Quadrennial Technology Review 2015

Chapter 5: Increasing Efficiency of Building Systems and Technologies

Supplemental Information

Building Energy Technology Roadmaps

Building Technologies Office
Potential Energy Savings Analysis

U.S. DEPARTMENT OF
ENERGY

Quadrennial Technology Review 2015

Building Technologies Office Potential Energy Savings Analysis

Chapter 5: Supplemental Information

Introduction

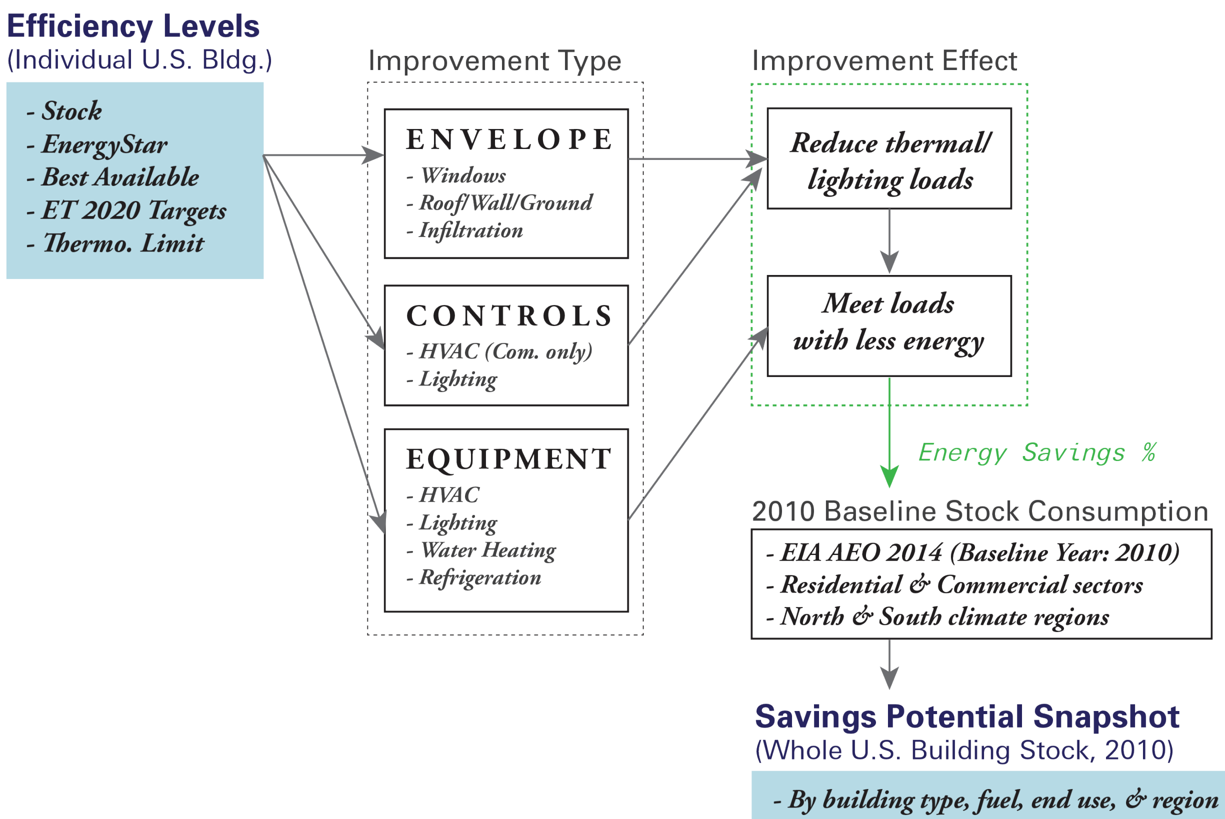
The analysis undertaken to support Chapter 5 compares the potential energy savings from research, development, demonstration, and deployment (RDD&D) targets developed by the Department of Energy Building Technologies Office (BTO) Emerging Technologies (ET) Program against energy use in the existing building stock and for several other energy efficiency scenarios, including the theoretical physical lower limit of energy use. While analytical tools exist for estimating and comparing the national energy savings potential of individual technologies, a simple method for estimating total energy savings across general end-use categories was needed. This analytical approach enables the consideration of technology improvements on an end-use basis, and furthermore separates the contribution to total savings from equipment and building envelope improvements for relevant end uses.

The BTO research portfolio is guided by a set of technology performance and cost objectives referred to in this analysis as the "ET 2020" efficiency scenario. These objectives were developed for various roadmaps that identify RDD&D frontiers for specific technologies in the ET portfolio, using technology-specific analyses that quantified future energy savings potential and cost-effectiveness. Given the existing ET 2020 efficiency scenario, this analysis sought to provide an estimate of the technical potential relative to other technology performance levels, some of which do not incorporate cost or payback as measurement criteria.

