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Prioritizing Investment in Residential Energy Efficiency and Renewable Energy: A Case Study for the U.S. Midwest

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Research Highlights

- Macro-scale estimates of building energy efficiency measures are not adequate for implementing policy decisions
- Measures taken to implement building energy efficiency upgrades will likely encounter practical limits given the existing building stock
- Energy efficiency measures combined with increases in renewable energy use will be necessary for climate change mitigation
- Regional and local variations in building energy use must be taken into account in energy and climate policy

Prioritizing Investment in Residential Energy Efficiency and Renewable Energy – A Case Study for the US Midwest

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Abstract

Residential building energy use is an important contributor to greenhouse gas emissions and in the United States represents about 20% of total energy consumption. A number of previous macro-scale studies of residential energy consumption and energy-efficiency improvements are mainly concerned with national or international aggregate potential savings. In this paper we look into the details of how a collection of specific homes in one region might reduce energy consumption and carbon emissions, with particular attention given to some practical limits to what can be achieved by upgrading the existing residential building stock. Using a simple model of residential, single-family home construction characteristics, estimates are made for the efficacy of i) changes to behavioral patterns that do not involve building shell modifications; ii) straightforward air-infiltration mitigation measures, and iii) insulation measures. We derive estimates of net lifetime savings resulting from these measures, in terms of energy, carbon emissions and dollars. This study points out explicitly the importance of local and regional patterns in decision-making about what fraction of necessary regional or national emissions reduction might be accomplished through energy-efficiency measures and how much might need to concentrate more heavily on renewable or other carbon-free sources of energy.

Keywords: Energy efficiency; residential buildings; greenhouse gas emissions

I. Introduction

Cost-effective, efficient paths toward lowering emissions of carbon dioxide and other greenhouse gases (GHG) are needed across all sectors of the economy, both in the United States and around the world. The latest assessment report by the Intergovernmental Panel on Climate Change leaves little doubt that climate-change mitigation is necessary and technologically feasible at reasonable costs (Solomon et al. 2007; Metz et al. 2007). Since buildings in the United States represent approximately 40% of primary energy use, with residential home energy use representing about half that amount, finding ways to reduce carbon dioxide emissions resulting from home energy use is critically needed. Several macro-level studies have previously looked at this sector (Koomey et al. 1998; Koomey et al. 2001; Granade et al. 2009)

Furthermore, and adding impetus to the effort, there has been a steady increase in energy prices paid by homeowners over the past decade, and especially within the past few years. The steady increase in energy prices has also been punctuated by sudden spikes, most notably in the price of natural gas in 2000-2001 and in oil around 2008. As examples, the average annual price of natural gas in the 1980s and 1990s for U.S. consumers was approximately $8/mmBtu (million British thermal units, approximately 10^9 J), whereas during 2006-2008 the price was approximately $13/mmBtu (both in constant 2006 dollars) (Energy Information Administration 2009; U.S. Dept. of Energy 2009) . Likewise, winter home heating oil prices in the U.S. during most of the 1990s were generally around $1.30/gal, compared to $2.50-$3.50/gal during the 2006-2008 period. U.S. Electricity prices have remained more stable over time, falling slightly (in real terms) through the 1980s and 1990s, and rising again more recently, with an overall average of $0.10 - $0.11/kWh cost for the consumer. Similar patterns have been seen worldwide. There are many reasons why fossil fuel energy prices have been so volatile in the recent past. Supply-side bottlenecks in oil production, whether due to fundamental constraints or to lacking infrastructure investment, have certainly played a role. In addition, increasing demand for energy from developing countries has placed pressure on supplies of all fossil fuel and raw materials. (International Energy Agency 2009; International Energy Agency 2010) As a consequence of the financial crisis starting in 2008, economic activity, and therefore demand, declined significantly in industrialized countries, relieving price pressure temporarily. The important point here is that the combination of higher prices and increased volatility is an important motivating factor for consumers to become more efficient in their use of energy, or to consider adoption of renewable energy technologies.

Additional grounds for changing residential energy consumption patterns include macroeconomic and energy security concerns. To the extent that oil is used for heating homes (mainly in the northeast part of the U.S.), the large and growing dependence on foreign sources of oil in the US is untenable in the long term. Even nearby and reliable energy-trading partners such as Canada and Mexico are having their own difficulties with maintaining or increasing oil supplies. Finally, there is a growing realization that many jobs could be created in association with increased attention to home energy-efficiency retrofitting and renewable energy installation and maintenance, thereby helping alleviate macroeconomic pressures. (Cleetus, Clemmer, and Friedman 2009)

Which of the driving factors discussed above is taken to be most important will have an effect on strategies used to reduce building energy use, and should be considered for policies put in place to achieve that goal. In the current paper we start with a macro-scale view of residential energy consumption in the United States at the national, regional and local levels. We analyze detailed aggregate energy consumption data for one town and make comparisons to energy consumption patterns for the census region, as made available through the Department of Energy. With these data as a starting point, we describe both a simple model for residential housing that allows estimates to be made for the level of energy reductions available to the existing building stock. We examine several scenarios for home energy-efficiency improvements, and how these reductions compare to current national energy and climate policy targets. Using previously published reports, some economic estimates are made of costs and benefits of energy efficiency retrofits on an aggregate basis.

In the context of climate mitigation policy it is not the consumption of energy *per se* that is problematic, but rather the combustion of fossil fuels and concomitant release of carbon dioxide into the atmosphere (and from there to the oceans) that must be avoided to the extent possible. Therefore, renewable energy sources with low-to-zero carbon emissions can and will play a role in helping dramatically reduce residential carbon dioxide emissions. The extent to which homes can be made more energy efficient will also determine the savings to consumers, whatever the source of energy used in the home. Potential tradeoffs between energy savings, economic savings and greenhouse gas emission reductions must be recognized and explicitly factored into policy decisions to avoid promotion of economically inefficient actions. These points will be addressed in our conclusions.

One further effect should be kept in mind. Current projections for climate change in the region depend greatly on the GHG emissions pathway followed over the course of the next few decades. A general trend to model projections is that winter temperatures will rise, thus reducing the need for heating fuels, primarily natural gas, but that increases in summer temperature extremes will tend to lead to more demand for air conditioning, currently powered to a large extent by coal-fired electricity. The net effect, all else being equal, would likely be an increase in GHG emissions under such a scenario, mainly due to increased demand for electricity used for cooling buildings. (CCSP 2007) Although important as part of a long-term view of energy use and climate policy, both here and worldwide, consideration of these climate feedbacks on building energy use will not be pursued in this paper.

II. U.S. Energy Use and CO_2 Emissions Patterns

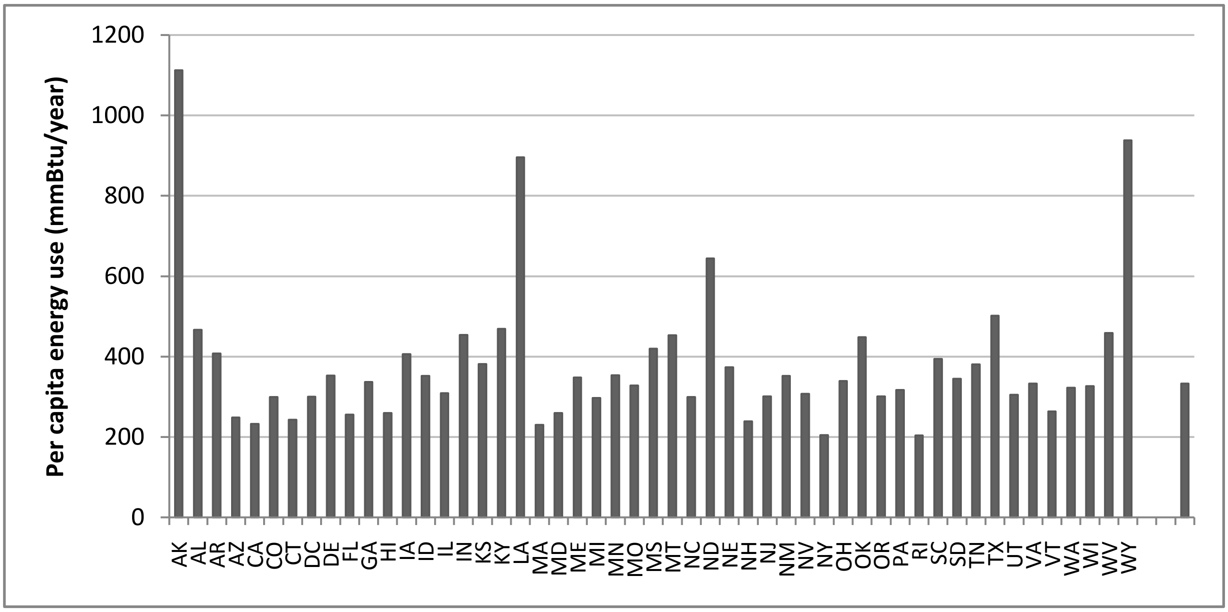


Figure 1 - Per capita total energy consumption per year for all states, and for the US as a whole. The last bar on the right represents the average for the country. 1000 mmBtu = 1054 GJ (Data from U.S. Energy Information Administration)

We begin with a brief comparison of energy use and emissions patterns for different areas of the United States.(EIA 2010a) Both energy use and CO_2 emissions vary widely from one state to another. Fig. 1 demonstrates a difference by more than a factor of five in per capita energy use between the highest and lowest consumption states. Per capita CO_2 emissions also show a large range between lowest and highest emissions, as shown in Fig. 2. An important issue that has not yet been addressed in initial energy and climate policy discussions is that of parity across state, regional and even local areas. Thus far it has been difficult enough to reach a national consensus on the necessity of a goal for reducing carbon emissions, especially to levels low enough to have a strong likelihood of mitigating climate damages in the future. Looking at the results shown in Fig. 2, it becomes clear that a simple statement of national emissions reductions must also be linked to policy for differentiating between already existing emissions levels. Will we require a citizen of California or Idaho to make 80% reductions in the next half century, although their current emissions are only ¼ of Indiana or Wyoming's per capita emissions? It is also true that combinations of electricity sources and personal behavior already make a large difference in carbon emissions. For example, per capita CO_2 emissions from electricity are eight times larger in Ohio than in California; a factor of nearly two comes from consumption differences, and the rest from the electricity generation mix. Again, climate policy in particular must take into account these widely varying regional differences. The same point can be made with respect to carbon dioxide emissions for residential space conditioning, as illustrated in Fig. 2. Emissions vary by more than a factor of ten from one state to another. These differences represent a significant barrier to the implementation of a uniform national emissions policy.

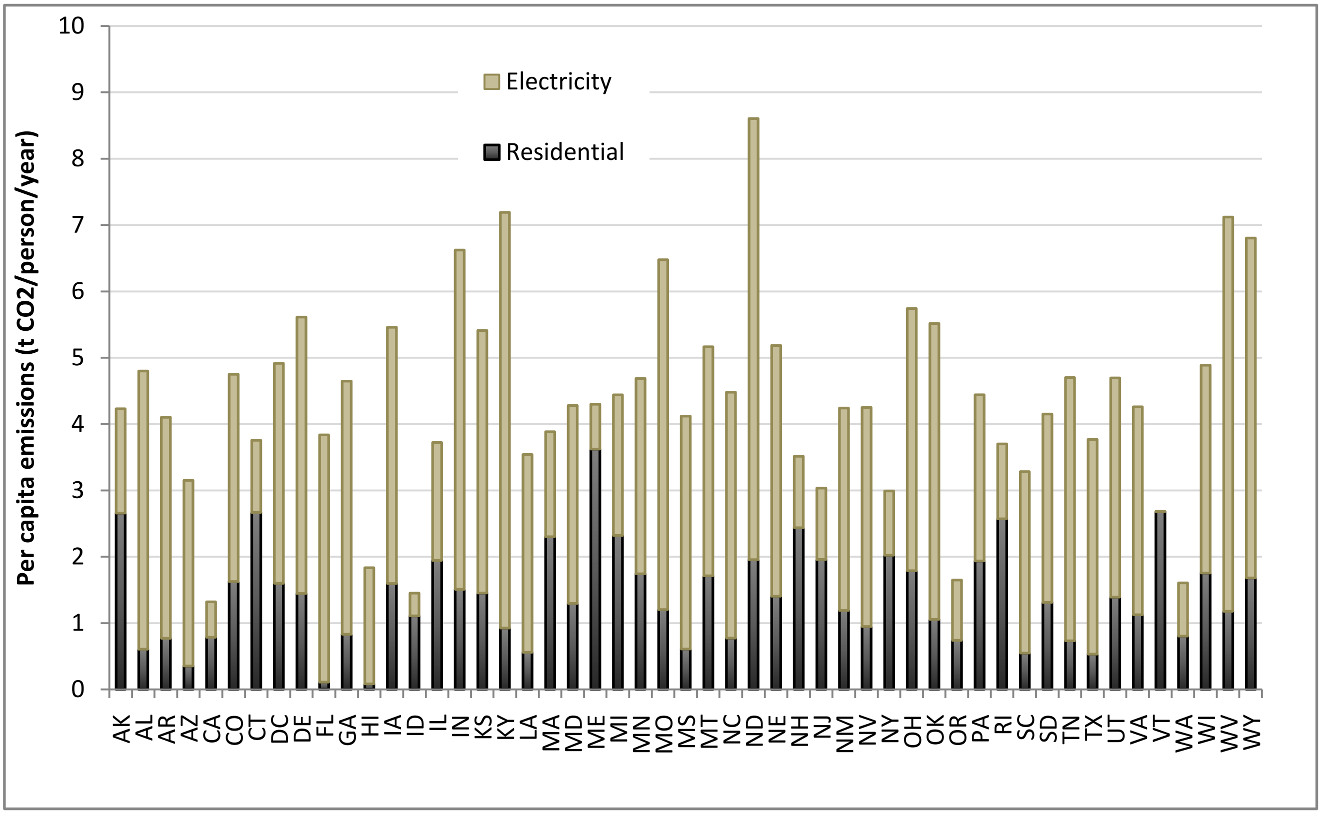


Figure 2 - Per capita carbon dioxide emissions from household electricity consumption and from other residential direct consumption (Data from EIA)

III. Baseline Residential Energy Use Patterns

Next we examine in more detail data for the East North Central Midwest census division, which includes the states Illinois, Indiana, Michigan, Ohio and Wisconsin. Table 1 shows summary data for homes, taken from the U.S. Department of Energy (DoE) Residential Energy Consumption Survey (RECS), a periodic compilation of data for various residential energy use categories. (EIA 2005) Data in Table 1 are broken down into categories relevant for the discussions in the remainder of this paper.

