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ORIGINAL ARTICLE

The value of energy efficiency programs for US residential and commercial buildings in a warmer world

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Abstract US residential and commercial buildings were responsible for about 41 exajoules (EJ) of primary energy use per year in 2002, accounting for approximately 9% of the world fossil-fuel related anthropogenic carbon (C) emissions of 6.7 Gt that contribute to climate change. US Government-sponsored building energy efficiency research and implementation programs are focused on reducing energy consumption in US residential and commercial buildings and reducing these carbon (C) emissions. Although not specifically intended for adaptation to a warmer climate and less effective than under today's cooler climate, these programs also could help reduce energy demand in a future warmer world. Warming scenarios projected by the United Nations Intergovernmental Panel on Climate Change (IPCC) in 2001 imply net overall decreases in both site energy and primary energy consumption in US residential and commercial buildings, largely because of the reduced need for heating. However, there would be as much as a 25% increase in building space cooling demand and a significant part of the increase could be offset by energy-efficiency improvements in buildings. Overall, in the US, buildings-related energy efficiency programs would reduce site energy consumption in buildings in the US by more than 2 EJ in 2020 and primary energy by more than 3.5 EJ, more than enough to offset the projected growth in cooling energy consumption due to climate change and growth in the US building stock. The savings would have an estimated annual net value at 2005 energy prices of between $45.0 and $47.3 billion to consumers.

Keywords Buildings · Climate change scenarios · Economic benefits · Energy efficiency · Energy modeling · Mitigation · Residential and commercial

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1 Introduction

In 2002, US residential and commercial buildings were responsible for about 41 EJ of annual primary energy consumption and accounted for 0.6 Gt of carbon emitted to the atmosphere (38% of US total emissions of 1.6 Gt and approximately 9% of the world fossil-fuel related anthropogenic emissions of 6.7 Gt [EIA 2004a, b]). US residential and commercial primary energy consumption is expected to increase to 55 exajoules and corresponding carbon emissions to 0.8 Gt by the year 2025 (EIA 2004c). These projections do not account for any temperature changes that occur as a result of climate change

Because many billions of tons of carbon dioxide (CO_2) and other greenhouse gases already have been emitted to the atmosphere, with much more expected, the Intergovermental Panel on Climate Change (IPCC) projects that climate could warm relative to 1990 by 0.4–1.2°C by the year 2030 and by 1.4–5.8°C by the end of the 21st century (Cubasch et al. 2001). Some world regions would change more than others. Ruosteenoja et al. (2003) performed a re-analysis for the IPCC of climate simulations for seven climate models at the regional level.[1] The results for the US are reported for three sub-regions, four seasons, and three major time steps, as summarized in Table 1.

These seasonal temperature increases imply that less heating and more cooling would be required in the future, increasing the demand for electricity (used primarily for cooling) and reducing the demand for natural gas and fuel oil (used primarily for heating). This paper examines these impacts and provides new estimates of the net effect on energy use in U.S, residential and commercial buildings. The paper also examines the effects of certain US Department of Energy (DOE) building energy efficiency programs in the context of the expected warmer climate. The DOE programs are primarily focused on saving energy in heating, lighting, and appliance loads and were not undertaken for adaptation to the warmer future climate, but they would continue to have value even if the climate warmed significantly.

Amato et al. (2005) observe that many studies worldwide have analyzed the climate sensitivity of energy use in residential, commercial, and industrial buildings and have used estimated relationships to explain energy consumption and to assist energy suppliers with short-term planning (Quayle and Diaz 1979; Le Comte and Warren 1981; Warren and LeDuc 1981; Downton et al. 1988; Badri 1992; Lehman 1994; Lam 1998; Yan 1998; Morris 1999; Pardo et al. 2002). However, these works largely assume that the statistics of temperatures (daily, monthly, and annual mean, standard deviation, etc.) and other features of climate would remain roughly constant into the future.

The number of studies analyzing the effects of climate *change* on energy demand, however, is much more limited. Some of the early work was done in northern Europe. Milbank (1989) showed that in the mild to cool conditions of northern Europe, a 4.5°C increase in temperature would more than double summer electricity consumption for space cooling and refrigeration. For a temperature change of 1.2–4.6°C, Aittoniemi (1991) found in a winter peaking system in Finland that annual electricity consumption would decrease by 7–23%, or about 5−5.8% per 1°C. Other early work was done in Japan. Moreno et al. (1996) reported that Tokyo Electric Company electricity consumption rose exponentially

[1] Transient climate simulations are based on a complete operation of the global climate models in which the climate is allowed to evolve over time. They contain realistic lagged climate responses to the composition of the atmosphere. As such, they are more realistic than are scenarios based on a simple addition of 1 or 2 degrees of warming to current temperatures or the equilibrium temperature response to a given input of greenhouse gases.

Table 1 Seasonal temperature increases for three U.S. regions in °C in winter (DJF), spring (MAM), summer (JJA), and fall (SON) (Derived from Ruosteenoja et al. (2003)

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

when temperature exceeded 17°C. For the year 2050, Matsui et al. (1993) projected an increase of 5% annual consumption in electricity and a 10% increase in peak demand (temperature change not given). Nishinomiya and Nishimura (1993) discussed Japanese findings that show increases in electrical demand with increasing summertime daily temperature and an inflection point at 24°C. Below that temperature, electricity demand increased at 1% per 1°C; above that temperature, the rate of increase doubled to 2%. They also discussed a U-shaped relationship between maximum daily power demand in Tokyo on the vertical axis and air temperature at 3 p.m. on the horizontal axis. The maximum Tokyo demand tended to fall approximately linearly between about 8°C and about 20°C at about 1.5% per 1°C as heating appliance usage fell; between 20°C and 32°C, it rose at an increasing rate that averaged about 3% per 1°C as air conditioning and refrigeration took over. This U-shaped relationship can also be expressed in terms of heating degree-days (HDD) and cooling degree-days (CDD) and has showed up in a number of other studies. The impact of climate warming in any particular regional study depends, among other things such as humidity, cultural conditions, building types, on where the particular region sits on that U. In heating-dominated systems, climate warming decreases the number of HDD and reduces energy demand; the reverse is true of cooling dominated systems. The US, a temperate-zone, continental-sized country, has many instances of both types of regions, but the heating-dominated regions are more populous, so savings in heating energy tend to dominate as the climate warms at the building site, even allowing for the fact that cooling energy demand increases non-linearly as temperature increases. In addition, even though electricity involves significant losses of energy in generation, transmission, and distribution and is more expensive per delivered joule, this paper shows that projected increases in temperature would lead to savings in primary energy consumption and to savings in energy expenditures for consumers. US studies are split on this question.

One of the very early studies of the electricity sector in the US projected that between 2010 and 2055, climate change could increase electric generation capacity requirements by 13.5–22.9% relative to non-climate change scenarios, requiring investments of $200–300 billion ($1990) (Linder and Inglis 1989). Following on that study in the early and mid-1990s, a handful of studies have attempted an ‘all fuels’ approach and have focused on whether net energy demand (decreases in heating balanced against increases in cooling) would increase or decrease in residential and commercial buildings as a result of climate change (e.g., Loveland and Brown 1990; Rosenthal et al. 1995; Belzer et al. 1996; Hadley et al. 2004, 2006; Mansur et al. 2005). Generally, these studies have found either a relatively small net increase or small net decrease in energy, depending in part on analysis method and climate scenario, but also on whether site energy consumption, primary energy consumption, or value of energy consumption is being reported.

Various approaches have been used to estimate the impact of climate change on energy use in US buildings. Most studies have used simple increases in annual average temperature as the ‘climate change’ scenario. It appears that research to date has not focused on transient temperature scenarios from circulation models such as those analyzed by the IPCC. One group of researchers has used building energy simulation models to analyze the impact of climate warming on the demand for energy in individual commercial buildings (Scott et al. 1994) and on energy consumption in a variety of commercial and residential buildings in a variety of locations (Loveland and Brown 1990; Rosenthal et al. 1995). Other researchers have used econometrics and statistical analysis techniques. Belzer et al. (1996) used a detailed data set on US commercial buildings, and calculated the effect of building characteristics and temperature on site energy consumption in all US commercial buildings. Sailor conducted this type of analysis for site electricity consumption in several categories of buildings and equipment (Sailor and Muñoz 1997, Sailor 2001, Sailor and Pavlova 2003). Mendelsohn and colleagues have performed increasingly sophisticated cross-sectional econometric analyses to determine how expenditures for energy in the residential and commercial building stock relates to climate (Morrison and Mendelsohn 1999; Mendelsohn 2001, 2003; Mansur et al. 2005), and have used the relationships to estimate the impact of climate change on energy expenditures for all residential and commercial buildings in specific regions and the US as a whole. Table 2 summarizes the results from a number of selected US studies of the effects of climate change on energy demand in US residential and commercial buildings.

Most studies have not taken into account the possibility of increased market penetration of air conditioning in historically cooler areas as an ‘autonomous’ or ‘unplanned’ adaptive response to climate change (in the US, warmer regions already have very high market penetrations). The omission may be important. For example, Sailor and Pavlova (2003) have found that potential increases in market penetration of air conditioning in response to warming might have an effect several times larger on electricity consumption than the warming itself. Similarly, in an earlier study summarized in Moreno et al. (1996), sales of air conditioning units in Japan increased by 40,000 units per day of maximum temperature above 30°C (Sakai 1988). The UK Climate Impacts Review Group (1991) also reported increased air conditioning penetration in the UK. Although the energy models used in this paper allow for greater market penetration of air conditioning in new buildings in the northern part of the country than in the existing building stock, no analysis has been done of the large-scale adoption of air conditioning as an adaptive response to warming by individual consumers.

