise
dist. heat price	average district heat price
elec. Price	average electric price
# floors	number of floors
fuel oil price	average fuel oil price
heat pump-cool	1 if heat pumps used for cooling, 0 otherwise
heat pump-heat	1 if heat pumps used for heating, 0 otherwise
ice/vending/wtr	1 if ice, vending or water machines used, 0 otherwise
Jan. temp	average January temperature(demeaned) – degrees C
Jan. temp ²	average January temperature(demeaned) squared
Jan. precip	average January precipitation(demeaned) – inches
Jan. precip ²	average January precipitation (demeaned) squared
July temp	average July temperature(demeaned) – degrees C
July temp ²	average July temperature(demeaned) squared
July. Precip	average July precipitation(demeaned) – inches
July precip ²	average July precipitation(demeaned) squared
metropolitan	1 if metropolitan statistical area, 0 otherwise
months open/year	number of months open
nat. gas price	average natural gas price
% food sale/serve	percent food sale and food service
% nonref wh/vac	percent non-refrigerated warehouse and vacant
% health	percent in-patient and skilled healthcare
% out. Patient	percent out-patient healthcare and public safety
% lab/ref whs	percent lab and refrigerated warehouse
% industry	percent industrial
% office	percent office
% retail/service	percent retail/services
% educ	percent education
roof: built up	1 if roof material = built up, 0 otherwise
roof : glass	1 if roof material = glass, 0 otherwise
roof: metal surf.	1 if roof material = metal surface, 0 otherwise
sqft	building size - square feet
tenant controls heat	1 if tenant controls heat, 0 otherwise
wall: masonry	1 if wall material = masonry/siding, 0 otherwise
wall: shingle	1 if wall material = siding/shingles, 0 otherwise
year built	year construction completed

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