Table 1 - Regional and local energy consumption for electricity and natural gas

	Number of households (Population)	Household electricity use per year	Lighting and appliance electricity use per year	Total natural gas use per year	Heated floor space	Cooled floor space	Water heating
East North Central Midwest	17.7 million (46.0 million)	10479 kWh	7560 kWh (of which, Refrigerators: 1440 kWh)	890 ccf (2600m^3)	1941 sq. ft. (184 m^2)	1269 sq. ft. (120m^2) (90% of homes)	Elec.: 2949 kWh NG: 240 ccf (700m^3)
Yellow Springs, OH	1587 (3761)	8310 kWh	6823 kWh	748 ccf (2180m^3)	1725 sq. ft. (163 m^3)	NA	NA

The U.S. Department of Energy publishes emissions data from various economic sectors, allowing one to generate baseline energy and GHG data. For the five states in the census region, there are again significant differences in emissions from residential electricity and from residential non-electric energy consumption. In Table 2 we summarize relevant data for the five states in the Midwest East North Central census region, including per capita electricity consumption, residential emissions from electricity and non-electric fuels, and total per capita CO_2 emissions. The fraction of total electricity generation for the region consumed by residential customers is 32%, (EIA 2010a; EIA 2005) and the share of total primary energy consumption in the United States that is attributable to residences is 21.7%.

Table 2 - Regional and state carbon dioxide emissions data. Midwest – East North Central census region (all data for 2008)

State	Total, 10^6 metric tonnes CO_2 (per capita, tonnes CO_2)	Residential (non-electric), 10^6 metric tonnes CO_2 (per capita, tonnes CO_2)	Residential Emissions from Electric Power Consumption, 10^6 metric tonnes CO_2 (per capita, tonnes CO_2)	Residential electricity consumption (MWh/capita/yr)	Population (million)
IL	250.4 (19.7)	24.7 (1.95)	22.6 (1.8)	3.7	12.90
IN	237.9 (38.1)	9.4 (1.51)	32.0 (5.1)	5.4	6.42
MI	192.3 (19.0)	23.4 (2.32)	21.4 (2.1)	3.4	9.97
OH	274.0 (23.9)	20.5 (1.79)	45.3 (3.9)	4.7	11.54
WI	112.1 (20.2)	9.7 (1.76)	17.4 (3.1)	4.0	5.66

For this same census region one may also look at the breakout for end-use energy, as shown in Fig. 3. The sections of the pie chart for refrigeration, water heating and other appliances are roughly the same size across different census regions; as should be expected, energy consumption for heating and air conditioning varies greatly across regions, both as a relative proportion of energy use and in absolute terms. Since heating energy is to a large extent natural gas or fuel oil, whereas cooling is universally from electricity, a careful regional analysis is necessary to determine the relative importance of cost, energy and carbon emissions. The guiding question as we proceed is to consider potential reductions in the residential sector that are consistent with proposed climate policy goals.

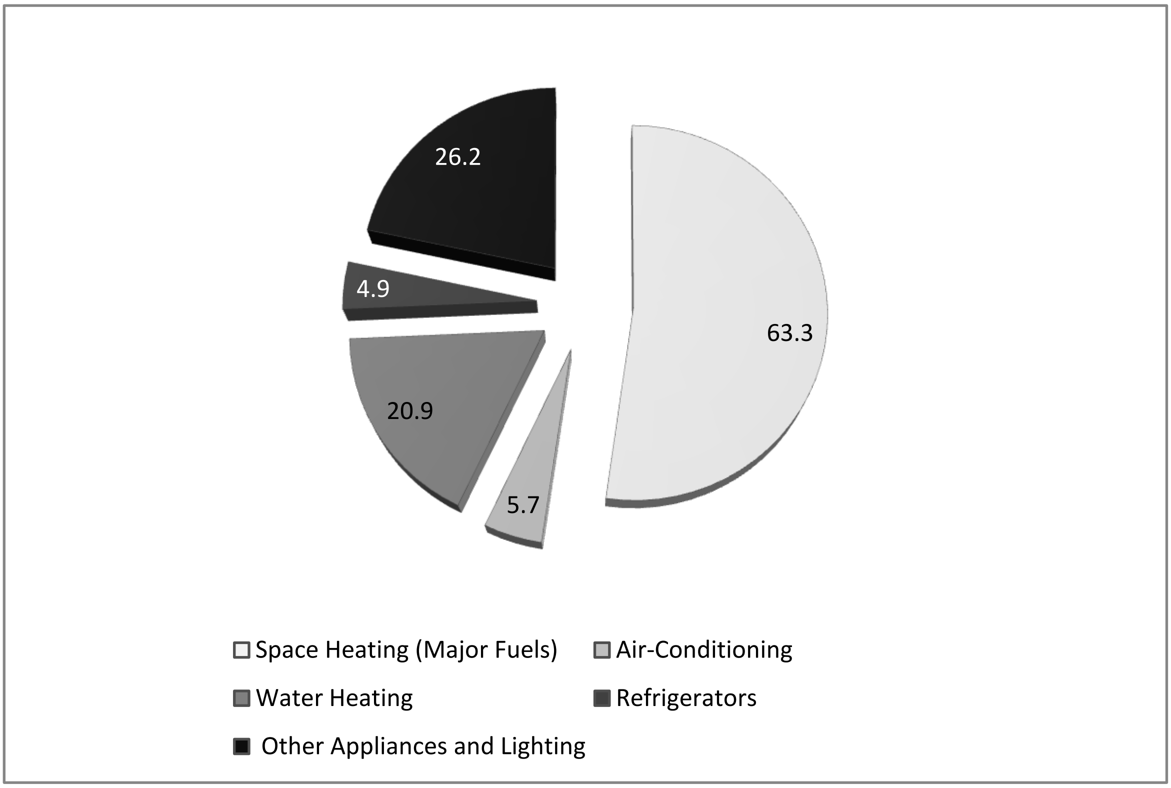


Figure 3 - Breakdown of residential energy consumption for the Midwest West North Central census region. Data given as mmBtu/household/year (approximately GJ/household/year)

IV. Case study – Yellow Springs, Ohio consumption patterns

As we work to become more specific in our analysis, information about energy consumption for one specific location will allow us to go beyond broad regional generalizations. The village of Yellow Springs, Ohio is in a mainly rural area 10 miles from the city of Springfield and 20 miles from Dayton. The village has a population 3761 as of the 2000 census; there are 1587 households, with an average of 2.1 persons per household; 35.9% of households made up of individuals (U.S. Census Bureau 2000). In this work we use aggregate data for both natural gas and electricity consumption over a period of several years to assess local consumption patterns. Results of the analysis of utility data for this one town are discussed in this section, with the aim of pointing out the similarities and substantial differences that can be present in energy and carbon dioxide emissions on a very local scale. We address energy-use patterns first, and treat greenhouse gas emissions separately.

Referring back to Table I, a first look at the aggregate data shows that homes in Yellow Springs, , use somewhat less energy than the regional average, a factor that is at least partly due to the fact that homes in that town are slightly smaller than the regional average and have fewer occupants.

Data for natural gas consumption from 2006 – 2008 were obtained for all residences in the Village, as were data from 2003 – 2008 for electricity consumption. For the electricity data we also had access to address information, and could therefore combine the utility data set with a county property records database so that information about residence square footage was available. Due to some inconsistencies in the formatting of these two databases, a filtering process was used to eliminate apartments and rental rooms, as well as any other residences that could not be matched with county home characteristics data. Also eliminated from consideration were residences where energy data was unavailable for extended periods of time, as these residences were likely vacant for such periods. After the filtering process, 1134 homes remained in the sample, representing 71% of households and a slightly larger fraction of residential electricity consumption. The average size of these residences was 1725 sq. ft. (163 m^2). The large majority of homes are heated primarily with natural gas. For the natural gas database we did not have address information for each property, but were able to determine an upper cut-off for consumption such that industries and commercial operations were excluded. The number of individual entries was 1552; although it will likely tend to overestimate the average area, since some of the additional units are apartments, we take the same average area as above for calculating the energy consumption intensity.

To determine baseline electricity use in Yellow Springs residences the filtered data described above were used along with hourly outdoor temperature data available from the U.S. EPA. The Yellow Springs (Dayton-Springfield) area is located in a humid temperate zone, with approximately 5700 heating degree days (HDD) and 890 cooling degree days (CDD) on a Fahrenheit basis with 65°F reference temperature, or 3170 HDD and 495 CDD on a Celsius basis. Average winter high (low) temperatures are -2°C (-6°C) and average summer high (low) temperatures are 28°C (22°C).

The next step in the process was to normalize electricity use data for each residence by dividing by the square footage. Both the natural gas and electricity consumption over the noted time periods of each data set were analyzed using Energy Explorer software (Raffio et al. 2007), which allows a weather normalization of the energy consumption. In Figs. 4 and 5 we plot energy intensity vs. monthly average temperature for actual natural gas (kBtu/ft^2/mo.) and electricity (kWh/ft^2/mo.) consumption for 2006-2008 and for 2003-2008, respectively. In each case we have divided the data into temperature-dependent and temperature-independent components. Linear regression fits to the data segments have been constructed to force a temperature-independent segment to have zero slope. In addition, we have separated out several data points in the electricity plot which seem to have abnormally high consumption for the corresponding temperature. This will be discussed briefly below.

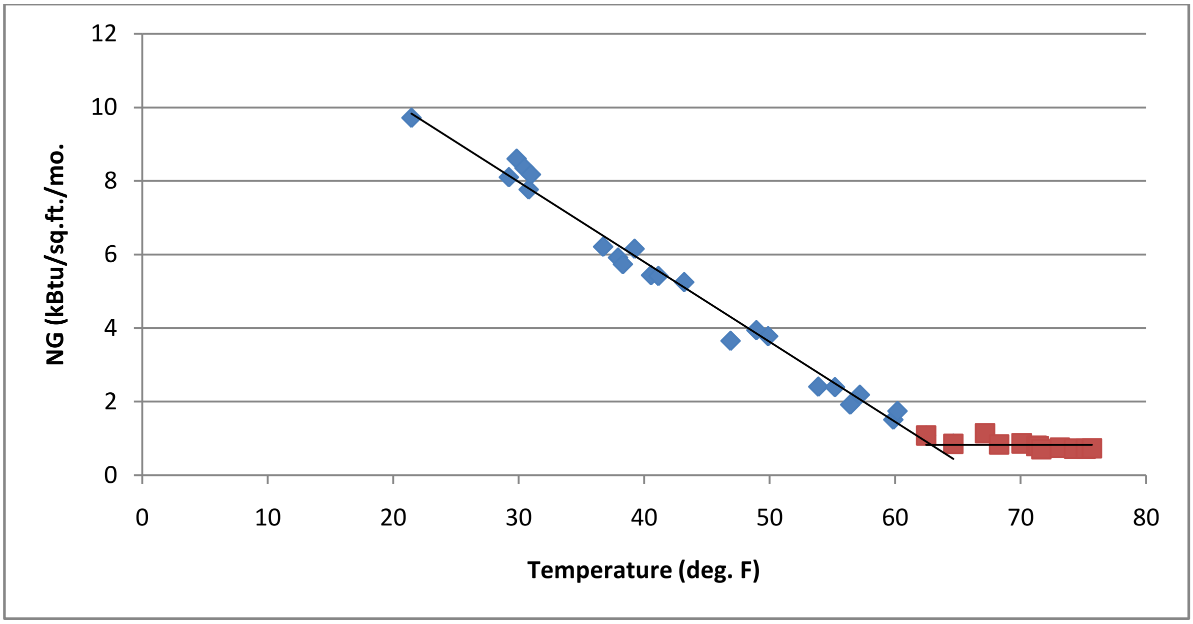


Figure 4 - Natural gas consumption intensity (kBtu/sq.ft./mo.) for the homes in Yellow Springs, plotted as a function of the average temperature over the billing period. (1 kBtu/sq.ft. = 11.1 MJ/m^2)