Loveland and Brown (1990), Scott et al. (1994), and Belzer et al. (1996) estimated the effects of energy-efficient buildings on energy consumption in the context of climate

Table 2 Climate change and estimated changes in energy demand in US residential and commercial buildings in selected US energy studies

Study: Author(s) and Date, Scope of Analysis	Temperature change (°C) and date for change	Change in site heating energy consumption (%)	Change in site electricity consumption (%) (mostly cooling)	Change in net site energy consumption (%)	Change in primary energy consumption (%)	Total consumer cost (savings) of energy consumption ($billion)	Change in site energy consumption from efficiency offset (%)
Linder and Inglis (1989), Residential and commercial buildings, 47 states and sub-state areas	0.6–1.6 (2010)			+0.8 to +1.6 (electric only)	+8.8 to +19.6 (capacity)	3.2–6.1	Not evaluated
	3.4–5.3 (2055)			+3.4 to +5.1 (electric only)	+13.5 to 22.9 (capacity)	33–73	
Loveland and Brown (1990), General office space heating and cooling; Single family home space heating and cooling (six cities)	3.7–4.7 ($2xCO_2$, no date)	Residential: −44 to −73	Residential: +55.7 to 146.7	Residential: −22.0 to +48.1	–	–	Residential: −31.5 to −44.4
		Office: −37.3 to −58.8	Office: +34.9 to +75.0	Office: +10.2 to +35.0			Office: −34.4 to −50.2
Scott et al. (1994), Space heating and air conditioning, commercial, 4 cities	3.9 (7.0°F) (no date)	−26.0 (Minneapolis); −43.1 (Phoenix)	+58.4 in Minneapolis; +36.3 in Phoenix	−8.0 to +6.3, depending on location	–	–	Yes, state of technology building envelope, reduced internal loads, −51.8 to −63.8
Rosenthal et al. (1995), Site energy-space heating and air conditioning	1.8 (2010)	Residential: −14.0, Commercial: −13.8	Residential: +20.4; Commercial +15.0	Residential: −11;		Commercial: −8.7	−5.70
−5.5 (1991)	Not evaluated						
Belzer et al. (1996),Site energy (commercial buildings)	4 (2030)	−29.0 to −35.0	+53.9	−13.10	–	–	Yes, advanced building envelope −4.5

Table 2 continued

Study: Author(s) and Date, Scope of Analysis	Temperature change (°C) and date for change	Change in site heating energy consumption (%)	Change in site electricity consumption (%) (mostly cooling)	Change in net site energy consumption (%)	Change in primary energy consumption (%)	Total consumer cost (savings) of energy consumption ($billion)	Change in site energy consumption from efficiency offset (%)
Sailor (2001), Per capita residential and commercial electricity (8 states)	3 (sensitivity analysis: no year given)			Residential: −7.2 to +11.6 Commercial: −0.3 to +5	–	–	Not evaluated
Ruth and Amato (2002) (Massachusetts)	2020 2050	−6.60 −13.90			–	–	Not evaluated
Sailor and Pavlova (2003), Residential electricity, 4 states	+20% in cooling degree days (about 1–2)		+13 to +29		–	–	Not evaluated

change. They found that much of the increase in site energy consumption due to climate change (electricity for cooling) could be offset by efficiency measures such as improvements in lighting and shading of windows, while other measures such as increased insulation reinforced the decrease in heating brought on by climate change. However, no previous analysis has been done of the national effects of actual energy efficiency programs in the context of climate change, although considerable analysis has been done on the benefits of energy efficiency in the US for current climate. Even where studies purport to address adaptive response to climate warming (e.g., Loveland and Brown 1990; Belzer et al. 1996; Mendelsohn 2001), they feature generalized improvements in efficiency and do not involve market penetration of particular combinations of technologies to offset the effects of future climate warming

In this paper, we provide estimates of the potential impacts of projected climate change scenarios on energy consumption in US residential and commercial buildings. We do this for all residential and commercial building types present in the estimated US building stock in 2005 for the seasonal temperature regimes projected to prevail in the years 2020, 2050, and 2080. In contrast to some previous studies, we find that the future climate, holding other things constant, would result in a net overall decrease in site building energy consumption nation-wide and that this decrease, although less in percentage terms, generally extends to primary energy as well. Moreover, although one would expect that with enough warming, increases in cooling would eventually dominate savings in heating; this was only observed at the highest temperature ranges projected late in the century in Table 1 for the US, and only for primary energy. Although cooling loads (and electricity use) increase dramatically, climate warming significantly reduces heating loads, which still dominate cooling for overall energy use in most parts of the country. As a result, overall site energy and primary energy both decrease. Below, we explicitly examine the potential impacts of climate warming in the year 2020, also allowing for projected changes to the types, geographic locations, sizes, and vintages of residential and commercial buildings and their associated major energy-using equipment. We then estimate the impact of DOE buildings-related energy efficiency programs on energy use in residential and commercial buildings in the year 2020, to show the energy-saving benefits of these programs in the context of climate change. These programs are projected to result in new technologies, practices, and performance standards that affect markets and reduce energy use. Reductions in primary energy use imply that less fossil fuel is burned and less carbon is emitted to the atmosphere. The economic value of the energy savings is substantial, with or without climate change.

2 Methods

The estimates of energy use and savings were calculated in three steps, as shown in Fig. 1. In the first step, seasonal climate change scenarios from Ruosteenoja et al. (2003) were used to modify the annual temperature profiles for 11 weighted individual cities that represent the climates in the nine major census divisions in the US (Hawaii and Alaska were omitted). The cities, and their weights in the analysis depicting the US climate zones, are shown in Table 3. The altered temperatures were forecasted by applying the transient IPCC data average seasonal temperature change data from the Ruosteenoja et al. (2003) analysis of general circulation model (GCM) runs in the US to historical average daily temperature profiles in each month of the year for weekdays, Saturdays, and Sundays in 11

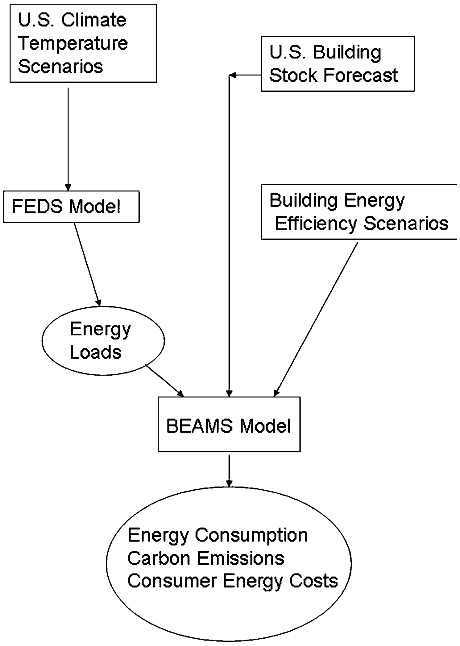

Fig. 1 Methods used to estimate energy consumption and savings

individual cities to project altered daily temperature profiles in the years 2020, 2050, and 2080 by month and day type.[2] Details of the process are discussed more fully in the Appendix. To account for climate uncertainty, the highest and lowest reported temperature changes from Ruosteenoja et al. were used. These results span the results from seven models and four different climate scenarios, and thus show the sensitivity of energy consumption to a significant range of uncertainty in future temperature projections. The main conclusions of the paper are not sensitive to this broad range of projections. We then used a two-step modeling procedure to estimate the impact of climate change on energy consumption. In the first step, we calculated the temperature-sensitive energy load associated with 15 building types (11 commercial and 4 residential), six sizes, and six vintages in each climate zone. As described below, this analysis was accomplished using the Federal Energy Decision System (FEDS) model, Version 5.0 (PNNL 2002). The annual building heating, cooling, water heating, and lighting end-use energy loads for 15 building types, six sizes, and six vintages of buildings in each of the 11 individual climate zones were aggregated via a weighted averaging scheme into the same end uses, building types, sizes, and vintages for only two zones: North and South. In the second step, as described below, the Building Energy Analysis and Modeling System (BEAMS) model (Elliott et al. 2004) was used to estimate energy consumption by fuel for each end use based on these

[2] Although some climate change projections predict increased variability, we were not able to make use of that information in this paper to systematically shift temperature profiles for individual day types in individual cities. It may be argued that greater daily extremes in temperatures, combined with heat island effects may interact with the non-linear cooling responses of buildings to cause the cooling energy consumption calculated in this paper to be underestimated. However, most recent IPCC analysis suggests that the diurnal temperature range has not shifted. We were not able to take into account greater probability of heat waves.

Table 3 Climate weights given to each city for each census US region (%) (from Elliott et al. 2004)

City	New England	Mid Atlantic	East North Central	West North Central	South Atlantic	East South Central	West South Central	Mountain	Pacific
Denver	0.0	0.0	0.0	0.0	0.0	0.0	0.0	64.0	2.2
Detroit	0.0	0.0	99.3	60.0	0.0	0.0	0.0	0.0	0.0
Fresno	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	13.3
Knoxville	0.0	0.0	0.0	0.0	50.7	67.4	13.4	0.0	0.0
Los Angeles	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	71.2
Minneapolis	0.0	0.0	0.7	40.0	0.0	0.0	0.0	0.0	0.0
Phoenix	0.0	0.0	0.0	0.0	0.0	0.0	0.0	36.0	0.0
Providence	100.0	100.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Seattle	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	13.2
Shreveport	0.0	0.0	0.0	0.0	17.7	32.6	80.6	0.0	0.0
Tampa	0.0	0.0	0.0	0.0	31.6	0.0	6.0	0.0	0.0

energy loads. Finally the energy savings effects of a group of DOE energy-efficiency programs of were estimated with the BEAMS model. A detailed example analyzing cooling energy consumption in new education buildings and energy savings associated with electrochromic windows in New England and the Mid-Atlantic U. S. states appears in the Appendix.

