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Calculating Impacts of Energy Standards on Energy Demand in U.S. Buildings under Uncertainty with an Integrated Assessment Model: Technical Background Data

December 2014

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U.S. DEPARTMENT OF
ENERGY

Prepared for the U.S. Department of Energy
under Contract DE-AC05-76RL01830

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Richland, Washington 99352

Executive Summary

This report presents data and assumptions employed in an application of PNNL's Global Change Assessment Model with a newly-developed Monte Carlo analysis capability. The model is used to analyze the impacts of more aggressive U.S. residential and commercial building-energy codes and equipment standards on energy consumption and energy service costs at the state level, explicitly recognizing uncertainty in technology effectiveness and cost, socioeconomics, presence or absence of carbon prices, and climate impacts on energy demand. The report provides a summary of how residential and commercial buildings are modeled, together with assumptions made for the distributions of state–level population, Gross Domestic Product (GDP) per worker, efficiency and cost of residential and commercial energy equipment by end use, and efficiency and cost of residential and commercial building shells. The cost and performance of equipment and of building shells are reported separately for current building and equipment efficiency standards and for more aggressive standards. The report also details assumptions concerning future improvements brought about by projected trends in technology.

Acknowledgments

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Acronyms and Abbreviations

BEDB	Building Energy Data Book
BEOpt	Building energy optimization computer program at National Renewable Energy Laboratory
CASCaDE	Computational Assessments of Scenarios of Change for the Delta Ecosystem
CDD	Cooling Degree-days
DEER	Database for Energy Efficient Resources
DOE	U.S. Department of Energy
DOE/BT	U.S Department of Energy, Building Technologies Program
EJ	exajoule (10^{18} joules)
EMF	Energy Modeling Forum
GCM	General Circulation Model
GCAM	Global Change Assessment Model
GCAM-USA	Global Change Assessment Model, with analysis of individual states
GDP	Gross domestic product
GFDL	General Fluid Dynamics Laboratory
GHG	Greenhouse gases
GJ	gigajoule (10^9 joules)
PRIMA	Platform for Regional Integrated Modeling and Analysis
HDD	Heating degree days
IPCC	Intergovernmental Panel on Climate Change
LBNL	Lawrence Berkeley National Laboratory
NREL	National Renewable Energy Laboratory
PCM	Parallel Climate Model
UN	United Nations
USCB	United States Census Bureau

Contents

Figures

Tables

1.0 Introduction

In 2010, scientists at Pacific Northwest National Laboratory launched a research initiative to develop an integrated regional modeling capability to address climate policy and consequences at regional (sub-national) scales relevant to regional decision making (Kraucunas et al. 2014). The Platform for Regional Integrated Modeling and Analysis (PRIMA) system of models that resulted from this effort has several important attributes, including extensive stakeholder engagement to identify desirable model characteristics and problems of interest, flexible coupling to customize approaches to the problem at hand, consistency with boundary climate conditions from general circulation models, portability and modularity, and open sources rather than proprietary code to maximize its usability by the climate community.

An important feature of the new modeling system was the ability to take uncertainty systematically into account. Climate systems and related human and natural systems are imperfectly understood and have many sources (only some of which are readily quantifiable), but an important insight of the PRIMA research that guides application of the framework is that for most applications it is necessary only to characterize those sources of uncertainty relevant to the particular stakeholder decision. In the study that this report supports, the question was under what circumstances, if any, more aggressive building energy codes and building equipment energy efficiency standards would produce energy savings and reduce costs to consumers; in other words, how “robust” the aggressive standards policy would be (Lempert et al. 2004). Based on discussions with a number of stakeholder groups, the PRIMA team decided that relative cost and performance of various improvements to building shells and equipment was a key uncertainty, as well as potential rates of economic and population growth. These uncertainties could be parameterized in the Global Change Assessment Model (GCAM), the integrated energy and climate policy assessment model within PRIMA, which was identified as the only model out of the PRIMA necessary to answer the stakeholder question at the level required.[1] Formal uncertainty analysis of energy policy has been conducted using predecessors to GCAM (Edmonds et al. 1987, Scott et al. 1999).

Two other key uncertainties were the impacts of energy or climate policies that might be pursued by national governments independently from the regional decision-makers, and the uncertainty of the climate regime itself (both the future rate of growth in greenhouse gas (GHG) emissions that would affect the atmospheric concentration of these gases, and uncertainty in climate response to greenhouse gas concentrations from different general circulation models (GCMs), given the time profile of concentrations. These uncertainties were captured by running GCAM in four states of the world defined by two emissions scenarios associated with different climate policies, and two different general circulation models (GCMs) climate models to provide different climates for each of the emissions scenarios. The two contrasting climate policies were: a business-as-usual reference policy with no explicit attempts to control GHG, and a control policy case that featured an increasing carbon tax to strongly control emissions. The cases were modeled so that they produced pathways of emissions concentrations similar to those in the Intergovernmental Panel on Climate Change (IPCC) A2 and B1 scenarios (Nakicenovic et al. 2000), for which downscaled climate model results were available in the U.S. Geological Survey’s CASCaDE Project climate dataset.[2] For purposes of the analysis supported by

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[1] For a detailed discussion of GCAM and its features, see the GCAM wiki page at http://wiki.umd.edu/gcam/index.php/Main_Page

[2] Available at http://cascade.wr.usgs.gov/data/Task1-climate/
.

this report, the uncertainty of climate policy affects the price of carbon and the cost of energy, thereby influencing the value of potential energy savings and the market demand for more efficient energy-saving technologies. Increasing the price of energy also reduces future climate warming, although the rate of that reduction varies by climate model. This influence on climate is captured by running GCAM for the number of heating degree-days and cooling degree-days reported for each region in each forecast period. Generally, a warming climate results in more demand for cooling and less demand for heating, increasing the demand for efficient cooling equipment and reducing the demand for efficient heating equipment.

This report provides details concerning the uncertainties in population forecasts used in GCAM/PRIMA and the details concerning the modeling of building equipment cost and building shell cost and performance, as affected by building and equipment standards. Section 2.0 provides a general overview of the buildings sector in GCAM. Section 3.0 provides information on the population forecasts used in GCAM/PRIMA. Section 4.0 gives details of the uncertainties in equipment performance and cost and how aggressive residential and commercial equipment standards have been modeled. Section 5.0 is less detailed, but discusses how residential and commercial building shell performance and cost were modeled. Section 6.0 provides a mapping from the literature to the specific assumptions made in Section 4.0 , and Section 7.0 provides a reference list.

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2.0 Information on the GCAM-USA Building Model

This section provides an overview of the salient features of the GCAM-USA building model affected by the policy experiment. A full description of the GCAM-USA building model is available in Zhou et al. 2014. A key feature of the building model is that it distinguishes between the consumers' desired level of energy services (e.g., heating or lighting) and the estimated performance and cost of technologies available to supply those services. Consumers choose the level of services, fuel, and technologies based on cost of service in logit market-share equations. In this paper, the building and equipment standards change the distributions of performance and cost of technologies available to consumers for each end use market share calculation. Temperature-sensitive heating and cooling service demands also respond to heating degree days (HDD) and cooling degree-days CDD (climate response) (Kim et al., 2006; University of Maryland, 2014).

The GCAM-USA building model calculates the amount of residential and commercial building space in each state as a function of population and *per capita* Gross Domestic Product (GDP), which is discussed in the next subsection. The *per capita* floor space equation has a minimum (zero square meters *per capita*) and an asymptotic maximum value in each state, and the amount of *per capita* space per unit of GDP is adjusted to local preferences. Energy-service demands from Eom et al. (2012) feature satiated comfort levels for heating and cooling and non-satiated demand for other energy services. Service demands in state i per unit of floor space for heating and cooling are affected by population-weighted heating degree-days (HDD^i) and cooling degree-days (CDD^i), building-shell efficiency and surface ratio, and the internal gains from the supply of services other than heating and cooling in state i. The service price is impacted by building standards, and there is a calibration parameter representing sector- and region-specific preferences.

The equations for heating and cooling feature a satiation impedance parameter, μ_j, which determines the degree of demand satiation given a particular level of affordability of the service as represented by *per capita* income over the service price, Y^i/P_j. Services other than heating and cooling do not have satiation impedance; their demand per unit of floor space is a function of affordability only. The service demand equations in each state have unique calibration coefficients. In the current paper, Eff_{ik} the building-shell and equipment efficiencies in state i for end use k, Y^i/P_j, HDD^i, and CDD^i are all uncertain in each time period.

In addition to modeling building equipment choices, GCAM-USA includes exogenous scenarios of the cost and efficiency of building shells. An initial efficiency index based on thermal loss expressed in watts/m^2, as determined by calibrating to estimated base-year heating demand, is applied to each state's base-year building stock. Shell thermal efficiency of the overall building stock then evolves in each state as each vintage of new construction, additions, and renovations comply with increasingly stringent building-energy codes. These marginal changes in building-shell efficiency (and their costs per square meter) come from technology scenarios.

3.0 Population Forecasts

Although it can be used independently, the Global Change Assessment Model (GCAM)-USA model is part of a group of models called the Platform for Regional Integrated Modeling and Analysis (PRIMA) (Kraucunas et al. (2014). The set of population forecasts used for the analysis in this paper comes from a broader population-estimating effort in the PRIMA initiative.

3.1 U.S. Population Projections for PRIMA Evaluations

PRIMA simulates interactions among climate, energy, water, and land at decision-relevant spatial scales. By bringing together models of climate, socioeconomics, hydrology, agriculture, buildings, electricity, and other sectors in a probabilistic framework, PRIMA helps regional stakeholders develop and evaluate strategies for responding to complex socioeconomic and environmental changes in an uncertain future. A significant input to a PRIMA evaluation is a joint probability distribution that summarizes the uncertainty in U.S. national and state population projections through the year 2100. This distribution does not exist, and must be estimated from a number of sources using several steps and assumptions.

The U.S. Census Bureau (USCB) models and develops projections of U.S. national population through 2060 (U.S. Census Bureau 2013). The United Nations (U.N.) Population Division provides U.S. national population forecasts through 2100 (United Nations 2013). These projections cover a diversity of birth, death, and migration scenarios resulting in a broad collection of “low,” “medium,” and “high” projections. The medium projections from the USCB and the U.N. are very similar through 2060, differing by no more than about 1.5 percent in any one year, and are virtually identical in 2050. The other U.S. national projections are not directly comparable because of differences between U.S. and U.N. scenarios. Also, the USCB has made state-level population projections only to the year 2030 (U.S. Census Bureau 2005), while the U.N. Population Division currently does not make state-level population projections.

Because PRIMA will be used for U.S. climate policy analysis, the USCB population forecasts are preferred when available. However, the common parameterization of PRIMA’s GCAM-USA component requires a set of U.S. national and state population projections through 2100. This is true for the component models that comprise PRIMA as well. Characterizing uncertainty resulting from variation in population using PRIMA requires a joint probability distribution of U.S. national and state population projections, so that one draw from this distribution results in one set of correlated national and state projections. Ideally, we would engage a probabilistic age-cohort model employing (unknown) associated probability distributions of 2010-to-2100 projected age-specific demographic parameters and international and intra-national migration rates and migrant demographic variables that fit with USCB national projections until 2060 and sensibly extrapolate to 2100. This approach would require many assumptions and judgments, and is far beyond the scope of PRIMA.

3.2 Fundamental Approach

Instead of the complex approach described above, we apply a simpler and more direct approach by first estimating the probability distribution for national population projections, and then extending this to a joint distribution covering state population projections. We estimate selected projection quantiles of the U.S. national distribution. We choose a year and use the set of that year's points from these quantiles to fit a probability distribution that summarized the uncertainty in the national population for that year. Then, for any quantile of that distribution, we mix the projection quantiles in proportion to differences in the appropriate quantiles to obtain the corresponding national population projection quantile.

We estimate state medium population projections from the 2005 USCB 2010-to-2030 state projections, and extend to 2100 with a combination of state growth factor predictions and regression to the national projection. We calculate the ratio of the medium state projection to the national medium projection to obtain a state-to-national proportionality profile. We then apply this proportionality profile to a quantile of the national projection distribution to obtain a state's corresponding population projection quantile.

3.3 Population Forecast Details

3.3.1 Estimating the probability distribution of U.S. total population projections

We estimate the projection quantiles of the U.S. national distribution using U.S. and U.N. projections. Our estimate of the median national projection is the USCB medium projection through 2060, extended to 2100 using a proportional weighting of the U.N. medium projection after 2060. We estimate the 1st and 99th national projection quantiles with the U.N. low and high projections. We have investigated using other projections to obtain other quantiles, such as the 10th, 20th, 80th and 90th. At this time, however, we rely only on the aforementioned 1st, 50th and 99th projection quantiles to underpin our distribution. We assume a population distribution model for a given year; say the year 2050, and a triangular distribution with three quantiles available. We then fit the assumed population distribution by matching the model's quantiles to the appropriate points of the projection quantiles. We assume the fitted population distribution for the chosen year applies, proportionally, to all years spanning 2010 to 2100.

The USCB medium population projection for 2050 is the virtually the same as the U.N. medium population projection and only 0.6% higher for 2060 (see Figure 3.1). Thus, if we adopt the U.N. medium projection as our PRIMA medium scenario, then PRIMA will be broadly consistent with both the USCB and the U.N. long-term forecast. The USCB high and low projections are not identical to the U.N. high and low projections. The USCB high and low cases have different underlying causes than the U.N. high and low cases. The big differences among the U.N. high, medium, and low projections result from differences in U.S. birth rates, ranging from as high as 2.49 children per woman in the high case down to as low as 1.49 children per woman in the low case, with the medium (median) case at 1.99 children per woman. The U.N. cases assume the same scenario of net immigration to the United States at about 1 million per year through 2050, with a slow decline following. The primary difference among the USCB cases is the different amounts and sources of net immigration to the United States. Immigration follows higher and lower trends in the USCB high and low cases, respectively, than in the medium case. While this difference in migration has some impact on the mix of age-specific birth rates and death rates (e.g., different for Latino, Asian, and European migrants), the spread between high and low populations is far less than in the corresponding U.N. projections.

The PRIMA medium scenario is the USCB medium projection through the year 2060. After 2060, the PRIMA projection gradually and linearly converges to the U.N. medium case, equaling the U.N. medium case from 2080 to 2100. Suppose P2060 (also the PRIMA projection) and U2060 are the 2060 USCB and U.N. medium population projections, respectively. Then, beginning in 2060, $Pt = Ut * (1 + Mt * (P2060 - U2060) / U2060)$ where t = 2060, 2065, 2070, 2075, and 2080, while Mt = 100%, 75%, 50%, 25%, and 0%. The U.N. medium case uses a consistent set of demographic and migration assumptions that are similar to the USCB assumptions and produce nearly identical values through the year 2060, but unlike the USCB, extend through 2100. As an added advantage, the U.N. projections for the United States are part of an international set of projections for every country that are internally consistent and extend through the year 2100.