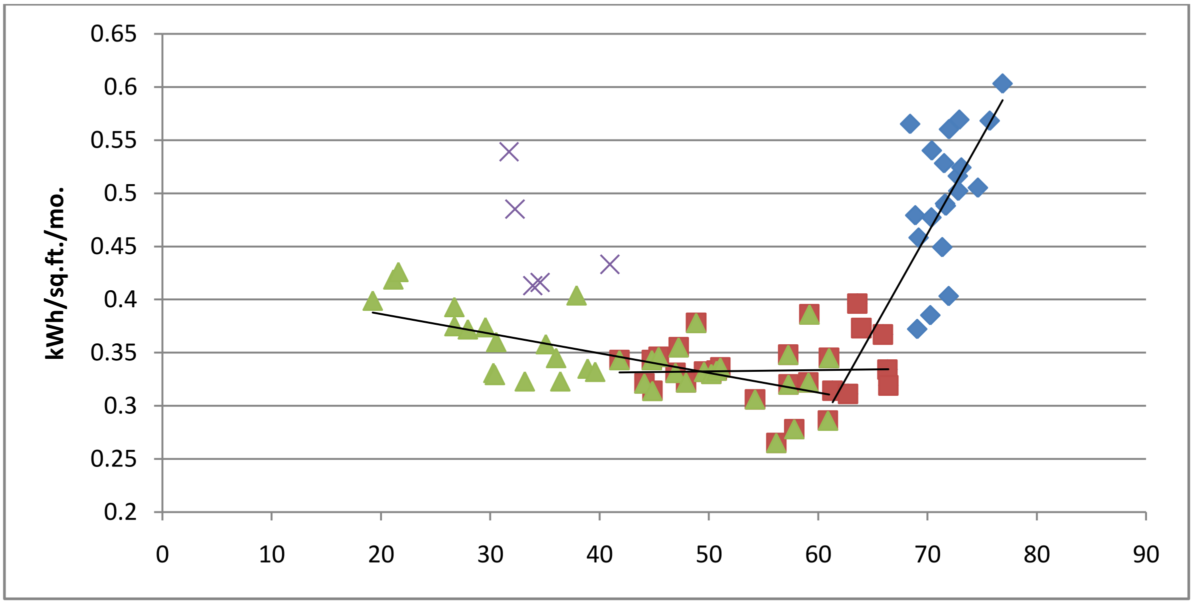


Figure 5- Electricity consumption intensity (kWh/sq.ft./mo.) for the homes in Yellow Springs, plotted as a function of the average temperature over the billing period. (1 kWh/sq.ft. = 10.6 kWh/m^2)

Looking first at the natural gas consumption, Fig. 4, we find a baseline value of 0.83 kBtu/sq. ft.-mo., (13.9 ccf or 1.5 GJ per home per month). The slope of the natural gas plot, the heating slope (HS), -0.22 (±0.01) kBtu/sq.ft.-mo.-ºF (R^2 = 0.986) is comparable to that for a typical regional house as will be discussed in Section V. Turning to the plot of residential electricity consumption in Fig. 5, we find a cooling slope (CS) of 0.018 (±0.003) kWh/sq.ft.-mo.-ºF (0.36 kWh/m^2-°C) (R^2 = 0.644) , again very close to that of a typical regional house in our model to be presented below. Energy independent consumption is 0.33 kWh/sq.ft.-mo (3.5 kWh/m^2-mo.). In addition, we find that there is a significant heating slope (HS) for electricity as well, -0.0019 (±0.0004) kWh/sq.ft.-mo.-ºF (-0.036 kWh/m^2-mo.-°C)(R^2 = 0.384).

Histograms of baseline (i.e. weather-independent) electricity consumption are shown in Figs. 6a and 6b, where 6a is the histogram for to the total baseline energy and 6b is that normalized by home square footage. It is clear that normalizing the electricity consumption data on a square-foot basis allows one to make a more accurate comparison; from the histograms in Fig. 6, the expected effect of the normalization is to significantly narrow the distribution. Knowing this information is important as one piece of input to pursuing an effective strategy toward implementing a strategy for reducing overall energy consumption, especially when viewed on an energy intensity basis. Examining the reasons for consumption at the high-energy tails of the distribution will help identify those residences for which the largest reductions may be possible. A strategic application of energy policy should ultimately prioritize these high energy-intensity users first.

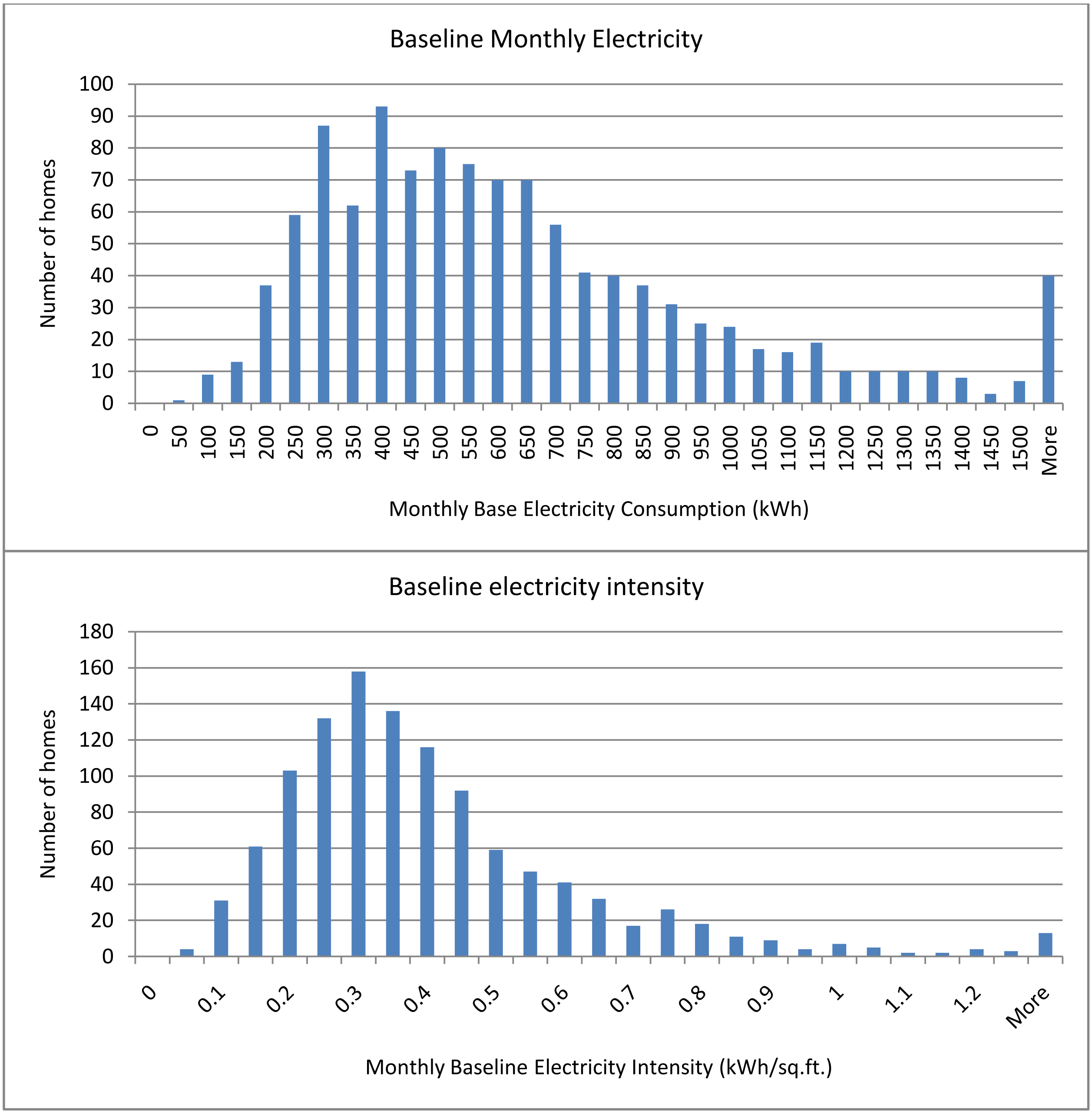


Figure 6 - In a) we plot a histogram of homes vs. average monthly baseline, or weather-independent, electricity consumption, and in b), the same data as intensities on a square foot basis. (1 kWh/sq.ft. = 10.6 kWh/m^2)

The heating and cooling slopes, as well as the baseline energy use, NG_{ind} and $Elec_{\text{ind}}$ are essential comparison parameters for the residential energy model developed for the typical

Yellow Springs home. The heating and cooling slopes can be related to building envelope characteristics and heating / cooling equipment efficiency according to the following relations:

$$HS = \frac{UA_{overall}}{\eta} \text{ and } CS = \frac{UA_{overall}}{\kappa}$$

where $UA_{overall}$ is the overall heat transfer coefficient for the residence, effectively characterizing the heat loss/gain through the building envelope and via infiltration, η is the efficiency of the heating system, and SEER is the seasonally adjusted energy efficiency for the air conditioning system. The fits shown in Figs. 4 and 5 determine the heating slope, *HS*, and independent natural gas energy use, NG_{ind}, as well as the cooling slope, *CS*, and independent electrical energy use, $Elec_{\text{ind}}$, and the balance point temperatures, $T_{bal,h}$ and $T_{bal,c}$ (i.e., the average monthly temperatures at which heating and cooling is initiated by the user). These values will in turn be used to compare the average annual natural gas and electrical energy for the 'typical' Yellow Springs residence on a square foot normalized basis with data for the region, as well as with model results discussed below. The heating degree hours, *HDH*, and cooling degree hours, *CDH*, (both in °F) are determined for the Yellow Springs area via the following curve fits based upon typical weather data.

$$\text{HDH} = 54963 - 3464.7 * T_b + 74.973 * T_b^2$$

$$\text{CDH} = 499358 - 12224.9 * T_b + 74.97396 * T_b^2$$

Given the heating and/or cooling slope (HS and CS, respectively) , the calculated heating and cooling degree hours, and the independent energy use, the total annual energy consumption can be calculated from

$$NG = HS \times HDH + NG_{ind}\ [mmBtu/year]$$

$$Elec = CS \times CDH + Elec_{ind}\ \ [kWh/year]$$

where natural gas (*NG*) and electricity (*Elec*) annual consumption are given by the sum of temperature-independent contributions (NG_{ind} and $Elec_{ind}$, respectively) and temperature-dependent pieces. The temperature-dependent contribution is found from the product of the heating (cooling) slope, HS (CS), in units of mmBtu/hr-°F (kWh/ hr-°F) and the number of heating (cooling) degree hours, HDH (CDH).

Two additional features are present in the electricity data that appear to deviate from our simple house model. First, there is an appreciable slope as a function of decreasing temperature (solid triangles in the plot) that we ascribe to the increase in electrical consumption due to heat pumps, some electrical heating, and furnace fans. Contributions from increased lighting use in the darker winter months are likely negligible to the level of uncertainty in these data, since lighting typically represents less than 10% of household electricity consumption. (Energy Information Administration) The exact nature of consumption for heating is challenging to separate out of the data; work in this direction will be reported elsewhere. The second feature in these data is a set of points, (X-symbol in the plot) that do not follow the linear trend of other points. A closer examination of these points in the raw data set reveals that each one represents the electricity consumption for period that spans December and January in a given year, and furthermore, that every December data point deviates from the rest of the temperature data. We postulate that these “anomalous” data represent the effect of the winter holidays, with (apparently) significant extra lighting and perhaps baking as well.

V. House Model

Having extracted the weather-dependent and weather-independent energy use for both natural gas and electrical energy for Yellow Springs, we are now poised to estimate energy and GHG reduction potential for various residential energy reduction measures. We construct a simple energy model of the typical home that reproduces equivalent weather independent and dependent energy use as observed from the collective data. With such a model developed, the effect of the various energy reduction measures can be assessed.

The model (available from the authors upon request) is a simple format for changing parameters to match characteristics of existing homes, as well as for evaluating the potential changes to individual residential building components. Inputs to the model are i) physical dimensions for the footprint, wall and window sizes and shape of the dwelling; ii) R-values for wall, slab/foundation, window, and ceiling insulation; iii) separate parameters for infiltration and for duct leakage and loss; iv) efficiencies for HVAC equipment; v) set-point temperatures for heating and cooling; vi) electricity consumption; and vii) natural gas consumption for domestic hot water. The output of the model separates energy consumption into weather-dependent (heating and cooling) and weather-independent components and calculates heating and cooling slopes, total energy consumption based on heating-degree-hours per year, and of balance-point temperatures. None of these features is novel, but this implementation allows one to easily compare data and the effects of upgrades to a standard typical home.