2.1 Calculation of building energy loads: FEDS analysis

The FEDS model analysis provides a comprehensive, fuel-neutral, technology-independent, integrated (energy) resource planning approach from the top down. The basic intent of the model is to provide information needed to determine the minimum life-cycle cost (LCC) configuration of energy generation and consumption infrastructure. The model has no fuel or technology bias; it simply selects the technologies that will provide an equivalent or superior level of service (e.g., heating, cooling, and illumination) at the minimum LCC. The default values of the parameters used to describe the prototypes are inferred from the input data; for instance, the climate zone is used in conjunction with the building type, vintage, and size to infer parameters relating to the building construction characteristics. This information is also used to infer the most likely heating equipment types for each user-supplied heating fuel type. The resulting building prototype parameter values are statistically the most likely values for a given building type, climate zone, average vintage, size, and fuel-technology mix. Building characteristics are primarily derived from three sources:

- Commercial Buildings Energy Consumption Survey (CBECS) (various dates: see EIA 2002) and Residential Energy Consumption Survey (RECS) building characteristics data (various dates: see EIA 2004d)
- End Use Load and Conservation Assessment Project (ELCAP) commercial and residential end-use load and building characteristics data (Pratt et al. 1989, 1990)
- American Society of Heating Refrigeration and Air Conditioning Engineers (ASHRAE) standard design and construction practices (various dates: see ASHRAE 1997).

The FEDS building model estimates energy consumption for the following end uses:

- Lighting
- Electric motors
- Miscellaneous equipment
- Water heating
- Heating
- Cooling
- Ventilation

Of these end uses, we selected four (heating, cooling, water heating, and lighting) as the end uses where energy use is most likely to be influenced by the temperature increases projected in Table 1.[3]

When the FEDS model is calculating the effects of equipment or equipment changes on energy consumption, the total effect on the building's energy consumption is considered. For example, the model determines the impact of a lighting system retrofit by determining not only the direct electrical consumption of the lighting system, but also the change in the heating, cooling, and energy consumption due to the change in the internal heat gains induced by the change in lighting loads. As the climate warms, the effect of a given lighting load is to reinforce the reduction in building heating loads and to exacerbate any increases in cooling loads.

The outcome of the analysis with FEDS is the effect of the change in temperature-sensitive annual energy loads for specific types, sizes, and vintages of buildings in the residential and commercial sectors in specific climate regions. This is not the same as the impact on total energy consumption because the mix in types and vintages of buildings is different in different regions and because both the types of buildings themselves and their fuels and the efficiency in heating, cooling, water heating, and lighting equipment change over time. The ultimate impact on energy consumption is calculated by the BEAMS model, using changes in energy loads from FEDS as input.

2.2 Impact on energy consumption: BEAMS model

BEAMS is a bottom-up accounting model that calculates energy use and specific scenarios of energy-saving technologies. In addition to energy consumption forecasts, model results include such items as associated changes in the level of environmental emissions and energy expenditures. To determine the effects of climate change on baseline energy use and cost of energy, the model needs information on the changes in energy loads in specific building types and end uses provided for the different time periods and climates. For this paper, the information on baseline energy loads is provided by the FEDS model, based on IPCC climate scenarios. The BEAMS model divides the required energy load for each piece of equipment by an efficiency factor that translates the provision of the load (e.g., energy required to achieve a certain amount of cooling) into actual energy consumption for that end use. For example, if a natural gas furnace were 80% efficient, the heating load

[3] Lighting interacts with the heating and cooling system to decrease heating loads and increase cooling loads. Those interaction effects would be expected to increase with warmer temperatures. Water heating likely would be affected by climate warming and is kept here for completeness, but scenarios of the impacts of climate on water temperatures and energy loads for water heating were not available and were not analyzed in this study.

would be divided by 0.80 to estimate the amount of energy that would be actually consumed to satisfy the heating load. The three temperature sensitive loads are heating, cooling, and water heating (plug loads and appliances are assumed to be unaffected). Lighting interactions with heating and cooling are treated separately, as described below. The BEAMS model also is used to calculate the savings in site energy, primary energy, consumer energy costs, and associated atmospheric emissions reductions associated with energy-efficiency programs and the adoption of energy-efficient systems and technologies in buildings. To do this, the model requires information related to target markets in terms of building sector (residential or commercial), building type (e.g., single family or educational), income level (for residential only), vintage (new or existing), and climate zone or region (with appropriately altered temperatures).

S-shaped technology diffusion curves are used to estimate the market penetration of new energy systems and technologies. The form was originally suggested by Bass (1969) based on a combination of external influences (such as advertising) and internal influences (or imitative effect of 'word of mouth,' which depends on the number of previous adopters). The rate of change in the cumulative number of adopters (dN(t)/dt) is proportional to the difference between the market potential M and the number of previous adopters.

An empirical version of the following form based on cumulative sales was discussed by Mahajan et al. (1986). PNNL researchers estimated non-linear equations of this form for ten technologies, and used the results to derive generic diffusion curves for lighting technologies, heating, ventilation, and air conditioning (HVAC) and related technologies, building envelope technologies, and 'other' programs (Elliott et al. 2004).

$$N(t_i) = mF(t) = \frac{m(1 - \exp(-(p+q)t)}{1 + q/p \times \exp(-(p+q)t)} + w_i$$

where

$N(t)$ = cumulative share of the market at time t
$F(t)$ = fraction of the market penetrated at a given time t
m = maximum market potential, a proportion of the total market based on exogenous information (m was also estimated empirically in some variants)
p = the coefficient of innovation or external influence
q = the coefficient of imitation or internal influence
w_i = an error term (errors are likely to be heteroscedastic, i.e., error variance increasing with i, and autocorrelated).

An example of a derived generic diffusion curve for HVAC technologies in BEAMS is shown in Fig. 2. This generic HVAC diffusion curve is based on the actual historical market penetration of the electric heat pump, flame retention burner, condensing gas furnace, and room air conditioners technologies, whose normalized market penetration curves are also shown in the figure. To develop a generic HVAC curve, the four HVAC technology curves were normalized by setting m^* (the maximum market potential) to 1.0.

There are three approaches to modeling the effects of energy-efficiency programs in the BEAMS model: (1) direct analysis within BEAMS of specific efficiency technologies, in which programs affecting the whole building, equipment, and lighting are treated differently from each other (further discussed below), (2) analysis in the Energy Information Administration's National Energy Modeling System (NEMS) model for the few

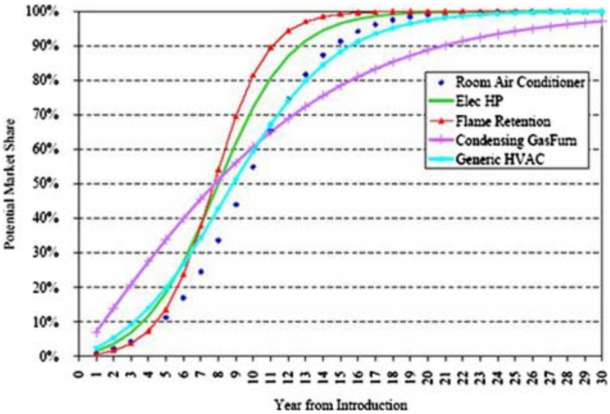

Fig. 2 Generic HVAC diffusion curve compared with other HVAC technology curves (normalized to $m^* = 1.0$) (from Elliott et al.2004, p. 3.19)

technologies that can be analyzed in that model, and (3) spreadsheet analysis of certain programs involving integrated practices. The list of programs can be further divided into programs that address or have effects on temperature-sensitive loads, and others that do not. A categorization of programs according to modeling approach and types of energy loads addressed is shown in Table 4 for programs reported in the fiscal year (FY) 2005 DOE budget request. The goals, content, and expected outcomes of these programs evolve over time as more research is performed and results become known, but the types and general level of expected savings illustrates the general point, which is that these programs have adaptive value that can be measured. Table 4 is a list of the DOE buildings-related energy efficiency programs, together with their incremental national energy savings beyond those expected as a result of ordinary market functioning (NREL 2004). These are estimates of the total expected site energy savings in the year 2020 if each subprogram were 100% successful in achieving its expected progress toward market penetration and if climate did not change. More details on actual calculations are provided in the Appendix. Their sum amounts to about 2.4 exajoules, or about 14% of the 17.1 exajoules of total delivered energy expected to be consumed for heating, cooling, water heating and lighting by residential and commercial buildings in that year and is enough to more than offset the growth in consumption in these end uses expected between 2005 and 2020 (about 1.7 exajoules).