Methods

To provide context for the energy savings opportunities offered by existing energy efficiency technologies and new technology advances supported by ongoing RDD&D activities, the energy use intensity (EUI) of the current residential and commercial building stock is compared to a range of efficiency scenarios, as shown in Figures 1–3. EUI is a metric that indicates the energy used per unit of activity and can be captured several different ways, such as kWh per person or BTU per dollar of gross domestic product (GDP). In this analysis, it is measured in thousands of BTU per square foot, thus facilitating a comparison between buildings of different sizes. The EUI measure employed here is based on source (or primary) energy, which incorporates power plant, transmission, and distribution system losses.[1] The 2010 data in the 2014 Energy Information Administration (EIA) *Annual Energy Outlook* (AEO) provided data on existing building technology stock as well as energy use estimates for various building types and end uses. The existing building stock, denoted as "Stock," and four higher efficiency scenarios were considered. For each of the higher efficiency scenarios, both equipment and the building envelope were improved to the indicated level of performance and applied to the entire residential or commercial building stock, and the corresponding energy savings were calculated. Equipment considered for these cases includes HVAC systems, water heaters, appliances, lighting, and controls. Building envelope elements included windows, insulation, and air sealing. Building envelope improvements were used to calculate a modified thermal load, with stock thermal load components taken from two Lawrence Berkeley National Laboratory (LBNL) reports.[2] This modified thermal load was then met with equipment corresponding to the given efficiency scenario (Figure 1).

Figure 1 Diagram of the procedure used to calculate national savings potential snapshots for four different efficiency scenarios—Energy Star specifications, the best available technologies today (Best Available), the Emerging Technology Program's targets for the year 2020 (ET 2020), and the estimated ideal limit of efficiency (Thermo. Limit)—relative to a baseline efficiency level. The baseline scenario corresponds to technology performance levels provided in the EIA AEO 2014 reference case for the year 2010. Improvements in the performance of the building envelope, controls, and equipment all contribute to each scenario's efficiency gains over the baseline scenario. Envelope and control improvements have the effect of reducing the load that the building equipment must meet (e.g., heating/cooling, lighting); equipment improvements meet a given load with less energy than in the baseline case.

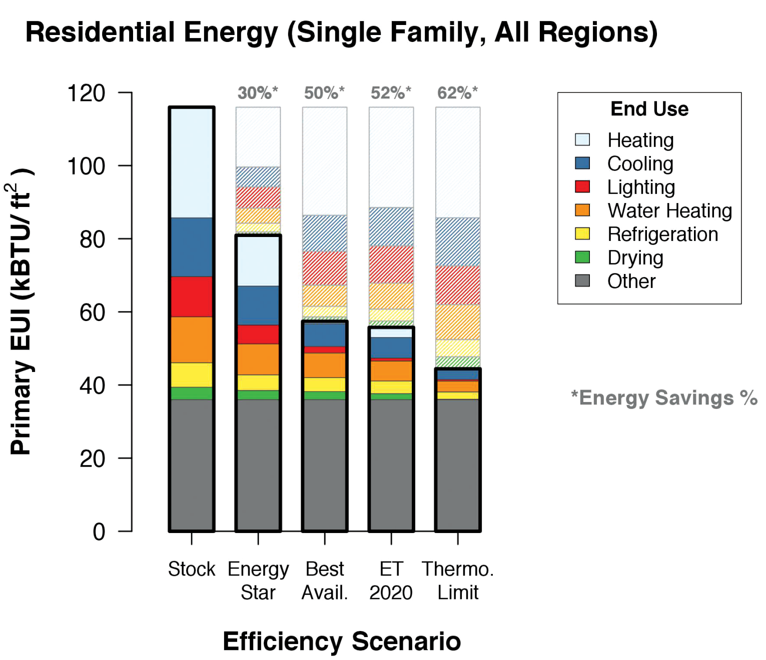


In the "Energy Star" scenario, the performance level specified for each technology or envelope component was based on the Energy Star program's specifications (http://www.energystar.gov/products). Similarly, the "Best Available" scenario incorporated the most efficient commercially available product for all equipment and envelope categories analyzed, regardless of the cost-effectiveness of those technologies. The "ET 2020" scenario was based on assuming performance levels equivalent to the 2020 targets for the ET program, as developed in the BTO multiyear program plan (MYPP) and roadmap documents (http://energy.gov/eere/buildings/program-plans-implementation-and-results). Finally, the "Thermo. Limit" scenario is an estimate of the thermodynamic limit, or the lowest ideal limit of building energy use, which cannot be improved on without reducing the services (e.g., heating and cooling) provided to the occupants. Estimates of the thermodynamic limit were drawn from theoretical efficiency bounds for the given equipment type (e.g., Carnot cycle heat pump), relevant literature sources, and expert assessments.

In the Results section below, each of the scenarios is represented as the sum of several equipment end use categories. While these end uses incorporate only equipment, as previously noted, the reduction in their contribution to EUI is due to both equipment efficiency improvements and, if applicable, improvements to the building envelope. Moreover, interactions between the lighting and HVAC end uses have been accounted for by first modifying the thermal load met by the HVAC end use to reflect changes in the lighting end use. With regards to heating energy, therefore, a lighting equipment improvement will result in less waste heat, thus increasing the heating energy needed to meet space comfort requirements; the reverse is true for the cooling energy end use.