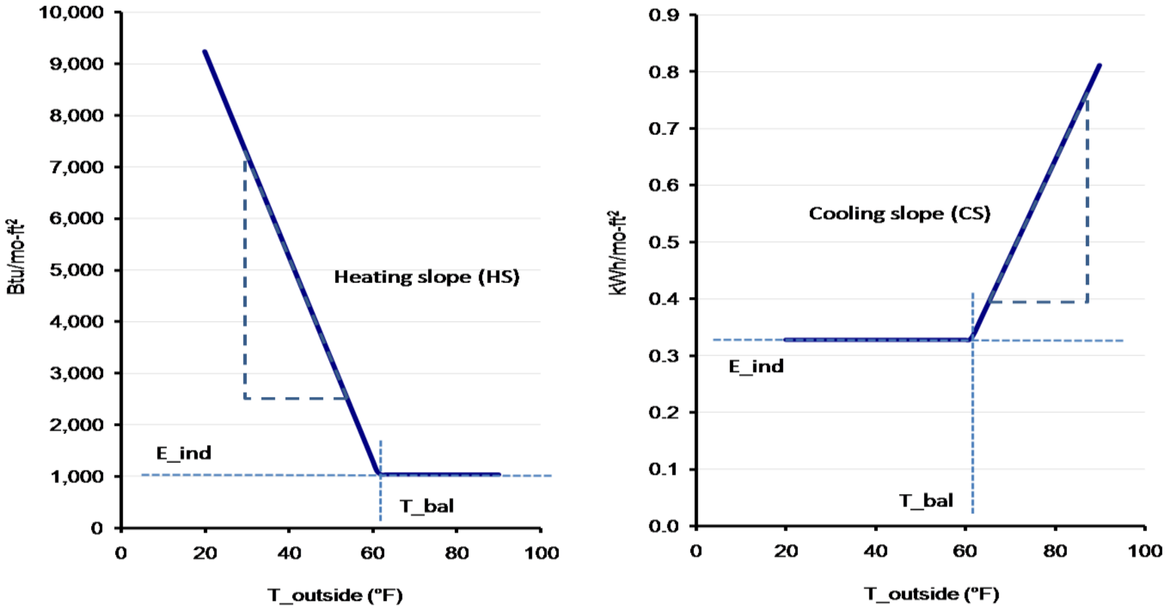
The main output quantities of interest are the heating- and cooling-slope. The former is calculated from

$$HS = \frac{UA_{Tot}}{\eta(1-\xi)} \quad \left[\frac{\text{Btu}}{\text{hr-°F}}\right]$$

where $UA_{Tot} = \sum_i U_i A_i$, as defined in Sec. IV; η is the efficiency of the heating equipment, and ξ is the duct-leakage and loss fraction. This quantity can then easily be put on a monthly and square-foot basis. The balance point temperature is calculated from $T_{bal} = T_{set} - \frac{Q_{int}}{UA_{tot}}$, where Q_{int} represents internal heat gains and T_{set} is the desired temperature set point. The total temperature dependent natural gas consumption is the product HS × HDH. Analogous relations are used to calculate the temperature-dependent electricity consumption (energy for cooling), with the cooling slope given by

$$CS = \frac{UA_{Tot}}{\kappa(1-\xi)} \quad \left[\frac{W}{°\mathrm{F}}\right]$$

where κ is the SEER rating for the air conditioner, and the mixed units of are simply easier to use with electrical energy units of kWh. With these calculated quantities, one can then generate plots of energy use vs. temperature, as shown in Fig. 7



a) b)

Figure 7 – Schematic example of output from spreadsheet house model. a) Monthly natural gas consumption as a function of temperature, normalized to area. b) Monthly electricity consumption as a function of temperature, normalized to area. The slopes provide a relative measure of energy efficiency, in the sense that a higher slope corresponds to either a lower equipment efficiency or to a larger thermal transfer.

VI. Results for estimated potential savings

Table 3 summarizes the parameters used for the model houses. The Baseline Characteristic scenario represents the home energy model which yields equivalent normalized energy consumption as obtained from the actual Yellow Springs energy data. For comparison, parameters are shown corresponding to standards for typical new construction. Since we are mainly interested in retrofits to existing homes four scenarios are considered: Behavior, Sealing Leaks, Sealing Leaks + Attic, and Deep Retrofit. The "Behavior" case is based on the assumption that there are a few straightforward measures that can be taken by a homeowner; it is clear, however, that there are many obstacles to effective acceptance and implementation of such measures (Dietz et al. 2009) and it is often not clear which measures and strategies are most effective (Guerin, Yust, and Coopet 2000). These encompass a 20% reduction in water heating fuel use and a 20% reduction in electricity use for appliances and lighting, consistent with the estimates of relative energy savings made by Dietz, et al. In addition, it is assumed that set point temperatures in the winter and summer are lowered and raised by 3°F and 4°F (1.7°C and 2.2°C), respectively, as well as 8-hour long, 8°F (4.5°C) setbacks during night and day, respectively. The Sealing Leaks scenario considers the impact of sealing ducts and reducing overall infiltration to the home. For this case we reduce duct losses from 10% to 0%, and air infiltration from 0.6 ACHn (Air Changes per Hour, natural) to 0.30 ACHn. The baseline value for infiltration was chosen partially because of the resulting consistency between the representative house model and the aggregate energy consumption, and partially because the experience of the authors in performing home energy audits shows that the 0.6 ACHn value is at the peak of the distribution of actual home leakage rates. The same distribution shows few homes with infiltration lower than 0.3 ACHn, and we choose this value as the target for improvements. In principle, infiltration could be reduced even further, but at additional cost, and more importantly, at the expense of needing additional equipment to ensure proper fresh air amounts for inhabitants. The Sealing Leaks + Attic scenario considers the impact of sealing and also the impact of maximizing attic insulation. We also present the combined effects of Behavior + Sealing Leaks. The Deep Retrofit scenario, to be discussed separately, considers the impact of maximal reduction in leakage, maximal insulation of the attic, floor, doors, and walls, upgrade of windows to the best technology available, and upgrade of the heating and cooling equipment to the best efficiency and coefficient of performance available.

Obviously we are making one set of choices as to which measures to consider. Another possibility would be to look at the impact of simply changing the window R-value, or of increasing the wall R-value. In the interest of being able to present a few case studies, we have limited our choices

Table 3 – Parameters used to describe houses in different cases. (Unit conversion: R – 10 ft^2-°F-h/Btu = 1.76 K-m^2/W)

	Baseline Characteristic	New Construction	Behavior	Sealing leaks	Sealing leaks + attic	Behavior + Sealing leaks	Deep Retrofit Characteristic
Windows	R – 2	R – 3	R – 2	R – 2	R – 2	R – 2	R-10
Doors	R – 2	R – 3	R – 2	R – 2	R – 2	R – 2	R - 3
Walls	R – 13	R – 15	R – 13	R – 13	R – 13	R – 13	R – 35
Floor	R – 17	R – 19	R – 17	R – 17	R – 17	R – 17	R – 20
Ceiling	R – 24	R – 30	R – 24	R – 24	R – 40	R – 24	R – 60
Heating equipment (natural gas assumed)	0.85	0.90	0.85	0.85	0.85	0.85	0.96
Cooling Equipment (SEER)	7	13	7	7	7	7	18
Set point	68°F, 68°F (20°C, 20°C)	68°F, 68°F (20°C, 20°C)	65°F, 72°F (18.3°C, 22.2°C)	68°F, 68°F (20°C, 20°C)	68°F, 68°F (20°C, 20°C)	65°F, 72°F (18.3°C, 22.2°C)	65°F, 74°F (18.3°C, 23.3°C)
Set back	2°F, 8 hrs.; none	2°F, 8 hrs.; none	8°F, 8 hrs.	2°F, 8 hrs.; none	2°F, 8 hrs.; none	8°F, 8 hrs.	8°F, 8 hrs.
Electricity use	0.52 W/sq.ft.	0.52	0.40	0.52	0.52	0.40	0.2
NG baseline	24 mmBtu/yr	24	19.2	24	24	19.2	12
Air leakage (ACHn)	0.6	0.3	0.6	0.3	0.3	0.3	0.05
Duct leakage	10%	5%	10%	0%	0%	0%	0%

Table 4 gives the results extracted from the spreadsheet model for different energy reduction scenarios considered. The table is divided into sections for natural gas and electricity consumption characteristics, as well as a section for carbon dioxide emissions reductions. For both natural gas and electricity, consumption is divided into weather-independent and weather-dependent contributions, as well as a total consumption given both as an absolute value and as intensity (energy per square foot). Carbon emission reductions are calculated based on a typical mix of electricity generation for the region, and on emissions factors for natural gas.

To summarize the results in Table 4, the respective percentage natural gas, electricity and greenhouse gas reductions for the various cases considered are as follows: (Behavior: 13%/26%/21% ; Sealing Leaks: 20%/2%/9% ; Leaks + Insulation: 28%/3%/13% ; Behavior + Leaks: 33%/27%/29%; Heavy Retrofit: 74% / 49%/ 59%). While the Behavior improvement model predicts modest energy reduction, these are achievable with little to no investment, to the extent that they can be achieved with some combination of compact fluorescent light bulbs, thermostat set-point choices, changing habits with regard to phantom loads, and reduced hot water energy consumption by using low-flow shower heads and turning down water heater temperatures. On the other hand, many of these same low-cost energy savings options are associated with a relatively low behavioral plasticity (Dietz et al. 2009), meaning effectively that it is difficult to effect change. Constructing effective policies to achieve these energy conservation measures will likely be challenging; barriers to increasing energy efficiency is one of the main themes addressed in the McKinsey report (Granade et al. 2009).

Table 4 - Model home summary data

Home	Typical Regional Home	New Cons-truction	Behavior	Sealing Leaks	Leaks + Attic	Behavior + Sealing Leaks	Heavy Retrofit
Annual Natural Gas Cons.							
NG indep. (mmBtu/yr or GJ/yr)	24.0	24.0	19.2	24.0	24.0	19.2	12.0
NG weather (mmBtu/yr or GJ/yr)	70.9	43.0	63.0	51.9	44.5	44.2	13.1
NG total (mmBtu/yr or GJ/yr)	95	67	82	76	69	63.4	25
Intensity (kBtu/ft^2-yr) (×11.1 for MJ/m^2-yr)	48.9	34.3	42.3	39.1	35.3	32.7	12.9
Levelized cost savings ($/year)	-	-	$110	$165	$228	$272	$603
Net cost savings ($/year)	-	-	$60-$111	$50	$17	$83	($95)
Annual Electricity Use							
E indep. (kWh/yr)	8,850	7,080	7,080	8850	8850	7080	5310
E weather (kWh/yr)	1,679	1,190	721	1450	1414	617	87
E total (kWh/yr)	10,529	8,270	7,801	10,300	10,264	7697	5397
Intensity (kWh/ft^2-yr) (×10.6 of kWh/m^2-yr)	8.3	4.3	6.2	8.1	8.1	6.1	4.3
Levelized cost savings ($/year)	-	-	$217	$18	$21	$225	$409
Net Cost savings ($/year)	-	-	$180-208	$14	$14	$167	$233
Estimated initial cost of upgrades	-	-	$880	$1190	$2180	$2470	$8700
Carbon dioxide emissions							
CO2 from NG (tonnes)	5.0	3.5	4.3	4.0	3.6	3.4	1.6
CO2 from electricity (tonnes)	7.5	5.9	5.6	7.3	7.3	5.5	3.8
Total CO2 (tonnes)	12.5	9.4	9.9	11.4	10.9	8.9	5.4
Value of saved CO2 emissions ($/year)	-	$78 $156	$65 $131	$30 $59	$40 $80	$90 $180	$178 $356

These results illustrate both the potential and the challenges facing any policy intended to reduce greenhouse gas emissions from the residential housing sector. Taking a “Typical Regional Home” as the baseline we see that emissions are divided 40%/60% between natural gas and electricity. Although we have included in this table data for typical new construction (Energy Star construction is about 15% less than “standard”), it should be clear that one of the great challenges will be the upgrading in energy efficiency for the existing 111 million homes in the US. This is especially apparent given the lack of dramatic improvement between new construction and existing building stock, at least with respect to proposed GHG reduction targets based on climate science criteria. Although the energy intensity for new construction will tend to be somewhat lower than for existing housing, there has been a trend for several decades of houses becoming larger, more than compensating for the lower energy consumption per square foot, as will be discussed below.

To examine the economics of the chosen energy-efficiency measures more closely, we look to a recently published report by McKinsey & Company (Granade et al. 2009), in which information from the EIA and other sources was used to estimate the potential for energy efficiency measures in the residential housing sector, with the key outcome for our purposes being an energy-savings cost-curve. That is, taken over the lifetime of any given measure or technological improvement, a ranked list of measures is created in order of increasing net-present-value cost per unit of end-use energy saved. For example, lighting improvements were found to have a cost of \$3.75/mmBtu saved, equivalent to \$0.013/kWh of electricity. Basement insulation and duct sealing are found to have costs of \$5.00/mmBtu and \$5.40/mmBtu saved, respectively. The key point found in the report is that all of the measures discussed in the first two examples above result in life-cycle costs that are significantly less than the projected cost of the energy that would be purchased if the improvements were not made. Some of the other savings potential falling into this category include upgrades to better HVAC equipment ($12.60/mmBtu), installing programmable thermostats ($4.40/mmBtu), sealing home leaks($8.30/mmBtu), upgrade windows ($8.50/mmBtu), attic insulation ($6.70/mmBtu), blow-in wall cavity insulation ($13.30/mmBtu) new appliances ($4.50/mmBtu), slab insulation ($15.30/mmBtu), electrical devices and small appliances (27% savings at $1.00/mmBtu) and many more.