2.2.1 Whole building approach

The whole-building or envelope approach starts with a determination of the size of the overall and potential market for the energy efficiency program. It then determines the number of units affected by the program, the base case space-conditioning (heating and cooling) and water heating loads, calculates changes in these loads after project implementation, and finally calculates energy savings based on stocks of buildings projected for each climate region. Estimates of the stocks of equipment necessary to perform these calculations come from the EIA Annual Energy Outlook (AEO) (EIA 2003c) and were used for the years up to 2025. The building stock was disaggregated into north and south regions using EIA climate zones published in the Residential Energy Consumption Survey RECS and CBECS. EIA zones 1 through 3, with more than 4,000 (°F) heating degree-days,

Table 4 Categorization of department of energy buildings energy efficiency programs

Program	Temperature-sensitive loads affected	Modeling approach	Expected energy savings in the year 2020 (petajoules)
Rebuild America	Heating, cooling, water	Whole building (BEAMS)	27.6
Commercial buildings R&D	Heating, cooling, water	Whole building (BEAMS)	141.6
Analysis tools and design strategy	Heating, cooling, water	Whole building (BEAMS)	68.5
State energy program: energy audits	Heating, cooling, water	Whole building (BEAMS)	26.4
State energy program: retrofits	Heating, cooling, water	Whole building (BEAMS)	11.4
State energy program: technical assistance	Heating, cooling, water	Whole building (BEAMS)	4.3
State energy program: workshops and training	Heating, cooling, water	Whole building (BEAMS)	36.4
Information outreach–outreach activities	Heating, cooling, water heating	Whole building (BEAMS)	3.9
Energy star: windows (shared 50% with low-E market acceptance)	Heating, cooling	Envelope (BEAMS)	312.2
Information outreach-pilot projects	Heating, cooling, water heating	Envelope (BEAMS)	0.5
Refrigeration R&D: residential HVAC distribution system	Cooling	Envelope (BEAMS)	44.8
Window technologies: electrochromic windows	Heating, cooling	Envelope (BEAMS)	18.9
Window technologies: superwindows	Heating, cooling	Envelope (BEAMS)	100.2
Window technologies: low-E market acceptance (shared 50% with energy star windows)	Heating, cooling	Envelope (BEAMS)	312.2
Refrigeration R&D: advanced electric heat pump water heater	Water	Equipment (BEAMS)	32.4
Refrigeration R&D: refrigerant meter	Heating, cooling	Equipment (BEAMS)	14.8
Energy star: CFLs	Heating, cooling	Lighting interaction (BEAMS)	212.1
Appliances and emerging technologies R&D: recessed can lights	Lighting interaction	Lighting interaction (BEAMS)	3.7
Appliances and emerging technologies R&D: R lamps	Lighting interaction	Lighting interaction (BEAMS)	0.0
Energy star: clothes washers	Water heating	NEMS-PNNL	48.7
Energy star: refrigerators	None	NEMS-PNNL	5.9
Energy star: electric water heaters	Water heating	NEMS-PNNL	25.3
Energy star: gas water heaters	Water heating	NEMS-PNNL	11.1
Energy star: room air conditioners	Cooling	NEMS-PNNL	1.5

Table 4 continued

Program	Temperature-sensitive loads affected	Modeling approach	Expected energy savings in the year 2020 (petajoules)
Energy star: dishwashers	Water heating	NEMS-PNNL	1.6
Appliances and emerging technologies R&D: heat pump water heater	Water	NEMS-PNNL	29.8
Appliances and emerging technologies R&D: roof top air conditioner	Cooling	NEMS-PNNL	1.6
Solid state lighting	Lighting interaction	NEMS-PNNL	95.7
Lighting R&D: controls	Lighting interaction	Spreadsheet	22.6
Residential buildings R&D	Heating, cooling, water	Spreadsheet	189.0
Residential building codes	Heating, cooling	Spreadsheet	52.6
Commercial building codes	Heating, cooling	Spreadsheet	31.1
State energy program: codes	Heating, cooling, water	Spreadsheet	52.6
State energy Program: rating and labeling	Heating, cooling, water	Spreadsheet	19.6
State energy program: loans	Heating, cooling, water	Spreadsheet	13.6
Weatherization assistance	Heating, cooling	Spreadsheet	114.9
Building codes training and assistance	Heating, cooling, water heating	Spreadsheet	154.5
Refrigeration R&D: commercial refrigeration	Heating, cooling	Spreadsheet	17.4
Standards: residential gas furnaces and boilers	Heating	Spreadsheet	32.6
Standards: EPAct standards	Heating, cooling	Spreadsheet	118.1
Total	–	–	2,411.7

were considered north and zones 4 and 5, with less than 4,000 heating degree-days, were considered south. Different proportions of the various building types and vintages were estimated for each region. For example, the model takes into account the gradual shift of the US population to the south. For commercial buildings, 59% of the existing building stock is in the north, but only 55% of new commercial buildings were assumed to be in the north. About 41% of the existing commercial building stock is in the south but 45% of new commercial building stock was assumed to be in the south. As with all other calculations in BEAMS, the number of units affected is calculated as a fraction of the installed base (or sales of new units, as appropriate) for sector s, building type b, vintage v, and region r. The existing stock gradually declines over time as it is replaced.

Baseline end use loads in BEAMS discussed in this paper represent heating, cooling, water heating, and lighting loads distinguished by building type (e.g., assembly, education, multifamily, etc.) as well as by vintage and climate zone. Ordinarily, energy improvements are calculated as reductions in space-conditioning and water heating loads, so that baseline energy does not have to be calculated. However, because climate changed in the scenarios examined in this paper, baseline energy use also was calculated. The model calculates regional loads and load reductions by first calculating building level loads and then multiplying the loads times the number of buildings affected. Existing equipment stock efficiencies and initial equipment market shares were developed from the AEO.

2.2.2 *Equipment*

Another set of energy programs and energy savings was calculated in BEAMS for groups of relatively short-lived equipment, which was tracked by region, end use, fuel, and vintage. Pieces of equipment are allowed to be replaced on a faster cycle than the buildings they occupy. Once a piece of equipment is installed, the market for remaining installations is limited until it next comes up for replacement and can be re-competed. Thus, installation of a ‘good’ efficient piece of equipment limits the immediate market for an ‘‘even better’’ piece of equipment. Fuel switching is allowed, along with changes in efficiency and market shares. The analysis is done annually. The number of units affected is multiplied by the load, and then divided by the applicable efficiency factor to obtain an estimate of energy consumption for all units of that piece of equipment.

2.2.3 *Lighting*

Lighting programs are targeted to specific markets. The equipment stock is derived by multiplying each appropriate market segments building stock by a market share(s) and penetration rate, and then dividing by the equipment life to get replacement rates.

Because lighting adds significant amounts of heat to buildings’ interior space, the effects of lighting on heating and cooling are recalculated for future climate. Loads for cooling and heating are adjusted up or down as appropriate, and then the effect of energy consumption is estimated by dividing the altered heating or cooling load by its appropriate efficiency. Interaction effects in BEAMS ordinarily are analyzed only for the current climate. To characterize the change in the interaction effects as climate warms, we recalculated the sensitivity of the interaction effects on heating and cooling in the baseline buildings for the maximum temperature scenario in 2050 and 2080 for six building sizes. The impact of lighting on heating and cooling as a function of temperature change was well-approximated by a linear regression with a forced intercept of 1.0. The R^2 was 0.99 for heating and 0.97 for cooling. The regression slope was used to adjust the regional coefficients for the lighting interaction effect for each climate scenario. The impact on heating and cooling load was then recalculated with the FEDS model for each building type for the warmer temperatures projected in Table 1. Finally, the impact of energy efficiency programs on lighting loads was used to scale the heating and cooling loads for each temperature regime, both adding a negative number to the negative-sign heating interaction effect on building energy use (thus increasing the absolute value of the effect) and adding a negative number to the positive-sign cooling interaction effect (thus reducing the absolute value of that effect). The lighting savings, as well as the interactive effect on heating and cooling energy use were then added to building energy savings from the other energy efficiency programs.

2.2.4 *NEMS-modeled equipment*

The market penetration of some of the equipment evaluated in BEAMS was estimated by the NEMS (Elliott et al. 2004, EIA 2003a, b). Much of the NEMS-modeled equipment is not usually thought of as climate-sensitive (e.g., clothes washers). For NEMS-modeled equipment likely to be climate-sensitive, we took the future baseline energy demands estimated by FEDS and BEAMS (run together) for similar equipment to calculate numerical scaling factors for climate sensitivity of energy savings, and then adjusted NEMS energy savings by these scaling factors to allow for the impacts of climate warming. The scaling factors were calculated by applying the percentage change in energy savings due to climate times the percentage energy savings estimated by NEMS with unchanged temperature.

2.2.5 Spreadsheet-modeled programs

Some programs' energy savings are calculated offline in spreadsheets because savings are derived from changes in integrated practices adopting whole suites of equipment (e.g., as a result of weatherization or a state program grant) rather than the single technologies in the BEAMS model. For this equipment, we took the future baseline energy demands estimated by the spreadsheet, and then adjusted energy demand by scaling factors to allow for the impacts of climate warming. The scaling factors were calculated by applying the percentage change in baseline energy use due to climate times the percentage energy savings estimated by the spreadsheet with unchanged temperature.

The BEAMS model calculates the carbon emitted to the atmosphere from site energy consumption using national average carbon emissions coefficients for natural gas, fuel oil, and electricity. (The latter, in turn, is based on a year-by-year estimate of electricity generation by fuel—the carbon intensity of electricity production is projected to decline about 20% between 2004 and 2030. See Elliott et al. 2004).