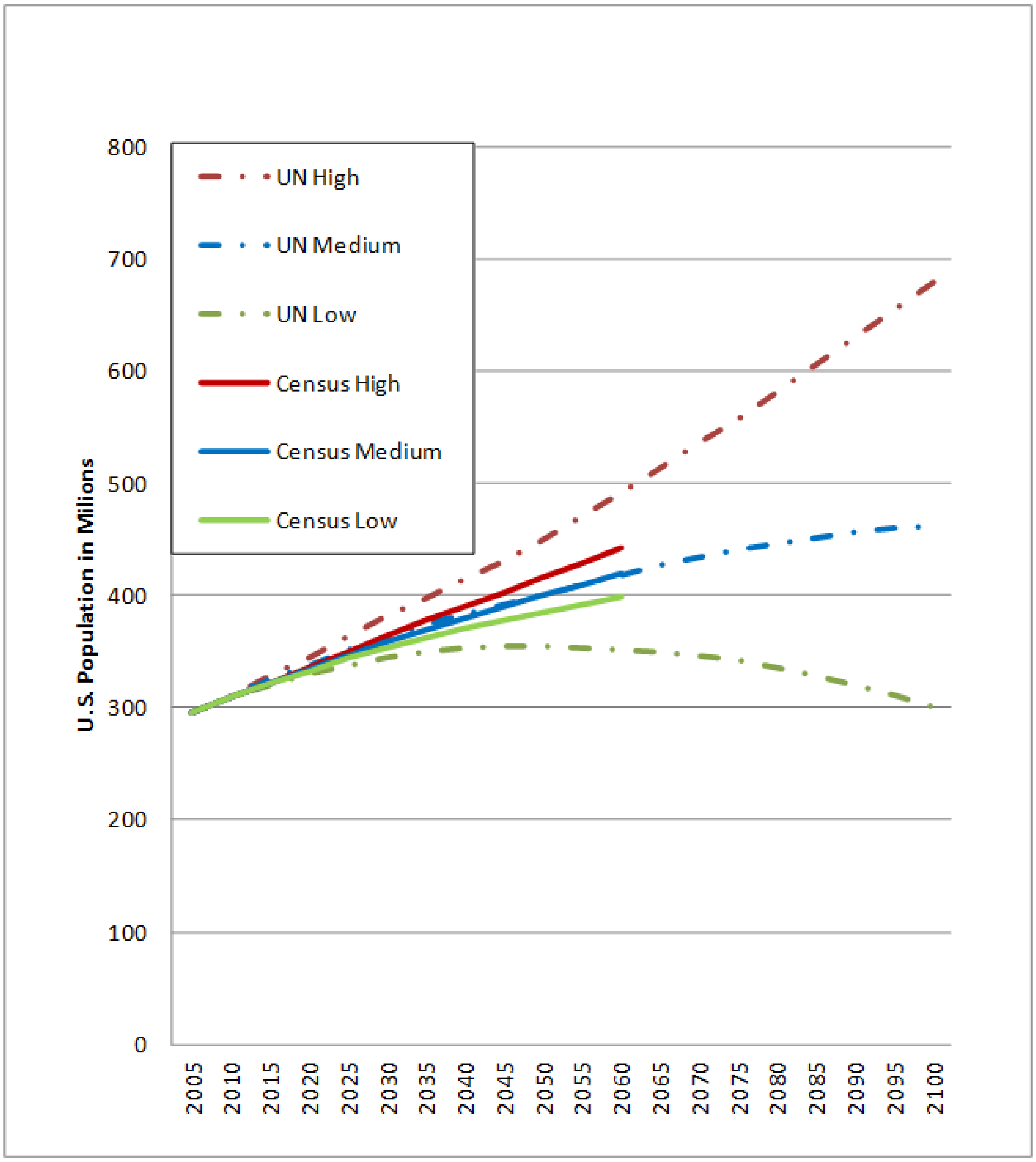

Figure 3.1 Comparison of USCB projections of U.S. total popualtion with UN projections

For the current version of the PRIMA model, we use the U.N. high and low projections for the high and low cases. Although the USCB treats future uncertainties in migration to the United States in a more sophisticated manner than the U.N. projections, the range of uncertainty in demographic values in the U.N. projections is much wider, and provides a wider range of values for uncertainty analysis. In addition, the U.N. high and low population projections for the rest of the world are internally consistent. Figure 2.2 shows the resulting PRIMA population projections until 2100.

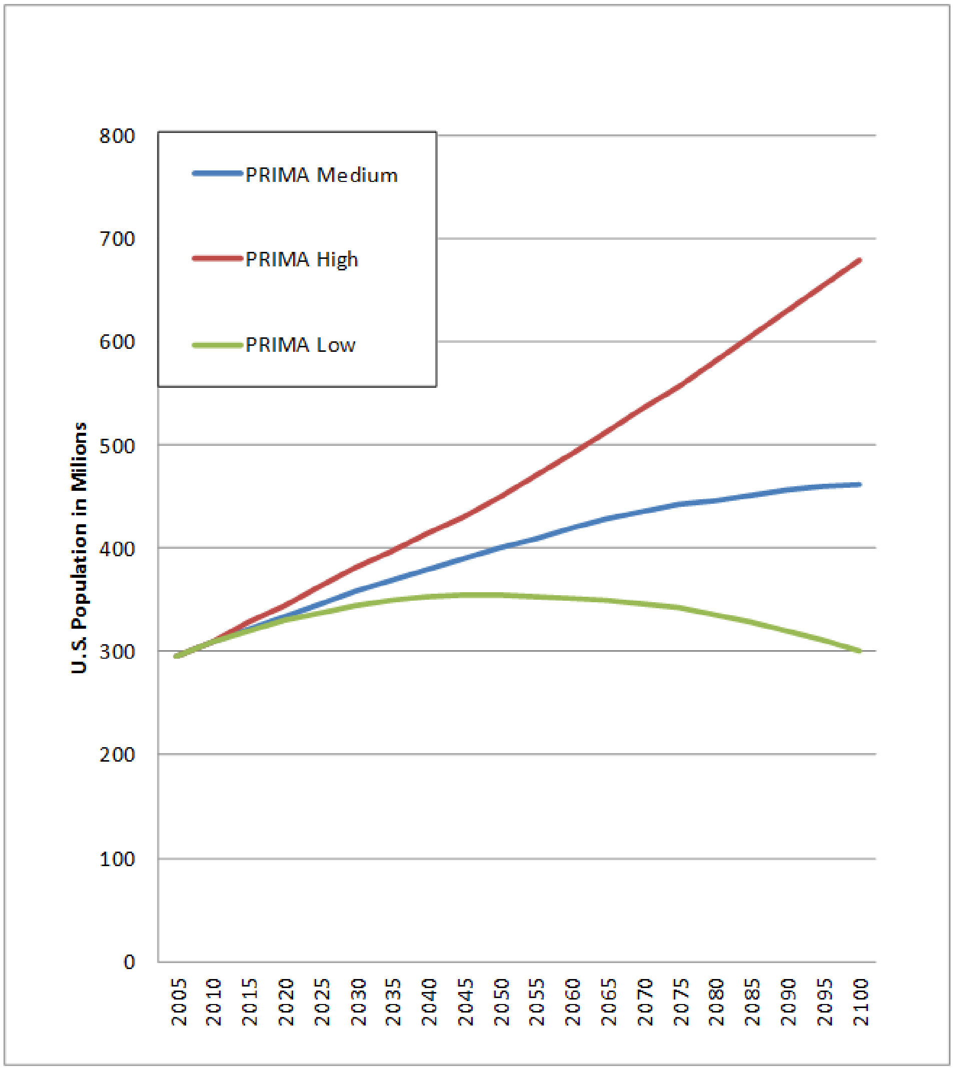

Figure 3.2 PRIMA projections of U.S. total population

We mix the known projection quantiles in proportion to differences in the appropriate quantiles to obtain the corresponding national population projection quantile. For example, suppose that Q78 is the 78th quantile of the 2050 total population distribution. Let P50 and P99 be the 50th and 99th projection quantiles estimated from the U.S. and U.N. medium and high projections with Q50 and Q99 denoting their 2050 values. Then the 78th projection quantile, P78, is equal to a proportional mix of P50 and P99:P78 = (Q99 – Q78)/ (Q99 – Q50)*P50 + (Q78 – Q50)/ (Q99 – Q50)*P99.

3.3.2 Estimating the Medium State Population Projections and Proportionality Profiles

The USCB only provides internally consistent state-level population forecasts through the year 2030. Although all but one U.S. state conduct and publish long-term forecasts, no state provides forecasts up to 2100, and the forecasting procedures, assumptions, and time periods used by states are not consistent across the country. As a result, the GCAM-USA state population projections are obtained by using the USCB forecasts through 2030 (U.S. Census Bureau 2005) to create smoothed trends in state population shares that are then extrapolated and applied to the U.S. national population projections. The state population forecasts thus take account of past trends in internal state-to-state population movements and also add to the long-term national total.

To provide consistent state forecasts through 2030, the original USCB forecasts for individual states through 2030 were used to create raw growth rates. These growth rates were applied to the actual populations in 2010 to provide scaled forecasts. The sum of the scaled forecasts was adjusted proportionately to provide a scaled national estimate; then, the growth rates were scaled to provide an adjusted round of state forecasts that, then, were proportionately adjusted a second time.

Two principles regarding projections are used to derive the post-2030 growth rates: 1) that the most recent trend is the best estimate of the near-term future trend and 2) that exponential growth rates do not continue forever and that differing growth rates converge to their mean growth rate over time. The individual state growth rates from 2025 to 2030 were calculated from the second-round adjusted 2025 and 2030 populations. These growth rates were weighted in combination with the aggregate (weighted mean across states) growth rate to project the individual state values for the years after 2030. After 2030, the procedure heavily weighted the current trend in the early years of a 25-year transition period and lightly weighted it in the latter years (e.g., the weight of the state rate was 80 percent in 2035, 60 percent in 2040, 40 percent in 2045, etc.). After the 25-year transition period, all states increase or decline in population at the aggregate U.S. rate. The state population values thus derived implies changing shares of population.

3.3.3 Estimating State Population Projections

We assume a state's state-to-national proportionality profile is constant for any corresponding pair of state and national population projections. That is, we assume that the ratio of a state projection quantile to its corresponding national projection quantile is the same no matter the quantile. Consequently, to determine a state projection quantile from a given national quantile, we multiply the national projection quantile for each projection year by the state's state-to-national proportionality profile. Suppose P50 denotes the U.S. medium total population projection with S50 being a state's medium population projection. Then, the state's state-to-national proportionality profile R is the ratio of these two, or R = S50/P50. Let Pq be the qth quantile of the U.S. total population projection distribution. Then, the corresponding qth quantile of the state's population projection distribution is the product of state's state-to-national proportionality profile and the U.S. total population projection qth quantile, or Sq = R*Pq = S50/P50 * Pq.

3.3.4 Simulating a Correlated set of U.S. Total and State Population Projections

Simulating one realization of a U.S. total population projection and the corresponding correlated state projections begins with a random draw of a quantile from the U.S. total population distribution for the chosen year. Following this draw, the corresponding random total population projection is computed as a weighted proportion of the appropriate total population projection quantiles. The random state population projection is then obtained as the product of this random total population projection and the state's state-to-national population proportionality profile. This process is repeated until the chosen sample size is accumulated.

Table 3.1shows the population shares used to calculate state populations in PRIMA.

Table 3.1 Population shares used to calculate state populations in PRIMA

	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060	2065	2070	2075	2080	2085	2090	2095	2100
U.S. National total	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
State Sum	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
.Alabama	1.5%	1.5%	1.4%	1.4%	1.4%	1.3%	1.3%	1.3%	1.3%	1.3%	1.3%	1.3%	1.3%	1.3%	1.3%	1.3%	1.3%	1.3%	1.3%	1.3%
.Alaska	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%
.Arizona	2.0%	2.1%	2.3%	2.5%	2.7%	2.9%	3.1%	3.3%	3.4%	3.4%	3.4%	3.4%	3.4%	3.4%	3.4%	3.4%	3.4%	3.4%	3.4%	3.4%
.Arkansas	0.9%	0.9%	0.9%	0.9%	0.9%	0.9%	0.9%	0.9%	0.9%	0.9%	0.9%	0.9%	0.9%	0.9%	0.9%	0.9%	0.9%	0.9%	0.9%	0.9%
.California	12.2%	12.3%	12.4%	12.6%	12.7%	12.8%	12.8%	12.9%	12.9%	12.9%	12.9%	12.9%	12.9%	12.9%	12.9%	12.9%	12.9%	12.9%	12.9%	12.9%
.Colorado	1.6%	1.6%	1.6%	1.6%	1.6%	1.6%	1.6%	1.6%	1.6%	1.6%	1.6%	1.6%	1.6%	1.6%	1.6%	1.6%	1.6%	1.6%	1.6%	1.6%
.Connecticut	1.2%	1.2%	1.1%	1.1%	1.1%	1.0%	1.0%	1.0%	0.9%	0.9%	0.9%	0.9%	0.9%	0.9%	0.9%	0.9%	0.9%	0.9%	0.9%	0.9%
.Delaware	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%
.District of Columbia	0.2%	0.2%	0.2%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%
.Florida	5.9%	6.2%	6.6%	7.0%	7.4%	7.9%	8.3%	8.6%	8.8%	8.9%	8.9%	8.9%	8.9%	8.9%	8.9%	8.9%	8.9%	8.9%	8.9%	8.9%
.Georgia	3.0%	3.1%	3.2%	3.2%	3.3%	3.3%	3.3%	3.3%	3.4%	3.4%	3.4%	3.4%	3.4%	3.4%	3.4%	3.4%	3.4%	3.4%	3.4%	3.4%
.Hawaii	0.4%	0.4%	0.4%	0.4%	0.4%	0.4%	0.4%	0.4%	0.4%	0.4%	0.4%	0.4%	0.4%	0.4%	0.4%	0.4%	0.4%	0.4%	0.4%	0.4%
.Idaho	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%	0.6%	0.6%	0.6%	0.6%	0.6%	0.6%	0.6%	0.6%	0.6%	0.6%	0.6%	0.6%	0.6%	0.6%
.Illinois	4.3%	4.2%	4.1%	3.9%	3.8%	3.7%	3.6%	3.5%	3.5%	3.4%	3.4%	3.4%	3.4%	3.4%	3.4%	3.4%	3.4%	3.4%	3.4%	3.4%
.Indiana	2.1%	2.1%	2.0%	2.0%	1.9%	1.9%	1.8%	1.8%	1.8%	1.8%	1.8%	1.8%	1.8%	1.8%	1.8%	1.8%	1.8%	1.8%	1.8%	1.8%
.Iowa	1.0%	1.0%	0.9%	0.9%	0.9%	0.8%	0.8%	0.8%	0.7%	0.7%	0.7%	0.7%	0.7%	0.7%	0.7%	0.7%	0.7%	0.7%	0.7%	0.7%
.Kansas	0.9%	0.9%	0.9%	0.9%	0.8%	0.8%	0.8%	0.8%	0.8%	0.8%	0.8%	0.8%	0.8%	0.8%	0.8%	0.8%	0.8%	0.8%	0.8%	0.8%
.Kentucky	1.4%	1.4%	1.3%	1.3%	1.3%	1.3%	1.2%	1.2%	1.2%	1.2%	1.2%	1.2%	1.2%	1.2%	1.2%	1.2%	1.2%	1.2%	1.2%	1.2%
.Louisiana	1.5%	1.5%	1.4%	1.4%	1.4%	1.3%	1.3%	1.3%	1.2%	1.2%	1.2%	1.2%	1.2%	1.2%	1.2%	1.2%	1.2%	1.2%	1.2%	1.2%
.Maine	0.4%	0.4%	0.4%	0.4%	0.4%	0.4%	0.4%	0.4%	0.4%	0.4%	0.4%	0.4%	0.4%	0.4%	0.4%	0.4%	0.4%	0.4%	0.4%	0.4%
.Maryland	1.9%	1.9%	1.9%	1.9%	1.9%	1.9%	1.9%	1.9%	1.9%	1.9%	1.9%	1.9%	1.9%	1.9%	1.9%	1.9%	1.9%	1.9%	1.9%	1.9%
.Massachusetts	2.2%	2.2%	2.1%	2.0%	2.0%	1.9%	1.9%	1.8%	1.8%	1.8%	1.8%	1.8%	1.8%	1.8%	1.8%	1.8%	1.8%	1.8%	1.8%	1.8%
.Michigan	3.5%	3.4%	3.3%	3.2%	3.1%	2.9%	2.8%	2.8%	2.7%	2.7%	2.7%	2.7%	2.7%	2.7%	2.7%	2.7%	2.7%	2.7%	2.7%	2.7%
.Minnesota	1.8%	1.8%	1.8%	1.8%	1.7%	1.7%	1.7%	1.7%	1.7%	1.7%	1.7%	1.7%	1.7%	1.7%	1.7%	1.7%	1.7%	1.7%	1.7%	1.7%
.Mississippi	1.0%	1.0%	0.9%	0.9%	0.9%	0.9%	0.8%	0.8%	0.8%	0.8%	0.8%	0.8%	0.8%	0.8%	0.8%	0.8%	0.8%	0.8%	0.8%	0.8%
.Missouri	2.0%	1.9%	1.9%	1.8%	1.8%	1.8%	1.7%	1.7%	1.7%	1.7%	1.7%	1.7%	1.7%	1.7%	1.7%	1.7%	1.7%	1.7%	1.7%	1.7%
.Montana	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%
.Nebraska	0.6%	0.6%	0.6%	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%
.Nevada	0.8%	0.9%	0.9%	1.0%	1.1%	1.2%	1.2%	1.3%	1.3%	1.3%	1.3%	1.3%	1.3%	1.3%	1.3%	1.3%	1.3%	1.3%	1.3%	1.3%
.New Hampshire	0.4%	0.4%	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%	0.4%	0.4%	0.4%	0.4%	0.4%	0.4%	0.4%	0.4%	0.4%	0.4%	0.4%	0.4%
.New Jersey	3.0%	2.9%	2.9%	2.8%	2.8%	2.7%	2.6%	2.6%	2.6%	2.6%	2.6%	2.6%	2.6%	2.6%	2.6%	2.6%	2.6%	2.6%	2.6%	2.6%