Using results from the McKinsey report as a starting point, we can calculate net cost savings for the measures described in our examples. To do so, we make some simplifying assumptions. For the “Behavior” case we assume that costs range from zero to $4/mmBtu saved, to get a range of net cost savings between $59 and $111 per year for natural gas and between $202 and $208 per year for electricity. For “Sealing leaks” we use an average cost of $6/mmBtu saved, based on numbers from the McKinsey report, leading to net savings of $111 per year from reduced natural gas consumption and $17 from reducing electricity consumption. Finally, for attic, basement and wall insulation, a figure of $10/mmBtu saved is estimated; in our scenario we do both sealing and insulating and therefore estimate $8/mmBtu levelized cost. The net savings in this case are $197 per year for natural gas and $20 per year for electricity. The question of availability of up-front capital for undertaking energy-efficiency measures is a separate issue that is recognized by the authors of the report, and is an important part of the series of recommendations made in the report.

The cost savings are based on a levelized cost of energy over the time period 2010 – 2020, to maintain consistency with the McKinsey report, using a discount rate of 7%. Energy cost projections are based on the Energy Information Administration’s Annual Energy Outlook, 2010 edition (EIA 2010b). For natural gas costs, we assume a 1.7% per year increase from \$5.00/Mcf to \$6.00/Mcf over the time period from 2010 – 2020, and that home-delivery natural gas prices are twice the wellhead price, which is in line with historical trends. Real electricity costs are assumed to increase at a rate of 1% per year from \$0.095/kWh over the relevant period, consistent with the AEO 2010 reference scenario. These baseline assumptions were tested for sensitivity; changing the cost increase rates to 3% or 5% makes the corresponding efficiency measures more favorable, but does not dramatically change the general conclusions. Likewise, one can experiment with different discount rates (Granade et al. 2009). For higher discount rates the levelized net savings per year decrease, as one would expect, but again, the general conclusions of the model do not change significantly. Even a high, but experientially-based discount rate of 40% serves to decrease the amount of economically-viable savings by only 50%.

The dollar value of the carbon emissions reductions is based on carbon costs of \$25/tonne and \$50/tonne of carbon dioxide, a mid-range value for projected carbon costs over the next few decades. Of course, at present there is no price on carbon dioxide emissions in the U.S., so this number is somewhat speculative.

VII. Further potential energy and greenhouse-gas saving measures

As we take a step back and reexamine these scenarios of increasing energy-efficiency, it seems clear that even fairly aggressive measures to retrofit existing homes will not be adequate to reduce GHG emissions by 80-90% by 2050, the likely amount needed to avoid dangerous anthropogenic climate change. In addition, the measures discussed above apply to any given building, but as population increases in the U.S., more housing will be built, and as already mentioned, trends over the past several decades have been toward larger homes and fewer persons in each home (Wilson and Boehland 2008), leading to an even stronger growth in per capita and total emissions, as will be discussed in more detail in Sec. VIII.

At this point there appears to be a bifurcation of possible efforts that might be considered. First, we can explore the potential for further significant upgrades to existing housing stock. The Department of Energy has proposed standards for new housing that would result in a 70% energy-use reduction in new construction by 2030. However, construction of new homes, even at rates seen before the recent economic recession, and even if all new construction were to these higher standards, could only contribute on the order of 10% to the goal of emissions reductions. If existing homes were retrofitted to this standard, significantly more progress could be made. The second option, after having achieved the efficiency improvements discussed in previous sections, is to transition sources of energy to lower carbon intensity. In practice, to do so will entail mainly changes to sources of electricity, and then perhaps a further transition from natural gas heating to electricity, for example with geothermal heat pumps.

We turn first to the task of further reductions in energy consumption to help meet the housing sector's contribution to more stringent requirements for long-term greenhouse gas reduction scenarios. The measures discussed above are representative of incremental steps that many homeowners might take to reduce energy costs. Considering the residence as a building system, however, it is clear that an ideal energy retrofit would consist of a well-planned set of synergistic upgrades. The first steps based on our model are not linearly additive, i.e., it is not necessarily the case that each individual case can be followed sequentially to compound all of the energy savings. In fact, one point of our analysis is to put concrete numbers, at least in aggregate, on energy efficiency upgrades to typical homes, thus going beyond the mere measure of "\$/mmBtu". It is clear that the actual savings realized by a given home will depend on the starting and ending points, for example of wall or attic insulation, and not only on the amount added.

Our final example based on the spreadsheet model, “Heavy Retrofit” is one example of such an approach. Taking the existing typical house as a baseline, we assume that the air infiltration is cut by 92% to 0.05 ACHn, a value nearly that required of houses meeting the “passive house” standard, and that all ducts are sealed to eliminate leaks. It must be noted that this level of air-sealing is very challenging to implement. Windows are replaced with units having a U-value of 0.1 Btu/ft^2-°F-hr , a furnace efficiency of 96% is assumed, and the insulation in walls and in the ceiling are more than doubled. Essentially, given the existing structure, a new sealed and insulated shell is constructed either inside or outside the current building. It is also assumed that personal behavior changes are undertaken, lowering temperature set points, using less electricity for lighting and other purposes, and cutting water heating energy consumption to one-third of the current average amount. The result of these efforts is a decrease in natural gas consumption by 74% and in electricity consumption by 49%; CO_2 emissions are cut by 59%.

Once again, the McKinsey report provides a range of numbers for various measures that might be incorporated in a heavy retrofit, with a corresponding range of net-savings values. Measures such as new windows, wall sheathing, and refrigerator replacement tend to have net costs of roughly \$7 - \$7.50 per mmBtu saved. New heating equipment and water heaters are more expensive at about \$12 per mmBtu saved. We estimate a cost of \$10/mmBtu savings for the “Heavy Retrofit” case, to arrive at a net savings figure of -\$94 per year for natural gas, and \$230 per year in net savings for electricity, without taking into account the potential price of carbon emissions. That is, overall this case is near the margin for net lifetime savings under the assumptions made here. However, if energy prices escalate more quickly than the model assumptions, the deep retrofit becomes more attractive.

Although we see from this example that the financial incentive is present for undertaking a deep retrofit, at least in principle, the shortcoming in considering this approach is that there are clearly large barriers to overcome in implementing such a program. The parameter changes used in developing this scenario imply essentially taking an existing home, stripping it to a shell and starting again with double-thickness walls, new windows, tight sealing to prevent air infiltration, new HVAC equipment, etc. It is reasonable to assume that only relatively few households are willing at present to commit to this type of retrofit, whether the lifetime financial payback is high or not. As discussed in the McKinsey report, households have very high effective discount rates, perhaps in the range of 40%, meaning that improvements in energy efficiency are typically undertaken only if the payback time is seen to be on the order of two years or less. The results from our model show that the net savings from the deep retrofit case are actually quite small, and the up-front costs will be large. Although the example discussed here does not reach this standard, as a reference point giving an indication that the initial costs here may be optimistically low, recent “deep retrofits” in Yellow Springs attempting to reach the passive house standard have had costs of roughly $50/sq.ft. (Murphy, 2011). On the other hand some of the higher cost measures actually have a much higher behavioral plasticity than those that are simpler and more economically favorable (Dietz et al. 2009).

Although it may be difficult to convince homeowners to make massive changes to the envelope and HVAC systems of their homes, once initial steps are taken as outlined in our examples above, the argument can be made for transitioning the energy system itself to rely much more heavily on renewable sources such as wind, solar and perhaps biomass, as well as potentially nuclear power and fossil sources with carbon capture and sequestration (CCS). These will clearly also be regionally varying in effectiveness, another sign that implementation of any climate or energy legislation must take these differences into account. Approximately 60% of remaining CO_2 emissions for the cases examined above are from electricity consumption, thereby making electricity a prime target for further mitigation measures. A detailed discussion of the options for renewable energy in the area of our current study would take us too far afield, but it is likely that building energy use will be both reduced in a future with carbon emissions limits, and that the sources of that energy will be increasingly from renewable (or perhaps, nuclear power) sources. Some initial examples are provided in the next section.

VIII. Discussion and Implications

In the work presented in this paper we build a case for differentiation in energy and greenhouse-gas policy-making. Furthermore, we argue for the need to dig more deeply into the practical potential savings in both energy and greenhouse gas emissions for existing residential buildings. There are several distinct and compelling reasons for reducing energy consumption and for moving to a greater dependence on renewable energy sources, including climate change concerns, economic efficiency, national security issues, job creation strategies and more. However, when crafting climate and energy policies, it must be clear that the best path will depend upon the exact goal being addressed. Furthermore, even implementation of, for example, a greenhouse-gas reduction policy, will be very dependent on the exact geographical location, perhaps even with spatial resolution at the level of individual communities.

As one example, the American Clean Energy and Security (ACES) Act of 2009 (Waxman and Markey 2009) that passed the House of Representatives in June 2009 calls for reductions of greenhouse gas emissions, with respect to 2005, of 17% by 2020, 42% by 2030 and

83% by 2050. (The Kyoto Protocol and targets set by other industrialized nations take 1990 as the baseline year; with respect to this standard, ACES proposals represent cuts of 1% by 2020, 30% by 2030 and 80% by 2050.) Once a greenhouse gas emissions and energy policy is enacted, it will become necessary to map out details of how emissions reductions are to be achieved. Given the wide range of climatic conditions in the U.S., along with significant differences in how energy is consumed in different areas, a "one size fits all" set of regulations would be unjustified. Equity is important to consider at local levels as well. For example, those who are already living in small, energy efficient homes cannot be expected to further cut energy consumption by the same amount as those living in large, energy inefficient homes. Even for those who do wish to make homes more energy efficient, there will be real, practical limits to the modifications likely to be made. The amount of insulation that can be added to a home's attic or walls has obvious constraints that significantly limit potential energy consumption and greenhouse-gas emission reductions at the individual-home scale; increasing levels of insulation have decreasing returns. Our examples discussed above for strategies to reduce energy consumption for individual residences are the clearest indicator that one must go beyond estimates in terms of "$/mmBtu saved".

We concentrate in this work on upgrades to existing homes; over the time scales dealt with in current legislative and international proposals for reducing GHG emission, which might be of the order of 50 years, it is clear that the bulk of the housing stock at the middle of this century is already in existence right now. Reducing electricity consumption is typically an effective means of cutting GHG emissions in the region considered in this work, the East North Central Midwest United States. However, as seen in Table 4 above, the large majority of electricity consumption is for temperature independent, i.e. non-air conditioning uses. On the other hand, reductions in natural gas consumption will also be important, with the large majority of this energy consumption being due to temperature-dependent use, i.e. heating in winter. Targeted programs and incentives should be developed that explicitly consider these differences. Concentrating on existing homes, while effective, is not sufficient for reaching aggressive goals of 80-90% reductions in energy use or GHG emissions.

Changes to guidelines for new construction at the level of those promoted by the Energy Star program are important as far as they go, but new homes represent, unless net-zero energy or better, an increase in total energy consumption. Thus, new housing stock that is more energy efficient than that currently in existence represents only a reduction in future emissions with respect to what otherwise might have been the case, but not a contribution toward overall targets set for emission reductions.

Furthermore, trends in new construction over the past few decades have been toward ever-larger homes, rising from about 1000 – 1200 sq. ft. (1000 m^2) in the 1940s and 1950s, to 1750 sq.ft. (165 m^2) in the 1980s, before increasing even more rapidly to 2400 sq.ft. (225 m^2) in recent years (Wilson and Boehland 2008; U.S. Dept. of Energy 2009), with concomitant increases in total GHG emissions when calculated from the typical energy intensities used in our model. In other words, given that the vast majority of new housing construction does not meet Energy Star standards, we must conclude that energy consumption intensity improvements of 15% have been more than offset by a doubling in the physical footprint of newly-built homes. Furthermore, since there has also been a trend toward smaller households, the per capita emissions from household energy use have grown even more rapidly than emissions measured on a per household basis. Climate change is obviously the result of absolute quantities of greenhouse gases in the atmosphere, and therefore reducing energy consumption intensity (per unit area) or economic intensity (Btu/$) is not as important as reducing the total quantity of emissions.

Since homes in our case-study town are very close in total energy consumption intensity to regional averages on a square foot basis, we see from Table 1 that greenhouse gas emissions in the typical Yellow Springs home are smaller by a factor 1 - 1725/1941 = 11% than those from the typical home in the region. This "accidental" greenhouse gas savings does, however, point up the systemic thinking that must go into any coherent policy for reducing greenhouse gas emissions. A textbook example of Jevons' paradox (Alcott 2005) would be to provide incentives for energy efficient homes that then effectively resulted in the building of larger homes, thus negating the energy- and carbon-efficiency measures. Only an overall cap on carbon emissions can ensure that this dynamic does not occur.