3 Analysis

In a warmer world, the value of energy efficiency programs change because building cooling loads would increase and heating loads decrease with climate change in the absence of any changes to building efficiency, and the impacts of warming would interact with the impacts of increased energy efficiency. Energy efficiency programs that save heating energy would experience reduced energy savings, while the programs that save on cooling loads would experience increased energy savings. We calculate the reductions in primary energy consumption associated with adaptive energy savings (customer site energy savings, adjusted for energy conversion, transmission, and distribution losses), and the associated reductions in carbon emitted to the atmosphere. There is evidence that energy-efficient buildings are more comfortable than their less-efficient counterparts (Abbazadeh et al. 2006), and some economists have begun to use non-market survey methods to discover how much consumers are willing to pay for reductions in the adverse impacts of climate change, including loss of comfort (e.g., Cameron 2000). However, the assumption made in this paper is that the interior comfort of buildings does not change with warming, because any change in energy use required to stabilize comfort is already included in the net energy savings.

To illustrate the potential importance of energy efficiency improvements in buildings technologies and practices in the context of climate change, we selected the buildings-related energy efficiency programs in the DOE's Weatherization and Intergovernmental Program and Building Technologies Program as described for DOE's FY 2005 budget submission to the US Congress. These were chosen for three reasons: (1) the programs are being pursued by DOE at least in part for their climate mitigation benefits, (2) enough information exists on these programs that the methods for planned market penetration and calculation of potential baseline energy and carbon savings already have been done, and (3) at least some of the programs would have additional benefits in the form of human comfort and energy savings if average seasonal temperatures increase as expected. For a further description of these programs see Elliott et al. (2004).

To estimate the impact of warmer temperatures on energy savings, the BEAMS analysis was repeated, both for technologies and practices modeled initially with BEAMS and those modeled initially with NEMS-PNNL and spreadsheets, for the higher average temperatures shown in Table 1 for the year 2020. Building energy consumption was re-simulated at the higher temperatures, and a comparison made to both the baseline case and the higher market penetration case.

4 Results

4.1 The effect of climate warming on energy consumption

Table 5 shows the 'pure' impact of projected climate change alone on site energy consumption in the US residential and commercial buildings sectors for the seasonal temperature scenarios outlined in Table 1 for the years 2020, 2050, and 2080. Table 5 assumes no change in the US building stock. Clearly, the changes in actual energy consumption likely would be more positive than shown because of growth in the number and size of buildings in the US building stock, and increases in the market penetration of air conditioning and other energy-using equipment. Although we have no way of knowing what the actual building stock in 2050 or 2080 will actually be like, we have some insights into the 2020 building stock from EIA (EIA 2004c). If current trends continue, much of the new building stock will be built in the southern part of the country in accord with the long-term demographic shift of the US population to the south and west. This would increase cooling loads relative to heating loads. Several sensitivity cases were also run for different amounts of warming, in line with the range in IPCC's climate scenarios.

In Table 5, the effect of climate alone on annual energy consumption in the US residential and commercial building sector measured at the building itself (site energy) is negative: the warming of the climate over the next century reduces the consumption of heating fuel more than it increases demand for electricity for cooling. The net pure effect of climate warming leaves net building site energy consumption between 80% and 94% of its 2005 level by 2080, in the same range as Rosenthal et al. (1995) (more about primary energy below). Interestingly, even though total site demand for energy falls, the electricity component increases by between 1% and 6% (about 0.06–0.2 EJ) in 2020, and by 4% and 25% (0.5–1.4 EJ) by 2080. Using nuclear power's 90% capacity factor for 2004 as an upper bound estimate of baseload power plant availability, 1.4 exajoules is equivalent to roughly 48 baseload power plants of 1,000 MW each. At the much lower 2003 average US generation/capacity ratio of 47%, 1.4 EJ corresponds to 93 GW of generation capacity. This component of demand would be added to other causes of increased demand for electricity such as population growth, economic growth, and increased electrification of the economy that the national power grid will be dealing with for the rest of the century. While not specifically addressed in this paper, the increased cooling demand also can be expected to significantly increase summer peak electricity demand and hence require a substantial increase in peak electrical generation capacity. Since these would be intermediate load and

Table 5 Baseline temperature-sensitive site energy consumption in residential and commercial buildings in the US as a result of projected low and high temperatures in 2020, 2050, and 2080

Load assumptions/ climate change scenarios	Commercial (exajoules)					Residential (exajoules)					US Combined (exajoules)	
	Heat, cool, WH, light	Heat	Cool	WH	Light	Heat, cool, WH, light	Heat	Cool	WH	Light	Heat, cool, WH, light	Site electricity[a]
Baseline climate site energy total in 2005	5.01	2.34	0.85	0.26	1.56	10.40	5.37	0.49	3.47	1.07	15.40	5.37
2020 Low temperature	4.93	2.22	0.90	0.26	1.56	10.20	5.14	0.53	3.47	1.07	15.14	5.43
% of 2005 baseline	99	95	106	100	100	98	96	108	100	100	98	101
2020 High temperature	4.70	1.78	1.10	0.26	1.56	9.54	4.32	0.68	3.47	1.07	14.25	5.69
% of 2005 baseline	94	76	129	100	100	92	80	140	100	100	93	106
2050 Low temperature	4.81	2.02	0.97	0.26	1.56	9.89	4.77	0.58	3.47	1.07	14.69	5.51
% of 2005 baseline	96	86	114	100	100	95	89	119	100	100	95	103
2050 High temperature	4.46	1.25	1.39	0.26	1.56	8.72	3.28	0.91	3.47	1.07	13.18	6.08
% of 2005 baseline	89	53	163	100	100	84	61	185	100	100	86	113
2080 Low temperature	4.73	1.88	1.03	0.26	1.56	9.68	4.51	0.63	3.47	1.07	14.41	5.59
% of 2005 baseline	95	81	121	100	100	93	84	129	100	100	94	104
2080 High temperature	4.36	0.70	1.84	0.26	1.56	7.92	2.14	1.24	3.47	1.07	12.27	6.73
% of 2005 baseline	87	30	216	100	100	76	40	255	100	100	80	125

[a] Electricity consumption assumes AEO 2004 values for electricity shares of the various end uses: for commercial buildings, heating, 8.67%; water heating, 17.95%; cooling and lighting, 100%. For residential buildings the corresponding values are 7.32%, 21.76%, and 100%. These values are held constant throughout the projections

peaking plants with inherently lower capacity factors on the order of perhaps 25%, the increment to capacity could be several times greater.

Table 6 shows the effect of climate change on the consumption of primary energy used in US residential and commercial buildings. Table 6 includes all energy directly or indirectly consumed by end users, including electricity consumption translated into the energy consumed at electric utilities to generate electricity. Electricity is used in about 7–8% of heating applications, about 16–20% of water heating, virtually all cooling, and all lighting. Electricity must be generated and transported over distance with some losses, so the increase in site energy use of electricity for cooling is multiplied by a factor of 3.20 in commercial buildings and 3.36 in residential buildings (all AEO estimates for 2005), which accounts for the energy consumed as electricity in buildings in the US and the energy consumed in power plants and lost in transmission and distribution to deliver that electricity. This adjustment translates into approximately zero change in overall the net demand for primary energy at the highest temperature increases, as illustrated in the last cell of Table 6. Allowing for projected AEO trends in the market percentages of electricity in heating and water heating and the efficiency in electrical generation, transmission, and distribution slightly decreases the impact of warming on primary energy use relative to site energy use, but makes little difference in the overall story.

The pure effect of the projected climate warming on net primary energy consumption by the US residential and commercial building sectors is very small–the net total primary energy consumption generally remains within about 2% of the amount it would have been, had the forecasted average seasonal temperatures not increased during the 21st century. Table 5 shows that by 2080 the net amount of site energy consumed decreases by as much as 20% as a result of climate change, so the much smaller net reduction in primary demand Table 6 demonstrates that energy losses in electricity generation, transmission, and distribution are important in considering whether the nation uses more energy or less energy However, cooling does not dominate, even at the primary energy level. Even though site energy used for cooling increases to as much 2.5 times current levels, as illustrated in Table 5, and even though cooling takes over three times the primary energy consumption as heating per unit of site energy consumed, the baseline dominance of heating demand and the corresponding saving in heating energy is large enough to almost perfectly balance the increase due to cooling at the primary energy level. This does not include any additional cooling energy impact that may occur due to growth in the market penetration of air conditioning in direct response to warmer temperatures, which is outside the scope of this paper.