.New Mexico	0.6%	0.6%	0.6%	0.6%	0.6%	0.6%	0.6%	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%
.New York	6.5%	6.3%	6.1%	5.8%	5.6%	5.4%	5.2%	5.0%	4.9%	4.9%	4.9%	4.9%	4.9%	4.9%	4.9%	4.9%	4.9%	4.9%	4.9%	4.9%
.North Carolina	2.9%	3.0%	3.1%	3.2%	3.3%	3.4%	3.4%	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%	3.5%
.North Dakota	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%
.Ohio	3.9%	3.7%	3.6%	3.5%	3.3%	3.2%	3.1%	3.0%	2.9%	2.9%	2.9%	2.9%	2.9%	2.9%	2.9%	2.9%	2.9%	2.9%	2.9%	2.9%
.Oklahoma	1.2%	1.2%	1.1%	1.1%	1.1%	1.1%	1.1%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%
.Oregon	1.2%	1.2%	1.2%	1.3%	1.3%	1.3%	1.4%	1.4%	1.4%	1.4%	1.4%	1.4%	1.4%	1.4%	1.4%	1.4%	1.4%	1.4%	1.4%	1.4%
.Pennsylvania	4.2%	4.1%	3.9%	3.8%	3.7%	3.5%	3.4%	3.3%	3.2%	3.2%	3.2%	3.2%	3.2%	3.2%	3.2%	3.2%	3.2%	3.2%	3.2%	3.2%
.Rhode Island	0.4%	0.4%	0.4%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%
.South Carolina	1.4%	1.4%	1.4%	1.4%	1.4%	1.4%	1.4%	1.4%	1.4%	1.4%	1.4%	1.4%	1.4%	1.4%	1.4%	1.4%	1.4%	1.4%	1.4%	1.4%
.South Dakota	0.3%	0.3%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%
.Tennessee	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%	2.0%
.Texas	7.7%	8.0%	8.2%	8.5%	8.8%	9.2%	9.4%	9.6%	9.8%	9.8%	9.8%	9.8%	9.8%	9.8%	9.8%	9.8%	9.8%	9.8%	9.8%	9.8%
.Utah	0.8%	0.8%	0.9%	0.9%	0.9%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%	1.0%
.Vermont	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%
.Virginia	2.6%	2.6%	2.6%	2.7%	2.7%	2.7%	2.7%	2.7%	2.7%	2.7%	2.7%	2.7%	2.7%	2.7%	2.7%	2.7%	2.7%	2.7%	2.7%	2.7%
.Washington	2.1%	2.1%	2.2%	2.2%	2.3%	2.4%	2.4%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%
.West Virginia	0.6%	0.6%	0.6%	0.5%	0.5%	0.5%	0.4%	0.4%	0.4%	0.4%	0.4%	0.4%	0.4%	0.4%	0.4%	0.4%	0.4%	0.4%	0.4%	0.4%
.Wisconsin	1.9%	1.9%	1.8%	1.8%	1.7%	1.7%	1.7%	1.6%	1.6%	1.6%	1.6%	1.6%	1.6%	1.6%	1.6%	1.6%	1.6%	1.6%	1.6%	1.6%
.Wyoming	0.2%	0.2%	0.2%	0.2%	0.2%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%

4.0 Uncertainty Experiment: Market Intervention Through Minimum Efficiency Standards

Building equipment intervention is modeled as an increase in the minimum value of efficiency available in the marketplace in 2020 and after for a wide variety of equipment. For example, the minimum efficiency of residential natural-gas fired furnaces increase from 78% to 88% by 2020. The average efficiency of residential furnaces chosen in the marketplace increases as a result of this action because furnaces below 88% efficient are no longer available, but so does the average first cost of the equipment. There can be shifts in the marketplace as a result of standards among and across technologies as well the efficiency of the technology subject to the more aggressive standard. For example, gas furnaces and electric air conditioners both compete with electric heat pumps for market share in heating and cooling end-uses, respectively, and there may be shifts in market share among the three technologies.

GCAM-USA calculates market shares first among fuels and then among technologies within each fuel based on relative energy service costs, using the nested logit formulation shown in Equation (1):

$$Share_j = \frac{\alpha_j \cdot P_j^{\beta}}{\sum_j \alpha_j \cdot P_j^{\beta}} \tag{1}$$

Where $Share_j$ is the share of the total market for a service (e.g., heating) allocated to technology j; α_j is the "share-weight" of technology j; P_j is the service cost of technology j; and β is the logit exponent, which determines the degree to which the model exhibits "winner-take-all" behavior. Share-weights are calibrated so that the model reproduces observed base-year technology shares. Relative energy-service costs are determined by the market-clearing delivered price of each fuel, as calculated by the model (including carbon taxes, if any), and the physical efficiency and installed cost of each technology in supplying the energy service, determined by energy technology performance and cost scenarios based on the literature.

This analysis with GCAM-USA allows policy makers to intervene in the technology marketplace by specifying minimum energy-performance standards. The available menus of technology performance and costs are correlated with each. However, the shares of technologies chosen for each end use and, therefore, the overall energy use are chosen within the model. When policy makers intervene (aggressive standards case), the lowest level energy technologies and the lowest first costs are no longer available. The first costs of building equipment and the amount (and value) of energy savings both increase simultaneously as a result of the efficiency standard (Table 4.1).

Table 4.1 Average efficiency distribution of residential building equipment with current building standards and aggressive building standards (generally expressed as the ratio of annual energy services out/energy in. Appliances and "other" equipment are indexes of energy efficiency relative to 2005. The effects of *aggressive* building-energy policies are shown in italics).

Residential Equipment		**2020 Efficiency Distribution with Today's Building Standards**			**2020 Efficiency Distribution with Aggressive Building Standards**		
Service	**Technology**	**Low**	**Default**	**High**	**Low**	**Default**	**High**
Heat	Wood furnace	0.400	0.406	0.418	*0.415*	*0.415*	0.418
	Coal Furnace	0.400	0.406	0.418	*0.415*	*0.415*	0.418
	Gas furnace	0.780	0.780	0.850	*0.880*	*0.880*	*0.880*
	Gas furnace-hi eff	0.850	0.920	0.970	*0.880*	0.920	0.970
	Electric Furnace	1.000	1.000	1.000	1.000	1.000	1.000
	Electric heat pump	2.256	2.405	2.929	*2.490*	*2.490*	2.929
	Oil furnace	0.780	0.780	0.850	*0.900*	0.900	0.900
	Oil furnace-hi	0.850	0.850	0.950	*0.900*	0.900	0.950
Cooling	Air conditioning	2.637	2.738	3.824	*3.823*	*3.823*	3.824
	Air conditioning-hi	3.824	4.107	5.538	*3.824*	4.107	5.538
Water Heating	Gas water heater	0.590	0.590	0.770	*0.620*	*0.620*	0.770
	Gas water heater-hi	0.630	0.770	0.860	0.620	0.770	0.860
	Electric water heater	0.900	0.900	0.950	*0.920*	*0.920*	0.950
	Electric water heater-hi	0.950	0.950	0.950	0.920	0.950	0.950
	Electric HP water heater	2.200	2.200	2.400	*2.300*	*2.300*	2.400
	Oil water heater	0.530	0.530	0.660	*0.600*	*0.600*	0.660
	Oil water heater-hi	0.660	0.680	0.680	0.660	0.680	0.680
Lighting	Incandescent	0.015	0.021	0.027	*0.024*	*0.024*	0.027
	Fluorescent	0.122	0.122	0.122	*0.122*	0.122	0.122
	Solid State	0.094	0.154	0.234	*0.154*	0.154	0.234
Appliances	Gas Appliances	1.000	1.007	1.030	*1.030*	*1.030*	1.030
	Electric Appliances	1.030	1.108	1.225	*1.108*	1.108	1.225
	Electric Appliances-hi	1.120	1.675	1.820	*1.675*	1.675	1.820
	Fuel Appliances	1.000	1.000	1.000	*1.000*	1.000	1.000
	Other appliances	0.826	0.913	1.000	*0.913*	0.913	1.000
Other	Other Gas	1.000	1.000	1.000	1.000	1.000	1.000
	Other Electric	1.015	1.091	1.119	*1.090*	1.091	1.119
	Other Oil	1.000	1.000	1.000	1.000	1.000	1.000

4.1 Uncertainty Experiment Table

The effectiveness and cost of an aggressive building codes policy is affected by a number of uncertainties. Table 4.2 summarizes some key uncertainties. A number of factors were previously found in a systematic fractional-factorial sensitivity analysis to be important in explaining variation in building-energy consumption, cost, and carbon emissions in the GCAM model (Scott et al. 2014). These uncertainties included rate of population growth, changes in wealth (measured by changes in Gross Domestic Product [GDP] per worker), aggressiveness of carbon policy in reducing emissions(measured by Ref business-as-usual vs. CP emissions-reduction scenario), differences in modeling of the global climate, based on a given emissions scenario (modeled here with the future population-weighted heating and cooling degree-days in each state projected by the Geophysical Fluid Dynamics Laboratory [GFDL] model (Delworth et al. 2006) and Parallel Climate Model [PCM]) (Meehl et al. 2005), and uncertainties in pathways of future building technology performance and cost due to market factors and technology. Most of the uncertainties are described briefly; technology is a complicated topic and is discussed more fully in the text.

Table 4.2 Summary of uncertainties evaluated

Source of Uncertainty	Influence on Energy-Use Forecast	Variables Modeled	Uncertainties Modeled	Remarks
General circulation model	Different global climate models project different weather patterns for the same time profile of emissions.	Model is solved independently for two global climate models: GFDL and PCM for each emissions scenario. CASCaDE datasets for temperature are provided from each model for each emissions scenario the 1/8th degree level for the United States.	Changes in population-weighted state-level annual heating degree-days and cooling degree-days for the two different models. The uncertainties (and forecasts) are discrete and independent.	Forecasts of seasonal energy consumption in buildings will be affected by future temperatures, especially the balance between heating and cooling. We do not try to attach probabilities concerning which is the “right” model.
Global emissions of greenhouse gases	Climate (and therefore regional energy demand) is sensitive to the amount of CO_2 and other greenhouse gases in the atmosphere.	Heating degree day and cooling degree day scenarios are provided: the Ref and CP scenarios for both global climate models. Parameters used in the GCAM-USA model also are set to approximately reproduce the Ref and CP emissions profile.	Changes in population-weighted state-level annual heating degree-days and cooling degree-days from the CASCaDE dataset for the two different scenarios. Ref (“business-as-usual”) results in higher temperatures than CP (control). The forecasts are discrete and independent.	We do not try to attach probabilities concerning which is the “right” emissions pathway.

Source of Uncertainty	Influence on Energy-Use Forecast	Variables Modeled	Uncertainties Modeled	Remarks
Population growth	At the regional level, population growth affects the amount of future building space that will consume energy.	Total human population in each state and future time period, based on USCB and U.N. population forecasts.	The influences of future age-specific birth, death, and migration rates are subsumed under population scenarios provided by the USCB and U.N. The forecasts are continuous and independent.	The U.N. Population Division provides probabilities for the various growth pathways, allowing the pathways to be modeled probabilistically.
GDP/worker	Higher GDP/worker is generally associated with higher personal wealth and higher demand both for more building space and for more energy services per unit of building space.	Probability-weighted scenarios of five-year growth patterns in state-level GDP/worker are provided to the model based on U.S. Bureau of Economic Analysis data since the 1960s.	Historically, different states have experienced much different timing and volatility in per capita GDP growth from each other. The scenarios correlate the individual rates with the corresponding national values. The forecasts are continuous and independent.	By sampling 15-year growth rates at the state level and correlating them with national patterns, the scenarios allow for uncertainties both in national economic growth and in its geographic distribution among the states. The state correlations vary from being very close with national rates to being uncorrelated and in a few cases, negatively correlated.
Building equipment efficiency and cost	For a given level of building service demand, more efficient equipment generally costs more to purchase but delivers more energy services at lower cost, thus reducing the energy consumed and sometimes the overall cost of the service (combined energy and non-energy costs).	GCAM-USA models consumer choice with both base-technology and high-efficiency equipment for each major energy end use. There is a performance range (efficiency level) and corresponding first cost for each end use, technology, and time step. Residential and commercial buildings have different end-uses, competing technologies.	Probability distributions have been constructed for the average efficiency and annualized first cost of each technology option in each time step in the future. For most end-uses, there is for each time step both a base-technology and a high-efficiency technology option, each with a range of potential efficiency levels and correlated non-energy costs.	All states are assumed to share the same technology options. The economic value of better energy performance is affected by the level of climate-sensitive building-energy loads. Therefore, the technology choices and energy consumption are not independent at the state level. There is an alternative advanced technology future with more optimistic energy performance and lower unit costs.
Technological Change	Technological change reduces unit energy consumption over time after 2020. Technological change also reduces unit first cost during the forecast period after 2020. Benefits of technological change before 2020 are assumed to be incorporated in year 2020 efficiency and unit costs, whether for baseline or high-efficiency units.	Percent energy efficiency and first cost per mega-joule of energy consumed for each type of equipment.	The rates of improvement in cost and performance is assumed to be uncertain, resulting in a “fan” of potential efficiencies and a correlated “fan” of first costs at any particular date.	The range of improvement rates is generally assumed to be faster in the short term than the long term, as potential improvements begin to encounter technological limits. The relationship between performance and cost is weakly correlated, because costs may fall either due to improvement of the technology or its method of manufacture.

4.2 Uncertainty in Residential Equipment Performance and Cost

Viewed from 2013, each building technology has an uncertain potential range of efficiency performance in the future. Corresponding to this performance, each technology also has an annualized non-energy cost per gigajoule (GJ) of energy consumed that is assumed to be positively correlated with the efficiency of the technology. For many of the services, there are both base-technology, low-cost units and high-efficiency, high-cost units available. Table 4.3 shows the assumed performance and costs of the lowest, most likely (default), and highest performing residential technologies. A similar set of technologies and costs also exists for commercial building services and is discussed in the commercial building section. The policy-maker is assumed to set a minimum 2020 value for the efficiency of a given building service by regulation. Cost values are shown in 1975 dollars because cost calculations in GCAM-USA were performed in 1975 dollars. Because non-energy costs are assumed to be correlated with efficiency performance, setting a lower limit on efficiency also limits the lower bound of the non-energy cost. Where two or more technologies are available, the share of each technology in the market is inversely proportional to its total service cost, including both energy and non-energy cost.