Finally, as noted above, it is very unlikely that energy efficiency improvements, new construction guidelines and personal behavior modifications will be enough to lead to the GHG emissions cuts needed over the next few decades. Meeting climate policy goals, or more importantly, meeting the stated commitment of avoiding dangerous anthropogenic interference in the climate system, will necessitate the rapid increase in low-carbon energy sources, especially for electricity generation. Likewise, it would be unwise to rely solely on technological advances in the energy sector for all GHG emissions advances. As pointed out clearly above, there is a great deal of potential for economically beneficial efficiency improvements that make sense, independent of the type of energy source.

For the census region under consideration here, the average carbon dioxide emission factor is 713 $g(CO_2)/kWh_e$. Currently, Yellow Springs, which is a member of the American Municipal Power (AMP) cooperative, has a distinctly different electricity mixture than the region as a whole. Roughly 62% of the electricity comes from coal-fired plants, and most of the remaining amount is from landfill gas, hydroelectricity and nuclear, all with very low greenhouse gas factors. Overall, the emissions factor for Yellow Springs' current electricity mix is about 600 $g(CO_2)/kWh_e$, or 16% lower than the regional average. Of course, there are states and regions that have far lower emissions factors for electricity generation. The carbon intensity of electricity will be further reduced in the future due to decisions made in the town to commit to hydroelectric and solar photovoltaic generation through AMP (Village of Yellow Springs 2009). Together with a Village commitment to energy consumption reductions of 3%/year for a period of five years, the projected result for carbon intensity of electricity of ~150 $g(CO_2)/kWh_e$, mainly coming from continued 15-20% reliance on the regional electricity mix. One could imagine a further mix of generating sources, perhaps including local wind power, solar photovoltaics for partial offset of peak-load demand, along with potential demand-side management technologies or agreements to further decrease carbon emissions.

A systemic approach will be needed to reach aggressive goals for greenhouse gas emissions reductions. Even with the future electricity mix strongly weighted toward renewable sources as described (~80% lower emissions intensity), overall reductions from these scenarios are between 60% and 70%, except for the "Heavy Retrofit" case. Of the remaining emissions, 70 – 75% are from natural gas consumption, mainly from heating. To make further decreases possible, it is likely that an increasing fraction of homes will rely on electricity for heating, perhaps in the form of geothermal heat pumps. For that change to take place, policies and incentives will be needed on a relatively short-term timescale, otherwise homeowners with energy efficiency in mind will likely replace existing furnaces with newer units, perhaps with higher efficiency, but still natural gas.

In any case, there will be tremendous opportunities in the future for tailoring local solutions to the requirements of greenhouse gas emissions reductions. While a national policy will undoubtedly be necessary to set overall targets for the United States, blanket policies for how to achieve these results would likely be stifling of innovation and, in the end, ineffective in achieving the overall goal of reducing emissions by economically effective means that also allow for local initiative and innovation.

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Table 1

	Number of households (Population)	Household electricity use per year	Lighting and appliance electricity use per year	Total natural gas use per year	Heated floor space	Cooled floor space	Water heating
East North Central Midwest	17.7 million (46.0 million)	10479 kWh	7560 kWh (of which, Refrigerators: 1440 kWh)	890 ccf ($2600m^3$)	1941 sq. ft. (184 m^2)	1269 sq. ft. ($120m^2$) (90% of homes)	Elec.: 2949 kWh NG: 240 ccf ($700m^3$)
Yellow Springs, OH	1587 (3761)	8310 kWh	6823 kWh	748 ccf ($2180m^3$)	1725 sq. ft. (163 m^3)	NA	NA

Table 2

State	Total, 10^6 metric tonnes CO_2 (per capita, tonnes CO_2)	Residential (non-electric), 10^6 metric tonnes CO_2 (per capita, tonnes CO_2)	Residential Emissions from Electric Power Consumption, 10^6 metric tonnes CO_2 (per capita, tonnes CO_2)	Residential electricity consumption (MWh/capita/yr)	Population (million)
IL	250.4 (19.7)	24.7 (1.95)	22.6 (1.8)	3.7	12.90
IN	237.9 (38.1)	9.4 (1.51)	32.0 (5.1)	5.4	6.42
MI	192.3 (19.0)	23.4 (2.32)	21.4 (2.1)	3.4	9.97
OH	274.0 (23.9)	20.5 (1.79)	45.3 (3.9)	4.7	11.54
WI	112.1 (20.2)	9.7 (1.76)	17.4 (3.1)	4.0	5.66

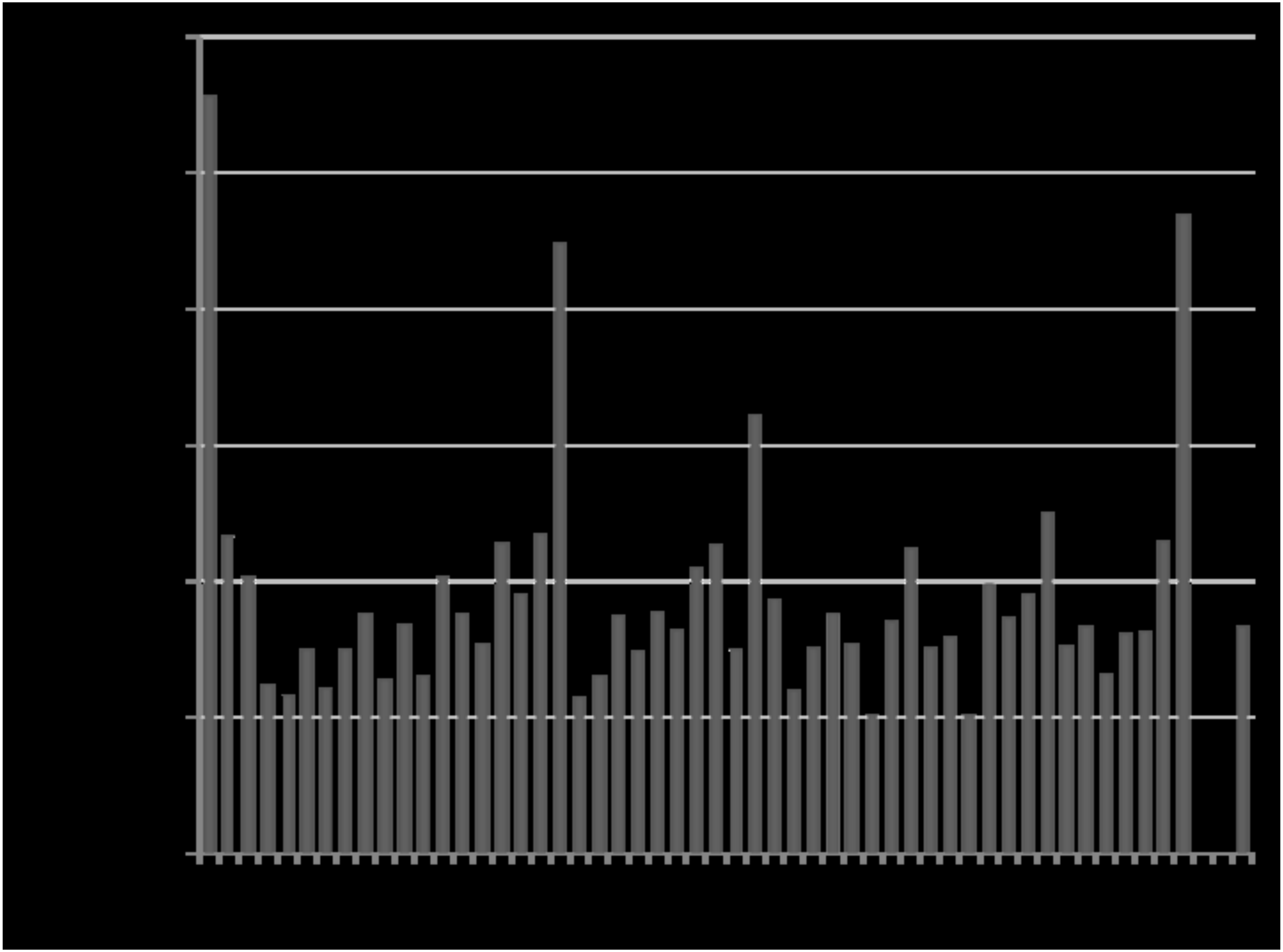
Table 3

	Baseline Characteristic	New Construction	Behavior	Sealing leaks	Sealing leaks + attic	Behavior + Sealing leaks	Deep Retrofit Characteristic
Windows	R – 2	R – 3	R – 2	R – 2	R – 2	R – 2	R-10
Doors	R – 2	R – 3	R – 2	R – 2	R – 2	R – 2	R - 3
Walls	R – 13	R – 15	R – 13	R – 13	R – 13	R – 13	R – 35
Floor	R – 17	R – 19	R – 17	R – 17	R – 17	R – 17	R – 20
Ceiling	R – 24	R – 30	R – 24	R – 24	R – 40	R – 24	R – 60
Heating equipment (natural gas assumed)	0.85	0.90	0.85	0.85	0.85	0.85	0.96
Cooling Equipment (SEER)	7	13	7	7	7	7	18
Set point	68°F, 68°F (20°C, 20°C)	68°F, 68°F (20°C, 20°C)	65°F, 72°F (18.3°C, 22.2°C)	68°F, 68°F (20°C, 20°C)	68°F, 68°F (20°C, 20°C)	65°F, 72°F (18.3°C, 22.2°C)	65°F, 74°F (18.3°C, 23.3°C)
Set back	2°F, 8 hrs.; none	2°F, 8 hrs.; none	8°F, 8 hrs.	2°F, 8 hrs.; none	2°F, 8 hrs.; none	8°F, 8 hrs.	8°F, 8 hrs.
Electricity use	0.52 W/sq.ft.	0.52	0.40	0.52	0.52	0.40	0.2
NG baseline	24 mmBtu/yr	24	19.2	24	24	19.2	12
Air leakage (ACHn)	0.6	0.3	0.6	0.3	0.3	0.3	0.05
Duct leakage	10%	5%	10%	0%	0%	0%	0%