Table 6 The pure impact of climate warming on primary energy demand associated with the US residential and commercial buildings sectors for the Years 2020, 2050, and 2080[a]

Load assumptions/climate change scenarios	Commercial (exajoules)			Residential (exajoules)			Total (exajoules)
	Heat, cool, WH, light	Heat, WH	Cool, light	Heat, cool, WH, light	Heat, WH	Cool, light	Heat, cool, WH, light
Baseline climate primary energy total in 2005	10.87	3.14	7.72	16.78	11.54	5.24	27.65
2020 Low temperature	10.88	3.00	7.88	16.64	11.27	5.37	27.53
% of 2005 baseline	100.2	95.4	102.1	99.2	97.7	102.5	99.6
2020 High temperature	11.01	2.49	8.53	16.21	10.31	5.89	27.22
% of 2005 baseline	101.3	79.1	110.4	96.6	89.4	112.5	98.4
2050 Low temperature	10.88	2.76	8.11	16.39	10.83	5.55	27.27
% of 2005 baseline	100.1	87.9	105.0	97.7	93.9	106.0	98.6
2050 High temperature	11.30	1.85	9.46	13.59	9.09	6.64	27.03
% of 2005 baseline	104.0	58.7	122.4	81.0	78.7	126.8	97.8
2080 Low temperature	10.91	2.60	8.30	16.24	10.53	5.71	27.15
% of 2005 baseline	100.4	82.8	107.5	96.8	91.3	108.9	98.2
2080 High temperature	12.08	1.20	10.89	15.52	7.75	7.77	27.60
% of 2005 baseline	111.2	38.1	140.9	92.5	67.1	148.4	99.8

[a] Conversion ratios from site energy to primary energy were derived from AEO 2004. They were 3.2 for commercial buildings and 3.36 for residential buildings

4.2 The impact of changes in building stock and climate change together (2020)

The US EIA forecasts residential and commercial building stock to the year 2025 (EIA 2004c). This forecast presents an opportunity to examine the effect of climate warming in the context of a changing US building stock in 2020. Table 7 illustrates the impact on site energy consumption of the combined effects of new buildings and equipment and turnover in buildings and equipment in the context of about 1.5°C climate warming. Site energy was then translated into impacts on primary energy using EIA-derived trended relationships between site energy and primary energy (see Table 8).

Table 7 shows that, in the absence of warming, changes in building stock and equipment between 2005 and 2020 would add about 1.7 exajoules (about 11%) to temperature-sensitive US building site energy consumption. At the high end, the projected climate warming almost offsets the effect of the growth in the building stock, resulting in a site energy demand only

Table 7 Impact of combined projected changes in building stock and climate change on site energy consumption by US residential and commercial buildings in the Year 2020[a]

Load assumptions/ climate change scenarios	Commercial (exajoules)					Residential (exajoules)					US combined(exajoules)
	Heat, cool, WH, light	Heat	Cool	WH	Light	Heat, cool, WH, light	Heat	Cool	WH	Light	Heat, cool, WH, light
Baseline climate—site energy total in 2005	5.01	2.34	0.85	0.26	1.56	10.40	5.37	0.49	3.47	1.07	15.40
Baseline climate—site energy total in 2020	6.07	2.76	1.29	0.35	1.67	11.01	5.37	0.49	3.98	1.17	17.08
% of 2005 baseline	121	118	151	136	107	106	100	101	115	109	111
2020 Low temperature increase	6.00	2.62	1.36	0.35	1.67	10.81	5.13	0.53	3.98	1.17	16.81
% of 2005 baseline	120	112	160	136	107	104	96	109	115	109	109
% of 2020 baseline	99	95	106	100	100	98	96	108	100	100	98
2020 High temperature increase	5.79	2.10	1.67	0.35	1.67	10.13	4.30	0.68	3.98	1.17	15.92
% of 2005 baseline	116	90	196	136	107	97	80	140	115	109	103
% of 2020 baseline	95	76	130	100	100	92	80	139	100	100	93

[a] In the baseline scenario for 2020, residential energy use is slightly lower for heating and slightly higher for cooling than in 2005, but the difference is in the third decimal place. By coincidence, effects of growth in building size, population shift to the south and west, and baseline improvements in efficiency almost exactly offset

Table 8 Impact of combined projected changes in building stock and climate change on primary energy consumption by US residential and commercial buildings in the Year 2020[a]

Load assumptions/ climate change scenarios	Commercial (exajoules)					Residential (exajoules)					US combined (exajoules)
	Heat, cool, WH, light	Heat	Cool	WH	Light	Heat, cool, WH, light	Heat	Cool	WH	Light	Heat, cool, WH, light
Baseline climate—site energy total in 2005	10.87	2.78	2.73	0.36	4.99	16.78	6.30	1.64	5.25	3.60	27.65
Baseline climate—site energy total in 2020	13.25	3.29	4.12	0.49	5.34	17.90	6.29	1.66	6.02	3.92	31.14
% of 2005 baseline	122	118	151	136	107	107	100	101	115	109	113
2020 Low temperature increase	13.32	3.12	4.37	0.49	5.34	17.75	6.02	1.79	6.02	3.92	31.07
% of 2005 Baseline	123	112	160	136	107	106	96	109	115	109	112
% of 2020 baseline	101	95	106	100	100	99	96	108	100	100	100
2020 High temperature increase	13.69	2.50	5.36	0.49	5.34	17.28	5.04	2.30	6.02	3.92	30.97
% of 2005 baseline	126	90	196	136	107	103	80	140	115	109	112
% of 2020 baseline	103	76	130	100	100	97	80	139	100	100	99

[a] For electricity shares, 2005 end use values are the same as in Table 5. For 2020, AEO 2004 trended shares were used: commercial building electricity shares are: heating, 7.66%; water heating, 15.84%, cooling and lighting 100%. For residential buildings: 7.5%, 20.65%, and 100%, respectively. The AEO primary energy/site energy ratio is 3.2 for commercial buildings, 3.36 for residential

3% above current demand. Table 8 shows that in the absence of warming, primary energy consumption in residential and commercial buildings would increase about 3.5 EJ (13%) by 2020. These increases would vary by subsector and end use.

Temperature increases due to climate change would reduce heating energy consumption and increase cooling energy consumption in 2020 relative to what otherwise would have been. For example, the high temperature case reduces year 2020 primary heating energy consumption by 0.79 EJ in commercial buildings (−24%) and 1.25 EJ in residential buildings (−20%), a combined 2.04 EJ (−21%), while increasing cooling energy consumption by 1.24 EJ in commercial buildings (+30%) and 0.64 EJ in residential buildings (+39%), a combined 1.88 EJ (+32%). Overall, primary energy consumption falls due to the dominance of baseline heating energy consumption relative to cooling, even though cooling is significantly more sensitive to warming in percentage terms. As with Table 6, EIA-projected trends in electricity market share of heating and water heating and in primary/site energy ratios reduce the baseline growth rates for electricity consumption and total energy consumption, but make virtually no difference in the impact of climate change on energy consumption. As before, however, additional market penetration of air conditioning (primarily in residential buildings in the northern part of the country) in response to climate change is not part of the scope of this paper, but could significantly increase on both baseline energy consumption growth and the impact of climate warming.

4.3 Impact of energy efficiency programs in the context of climate change

The DOE building energy efficiency programs listed in Table 4 are heavily oriented toward reducing heating loads through deploying improvements to building shells and windows, and to improving the efficiency of lighting in both residential and commercial buildings. The programs were designed to reduce US energy use to save consumers money and improve US energy security. These programs also take credit for reducing the emissions of CO_2 (measured as metric tons of carbon) that is believed to result in climate change. How effective are these programs if climate change is reducing heating loads anyway? The answer is: less effective than if climate did not change, but still very worthwhile. All of the programs were rerun through the BEAMS model for the year 2020 with the temperature changes described in Table 1. The results for savings in temperature-sensitive site energy, primary energy, C emissions, and cost savings for consumers are shown in Table 9.

Net program savings are about $0.7–3.0 billion less (2005 prices) than if climate did not change. Comparing across the columns of Table 9, integrated programs, heating-only, windows, and lighting programs generally show less effectiveness and value as climate warms. However, the comparative handful of programs devoted to saving cooling energy is, as expected, more effective and valuable in a warmer world.

Table 9 shows that although the amount and value of energy and C saved is less under a warmer climate in 2020 than it would be without warming, implementation of the DOE energy efficiency programs still would have substantial economic value, saving energy consumers about $45.0–47.3 billion per year compared with a case where no programs were implemented. The savings in customer energy expenditures shown in Table 9 approximately reflect national savings, since national resource costs and energy losses in the generation, transmission, and distribution of electricity are reflected in site-level electricity prices per delivered kWh. Comparing the site energy projected to be saved by these programs with the increase in energy use due to climate and growth in the building stock shown in Table 7, the site energy saved (2.2–2.4 EJ) would more than offset the growth in temperature-sensitive energy consumption due to climate and growth in building stock combined. The corresponding primary energy savings range from 3.7 to 3.9 EJ, and C savings related to those primary energy saving range from 63.7 to 67.2 million metric tons per year. (Carbon emissions factors were derived from EIA forecasts documentation and were provided by DOE for use in the BEAMS model. The values appear in Appendix C.7 of Anderson et al. 2003.) We would expect an increasing adaptive value (offsetting increased cooling energy consumption) after 2020 due to increasing temperatures, further growth in the building stock, and further increasing market penetration of DOE's buildings-related technologies and practices.