Table 4.3 Residential building technology performance and cost assumptions for the year 2020 with current building equipment standards

Resiential Equipment		**2020 Efficiency Distribution (out/in)**			**2020 Cost Distribution (1975$)[a]**		
Service	**Technology**	**Low**	**Default**	**High**	**Low**	**Default**	**High**
Heat	Wood furnace	0.400	0.406	0.418	1.257	1.335	1.355
	Coal Furnace	0.400	0.406	0.418	1.257	1.335	1.355
	Gas furnace	0.780	0.780	0.850	2.473	2.473	2.740
	Gas furnace-hi eff	0.850	0.920	0.970	3.150	3.325	4.320
	Electric Furnace	1.000	1.000	1.000	1.930	1.930	1.930
	Electric heat pump	2.256	2.405	2.929	7.855	8.365	10.201
	Oil furnace	0.780	0.780	0.850	2.839	2.839	3.360
	Oil furnace-hi	0.850	0.850	0.950	3.090	3.363	3.759
Cooling	Air conditioning	2.637	2.738	3.824	8.775	8.775	10.720
	Air conditioning-hi	3.824	4.107	5.538	10.903	10.903	13.000
Water Heating	Gas water heater	0.590	0.590	0.770	7.258	7.258	12.344
	Gas water heater-hi	0.630	0.770	0.860	7.590	12.344	12.344
	Electric water heater	0.900	0.900	0.950	5.733	5.733	6.600
	Electric water heater-hi	0.950	0.950	0.950	6.601	6.601	6.601
	Electric HP water heater	2.200	2.200	2.400	8.329	8.329	11.661
	Oil water heater	0.530	0.530	0.660	12.252	12.252	13.477
	Oil water heater-hi	0.660	0.680	0.680	14.975	16.005	16.005
Lighting	Incandescent	0.015	0.021	0.027	22.170	32.555	40.987
	Fluorescent	0.122	0.122	0.122	55.322	55.322	55.322
	Solid State	0.094	0.154	0.234	236.234	387.571	590.585
Appliances	Gas Appliances	1.000	1.007	1.030	10.362	10.435	13.638
	Electric Appliances	1.030	1.108	1.225	13.589	14.618	19.401
	Electric Appliances-hi	1.120	1.675	1.820	14.618	19.401	19.401
	Fuel Appliances	1.000	1.000	1.000	12.949	12.949	13.145
	Other appliances	0.826	0.913	1.000	195.316	198.269	201.267
Other	Other Gas	1.000	1.000	1.000	19.702	19.702	20.000
	Other Electric	1.015	1.091	1.119	61.197	65.779	66.773
	Other Oil	1.000	1.000	1.000	19.702	19.702	20.000

[a] Cost calculations in GCAM-USA were performed in 1975 dollars.

4.2.1 Residential Technological Change

Future changes in individual technologies increase the efficiency in building equipment. For purposes of this paper, at the slow end of technological change, equipment gets about 0.1% more efficient per year after 2020, and non-energy cost per GJ consumed also declines at 0.1% per year. With faster technological change, equipment assumed to improve more quickly, with efficiency performance improving at the minimum rate of about 0.1% per year for the most mature technologies, but faster for equipment assumed to have significant "head room" for improvement (i.e., well below its theoretical maximum efficiency). There are three time periods considered, 2020 to 2035, 2036 to 2050, and after 2050. For each of the time periods, each technology is considered to have a range of efficiency growth rates and cost decline rates. Table 4.4 shows the annual rates associated with these distributions. Table 4.5 shows which distributions apply in which time periods for residential equipment. Table 4.6 shows the results for residential equipment efficiency change. Similar tables are shown in the commercial equipment section for commercial equipment.

Table 4.4 Distributions for rates of technological change for efficiency and costs[a]

	Distribution Values: Annual Rates of Change (%)			
	Default	**Low**	**Medium**	**High**
Zero_Slow	0.050	0	0.050	0.250
Slow	0.100	0.050	0.100	0.250
Slow_Medium	0.150	0.050	0.150	0.500
Medium	0.250	0.100	0.250	0.500
Slow_Fast	0.300	0.050	0.300	0.750
Medium_Fast	0.375	0.100	0.375	0.750
Slow_Very_Fast	0.475	0.050	0.475	1.000
Fast	0.500	0.250	0.500	0.750
Medium_Very_Fast	0.500	0.250	0.500	1.000
Slow_Extremely_Fast	0.550	0.100	0.550	1.500
Medium_Extremely_Fast	0.625	0.100	0.625	1.500
Very_Fast	0.750	0.500	0.750	1.000
Extremely_ Fast	1.000	0.750	1.000	1.500

[a] Rates for cost change have a negative sign. Technological change reduces first cost.

Table 4.5 Technological changes in residential building equipment performance and cost after 2020

Residnetial Equipment		**Post-2020 Efficiency Growth Rates**			**Post-2020 Cost Decline Rates**		
Service	**Technology**	**2020-2035**	**2036-2050**	**After 2050**	**2020-2035**	**2036-2050**	**After 2050**
Heat	Wood furnace	=Dist_Slow	=Dist_Slow	=Dist_Slow	=Dist_Slow_Cost	=Dist_Slow_Cost	=Dist_Slow_Cost
	Coal Furnace	=Dist_Slow	=Dist_Slow	=Dist_Slow	=Dist_Slow_Cost	=Dist_Slow_Cost	=Dist_Slow_Cost
	Gas furnace	=Dist_Slow	=Dist_Slow	=Dist_Slow	=Dist_Slow_Cost	=Dist_Slow_Cost	=Dist_Slow_Cost
	Gas furnace-hi eff	=Dist_Medium	=Dist_Slow_Medium	=Dist_Slow	=Dist_Slow_Extremely_Fast_Cost	=Dist_Slow_Fast_Cost	=Dist_Slow_Cost
	Electric Furnace	=Dist_Zero_Slow	=Dist_Zero_Slow	=Dist_Slow	=Dist_Slow_Cost	=Dist_Slow_Cost	=Dist_Slow_Cost
	Electric heat pump	=Dist_Medium	=Dist_Medium	=Dist_Slow	=Dist_Slow_Extremely_Fast_Cost	=Dist_Slow_Fast_Cost	=Dist_Slow_Cost
	Oil furnace	=Dist_Slow	=Dist_Slow	=Dist_Slow	=Dist_Slow_Cost	=Dist_Slow_Cost	=Dist_Slow_Cost
	Oil furnace-hi	=Dist_Slow	=Dist_Slow	=Dist_Slow	=Dist_Slow_Cost	=Dist_Slow_Cost	=Dist_Slow_Cost
Cooling	Air conditioning	=Dist_Medium	=Dist_Medium	=Dist_Slow	=Dist_Slow_Cost	=Dist_Slow_Cost	=Dist_Slow_Cost
	Air conditioning-hi	=Dist_Medium	=Dist_Medium	=Dist_Slow	=Dist_Slow_Extremely_Fast_Cost	=Dist_Slow_Fast_Cost	=Dist_Slow_Cost
Water Heating	Gas water heater	=Dist_Slow	=Dist_Slow	=Dist_Slow	=Dist_Slow_Cost	=Dist_Slow_Cost	=Dist_Slow_Cost
	Gas water heater-hi	=Dist_Slow	=Dist_Slow	=Dist_Slow	=Dist_Slow_Medium_Cost	=Dist_Slow_Medium_Cost	=Dist_Slow_Cost
	Electric water heater	=Dist_Zero_Slow	=Dist_Zero_Slow	=Dist_Slow	=Dist_Slow_Cost	=Dist_Slow_Cost	=Dist_Slow_Cost
	Electric water heater-hi	=Dist_Slow	=Dist_Slow	=Dist_Slow	=Dist_Slow_Medium_Cost	=Dist_Slow_Medium_Cost	=Dist_Slow_Cost
	Electric HP water heater	=Dist_Slow	=Dist_Slow	=Dist_Slow	=Dist_Slow_Extremely_Fast_Cost	=Dist_Slow_Fast_Cost	=Dist_Slow_Cost
	Oil water heater	=Dist_Slow	=Dist_Slow	=Dist_Slow	=Dist_Slow_Cost	=Dist_Slow_Cost	=Dist_Slow_Cost
	Oil water heater-hi	=Dist_Slow	=Dist_Slow	=Dist_Slow	=Dist_Slow_Fast_Cost	=Dist_Slow_Medium_Cost	=Dist_Slow_Cost

Residnetial Equipment		Post-2020 Efficiency Growth Rates			Post-2020 Cost Decline Rates		
Service	**Technology**	**2020-2035**	**2036-2050**	**After 2050**	**2020-2035**	**2036-2050**	**After 2050**
Lighting	Incandescent	=Dist_Slow	=Dist_Slow	=Dist_Slow	=Dist_Slow_Cost	=Dist_Slow_Cost	=Dist_Slow_Cost
	Fluorescent	=Dist_Slow	=Dist_Slow	=Dist_Slow	=Dist_Slow_Medium_Cost	=Dist_Slow_Medium_Cost	=Dist_Slow_Cost
	Solid State	=Dist_Fast	=Dist_Fast	=Dist_Slow	=Dist_Slow_Extremely_Fast_Cost	=Dist_Slow_Fast_Cost	=Dist_Slow_Cost
Appliances	Gas Appliances	=Dist_Slow	=Dist_Slow	=Dist_Slow	=Dist_Slow_Medium_Cost	=Dist_Slow_Medium_Cost	=Dist_Slow_Cost
	Electric Appliances	=Dist_Slow	=Dist_Slow	=Dist_Slow	=Dist_Slow_Medium_Cost	=Dist_Slow_Medium_Cost	=Dist_Slow_Cost
	Electric Appliances-hi	=Dist_Zero_Slow	=Dist_Zero_Slow	=Dist_Slow	=Dist_Slow_Extremely_Fast_Cost	=Dist_Slow_Fast_Cost	=Dist_Slow_Cost
	Fuel Appliances	=Dist_Slow	=Dist_Slow	=Dist_Slow	=Dist_Slow_Cost	=Dist_Slow_Cost	=Dist_Slow_Cost
	Other appliances	=Dist_Medium	=Dist_Medium	=Dist_Slow	=Dist_Slow_Medium_Cost	=Dist_Slow_Medium_Cost	=Dist_Slow_Cost
Other	Other Gas	=Dist_Slow	=Dist_Slow	=Dist_Slow	=Dist_Slow_Cost	=Dist_Slow_Cost	=Dist_Slow_Cost
	Other Electric	=Dist_Very_Fast	=Dist_Very_Fast	=Dist_Slow	=Dist_Slow_Cost	=Dist_Slow_Cost	=Dist_Slow_Cost
	Other Oil	=Dist_Zero_Slow	=Dist_Zero_Slow	=Dist_Slow	=Dist_Slow_Cost	=Dist_Slow_Cost	=Dist_Slow_Cost

Table 4.6 Residential sector technology-change-related annual percentage efficiency improvements for the periods from 2020 to 2035 and 2036 to 2050

Residential Equipmernt		**2020–2035**			**2036–2050**		
Service	**Technology**	**Low %**	**Default %**	**High %**	**Low %**	**Default %**	**High %**
Heat	Wood furnace	0.05	0.10	0.25	0.05	0.10	0.25
	Coal Furnace	0.05	0.10	0.25	0.05	0.10	0.25
	Gas furnace	0.05	0.10	0.25	0.05	0.10	0.25
	Gas furnace-hi eff	0.10	0.25	0.50	0.05	0.15	0.50
	Electric Furnace	0.00	0.05	0.25	0.00	0.05	0.25
	Electric heat pump	0.10	0.25	0.50	0.10	0.25	0.50
	Oil furnace	0.05	0.10	0.25	0.05	0.10	0.25
	Oil furnace-hi	0.05	0.10	0.25	0.05	0.10	0.25
Cooling	Air conditioning	0.10	0.25	0.50	0.10	0.25	0.50
	Air conditioning-hi	0.10	0.25	0.50	0.10	0.25	0.50
Water Heating	Gas water heater	0.05	0.10	0.25	0.05	0.10	0.25
	Gas water heater-hi	0.05	0.10	0.25	0.05	0.10	0.25
	Electric water heater	0.00	0.05	0.25	0.00	0.05	0.25
	Electric water heater-hi	0.05	0.10	0.25	0.05	0.10	0.25
	Electric HP water heater	0.05	0.10	0.25	0.05	0.10	0.25
	Oil water heater	0.05	0.10	0.25	0.05	0.10	0.25
	Oil water heater-hi	0.05	0.10	0.25	0.05	0.10	0.25
Lighting	Incandescent	0.05	0.10	0.25	0.05	0.10	0.25
	Fluorescent	0.05	0.10	0.25	0.05	0.10	0.25
	Solid State	0.25	0.50	0.75	0.25	0.50	0.75
Appliances	Gas Appliances	0.05	0.10	0.25	0.05	0.10	0.25
	Electric Appliances	0.05	0.10	0.25	0.05	0.10	0.25
	Electric Appliances-hi	0.00	0.05	0.25	0.00	0.05	0.25
	Fuel Appliances	0.05	0.10	0.25	0.05	0.10	0.25
	Other appliances	0.10	0.25	0.50	0.10	0.25	0.50
Other	Other Gas	0.05	0.10	0.25	0.05	0.10	0.25
	Other Electric	0.50	0.75	1.00	0.50	0.75	1.00
	Other Oil	0.00	0.05	0.25	0.00	0.05	0.25

Finally, whether or not the physical energy efficiency of a building service improves, the non-energy cost of each technology declines as a result of technological change over time. The range of rates of cost decline in the Fast Tech Change case are assumed to be uncertain but generally faster in the period 2020 to 2035, slower in 2036 to 2050, and still slower after 2050, as technologies mature. Some technologies are assumed to be mature and do not fall much in cost. For example, consider the case of residential electric furnaces and heat pumps. Resistance electric furnaces are already at the limits of potential efficiency and methods of manufacture are assumed to be near the limits of improvement. In contrast, electric heat pumps have some distance to go before they reach their maximum potential for performance and cost savings. This effect on non-energy service cost is illustrated in Figure 4.1, where the 2020 non-energy cost per GJ for electric furnaces starts at its default value of $1.93, but only declines at 0.1% per year. In the default case, the non-energy cost of a heat pump starts at its 2020 value of $8.36 per GJ, but then declines at 0.55% per year between 2020 and 2035, 0.3% per year between 2035 and 2050, and 0.1% per year after 2050. The cost ratio declines from 4.33 to 3.96. Because the heat pump initially is about 2.4 times as energy efficient as resistance heating and continues to advance, this represents a considerable change in the relative attractiveness of resistance heating versus heat pumps.