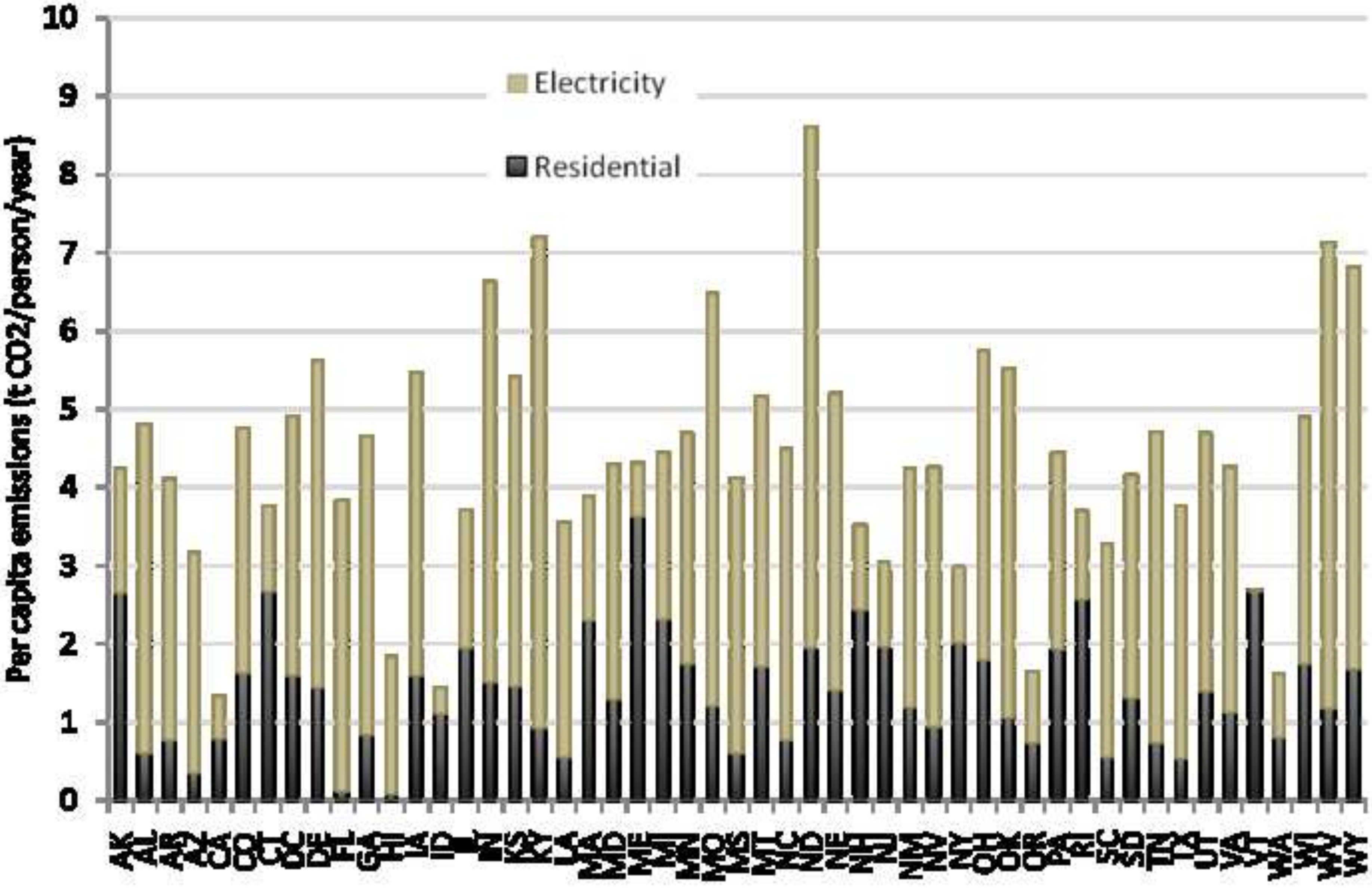
Table 4

Home	Typical Regional Home	New Cons-truction	Behavior	Sealing Leaks	Leaks + Attic	Behavior + Sealing Leaks	Heavy Retrofit
Annual Natural Gas Cons.							
NG indep. (mmBtu/yr or GJ/yr)	24.0	24.0	19.2	24.0	24.0	19.2	12.0
NG weather (mmBtu/yr or GJ/yr)	70.9	43.0	63.0	51.9	44.5	44.2	13.1
NG total (mmBtu/yr or GJ/yr)	95	67	82	76	69	63.4	25
Intensity (kBtu/ft^2-yr) (×11.1 for MJ/m^2-yr)	48.9	34.3	42.3	39.1	35.3	32.7	12.9
Levelized cost savings ($/year)	-	-	$110	$165	$228	$272	$603
Net cost savings ($/year)	-	-	$60-$111	$50	$17	$83	($95)
Annual Electricity Use							
E indep. (kWh/yr)	8,850	7,080	7,080	8850	8850	7080	5310
E weather (kWh/yr)	1,679	1,190	721	1450	1414	617	87
E total (kWh/yr)	10,529	8,270	7,801	10,300	10,264	7697	5397
Intensity (kWh/ft^2-yr) (×10.6 of kWh/m^2-yr)	8.3	4.3	6.2	8.1	8.1	6.1	4.3
Levelized cost savings ($/year)	-	-	$217	$18	$21	$225	$409
Net Cost savings ($/year)	-	-	$180-208	$14	$14	$167	$233
Estimated initial cost of upgrades	-	-	$880	$1190	$2180	$2470	$8700
Carbon dioxide emissions							
CO2 from NG (tonnes)	5.0	3.5	4.3	4.0	3.6	3.4	1.6
CO2 from electricity (tonnes)	7.5	5.9	5.6	7.3	7.3	5.5	3.8
Total CO2 (tonnes)	12.5	9.4	9.9	11.4	10.9	8.9	5.4
Value of saved CO2 emissions ($/year)	-	$78 $156	$65 $131	$30 $59	$40 $80	$90 $180	$178 $356

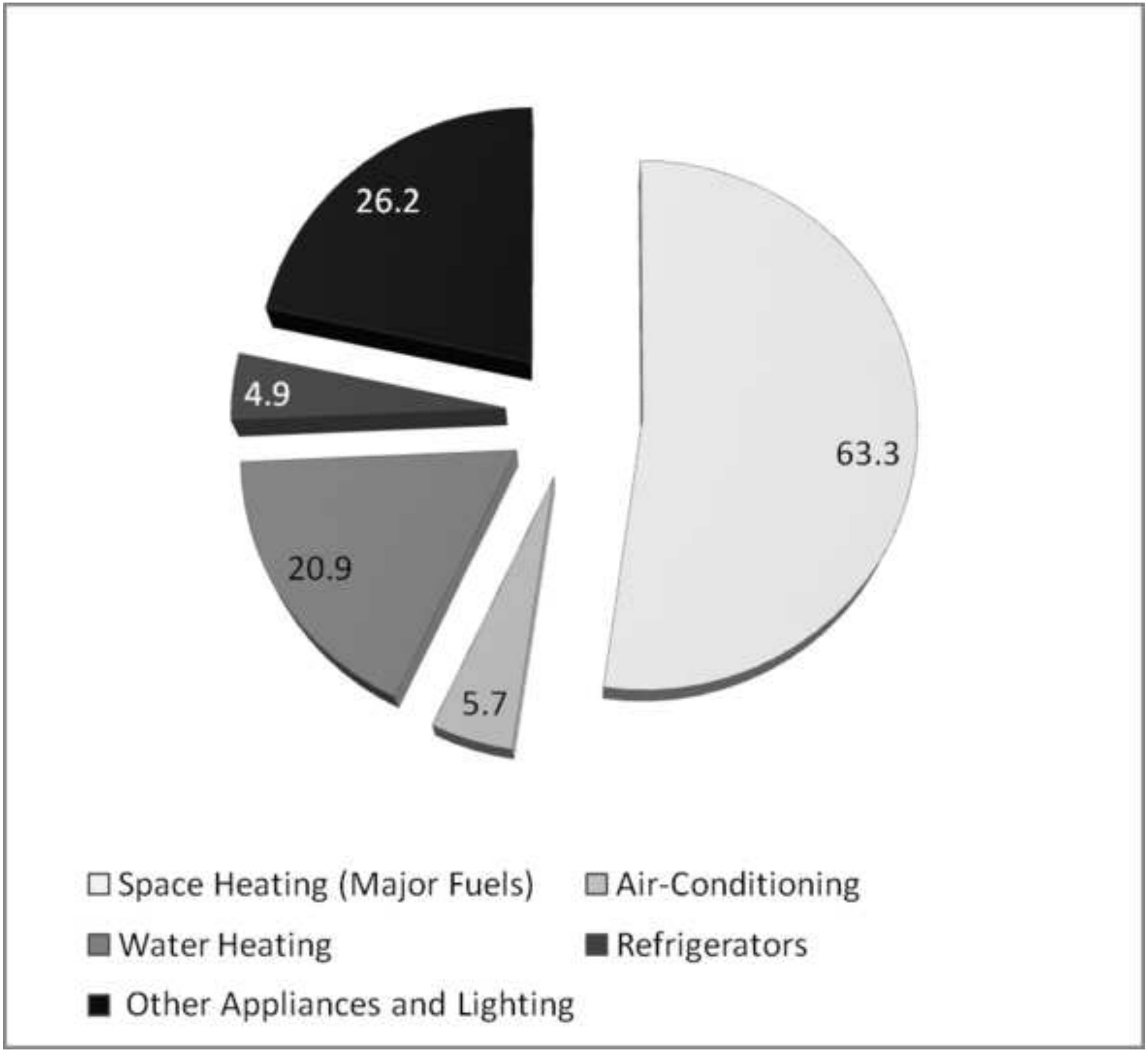
Figure(s)



Figure(s)

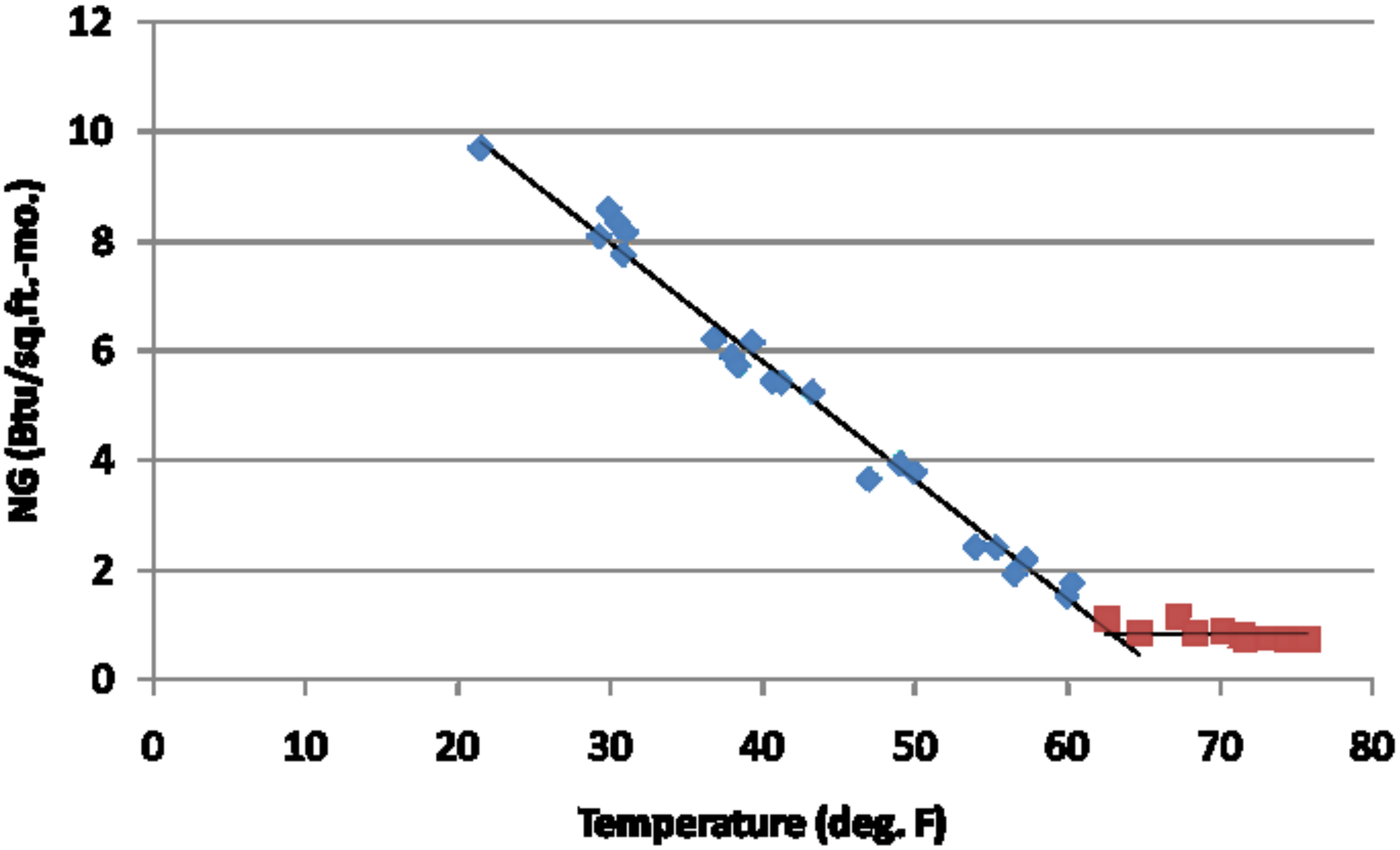

Electricity
Residential
Per capita emissions (t CO2/person/year)
0
1
2
3
4
5
6
7
8
9
10
AK
AL
AR
AZ
CA
CO
CT
DC
DE
FL
GA
HI
IA
ID
IL
IN
KS
KY
LA
MA
MD
ME
MI
MN
MO
MS
MT
NC
ND
NE
NH
NJ
NM
NV
NY
OH
OK
OR
PA
RI
SC
SD
TN
TX
UT
VA
VT
WA
WI
WV
WY

Figure(s)



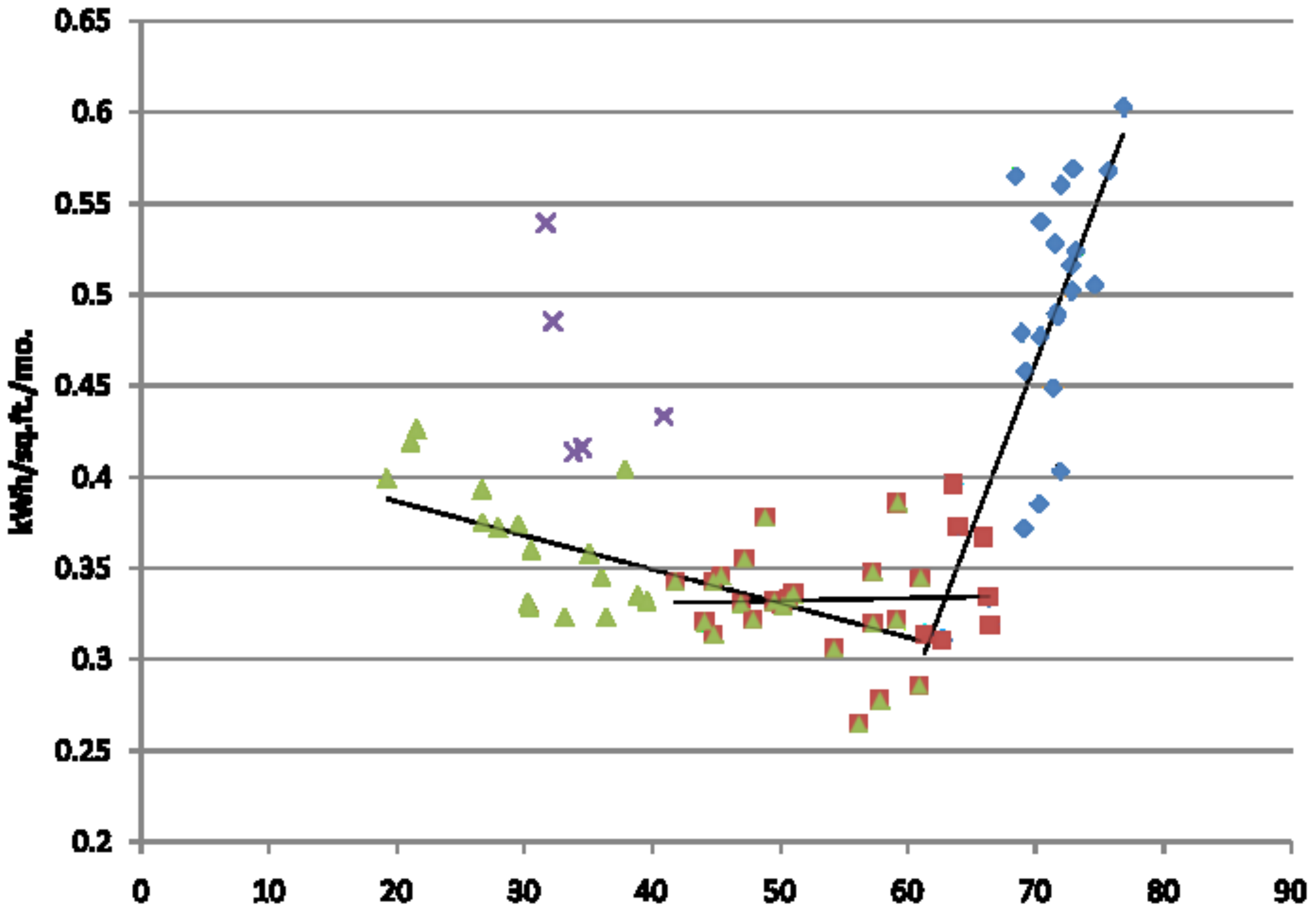
26.2
4.9
63.3
20.9
5.7
☐ Space Heating (Major Fuels)
▨ Air-Conditioning
▨ Water Heating
■ Refrigerators
■ Other Appliances and Lighting