5 Conclusions

Previous studies of building energy efficiency programs in the US have not considered their effectiveness and value in the context of climate change. Based on regionalized results from seven climate models, this paper shows that the pure impact of climate change is a net reduction in site energy in US residential and commercial buildings and approximately zero change in primary energy demand. By reducing heating energy demand, climate change also undercuts the cost-effectiveness of US energy efficiency

Table 9 Savings in site energy, primary energy, carbon, and consumer costs from DOE buildings energy efficiency programs by program area in the context of climate change

Projected impacts		Whole building programs (heating, cooling, water, lighting)	Heating-only programs	Cooling-only programs	Windows programs	Water-heating programs	Lighting and lighting Interactions	Plug loads and other	Total
Site energy saved (exajoules)									
Baseline	No temperature change	1.112	0.033	0.018	0.744	0.149	0.334	0.023	2.412
Low	0–0.6°C	1.095	0.032	0.019	0.709	0.149	0.332	0.023	2.359
High	1.9–2.8°C	1.043	0.029	0.024	0.585	0.149	0.315	0.023	2.168
Primary Energy Saved (exajoules)									
Baseline	No temperature Change	1.763	0.033	0.041	0.975	0.284	0.798	0.050	3.944
Low	0–0.6°C	1.743	0.032	0.044	0.933	0.284	0.794	0.050	3.880
High	1.9–2.8°C	1.684	0.030	0.056	0.784	0.284	0.767	0.050	3.655
Carbon saved (million metric tons)									
Baseline	No temperature change	30.677	0.444	0.757	15.499	5.043	14.803	0.912	68.134
Low	0–0.6°C	30.372	0.436	0.812	14.849	5.043	14.734	0.912	67.158
High	1.9–2.8°C	29.464	0.411	1.031	12.558	5.043	14.296	0.912	63.715
Value of Customer Savings (Billion 2005$)									
Baseline	No temperature Change	$20.4	$0.3	$0.6	$11.2	$4.0	$11.0	$0.6	$48.0
Low	0–0.6°C	$20.2	$0.3	$0.6	$10.7	$4.0	$11.0	$0.6	$47.3
High	1.9–2.8°C	$19.5	$0.3	$0.8	$9.1	$4.0	$10.6	$0.6	$45.0

programs and investments that primarily reduce the demand for energy used for heating. However, those programs that primarily save cooling energy are made more effective by climate change and, and on balance, the programs still have considerable economic value. Although climate warming alone would cause total site energy use in US buildings to fall during the 21st century, climate warming would also cause a significant 1.4 exajoules increase in the consumption of electricity, and likely would encourage the further market penetration of air conditioning, a factor not directly evaluated in this paper. The total adaptive value of energy efficiency (offsetting of climate change) is expected to rise throughout the century because of a combination of increasing building stock and of technologies, practices and standards resulting from DOE programs.

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Appendix: Example of detailed computations on energy impacts

This appendix demonstrates the interaction of the FEDS and BEAMS models in estimating climate effects on energy consumption in US residential and commercial buildings. Throughout this appendix, the modeling interactions and calculations are demonstrated by following the step-by-step process that is used to determine the changes in energy usage under different climate scenarios for *cooling loads* in *newly* constructed *education* buildings in the New England and Mid-Atlantic US climate regions in the year *2020*. Fig. A.1 illustrates how energy consumption estimates are calculated by working through the step-by-step process using the example sub-set (Mid-Atlantic/New England new education cooling) of the data. As shown in the main text Table 2, the climate of Providence, Rhode Island, represents the New England and Mid-Atlantic climate regions. The example concentrates on space cooling only. Similar calculations are performed for space heating and interactive effects with lighting. First, it is necessary to apply a climate change scenario to modify the existing climate regime. As outlined in the main text, for the year 2020 this was done by increasing the seasonal average temperature forecasts in 2020 by the values shown in Table 1.[4] These seasonal increases in temperature values are added to the hourly temperature in FEDS for each hour of the day for three types of days (weekday, Saturday, and Sunday) during each month of the year in 2020, and the corresponding building energy loads for cooling and heating computed for each type of building, since different sizes, vintages, and types of

[4] Climate estimates are derived from Ruosteenoja et al. (2003) from a large group of scenarios and climate models. For example, in the eastern US, the low end increases are 0.4°C in winter, 0.6°C in spring, 0.8°C in summer, 0.6°C in autumn (Ruosteenoja et al. 2003).

buildings have different climate sensitivities. Table A.1 shows a typical hourly load calculation for cooling load for a new, occupied 4,000 square foot education building in Providence in January, April, July, and October at 2 p.m. This building represents 3.2% of the new education building square footage for the climate zones (New England and Mid Atlantic) represented by Providence. The same calculations are performed for other size new education buildings.

Fig. A1 Steps in constructing an estimate of cooling energy consumption and savings

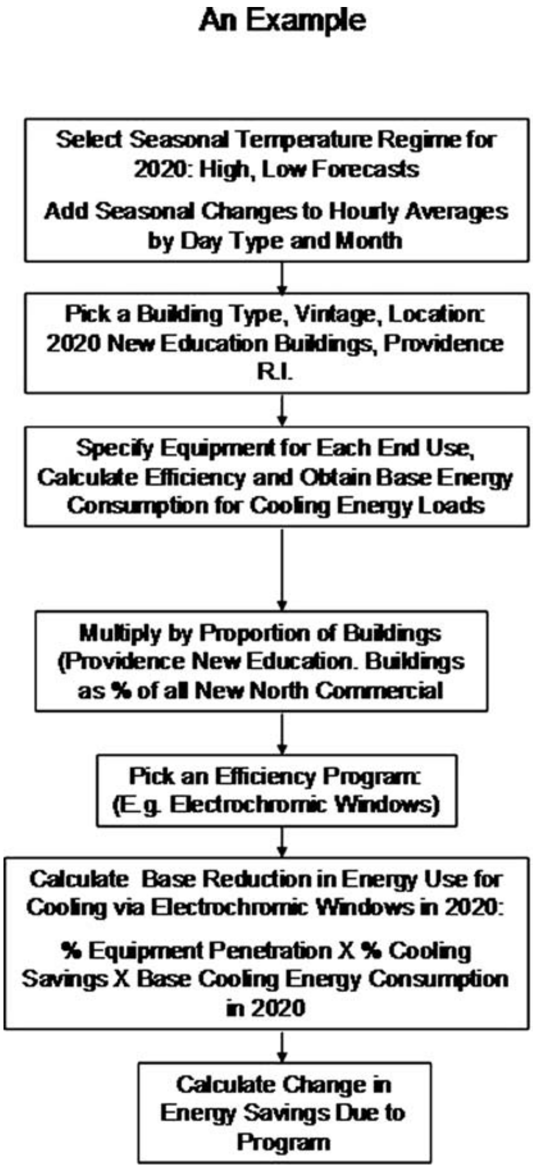

Table A.1 Hourly cooling loads, providence 2020: 4000 square foot new education building, typical weekday, Saturday, and Sunday at 2 pm–3 pm in January, April, July, and. October (Cooling Wh)

Months	Day type	Cooling Wh Load for 2–3 p.m.		
		Base	Low	High
Winter (January)	Weekday	0	0	0
	Saturday	0	0	0
	Sunday	0	0	0
Spring (April)	Weekday	1,598	1,704	3,290
	Saturday	295	397	918
	Sunday	295	397	918
Summer (July)	Weekday	24,915	25,625	28,650
	Saturday	13,819	14,443	17,132
	Sunday	13,819	14,443	17,132
Fall (October)	Weekday	5,704	6,622	7,875
	Saturday	1,505	1,965	2,633
	Sunday	1,505	1,965	2,633

Table A.2 shows the overall computations for deriving changes in cooling load in new education buildings of all sizes represented by the Providence climate for both the seasonal minimum and maximum temperature increases for 2020 reported by Ruosteenoja et al. (2003). As described in Elliott et al. (2004), the six prototype education building sizes that represent new education buildings have their hourly cooling loads estimated for baseline average temperatures in Providence for three types of day for each month of the year. These loads are aggregated to monthly values and then annual values for each building type, and weights reflecting square footage by building type are applied to yield weighted annual cooling energy consumption for new education buildings. The same computation is then done for the low and high temperature increases, and the annual aggregate cooling energy requirements calculated in watt-hours and kilojoules (KJ). Note that larger buildings have smaller cooling loads per square foot than smaller buildings because the ratio of external wall area to internal volume is less for larger buildings than for smaller ones. Larger buildings' cooling requirements thus are more likely to be influenced by internal loads than are smaller buildings, which are relatively more sensitive to their external climate. Larger buildings also dominate the total square footage to be cooled, and the weighted average energy requirement per square foot is closer to that of the larger buildings than to that of the smaller ones. When temperature increases, the per-square-foot cooling loads of the larger buildings also increase less than do those in smaller buildings. (The opposite is true on a percentage basis, because the difference in cooling load increases between large and small buildings is smaller on a square footage basis than is the initial spread in cooling loads between them, leading to a larger percentage change in cooling

Table A.2 Calculation of cooling loads, new education buildings, Providence, Rhode Island, base case and low and high temperature cases, Year 2020

Iteration	Prototype building size in square feet	Floor area weights	Annual cooling load (wh/sq. ft.) 2020 Base	Annual cooling load (Wh) 2020 Base	Change from base, per square foot 2020 Base	Percentage change from base, per square foot 2020 Base
75	4,000	3.2%	4,970	1.99E+07	–	–
86	7,500	5.2%	4,962	3.72E + 07	–	–
97	17,500	13.5%	4,300	7.52E + 07	–	–
108	37,500	23.6%	4,129	1.55E + 08	–	–
119	75,000	22.6%	3,270	2.45E + 08	–	–
130	125,000	31.8%	2,747	3.43E + 08	–	–
	Weighted		3,588	2.14E + 08	–	–
			2020 Low temperature (+0.4–0.8°C)	2020 Low temperature (+0.4–0.8°C)	2020 Low temperature (+0.4–0.8°C) (Wh/Sq. ft.)	2020 Low temperature (+0.4–0.8°C)
75	4,000	3.2%	5,400	2.16E + 07	430	8.6%
86	7,500	5.2%	5,372	4.03E + 07	410	8.3%
97	17,500	13.5%	4,660	8.15E + 07	360	8.4%
108	37,500	23.6%	4,473	1.68E + 08	344	8.3%
119	75,000	22.6%	3,563	2.67E + 08	293	8.9%
130	125,000	31.8%	3,023	3.78E + 08	276	10.0%
	Weighted		3,907	2.34E + 08	319	8.9%
			2020 High temperature (+1.9–3.2°C)	2020 High temperature (+1.9–3.2°C)	2020 High temperature (+1.9–3.2°C) (Wh/Sq. ft.)	2020 High temperature (+1.9–3.2°C)
75	4,000	3.2%	7,139	2.86E + 07	2,168	43.6%
86	7,500	5.2%	7,095	5.32E + 07	2,132	43.0%
97	17,500	13.5%	6,160	1.08E + 08	1,860	43.3%
108	37,500	23.6%	5,841	2.19E + 08	1,712	41.5%
119	75,000	22.6%	4,728	3.55E + 08	1,458	44.6%
130	125,000	31.8%	4,110	5.14E + 08	1,363	49.6%
	Weighted		5,189	3.14E + 08	1,600	44.6%
			Cooling load per Sq. Ft. (KJ)	Cooling load (GJ) per Building	Change from base, per square foot (KJ)	% of change from base, per square ft.
	Base	New	12,921	771	–	–
	2020 Low	New	14,070	843	1,149	8.9
	2020 High	New	18,683	1,130	5,762	44.6

requirements for the larger buildings, with their smaller initial loads per square foot—see Table A.2, columns 6 and 7).