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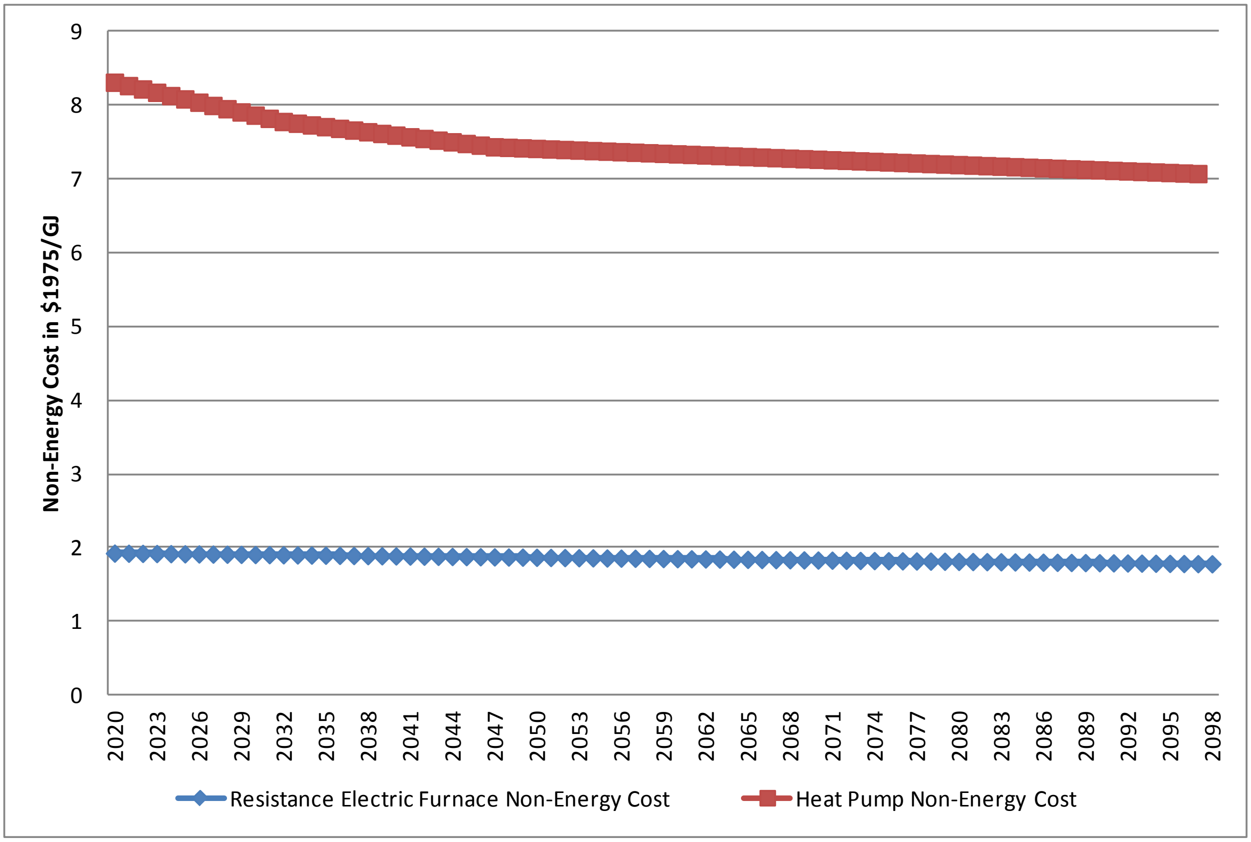

Figure 4.1 Effect of technological change on non-energy cost of residential heating equipment

The rate of cost decline is assumed to be weakly correlated with the rate of efficiency improvement. This happens for two reasons. First, the technology itself improves and costs less per unit of energy used. Second, the process of producing the equipment improves over time and lowers the unit cost. The first of these cost components is correlated with efficiency; the second is not necessarily correlated. Therefore, the rate of cost decline is correlated with the rate of efficiency improvement, but not closely correlated. We have assumed a correlation of 0.7. The ranges of rates of cost decline for each type of residential building equipment in the periods 2020 to 2035 and 2036 to 2050 are shown in Table 4.7. All technologies decline in cost at the same range of annual rates between 2051 and 2095; that is, -0.05% to -0.25%, with a default value of -0.1%. Generally speaking, the high-efficiency equipment currently occupies niche markets. As the higher-efficiency equipment becomes more commonplace through technology maturation and economies of scale, its costs should decline more rapidly than costs for lower-efficiency units. For equipment at an earlier stage of adoption such as solid-state lighting, the costs are expected to decline even faster (Figure 4.2).

Table 4.7 Residential building technology-change-related annual percentage cost decline for the periods 2020 to 2035 and 2036 to 2050

Residential Equipment		**2020–2035**			**2036–2050**		
Service	**Technology**	**Low %**	**Default %**	**High %**	**Low %**	**Default %**	**High %**
Heat	Wood furnace	-0.05	-0.10	-0.25	-0.05	-0.10	-0.25
	Coal Furnace	-0.05	-0.10	-0.25	-0.05	-0.10	-0.25
	Gas furnace	-0.05	-0.10	-0.25	-0.05	-0.10	-0.25
	Gas furnace-hi eff	-0.10	-0.55	-1.50	-0.05	-0.30	-0.75
	Electric Furnace	-0.05	-0.10	-0.25	-0.05	-0.10	-0.25
	Electric heat pump	-0.10	-0.55	-1.50	-0.05	-0.30	-0.75
	Oil furnace	-0.05	-0.10	-0.25	-0.05	-0.10	-0.25
	Oil furnace-hi	-0.05	-0.10	-0.25	-0.05	-0.10	-0.25
Cooling	Air conditioning	-0.05	-0.10	-0.25	-0.05	-0.10	-0.25
	Air conditioning-hi	-0.10	-0.55	-1.50	-0.05	-0.30	-0.75
Water Heating	Gas water heater	-0.05	-0.10	-0.25	-0.05	-0.10	-0.25
	Gas water heater-hi	-0.05	-0.15	-0.50	-0.05	-0.15	-0.50
	Electric water heater	-0.05	-0.10	-0.25	-0.05	-0.10	-0.25
	Electric water heater-hi	-0.05	-0.15	-0.50	-0.05	-0.15	-0.50
	Electric HP water heater	-0.10	-0.55	-1.50	-0.05	-0.30	-0.75
	Oil water heater	-0.05	-0.10	-0.25	-0.05	-0.10	-0.25
	Oil water heater-hi	-0.05	-0.30	-0.75	-0.05	-0.15	-0.50
Lighting	Incandescent	-0.05	-0.10	-0.25	-0.05	-0.10	-0.25
	Fluorescent	-0.05	-0.15	-0.50	-0.05	-0.15	-0.50
	Solid State	-0.10	-0.55	-1.50	-0.05	-0.30	-0.75
Appliances	Gas Appliances	-0.05	-0.15	-0.50	-0.05	-0.15	-0.50
	Electric Appliances	-0.05	-0.15	-0.50	-0.05	-0.15	-0.50
	Electric Appliances-hi	-0.10	-0.55	-1.50	-0.05	-0.30	-0.75
	Fuel Appliances	-0.05	-0.10	-0.25	-0.05	-0.10	-0.25
	Other appliances	-0.05	-0.15	-0.50	-0.05	-0.15	-0.50
Other	Other Gas	-0.05	-0.10	-0.25	-0.05	-0.10	-0.25
	Other Electric	-0.05	-0.10	-0.25	-0.05	-0.10	-0.25
	Other Oil	-0.05	-0.10	-0.25	-0.05	-0.10	-0.25

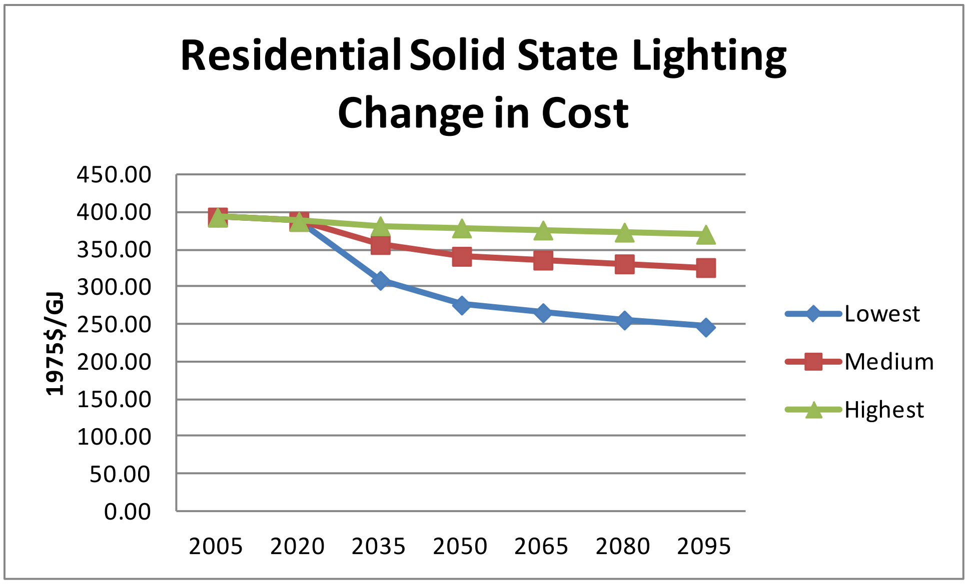

Figure 4.2 Example change in unit non-energy cost for residential solid state lighting due to technological change after 2020

4.3 Uncertainty in Commercial Equipment Performance and Cost

Although specific commercial building equipment is different than residential equipment (e.g., there are different end-uses in the commercial sector), the calculations of cost and performance for the equipment follow a similar pattern. Table 4.8, which shows the efficiency distributions for commercial equipment in 2020 under current and aggressive standards, is analogous to Table 4.1 for the residential building sector. Similarly, Table 4.9 is analogous to Table 4.3.

Table 4.8 Average efficiency distribution of commercial building equipment with current building standards and with aggressive building standards (generally expressed as the ratio of annual energy services out/energy in). Appliances and "other" equipment are indexes of energy efficiency relative to 2005. The effects of *aggressive* building-energy policies are shown in italics)

Commercial Equipment		**2020 Efficiency Distribution with Today's Building Standards**			**2020 Efficiency Distribution with Aggressive Building Standards**		
Service	**Technology**	**Low**	**Default**	**High**	**Low**	**Default**	**High**
Heat	Biomass boiler	0.650	0.660	0.675	*0.660*	0.660	0.675
	Coal Furnace	0.650	0.660	0.675	*0.660*	0.660	0.675
	Gas furnace	0.700	0.775	0.855	*0.880*	*0.880*	*0.880*
	Gas furnace-hi eff	0.800	0.868	0.900	*0.880*	*0.880*	0.900
	Electric Furnace	1.000	1.000	1.000	1.000	1.000	1.000
	Electric heat pump	3.100	3.300	3.400	*3.300*	3.300	3.400
	Oil furnace	0.780	0.810	0.830	*0.830*	*0.830*	0.830
	Oil furnace-hi	0.830	0.850	0.890	0.830	0.850	0.890
Cooling	Gas Cooling	0.898	0.919	0.932	*0.919*	0.919	0.932
	Air conditioning	2.782	2.782	3.514	*3.280*	*3.280*	3.514

Commercial Equipment		**2020 Efficiency Distribution with Today's Building Standards**			**2020 Efficiency Distribution with Aggressive Building Standards**		
Service	**Technology**	**Low**	**Default**	**High**	**Low**	**Default**	**High**
	Air conditioning-hi	3.280	3.514	3.748	3.280	3.514	3.748
Water Heating	Gas water heater	0.792	0.792	0.940	*0.800*	*0.800*	0.940
	Gas water heater-hi	0.940	0.954	0.969	0.800	0.954	0.969
	Electric water heater	0.980	0.990	0.990	0.950	0.990	0.990
	Electric HP water heater	2.200	2.200	2.400	*2.300*	*2.300*	2.400
	Oil water heater	0.780	0.801	0.805	*0.800*	0.801	0.805
Ventilation	Ventilation	0.710	0.721	0.854	*0.721*	0.721	0.854
	Ventilation hi-eff	0.854	0.867	0.867	0.721	0.867	0.867
Cooking	Gas stove	0.521	0.527	0.533	*0.527*	0.527	0.533
	Electric stove	0.724	0.748	0.755	*0.750*	0.750	0.755
Lighting	Incandescent	0.014	0.021	0.024	*0.024*	*0.024*	0.024
	Fluorescent	0.085	0.120	0.131	*0.131*	*0.131*	0.131
	Solid State	0.094	0.154	0.234	*0.154*	0.154	0.234
Refrigeration	Refrigeration	1.994	2.482	2.668	*2.482*	2.482	2.668
	refrigeration hi-eff	2.668	3.141	3.212	2.482	3.141	3.212
Office	Office Equipment	1.015	1.038	1.078	*1.240*	*1.240*	1.240
Other	Other Gas	1.015	1.038	1.078	*1.038*	1.038	1.078
	Other Electric	0.970	0.973	1.069	*1.050*	*1.050*	1.069
	Other Oil	1.015	1.015	1.078	*1.050*	*1.050*	1.078

Table 4.9 Commercial building technology performance and cost assumptions for 2020 with current building equipment standards

Commercial Equipment		**2020 Efficiency Distribution (out/in)**			**2020 Cost Distribution (1975$)[a]**		
Service	**Technology**	**Low**	**Default**	**High**	**Low**	**Default**	**High**
Heat	Biomass boiler	0.650	0.660	0.675	1.315	1.335	1.355
	Coal Furnace	0.650	0.660	0.675	1.315	1.335	1.355
	Gas furnace	0.700	0.775	0.855	2.609	2.888	2.932
	Gas furnace-hi eff	0.800	0.868	0.900	3.760	4.079	4.141
	Electric Furnace	1.000	1.000	1.000	1.728	1.728	1.754
	Electric heat pump	3.100	3.300	3.400	3.115	3.316	3.366
	Oil furnace	0.780	0.810	0.830	0.923	0.958	0.958
	Oil furnace-hi eff	0.830	0.850	0.890	1.377	1.411	1.411
Cooling	Gas Cooling	0.898	0.919	0.932	4.811	4.926	5.000
	Air conditioning	2.782	2.782	3.514	2.233	2.233	2.586

Commercial Equipment		**2020 Efficiency Distribution (out/in)**			**2020 Cost Distribution (1975$)[a]**		
Service	**Technology**	**Low**	**Default**	**High**	**Low**	**Default**	**High**
	Air conditioning-hi	3.280	3.514	3.748	2.414	2.586	4.240
Water Heating	Gas water heater	0.792	0.792	0.940	0.420	0.420	0.441
	Gas water heater-hi	0.940	0.954	0.969	0.749	0.761	0.772
	Electric water heater	0.980	0.990	0.990	0.486	0.491	0.550
	Electric HP water heater	2.200	2.200	2.400	1.025	1.025	1.040
	Oil water heater	0.780	0.801	0.805	0.471	0.484	0.491
Ventilation	Ventilation	0.710	0.721	0.854	10.047	10.199	10.199
	Ventilation hi-eff	0.854	0.867	0.867	13.056	13.253	29.039
Cooking	Gas stove	0.521	0.527	0.533	25.119	25.390	25.774
	Electric stove	0.724	0.748	0.755	40.600	41.968	42.603
Lighting	Incandescent	0.014	0.021	0.024	16.666	25.798	26.188
	Fluorescent	0.085	0.120	0.131	13.362	18.873	19.158
	Solid State	0.094	0.154	0.234	68.667	112.852	114.559
Refrigeration	Refrigeration	1.994	2.482	2.668	4.225	5.260	5.340
	refrigeration hi-eff	2.668	3.141	3.212	6.715	7.905	7.905
Office	Office Equipment	1.015	1.038	1.078	42.562	43.529	44.187
Other	Other Gas	1.015	1.038	1.078	19.265	19.702	20.000
	Other Electric	0.970	0.973	1.069	39.349	39.467	40.064
	Other Oil	1.015	1.015	1.078	19.702	19.702	20.000

[a] Cost calculations in GCAM-USA were performed in 1975 dollars.

4.3.1 Technological Change in Commercial Equipment

Although the services and technologies are different from those in the residential buildings, a similar approach was followed to develop scenarios of changes in energy efficiency performance and non-energy costs for technologies used in the commercial building sector. Similar to residential equipment, some commercial equipment is assumed to improve at the minimum rate of 0.1% per year, but the rate will be faster for equipment assumed to have significant “head room” for improvement (i.e., equipment that, in its current state of development, is well below its theoretical maximum efficiency).