Figure(s)



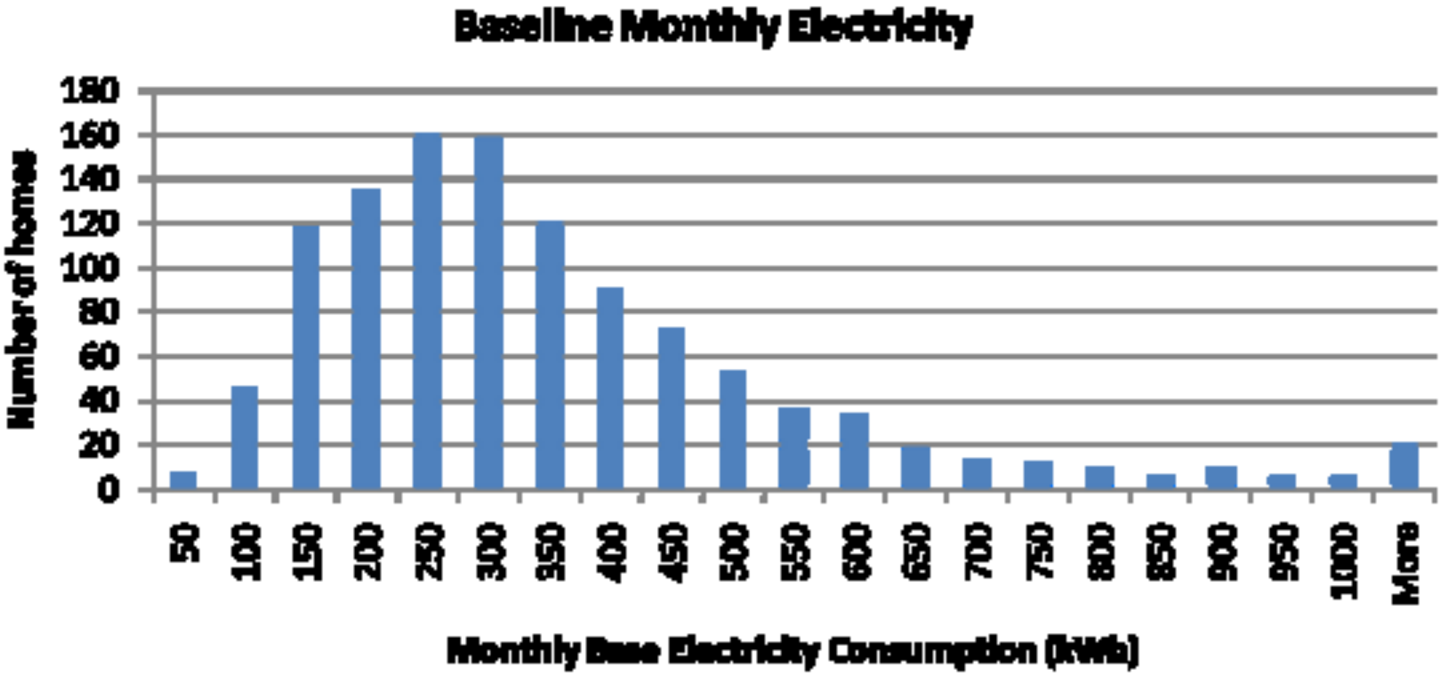
NG (Btu/sq.ft.-mo.)
12
10
8
6
4
2
0
0
10
20
30
40
50
60
70
80
Temperature (deg. F)

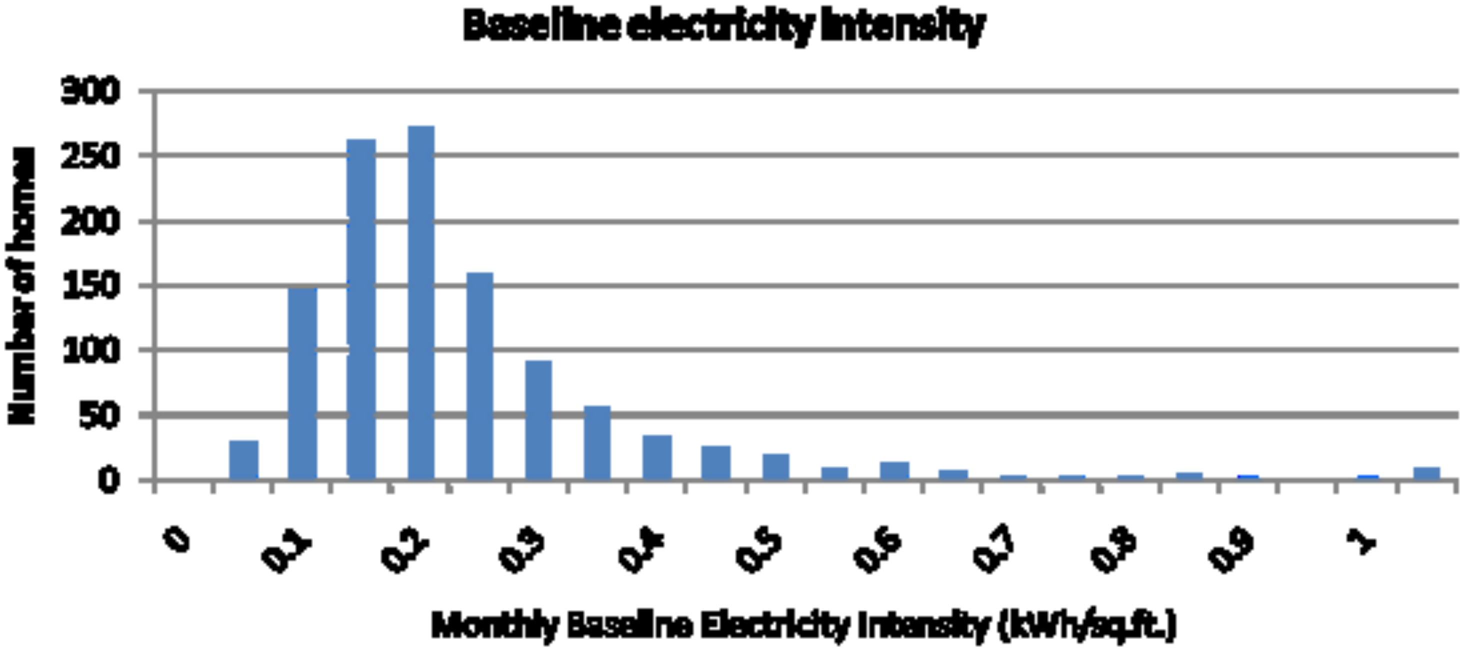
Figure(s)



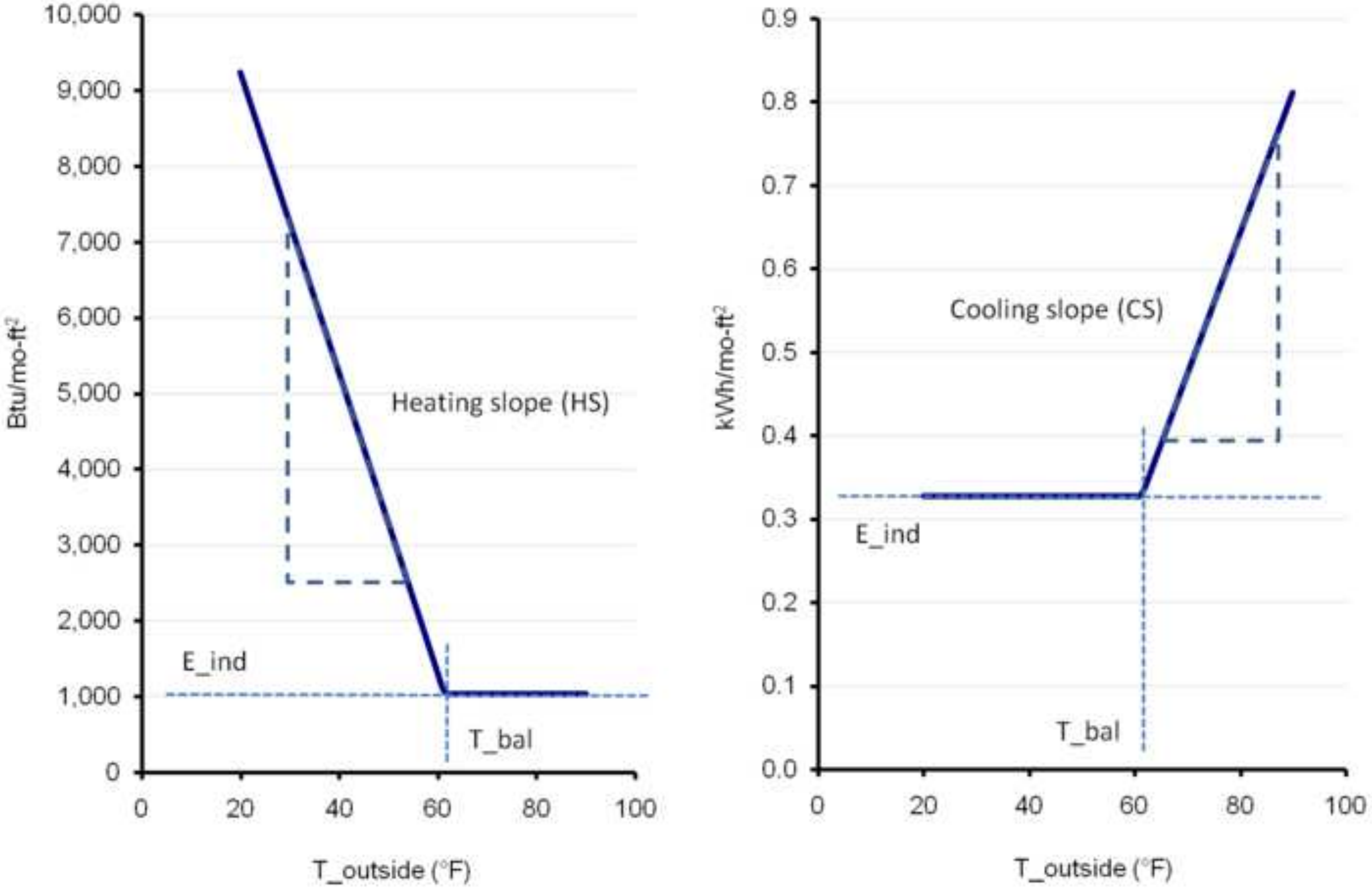
kWh/sq.ft./mo.
0.65
0.6
0.55
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0
10
20
30
40
50
60
70
80
90

Figure(s)


Baseline Monthly Electricity
Number of homes
180
160
140
120
100
80
60
40
20
0
50
100
150
200
250
300
350
400
450
500
550
600
650
700
750
800
850
900
950
1000
More
Monthly Base Electricity Consumption (kWh)


Baseline electricity intensity
Number of homes
300
250
200
150
100
50
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Monthly Baseline Electricity Intensity (kWh/sq.ft.)

Figure(s)


10,000
9,000
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
Btu/mo-ft^2
Heating slope (HS)
E_ind
T_bal
0
20
40
60
80
100
T_outside (°F)
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
kWh/mo-ft^2
Cooling slope (CS)
E_ind
T_bal
0
20
40
60
80
100
T_outside (°F)

a)

b)