Table A.3 shows the mix of equipment used to provide cooling in new education buildings, as well as each type's rated efficiency in Coefficient of Performance (COP) or

Table A.3 Calculating impact of temperature on buildings heating energy consumption, new education buildings in Providence, Rhode Island and new education buildings (north) in 2020

	2020 Heating equipment/fuel (%) education, north (New)	2020 Equipment Efficiencies (New) (COP or SCOP)	2020 Equipment 1/ Efficiencies
HP/electric	5.0	3.810	0.26
None/none	0.2	1.000	1.00
Other/electric	0.9	2.930	0.34
Other/gas	6.6	1.000	1.00
Packaged unit/electric	6.0	3.000	0.33
Packaged unit/gas	19.0	0.700	1.43
Packaged unit/other	0.4	1.000	1.00
CAC/electric	6.4	3.810	0.26
Central chiller/electric	43.2	7.000	0.14
Central chiller/gas	4.6	1.000	1.00
Individual AC/electric	27.9	3.220	0.31
	Cooling consumption per Sq. Ft. (KJ)	% change from base	
2020 Base case	7,634	–	
2020 Low forecast	8,312	8.9	
2020 High forecast	11,038	44.6	
% of north new education building stock that Providence RI represents		36.7	
Cumulative new education building stock in north 2005–2020 (billion Sq. Ft.)		3.42	
Consumption for new education buildings in the north represented by Providence RI (TBtu)	Total cooling (PJ)	Change from base (PJ)	
Base	9.59	–	
2020 Low	10.45	0.85	
2020 High	13.87	4.28	

Seasonal Coefficient of Performance (SCOP), and the cooling energy required to address the cooling loads in Table A.2. Cooling equipment with a COP of 3.5 is able to remove 3.5 kWh of heat for every kWh of electricity consumed. SCOP is the COP averaged over the cooling season. These ratios are stated directly for heat pumps and are translated from energy efficiency ratios (EERs) for the other types of cooling equipment. The inverse of COP is, in effect, the amount of energy consumed per unit of cooling, and the lower the efficiency (lower the COP), the more energy that is required to address a given cooling load. The increase in the weighted average cooling energy requirement per square foot in new education buildings in Table A.3 is non-linear. For example, the low temperature increase of about 0.6°C results in an 8.9% increase in cooling energy consumption or 14.8% (and 1,130 KJ) per 1°C over the base case, while at 2.5°C in the high temperature case the increase in cooling is 44.6%, or 17.8% (4,415 KJ) per 1°C. Finally, since the climate and load estimates from Providence are used in FEDS and BEAMS to represent 36.7% of the new education building stock in the North,[5] the square footage energy use rates calculated for Providence are multiplied by the estimated 2020 stock of new education buildings in the North times the 36.7% represented by Providence to obtain an overall estimate of cooling energy requirements at the expected energy efficiencies prevailing in the year 2020 in new education buildings in New England and the Mid-Atlantic region. To this must be added the impacts in portions of the 2020 building stock represented by other locations.

Table A.4 shows the impact of a specific DOE program (Electrochromic Windows) on cooling energy consumption in the context of the climate warming in 2020 in new education buildings in New England and the Mid-Atlantic region (represented by Providence, Rhode Island). As with all of the programs, the specifics of the program were estimated in a previous project via a dialog process with the responsible DOE project managers. Project managers articulate a market segment target, the market penetration rate, and technical performance goals for their programs, modified by technical peer reviews and technical studies to assess the feasibility of the program's goals. The goals, thus, are not 'maximum technical performance' or 'maximum market penetration,' but expected based on these market and technical assumptions. The performance target of the Electrochromic Windows program in 2005 was to reduce unwanted heat gains and losses and perimeter lighting by replacing conventional double-glazed, low-emissivity windows currently in the marketplace. The overall market was assumed to be both new and commercial buildings. Market introduction was projected to begin in 2010, and the program was projected to accelerate market introduction of the technology by 10 years (relative to normal private industry market introduction). Based on simulations of energy performance of the building shell in the FEDS model, Release 5.0, these windows were expected to average a specific performance target of 38.54% reduction in cooling in new education buildings in the North. The program managers projected market penetration by the year 2020 to be about 20% of new sales for commercial buildings.

To actually perform the program savings calculations for new education buildings required two steps, as follows.

1. Apply the market penetration rate in each year from 2005 to 2020 times the new units sold in that year and accumulate the resulting number of new units with electrochromic windows from 2005 to 2020. That would give us the total and percentage of new education buildings in the North in 2020 that would have electrochromic windows. That figure, multiplied by 36.7%, would equal the number of new education buildings in New England and the Mid-Atlantic region (represented by Providence, RI).
2. To calculate program savings for new education buildings represented by Providence, RI, we take baseline, low, temperature, and high temperature total cooling energy consumption without electrochromic windows from Table A.3 and multiply times the weighted average savings weight as follows: (Percent of 2005–2020 new cumulative stock with electrochromic windows $\times$ 38.54% savings + percent of 2005–2020 new cumulative stock without electrochromic

[5] The North is climate zones 1 through 3 (i.e., zones with >4,000 heating-degree days) as defined for the Energy Information Administration's Commercial Buildings Energy Consumption Survey. It is roughly the region encompassed by the following Census Divisions: New England, Mid-Atlantic, East North Central, West North Central, Mountain (minus southern New Mexico and Arizona) and Pacific (minus most of California).

Table A.4 Calculation of cooling energy savings from electrochromic windows, northern new education buildings represented by Providence, RI

Year	New education buildings, north	Cumulative new education buildings, north	Penetration into new sales (%)	Number with electrochromic windows (billion sq. ft.)	Number without electrochromic windows (billion sq. ft.)	Cumulative percent with electro-chromic windows (%)	Cumulative Savings (%)
2005	0.25	0.25	0.000	0.000	0.250	0.00	0.00
2006	0.24	0.49	0.000	0.000	0.490	0.00	0.00
2007	0.24	0.73	0.000	0.000	0.730	0.00	0.00
2008	0.23	0.96	0.000	0.000	0.960	0.00	0.00
2009	0.22	1.18	0.000	0.000	1.180	0.00	0.00
2010	0.22	1.40	0.477	0.001	1.399	0.07	0.03
2011	0.22	1.62	1.110	0.003	1.617	0.22	0.08
2012	0.21	1.83	1.943	0.008	1.822	0.41	0.16
2013	0.21	2.04	3.023	0.014	2.026	0.68	0.26
2014	0.21	2.25	4.404	0.023	2.227	1.03	0.40
2015	0.20	2.45	6.133	0.035	2.415	1.45	0.56
2016	0.20	2.65	8.244	0.052	2.598	1.96	0.76
2017	0.20	2.85	10.744	0.073	2.777	2.58	0.99
2018	0.19	3.05	13.599	0.099	2.951	3.25	1.25
2019	0.19	3.23	16.726	0.131	3.099	4.06	1.56
2020	0.18	3.42	20.000	0.167	3.253	4.88	1.88

Impact of Electrochromic Windows on Consumption of Cooling Energy for New Education Buildings in the North Represented by Providence RI (PJ)

	Original Consumption (PJ)	Savings (PJ)
Base	9.59	0.18
2020 Low	10.45	0.20
2020 High	13.87	0.26

windows × 0 savings) × total cooling energy consumption in new education buildings represented by Providence, RI.

As shown in Table A.4, the increase in temperature increases the cooling energy savings associated with a program like Electrochromic Windows. At the same time, warmer winters reduce the need for heating and reduce the heating energy savings. However, even though the change in energy consumption for heat due to climate in new Providence education buildings is three times larger than is the change in cooling energy consumption, the percentage energy savings from electrochromic windows is seven times larger (38.54%) for cooling than for heating (4.9%). On balance, electrochromic windows save more energy under a warmer climate than under a baseline climate in 2020 in new Northern education buildings represented by Providence, R.I. However, when all the energy efficiency programs are taken together, with all types of buildings and all U.S. baseline climates, the opposite is true. The energy programs in aggregate save more energy in the 2020 baseline climate than if the climate were to get warmer. Even so, as stated in the main text, the energy efficiency programs still offset some of the impact of climate warming and therefore have adaptive value.

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