The distribution of rates is selected in a similar manner to the residential sector. The distributions for the commercial building sector are shown in Table 4.10. The corresponding improvement rates for various technologies are shown in Table 4.11.

Table 4.10 Technological changes in commercial building equipment performance and cost after 2020

Commercial Equipment		**Post-2020 Efficiency Growth Rates**			**Post-2020 Cost Decline Rates**		
Service	**Technology**	**2020–2035**	**2036–2050**	**After 2050**	**2020–2035**	**2036–2050**	**After 2050**
Heat	Biomass Boiler (Wood Furnace)	Dist_Slow	Dist_Slow	Dist_Slow	Dist_Slow_Cost	Dist_Slow_Cost	Dist_Slow_Cost
	Coal Furnace	Dist_Slow	Dist_Slow	Dist_Slow	Dist_Slow_Cost	Dist_Slow_Cost	Dist_Slow_Cost
	Gas furnace	Dist_Slow	Dist_Slow	Dist_Slow	Dist_Slow_Medium_Cost	Dist_Slow_Medium_Cost	Dist_Slow_Cost
	Gas furnace-hi	Dist_Slow	Dist_Slow	Dist_Slow	Dist_Slow_Medium_Cost	Dist_Slow_Medium_Cost	Dist_Slow_Cost
	Electric Furnace	Dist_Zero_Slow	Dist_Zero_Slow	Dist_Slow	Dist_Slow_Cost	Dist_Slow_Cost	Dist_Slow_Cost
	Electric heat pump	Dist_Medium	Dist_Medium	Dist_Slow	Dist_Slow_Extremely_Fast_Cost	Dist_Slow_Fast_Cost	Dist_Slow_Cost
	Oil furnace	Dist_Slow	Dist_Slow	Dist_Slow	Dist_Slow_Cost	Dist_Slow_Cost	Dist_Slow_Cost
	Oil furnace-hi	Dist_Slow	Dist_Slow	Dist_Slow	Dist_Slow_Fast_Cost	Dist_Slow_Medium_Cost	Dist_Slow_Cost
Cooling	Gas cooling	Dist_Slow	Dist_Zero_Slow	Dist_Zero_Slow	Dist_Slow_Medium_Cost	Dist_Slow_Medium_Cost	Dist_Slow_Cost
	Air conditioning	Dist_Medium	Dist_Medium	Dist_Slow	Dist_Slow_Cost	Dist_Slow_Cost	Dist_Slow_Cost
	Air conditioning-hi	Dist_Medium	Dist_Medium	Dist_Slow	Dist_Slow_Extremely_Fast_Cost	Dist_Slow_Fast_Cost	Dist_Slow_Cost
Water Heating	Gas water heater	Dist_Slow	Dist_Slow	Dist_Slow	Dist_Slow_Cost	Dist_Slow_Cost	Dist_Slow_Cost
	Gas water heater-hi	Dist_Slow	Dist_Slow	Dist_Slow	Dist_Slow_Cost	Dist_Slow_Cost	Dist_Slow_Cost
	Electric water heater	Dist_Zero_Slow	Dist_Zero_Slow	Dist_Slow	Dist_Slow_Cost	Dist_Slow_Cost	Dist_Slow_Cost
	Electric HP water heater	Dist_Slow	Dist_Slow	Dist_Slow	Dist_Slow_Extremely_Fast_Cost	Dist_Slow_Fast_Cost	Dist_Slow_Cost
	Oil water heater	Dist_Slow	Dist_Slow	Dist_Slow	Dist_Slow_Cost	Dist_Slow_Cost	Dist_Slow_Cost
Ventilation	Ventilation	Dist_Slow	Dist_Slow	Dist_Slow	Dist_Slow_Cost	Dist_Slow_Cost	Dist_Slow_Cost
	Ventilation hi-eff	Dist_Slow	Dist_Slow	Dist_Slow	Dist_Slow_Medium_Cost	Dist_Slow_Medium_Cost	Dist_Slow_Cost

Commercial Equipment		Post-2020 Efficiency Growth Rates			Post-2020 Cost Decline Rates		
Service	**Techno-logy**	**2020–2035**	**2036–2050**	**After 2050**	**2020–2035**	**2036–2050**	**After 2050**
Cooking	Gas stove	Dist_Slow	Dist_Slow	Dist_Slow	Dist_Slow_Cost	Dist_Slow_Cost	Dist_Slow_Cost
	Electric stove	Dist_Slow_Medium	Dist_Slow_Medium	Dist_Slow	Dist_Slow_Cost	Dist_Slow_Cost	Dist_Slow_Cost
Lighting	Incandescent	Dist_Slow	Dist_Slow	Dist_Slow	Dist_Slow_Cost	Dist_Slow_Cost	Dist_Slow_Cost
	Fluorescent	Dist_Slow	Dist_Slow	Dist_Slow	Dist_Slow_Medium_Cost	Dist_Slow_Medium_Cost	Dist_Slow_Cost
	Solid State	Dist_Medium_Fast	Dist_Medium_Fast	Dist_Slow	Dist_Slow_Extremely_Fast_Cost	Dist_Slow_Fast_Cost	Dist_Slow_Cost
Refrigeration	refrigeration	Dist_Medium	Dist_Medium	Dist_Slow	Dist_Slow_Medium_Cost	Dist_Slow_Medium_Cost	Dist_Slow_Cost
	Refrigeration hi-eff	Dist_Slow	Dist_Slow	Dist_Slow	Dist_Slow_Medium_Cost	Dist_Slow_Medium_Cost	Dist_Slow_Cost
Office	Office Equipment	Dist_Medium_Very_Fast	Dist_Medium	Dist_Slow	Dist_Slow_Medium_Cost	Dist_Slow_Medium_Cost	Dist_Slow_Cost
Other	Other Gas	Dist_Medium	Dist_Medium	Dist_Slow	Dist_Slow_Cost	Dist_Slow_Cost	Dist_Slow_Cost
	Other Electric	Dist_Medium_Very_Fast	Dist_Medium_Very_Fast	Dist_Slow	Dist_Slow_Extremely_Fast_Cost	Dist_Slow_Fast_Cost	Dist_Slow_Cost
	Other Oil	Dist_Medium	Dist_Medium	Dist_Slow	Dist_Slow_Cost	Dist_Slow_Cost	Dist_Slow_Cost

Table 4.11 Annual efficiency improvement rates for selected commercial building equipment for the periods from 2020 to 2035 and 2036 to 2050

Commercial Equipment		2020–2035			2036–2050		
Service	**Technology**	**Low %**	**Default %**	**High %**	**Low %**	**Default %**	**High %**
Heat	Biomass Boiler (Wood Furnace)	0.05	0.10	0.25	0.05	0.10	0.25
	Coal Furnace	0.05	0.10	0.25	0.05	0.10	0.25
	Gas furnace	0.05	0.10	0.25	0.05	0.10	0.25
	Gas furnace-hi	0.05	0.10	0.25	0.05	0.10	0.25
	Electric Furnace	0.00	0.05	0.25	0.00	0.05	0.25
	Electric heat pump	0.10	0.25	0.50	0.10	0.25	0.50
	Oil furnace	0.05	0.10	0.25	0.05	0.10	0.25
	Oil furnace-hi	0.05	0.10	0.25	0.05	0.10	0.25
Cooling	Gas cooling	0.05	0.10	0.25	0.00	0.05	0.25
	Air conditioning	0.10	0.25	0.50	0.10	0.25	0.50
	Air conditioning-hi	0.10	0.25	0.50	0.10	0.25	0.50
Water Heating	Gas water heater	0.05	0.10	0.25	0.05	0.10	0.25
	Gas water heater-hi	0.05	0.10	0.25	0.05	0.10	0.25
	Electric water heater	0.00	0.05	0.25	0.00	0.05	0.25

Commercial Equipment		2020–2035			2036–2050		
Service	**Technology**	**Low %**	**Default %**	**High %**	**Low %**	**Default %**	**High %**
	Electric HP water heater	0.05	0.10	0.25	0.05	0.10	0.25
	Oil water heater	0.05	0.10	0.25	0.05	0.10	0.25
Ventilation	Ventilation	0.05	0.10	0.25	0.05	0.10	0.25
	Ventilation hi-eff	0.05	0.10	0.25	0.05	0.10	0.25
Cooking	Gas stove	0.05	0.10	0.25	0.05	0.10	0.25
	Electric stove	0.05	0.15	0.50	0.05	0.15	0.50
Lighting	Incandescent	0.05	0.10	0.25	0.05	0.10	0.25
	Fluorescent	0.05	0.10	0.25	0.05	0.10	0.25
	Solid State	0.10	0.38	0.75	0.10	0.38	0.75
Refrigeration	Refrigeration	0.10	0.25	0.50	0.10	0.25	0.50
	refrigeration hi-eff	0.05	0.10	0.25	0.05	0.10	0.25
Office	Office Equipment	0.25	0.50	1.00	0.10	0.25	0.50
Other	Other Gas	0.10	0.25	0.50	0.10	0.25	0.50
	Other Electric	0.25	0.50	1.00	0.25	0.50	1.00
	Other Oil	0.10	0.25	0.50	0.10	0.25	0.50

Similar to the ranges of rates of cost decline for each type of residential building equipment in the years from 2020 to 2035 and 2036 to 2050, Table 4.12 shows these rates for the commercial building sector. All technologies decline in cost at the same range of annual rates between 2051 and 2095; that is, between -0.05% and -0.25%, with a default value of -0.1%. As with the residential building sector, the high-efficiency equipment currently occupies niche markets. As the equipment becomes more widely used because of technology maturation and economies of scale, its cost will decline more rapidly than that of lower-efficiency units. For equipment at an earlier stage of adoption such as solid-state lighting, costs are expected decline even faster, but with a relatively high degree of uncertainty.

Table 4.12 Commercial building baseline technology cost change for the periods from 2020 to 2035 and 2036 to 2050

Commercial Equipment		**2020–2035**			**2036–2050**		
Service	**Technology**	**Low %**	**Default %**	**High %**	**Low %**	**Default %**	**High %**
Heat	Wood furnace	-0.05	-0.10	-0.25	-0.05	-0.10	-0.25
	Coal Furnace	-0.05	-0.10	-0.25	-0.05	-0.10	-0.25
	Gas furnace	-0.05	-0.15	-0.50	-0.05	-0.15	-0.50
	Gas furnace-hi eff	-0.05	-0.15	-0.50	-0.05	-0.15	-0.50
	Electric Furnace	-0.05	-0.10	-0.25	-0.05	-0.10	-0.25
	Electric heat pump	-0.10	-0.55	-1.50	-0.05	-0.30	-0.75
	Oil furnace	-0.05	-0.10	-0.25	-0.05	-0.10	-0.25
	Oil furnace-hi	-0.05	-0.30	-0.75	-0.05	-0.15	-0.50
Cooling	Gas Cooling	-0.05	-0.15	-0.50	-0.05	-0.15	-0.50
	Air conditioning	-0.05	-0.10	-0.25	-0.05	-0.10	-0.25
	Air conditioning-hi	-0.10	-0.55	-1.50	-0.05	-0.30	-0.75
Water Heating	Gas water heater	-0.05	-0.10	-0.25	-0.05	-0.10	-0.25
	Gas water heater-hi	-0.05	-0.10	-0.25	-0.05	-0.10	-0.25
	Electric water heater	-0.05	-0.10	-0.25	-0.05	-0.10	-0.25
	Electric HP water heater	-0.10	-0.55	-1.50	-0.05	-0.30	-0.75
	Oil water heater	-0.05	-0.10	-0.25	-0.05	-0.10	-0.25
Ventilation	Ventilation	-0.05	-0.10	-0.25	-0.05	-0.10	-0.25
	Ventilation hi eff	-0.05	-0.15	-0.50	-0.05	-0.15	-0.50
Cooking	Gas stove	-0.05	-0.10	-0.25	-0.05	-0.10	-0.25
	Electric stove	-0.05	-0.10	-0.25	-0.05	-0.10	-0.25
Lighting	Incandescent	-0.05	-0.15	-0.50	-0.05	-0.15	-0.50
	Fluorescent	-0.05	-0.15	-0.50	-0.05	-0.15	-0.50
	Solid State	-0.10	-0.55	-1.50	-0.05	-0.30	-0.75
Refrigeration	Refrigeration	-0.05	-0.15	-0.50	-0.05	-0.15	-0.50
	Refrigeration -hi	-0.05	-0.15	-0.50	-0.05	-0.15	-0.50
Office	Office Equipment	-0.05	-0.15	-0.50	-0.05	-0.15	-0.50
Other	Other Gas	-0.05	-0.10	-0.25	-0.05	-0.10	-0.25
	Other Electric	-0.10	-0.55	-1.50	-0.05	-0.30	-0.75
	Other Oil	-0.05	-0.10	-0.25	-0.05	-0.10	-0.25

5.0 Building Shell

For purposes of GCAM-USA, the building shell is defined as the envelope or “skin” of the building; that is the roof, walls, windows, doors, and foundation, and other built-in features of the building that are subject to building-energy codes such as overall lighting; heating, ventilation, and air conditioning; and water heating. Energy use related to the building shell (expressed as overall watts per square meter of floor space) is a function of several factors, including the age, rate of turnover, and mix of the building stock among building types. For example, residential buildings are divided into single-family, multifamily, and manufactured housing, each with several subtypes, vintages, and sizes. Regulations address energy use related to the building shell through building-energy codes that have stated standards for the overall resistance of the building envelope to heat flow (loss or gain) through walls, roof, windows, doors, foundation, etc. State and local agencies adopt and enforce these requirements for new buildings and for code-significant additions, alterations, and renovations. The rate of improvement in such efficiency required by the codes, the rate of code adoption, and rate of code enforcement are all uncertain. In this analysis, uncertainty is captured by assuming a base rate of shell improvement over time for new buildings, then multiplying this base rate by multipliers that vary over time and are also uncertain for whichever period they apply. The average stock improvement rate is calculated as the change in the vintage-weighted efficiency of existing buildings at each date. Table 5.1 shows the multipliers adopted for the new residential building stock.

These standards are loosely based on analyses that have been conducted in support of International Energy Codes Council model building-energy codes. At the low end of current standards, new building shells built in 2020 would be about 9% more efficient than new buildings built in 2005, and at the high end, about 23%. With aggressive standards, the new building in 2020 would be 26% more efficient and at the high end, 33% more efficient than the new building in 2005. Incremental costs to meet the 2020 standards are slightly more than \$1.44 per ft^2 in 2011\$ for a roughly 20% improvement in shell efficiency, or \$3.60 per m^2 in 1975\$. Residential retrofit costs are about 40 to 50% higher. The annualized mortgage charges in 1975\$ used by GCAM-USA are \$0.210 and \$0.307 per $m^2$for new and retrofit projects, respectively. Commercial rates for 20% efficiency improvement in new buildings are about \$2.07 per m^2 in 1975\$, but available data on retrofit costs for similar efficiency improvements suggests that commercial retrofit costs are considerably higher—about \$6 per ft^2 in 2008\$ or \$12.64 per m^2 in 1975\$. The corresponding mortgage charges in 1975\$ are \$0.147 and \$0.897 per m^2.

The vintage-weighted-average improvement rates in watts per m^2 of energy loss are shown in Table 5.2 for residential buildings. The same vintage-weighted-average annual rates of improvement in energy efficiency are assumed to apply to commercial buildings. When combined with the spread in year 2020 efficiencies and spreads in improvement rates over the century, current standards could lead new buildings to be 28 to 41 percent more efficient than a 2005 building. With aggressive standards, the 2095 buildings could be 41 to 48 percent more efficient. Table 5.3 shows the estimated weighted-average annual stock efficiency improvement rates in GCAM-USA. Similar to what GCAM-USA does for population path uncertainty, the model samples the improvement pathways implicit in the triangular density functions that are spanned by the rates in Table 5.3. The same improvement scenarios are currently used for residential and commercial buildings.

Table 5.4 shows the estimated first costs of energy standards in 2020 and after; Table 5.5 contains equivalent data for commercial buildings. In Table 5.1 through Table 5.5, building-energy codes are assumed to be adopted as the available energy technology improves. Costs per m^2 are assumed to increase as more stringent codes are adopted, but technological change also slows the rate of cost increase.

Table 5.1 Building-energy standard, new residential construction improvement, and costs per m^2 in 2020 relative to 2005

	Current Standards		**Aggressive Standards**	
	Efficiency	**$/m^2**	**Efficiency**	**$/m^2**
Low	1.100	1.009	1.350	1.030
Default	1.200	1.018	1.380	1.036
High	1.300	1.025	1.500	1.040

Table 5.2 Building technology scenarios, reference growth assumptions

	Efficiency		**Cost**	
	2021–2050	**2051–2095**	**2021–2050**	**2051–2095**
Slowest	4% per decade	2.5% per decade	2.4% per decade	2.4% per decade
Fastest	5% per decade	2.5% per decade	1.2% per decade	1.2% per decade

Table 5.3 Weighted-average annual stock efficiency improvement rates

	2020	**2035**	**2050**	**2065**	**2080**	**2095**
Current Building Standards, Slowest and Fastest Technological Growth						
Low, Slow	0.504%	0.473%	0.437%	0.360%	0.319%	0.289%
Low, Fast	0.504%	0.486%	0.472%	0.395%	0.346%	0.308%
Default, Slow	0.597%	0.609%	0.541%	0.426%	0.365%	0.321%
Default, Fast	0.597%	0.624%	0.578%	0.461%	0.391%	0.340%
High, Slow	0.687%	0.741%	0.638%	0.485%	0.405%	0.349%
High, Fast	0.687%	0.756%	0.675%	0.521%	0.432%	0.368%
Aggressive Building Standards, Slowest and Fastest Technological Growth						
Low, Slow	0.730%	0.804%	0.684%	0.513%	0.424%	0.362%
Low, Fast	0.730%	0.820%	0.721%	0.549%	0.450%	0.381%
Default, Slow	0.756%	0.842%	0.710%	0.529%	0.435%	0.370%
Default, Fast	0.756%	0.858%	0.748%	0.565%	0.461%	0.389%
High, Slow	0.857%	0.988%	0.812%	0.589%	0.474%	0.397%
High, Fast	0.857%	1.004%	0.851%	0.626%	0.501%	0.416%

Table 5.4 Weighted average initial cost of meeting new residential building codes and retrofitting existing buildings (1975$ per m^2)

	2020	2035	2050	2065	2080	2095
Current Building Standards and Rate of Technological Change						
Low, Slow	5.02	5.23	5.43	5.64	5.83	6.03
Low, Fast	5.02	5.13	5.24	5.36	5.45	5.55
Default, Slow	5.07	5.27	5.48	5.69	5.88	6.08
Default, Fast	5.07	5.18	5.29	5.41	5.50	5.60
High, Slow	5.10	5.31	5.52	5.73	5.92	6.12
High, Fast	5.10	5.22	5.33	5.45	5.54	5.64
Aggressive Building Standards and Rate of Technological Change						
Low, Slow	5.13	5.33	5.54	5.76	5.95	6.15
Low, Fast	5.13	5.24	5.35	5.47	5.57	5.67
Default, Slow	5.16	5.37	5.58	5.79	5.98	6.19
Default, Fast	5.16	5.27	5.38	5.50	5.60	5.70
High, Slow	5.18	5.39	5.60	5.81	6.01	6.21
High, Fast	5.18	5.29	5.40	5.53	5.62	5.72

Table 5.5 Weighted average initial cost of meeting new commercial building codes and retrofitting existing buildings (1975$ per m^2)

	2020	2035	2050	2065	2080	2095
Current Building Standards and Rate of Technological Change						
Low, Slow	7.87	8.03	8.08	8.05	8.07	8.13
Low, Fast	7.87	8.01	8.05	8.00	8.00	8.04
Default, Slow	7.87	8.04	8.09	8.06	8.08	8.14
Default, Fast	7.87	8.02	8.06	8.00	8.01	8.05
High, Slow	7.88	8.05	8.10	8.07	8.09	8.15
High, Fast	7.88	8.03	8.07	8.01	8.01	8.05
Aggressive Building Standards and Rate of Technological Change						
Low, Slow	7.89	8.05	8.11	8.07	8.09	8.16
Low, Fast	7.89	8.03	8.07	8.02	8.02	8.06
Default, Slow	7.89	8.06	8.11	8.08	8.10	8.16
Default, Fast	7.89	8.04	8.08	8.02	8.02	8.07
High, Slow	7.89	8.06	8.11	8.08	8.10	8.17
High, Fast	7.89	8.04	8.08	8.03	8.03	8.07

6.0 Sources for Energy Efficiency and Cost Information

Table 6.1 through Table 6.4 provide detail on energy efficiency and cost assumptions. A key for the references appears after Table 6.4.

Table 6.1 Sources for 2020 residential efficiency

Residential Equipment		2020 Efficiency Distribution Values (Out/In) and Source		
Service	**Technology**	**Low**	**Default**	**High**
Heat	Wood furnace	0.400: No improvement from 2005	0.406: Performance increases from 2005 at 0.1% per year	0.418: 2050 default value reached early
	Coal Furnace	Same as wood	Same as wood	Same as wood
	Gas furnace	0.780: Already at 0.78. Cannot go lower	0.780: Assumed rate in LBNL 2020	0.850: Same as oil furnace
	Gas furnace-hi eff	0.850: no improvement from 2005	0.920 Assumed rate in NECost_ LBNL_ Res_2020	0.945: Average of 2020 and 2050 default values
	Electric Furnace	1.000	1.000	1.000
	Electric heat pump	2.256: Minimum HSPF of 7.7 in DOE Appliance Stds for 2006-2015 Split System HP	2.405: AEO 2007, Table 31 for the yr 2020	2.929: Max HSPF = 10 (current max tech is about 9.9
	Oil furnace	0.780: Same as Typical model in Navigant 2007	0.780: NECost_LBNL_2020_Res min eff equipment	0.850: Based on NECost_LBNL_2020_Res high end
	Oil furnace-hi	0.850: Assumed to be next level down to the default case in NECosts, LBNL_Res_2020.	0.850: NECost _LBNL_Res_2020 max eff equipment	0.950: High value for 2020 in Navigant 2007
Cooling	Air conditioning	2.637 Assume no change from 2005 (SEER = 10). However, min standard is already at SEER = 12, and 13-14 have been proposed by DOE:	2.738: Equals 2005 escalated at 0.25% per year. SEER = 10.37	3.824: High end "low tech" equipment is at about SEER = 14.5
	Air conditioning-hi	3.824: Minimum Advanced unit Currently is about SEER = 14.5	4.107: 2005, escalated at 0.25% per year. SEER =15.57	5.538: Max for 2020 in AEO 2012 for 2010 is about 21. Consistent with max tech in the Central Air Conditioning Rulemaking in 2011.
Water Heating	Gas water heater	0.590: Min Standard Navigant 2007	0.590: NECost_LBNL_Res_2020_ min efficiency	0.770: NECost_LBNL_Res_2020 highest efficiency
	Gas water heater-hi	0.630: Navigant 2007, Typical for 2020	0.770: NECost_LBNL_Res 2020 highest efficiency	0.860: Navigant 2007, highest available for 2020
	Electric water heater	0.900: NECost_LBNL_Res_2000 , low value. Also current standard	0.900: Same as low value	0.950: NECost, LBNL_res_2020, max level
	Electric water heater-hi	0.950: NECost_LBNL_2020 res high value. Assumed to be max tech.	0.950: same as low	0.950: Same as low
	Electric HP water heater	2.200: Navigant 2007 base for pre-2010 (no	2.200: NECost_LBNL_Res_2020	2.400: Navigant 2007 high value for 2020

Residential Equipment		2020 Efficiency Distribution Values (Out/In) and Source		
Service	Technology	Low	Default	High
		improvement)		
	Oil water heater	0.530: Navigant today's (2004) standard	0.530: Same as low	0.660: Appears to be the high end of conventional equipment. Costs are greater for units at 0.68. See high-eff
	Oil water heater-hi	0.660: Based on the lower of two upper-end values in NECost_LBN_Res_2020:	0.680: Highest value found in NECost_LBNL_Res_2020 and in Navigant 2007	0.680: Highest value found in NECost_LBNL_Res_2020 and in Navigant 2007. Same as default
Lighting	Incandescent	0.015: Based on Energy-Other_Bldgs-Lighting. Weighted avg percent of mean value = 60.6%	0.021: Highest value found in NECost_LBNL_Res_2020 and in Navigant 2007	0.027: NECost_LBNL_Res_2020 and in Navigant 2007. Same as default
	Fluorescent	0.122: All three cases are assumed to have the same efficiencies and same costs. Approximately today's level	0.122: Same as low	0.122: Same as low
	Solid State	0.094: 64 lumens per watt is the DOE/BT multiyear plan value for 2011 (best is about 105). See April 2012 multiyear plan, Table 4.1 Assumes that 2015 goal is not achieved until after 2020.	0.154: 105 lumens per watt from NECost_Cost Lighting divided by 683 standardization factor.	0.234: 160 lumens per watt by 2020. Same as "advanced case" in NECost_Cost_lighting.
Appliances	Gas Appliances	1.000: No improvement for gas stoves	1.007: Other_Energy_Bldg.xls, Res_appliance. Percent improvement was 0.048% per year from 2005 to 2035, 0.1% per yr thereafter	1.030: Improvement for gas dryers at 0.2% per year in source for default value
	Electric Appliances	1.030: Slow end of improvement among classes = 0.2% per year	1.108: Based on weighted average improvement in electric appliances from 2005 to 2020 of 0.687%. Based on Other _Energy_bldg, Res_appliances	1.225: Fast end of improvement among classes from 2005-2020 = 1.136% per year
	Electric Appliances-hi	1.120: Value of efficiency index for 2020 cited in Other Appliances for Electric Ovens	1.675: Weighted avg of Refrigerators and Ovens in 2020 from NECCost_LBNL_Res_2020	1.820: Value of index cited in Other Appliances for refrigerators
	Fuel Appliances:	1.000: No change form 2005	1.000: Same as low	1.000: Same as low
	Other appliances	0.826: Other-energy_Bldg Res_other_elec. Based on set-top boxes, which have the worst ROI of the equipment shown	0.913: From Other-energy_Bldg Res_other_elec. Wtd rate of improvement for set-top boxes and TVs	1.000: Based on no change: no negative rate of improvement
Other	Other Gas	1.000: No change from 2005	1.000: Same as low	1.000: Same as low
	Other Electric	1.015: 2005 level, plus 0.1% per year	1.091: Other bldgs, Res-other-elect for misc electrical uses. 2020 =	1.119: 2005, plus 0.75% per year

Residential Equipment		**2020 Efficiency Distribution Values (Out/In) and Source**		
Service	**Technology**	**Low**	**Default**	**High**
			2005 +0.58% per year	
	Other Oil	1.000: No change from 2005	1.000: Same as low	1.000: Same as low

Table 6.2 Sources for 2020 building equipment efficiency, commercial sector

Commercial Equipment		**2020 Efficiency Distribution (Out/In) and Source**		
Service	**Technology**	**Low Value**	**Default Value**	**High Value**
Heat	Biomass Boiler (Wood Furnace)	0.650: No improvement over 2005	0.660: 2005 level, escalated by 0.1% per yea	0.675: 2005 improves at 0.25% per year
	Coal Furnace	0.650: Same as wood	0.660: same as wood	0.675: Same as wood
	Gas furnace	0.700: Same value as 2005 (no improvement) in NECost	0.775: NECost_LBNL_Comm_2005, low value	0.855: High value in NECost_LBNL_Comm_2005 Costs for small furnaces
	Gas furnace-hi	0.800: Highest available Ngas furnace, AEO 2012 for 2010	0.868: NECost_LBNL_Comm_ 2005 high value escalated to 2020 at 0.1% per year	0.900: Highest available Commercial Natural Gas Furnace in Navigant 2007 for 2020
	Electric Furnace	1.000	1.000	1.000
	Electric heat pump	3.100: No improvement over 2005	3.300: NECost_ NCI_comm, mid-cost rooftop heat pump	3.400: Navigant 2007. High Value for Rooftop heat pump in 2020
	Oil furnace	0.780: No improvement over 2007	0.810: NECost_LBNL_comm_2020 min eff equipment = 0.81	0.830: NECosts_EMF25 for 2020
	Oil furnace-hi	0.830: NECosts_EMF25 for 2020	0.850: NECost _LBNL_Res_2020 maximum efficiency equipment	0.890: High level for 2020 in Navigant 2007
Cooling	Gas cooling	0.898: 2.3% less than default. 2005 value escalated at 0.5% per year	0.919: Annual Energy Outlook 2008 value for 2020, average stock efficiency	0.932: 1.4% greater than default. 2005 value escalated at 0.75% per year
	Air conditioning	2.782: Navigant 2007 "Typical" for 2020: EER=11.2. COP = 3.280	2.782: NECost_LBNL_comm_ 2020. Large air conditioner min value. EER = 9.5	3.514: Navigant High value for 2020 is EER = 12.0, a COP of 3.514. NECost_LBNL_Comm_2020 shows same
	Air conditioning-hi	3.280: Navigant 2007 "Typical" for 2020: EER = 11.2. COP = 3.280	3.514: Highest value for large-size AC units in NECOst_LBNL_Comm_2020_ EER = 12.0	3.748: Assumed availability of EER= 12.8 Units.
Water Heating	Gas water heater	0.792: Same as default	0.792: NECost_LBNL_Comm_2005 min efficiency in 2005, escalated by0.1% per yr. Note ASHRAE 90.1-1999 requires 80%	0.940: Navigant 2007 high end for 2020
	Gas water heater-hi	0.940: Navigant 2007 high case for 2020	0.954: NECost_LBNL_Comm_2005 highest efficiency in 2005, escalated by0.1% per year	0.969: Same as Conventional high case for 2050

Commercial Equipment		**2020 Efficiency Distribution (Out/In) and Source**		
Service	**Technology**	**Low Value**	**Default Value**	**High Value**
	Electric water heater	0.980: NECosts_NCI_Com_2020 value = 0.98	0.990: NECost_LBNL_Comm_2020 res high Value	0.990: Same as default
	Electric HP water heater	2.200: Same as default	2.200: NECost_NCI_res (commercial data not available). 2020 low COP = 2.2 used for 2015. 2020 hi COP = 2.4 used for 2035	2.400: High end. See note for 2020 default case
	Oil water heater	0.780: Current std value of 78%	0.801: AEO avg efficiencies, 2020 value	0.805: Use the 2035 value from the same source as the default case
Ventilation	Ventilation	0.710: No improvement over 2005	0.721: 2005 value , plus 0.1% per year improvement	0.854: NECosts, LBNL_comm_2020, third to highest efficiency, (83.7%) for 2005, escalated at 0.1% per year = 0.850. Stretched upward to meet minimum hi-eff Tech
	Ventilation hi-eff	0.854: No improvement over 2005	0.867: 2005 value , plus 0.1% per year improvement	0.867: NECost_LBNL_Comm_2020, second to highest efficiency, (85.4%) for 2005, escalated at 0.1% per year
Cooking	Gas stove	0.521: Res_Comm_eff, 2005 value+0.1% per year improvement	0.527: Res_comm_eff, 2020 value	0.533: Res_Comm_eff, 2005 value+0.25% per year improvement
	Electric stove	0.724: Res_Comm_eff, 2005 value+0.1% per year improvement	0.748: Res_comm_eff, 2020 value	0.755: Res_Comm_eff, 2035 default value early
Lighting	Incandescent	0.014: Based on Energy-Other_Bldgs-Lighting. Weighted avg percent of mean value = 64.6%	0.021: Commercial avg efficiency (Other_Energy_Bldg) of 14.3 lumens per watt/683 lumens per watt, std luminescence value	0.024: Based on Energy-Other_Bldgs-Lighting. Weighted avg percent of mean value. Value = 115.1% of mean
	Fluorescent	0.085: Base median value times ratio of weighted avg lowest efficiency to median = 70.8%	0.120: Median energy efficiency of fluorescents from Other-Energy_Bldg, Lighting efficiency = 82 lumens per watt/std luminescence lumens per watt (683), escalated at 0.1% per year	0.131: Default median value times ratio of weighted avg high efficiency to median efficiency = 109.4%
	Solid State	0.094: 64 lumens per watt is the DOE/BT multiyear plan value for 2011 (best is about 105). See April 2012 multiyear plan, Table 4.1 Assumes that 2015 goal is not achieved until after 2020.	0.154: 105 lumens per Watt divided by 683 from NECost_Cost_Lighting.	0.234: 160 lumens per watt by 2020. Same as "advanced case" in NECost_Cost_lighting.
Refrigeration	refrigeration	1.994: Value for 2005 improves at 0.1% per year	2.482: Res-Comm_eff,supple2 for 2020	2.668: Value for 2035 achieved early

Commercial Equipment		2020 Efficiency Distribution (Out/In) and Source		
Service	**Technology**	**Low Value**	**Default Value**	**High Value**
	refrigeration hi-eff	2.668: Value for 2005 does not improve before 2020 Extended downward to meet conventional equipment	3.141: 2005, improved at 0.1% per year	3.212: Value for 2005 improves at 0.25% per year
Office	Office Equipment	1.015: Slow rate of improvement (0.1% per year) from 2005	1.038: Medium rate of improvement (0.25%/yr) from 2005	1.078: Fast rate of improvement (0.5% per year) form 2005
Other	Other Gas	1.015: Slow rate of improvement (0.1% per year) from 2005	1.038: Medium rate of improvement (0.25%/yr) from 2005	1.078: Fast rate of improvement (0.5% per year) form 2005
	Other Electric	0.970: Efficiency declines at slightly higher rate than default = -0.002	0.973: Other_Energy_Bldgs, Res-other-elec for misc electrical uses. 0.974 (minus 0.178% per year, based on potential savings of a broad group of commercial electric equipment. Data in Other_Energy_Bldg, Tab Comm_other_elec	1.069: Adjustment to refrigeration in the default case to take into account recent refrigeration standards
	Other Oil	1.015: Slow rate of improvement (0.1% per year) from 2005	1.015: Slow rate of improvement (0.1% per year) from 2005	1.078: Fast rate of improvement (0.5% per year) form 2005

Table 6.3 Sources for residential technology costs in 2020

		Year 2020 Residential Cost Distribution and Source		
Service	**Technology**	**Low**	**Default**	**High**
Heat	Wood furnace	1.257: Default value for 2050 reached early	1.335: 2005 value in NECost_ NCI_res, reduced by 0.1% per year	1.355: Cost not changed from 2005
	Coal Furnace	1.257: Same as wood (biomass)	1.335: Same as wood (biomass):	1.355: Same as wood (biomass)
	Gas furnace	2.473: Same as Default	2.473: NECost_Res_ LBNL_2020, 78% efficiency furnace (lowest eff)	2.740: Same eff as Default case in 2050 (0.804), but at 2020 prices, estimated at higher price of 0.8 eff (2.74).
	Gas furnace-hi	3.150: Lowest cost of 90% efficient furnace	3.325: NECost, LBNL 2020, Lowest cost of 92% efficient furnace	4.320: Cost estimated as ratio of 97% to 96%, times price of 96% efficient unit
	Electric Furnace	1.93: Same as default	1.93: NECost_NCI _res value, reduced at 0.1% per yea	1.93: Same as default
	Electric heat pump	7.855: Cost of HSPF of 7.7 in DOE Appliance Studs for 2006-2015 Split System HP. Scaled from HSPF 8.2 in Default case	8.365: NECosts_NCI_res for 2005 (approximately HSPF = 8.2 and COP = 2.405), reduced at 0.1% per year.	10.201: Cost of Max HSPF = 10 (current max tech is about 9.9)
	Oil furnace	2.839: Same as default case (cost of 78% efficient unit)	2.839: Cost for 78% efficient unit in NECost_ LBNL_Res_2020	3.360: Cost for 85% efficient unit from NECost_LBNL_Res_ 2020
	Oil furnace-hi	3.090: Mid-Value for Cost of 84% efficient equipment in NECost_LBNL_Res_2020	3.363: Cost of 85% efficient unit in NECost_LBNL_Res_2020	3.759: Scaled based on relative efficiency from default case
	Air conditioning	8.775: Cost assumes no change from 2005 (SEER = 10). However, min standard is already at SEER=12, and 13-14 have been proposed by DOE	8.775: Cost of a SEER 10.7 unit (COP = 2.72). Cost is for a SEER 10 unit from NECost_LBNL_Res_2020. COP approx 2.67	10.72: Cost of high end "low tech" equipment is at about SEER=14.5. Based on NECosts, LBNL_2020, halfway between SEER 14 and 15 at 10.72
	Air conditioning-hi	10.903: Costs are for a 15 SEER unit from NECost_ LBNL_res_2020	10.903: Cost from NECost, LBNL_Res_2020, for a SEER 15.5 unit. Costs in the Source are for a 15 SEER unit.	13.000: Costs scaled upward from 16 SEER to 21 SEER at 0.35 per SEER unit.
Water Heating	Gas water heater	7.258: Min current std, same as default (Navigant 2007)	7.258: Cost is from NECosts_LBNL_Res_2020 for a unit with an efficiency of 59%	12.344: Cost for NECost_LBNL_2020 highest eff (77% efficient)
	Gas water heater-hi	7.590: Minimum current standard, same as default (Navigant 2007)	12.344: Costs from NECost, LBNL_Res_2020, max efficiency (77%) unit	12.344: Same as default
	Electric water heater	5.733: Cost for Current Standard. Navigant 2007 Base for pre-2010	5.733: NECost_LBNL_Res_2020 low value. Also Current Standard	6.600: Cost from NECost_LBNL_res_2020, for max level (0.95)
	Electric water heater-hi	6.601: Same as default	6.601: Cost from NECost_LBNL_Res_2020 high Value	6.601: Same as default
	Electric HP water heater	8.329: Costs same as default. Navigant 2007 Base for pre-2010.	8.329: Cost from NECost_LBNL_Res_2020 Efficiency 2.20	11.661: Costs for Navigant 2007 high for 2020 (COP2.4). Costs scaled upward by ratio of

Service	Technology	Year 2020 Residential Cost Distribution and Source Low	Default	High
				installed costs for best and typical equipment for 2020. Ratio is between 1.13 and 1.66. Midpoint is 1.4
	Oil water heater	12.252: Same as default	12.252: Cost from NECost_ LBNL_Res_2020 for today's (2004) standard of 53% efficient. (Navigant 2007)	13.477: Appears to be the high end of conventional equipment. Costs greater for 0.66 and 0.68 units
	Oil water heater-hi	14.975: Based on the lower of two upper-end values in NECost_LBNL_Res_2020	16.005: Costs for 68% efficient unit. Highest value found in NECost_LBNL_Res_2020 and in Navigant 2007	16.005: Same as default
Lighting	Incandescent	22.170: Costs calculated by assuming cost is proportional to relative efficiency	32.555: Costs from NECost_ Cost_lighting. Equals 2005 value (converted to 1975$), reduced by 0.1% per year after 2005	40.987: Costs calculated by assuming cost is proportional to relative efficiency.
	Fluorescent	55.322: Same as default	55.322: Cost based on 2005 value from NECost_ Cost_lighting. The 2005 value is assumed to fall at 0.1% per year. All three cases are assumed to have the same efficiencies and same costs	55.322: Same as default
	Solid State	236.234: Cost is scaled by lumens/watt compared with default. DOE/BT multiyear plan value for 2011 (best is about 105). See April 2012 multiyear plan, Table 4.1 Assumes that 2015 goal is not achieved until after 2020.	387.571: Cost based on 2005 value from NECost_ Cost_lighting. The 2005 value is assumed to fall at 0.1% per year. Efficacy = 105 lumens per Watt divided by 683 from NECost_Cost Lighting.	590.585: Scaled by lumens/watt. 160 lumens per watt by 2020. Same as "advanced case" in NECost_Cost_lighting.
Appliances	Gas Appliances	10.362: Scaled from default case base on relative efficiency:	10.435: Costs from NECost_ LBNL_Res_2020 for "low" efficiency gas appliances	13.638: Costs from NECost_ LBNL_res_2020 for "high" efficiency gas appliances
	Electric Appliances	13.589: Scaled from default based on relative efficiency	14.618: Based on NECost_ LBNL_Res_2020, Least Efficient refrigerators in 2005 and least efficient electric ovens	19.401: Use high value of range and refrigerator in NECost_ LBNL_Res_2020.
	Electric Appliances-hi eff	14.618: Same as low-efficiency default case	19.401: Use high value of refrigerator and electric range in NECost_LBNL_Res_2020	19.401: Use high value of refrigerator and electric range in NECost, LBNL_Res_2020
	Fuel Appliances	12.949: Equals default case	12.949: 2005 value, less 0.1% per year	13.145: No improvement from 2005
Other appliances	Electricity	198.269: Same as default case	198.269: 2005 value, less 0.1% per year	201.267: No improvement from 2005
Other	Other Gas	19.702: Same as default case	19.702: 2005 value, less 0.1% per year: 2005 value is simply an assumption	20.000: No improvement from 2005

		Year 2020 Residential Cost Distribution and Source		
Service	**Technology**	**Low**	**Default**	**High**
	Other Electric	61.197: Scaled from default case by relative efficiency	65.779: 2005 value, less 0.1% per year. 2005 value is from NECost_Cost_others	66.773: No improvement from 2005
	Other Oil	19.702: Same as default case	19.702: 2005 value, less 0.1% per year. 2005 value is simply an assumption	20.000: No improvement from 2005

Table 6.4 Sources for commercial technology costs in 2020

		Year 2020 Commercial Cost Distribution and Source		
Service	**Technology**	**Low**	**Default**	**High**
Heat	Wood furnace	1.315: Scaled from default case by relative efficiency	1.335: 2005 value, reduced at 0.1% per year	1.355: No improvement 2005-2020
	Coal Furnace	1.3156: Same as wood	1.335: Same as wood	1.355: Same as wood
	Gas furnace	2.609: Scaled from default by relative efficiency	2.888: 2005, with cost reduced at 0.1% per year	2.932: No improvement 2005-2020
	Gas furnace-hi	3.760: Scaled from default by relative efficiency	4.079: 2005, with cost reduced at 0.1% per year	4.141: No improvement 2005-2020
	Electric Furnace	1.728: Scaled from default by relative efficiency	1.728: 2005, reduced at 0.1% per yea	1.754: No improvement 2005-2020
	Electric heat pump	3.115: Scaled from default by relative efficiency	3.316: 2005, reduced at 0.1% per year	3.366: No improvement 2005-2020
	Oil furnace	0.923: Scaled from default by relative efficiency	0.958: Equals 2005 low value from NECosts, LBNL_comm_2020	0.958: No improvement 2005-2020
	Oil furnace-hi eff	1.377: Scaled from default by relative efficiency	1.411: Equals 2005 high value from NECost_LBNL_Comm_2020	1.411: No improvement 2005-2020
Cooling	Gas cooling	4.811: Scaled from default by relative efficiency	4.926: 2005, reduced at 0.1% per year	5.000: No improvement 2005-2020
	Air conditioning	2.233: Scaled from default by relative efficiency	2.233: NECosts, LBNL_comm_2020, min cost for large units (EER = 9.5). Consistent with Navigant 2007	2.586: No improvement 2005-2020
	Air conditioning-hi eff	2.414: Scaled from default by relative efficiency	2.586: NECosts, LBNL_comm_2020, max cost for large comm. AC unit (EER = 12). Consistent with Navigant 2007.	4.24: No improvement 2005-2020
Water Heating	Gas water heater	0.420: Scaled from default by relative efficiency	0.420: 2005, reduced at 0.1% per year	0.441: No improvement 2005-2020
	Gas water heater-hi eff	0.749: Scaled from default by relative efficiency	0.761: 2005, reduced at 0.1% per year	0.772: No improvement 2005-2020
	Electric water heater	0.486: Scaled from default by relative efficiency	0.491: NECost_ NCI_comm	0.550: No improvement 2005-2020

		Year 2020 Commercial Cost Distribution and Source		
Service	**Technology**	**Low**	**Default**	**High**
	Electric HP water heater	1.025: Scaled from default by relative efficiency	1.025: 2005, reduced at 0.1% per year	1.040: No improvement 2005-2020
	Oil water heater	0.471: Scaled from default by relative efficiency	0.484: 2005, reduced at 0.1% per year	0.491: No improvement 2005-2020
Ventilation	Ventilation	10.047: Scaled from default by relative efficiency	10.199: Same as 2005	10.199: No improvement 2005-2020
	Ventilation hi-eff	13.056: Scaled from default by relative efficiency	13.253: Same as 2005	29.039: No improvement 2005-2020
Cooking	gas stove	25.119: Scaled from default by relative efficiency	25.390: 2005, reduced at 0.1% per year	25.774: No improvement 2005-2020
	electric stove	40.600: Scaled from default by relative efficiency	41.968: 2005, reduced at 0.1% per year	42.603: No improvement 2005-2020
Lighting	Incandescent	16.666: Scaled from default by relative efficiency	25.798: 2005, reduced at 0.1% per year	26.188: No improvement 2005-2020
	Fluorescent	13.362: Scaled from default by relative efficiency	18.873: 2005, reduced at 0.1% per year	19.158: No improvement 2005-2020
	Solid State	68.667: Scaled from default by relative efficiency	112.852: 2005, reduced at 0.1% per year	114.559: No improvement 2005-2020
Refrigeration	Refrigeration	4.225: Scaled from default by relative efficiency	5.260: 2005, reduced at 0.1% per year	5.340: No improvement 2005-2020
	Refrigeration hi-eff	6.715: Scaled from default by relative efficiency	7.905: No improvement from 2005 to 2020	7.905: Does not improve from 2005 level: No improvement 2005-2020
Office	Office Equipment	42.562: Scaled from default by relative efficiency	43.529: 2005, reduced at 0.1% per year	44.187: No improvement 2005-2020
Other	Other Gas	19.265: Scaled from default by relative efficiency	19.702: 2005, reduced at 0.1% per year	20.000: No improvement 2005-2020
	Other Electric	39.349: Scaled from default by relative efficiency	39.467: 2005, reduced at 0.1% per year	40.064: No improvement 2005-2020
	Other Oil	19.702: Scaled from default by relative efficiency	19.702: 2005, reduced at 0.1% per year	20.000: No improvement 2005-2020

References Key for Table 6.1 through Table 6.4

(See references list at the end of the report in Section 7.0 . spreadsheets are available from the authors)

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- Other_Energy_Bldgs, Res-other-elec: Tab in Other_Energy_Bldg spreadsheet
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4.	Computers shipped	BEDB 2005
5.	Copier cost	DEER 2005
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