Note that in defining the performance levels for each efficiency scenario, product cost was an important consideration for only the Energy Star and ET 2020 scenarios. Taken together, the best available technologies today nearly reach the ET 2020 EUI, but those technologies are often very expensive, making the products economically unattractive. While these technologies often far exceed Energy Star specifications in terms of energy performance, to meet the ET 2020 goals, they will need to be more cost-effective.

Figure 2 The stacked bars shown represent the energy use intensity (EUI) of the existing stock of single-family homes, and those same homes subject to four scenarios where the efficiency of both the equipment within and envelope of the building are improved to the indicated level of performance—Energy Star specifications, the best available technology today (Best Avail.), the Emerging Technology Program's targets for the year 2020 (ET 2020), and the estimated ideal limit of efficiency (Thermo. Limit). The total EUI in each case is broken into several constituent end uses, and the energy use reductions in each efficiency scenario are also broken down by end use in the dimmed stacked bar above each scenario. There are significant opportunities for efficiency improvements in all of the indicated end uses. For example, modifying an average home with the best available technologies today would reduce its energy use by 50%. As the thermodynamic limit is approached, the "Other" end use category comprises an ever growing share of the total EUI. This category represents a wide array of small energy uses that might need to be measured and assessed in the future.

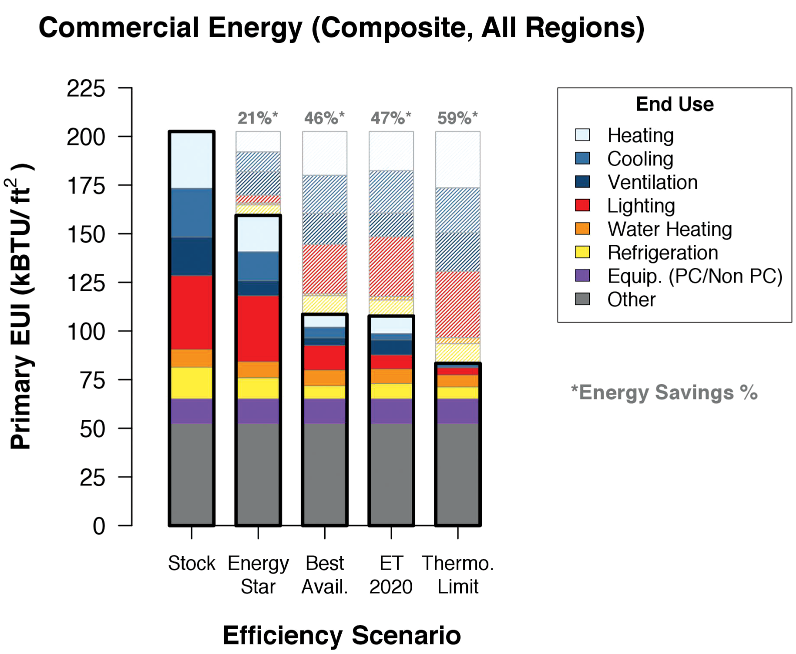


Results

Figure 2 shows the four efficiency scenarios compared to the existing stock for residential single-family homes, averaged across northern and southern U.S. census divisions (see "Assumptions and Limitations" section below). The figure demonstrates that as envelope performance improves and end use equipment becomes more efficient, the EUI of residential buildings diminishes considerably. For example, at the thermodynamic limit, the energy required to serve lighting loads is nearly eliminated through improved daylighting and window technologies as well as highly efficient solid-state lamps. At this efficiency level, the heat generated from occupants and devices in the home is also able to provide nearly all of the heating required, necessitating only minimal cooling energy to maintain thermal comfort. It is furthermore noted that as the performance of installed equipment and the building envelope moves towards the thermodynamic limit, the "Other" end use category, which incorporates a diverse array of end-use subcategories (see Table 1a), becomes the dominant contributor to EUI. While these "Other" end use subcategories are not addressed in the current analysis, it is clear that as the performance of other building systems improves, finding ways to manage them will become increasingly important.

Figure 3 shows the composition of EUI for a "composite" commercial building under the same four efficiency scenarios as in Figure 2, where the composite building represents a floor area-weighted average of the 11 different commercial building types included in the AEO. Note that the major end-use categories contributing to commercial building EUI are slightly different than those shown for residential buildings, with certain end uses such as ventilation only broken out for commercial buildings and others like secondary heating only broken out for residential buildings. Moreover, the EUI contributions of end uses that are broken out for both commercial and residential buildings sometimes change differently across efficiency levels for the two building types. For example, heating EUI reductions are somewhat less in commercial buildings due to the smaller influence commercial envelope improvements have on heating load than in the residential sector.

Figure 3 The stacked bars show the energy use intensity (EUI) for commercial buildings. The building indicated represents a composite of 11 modeled commercial building types. The stock composite commercial building is subject to four efficiency scenarios, corresponding to the indicated level of performance for both the equipment and building envelope—Energy Star specifications, the best available technology today (Best Avail.), the Emerging Technology Program's targets for the year 2020 (ET 2020), and the estimated ideal limit of efficiency (Thermo. Limit). HVAC loads comprise the largest single category of energy use in the current building stock and are reduced dramatically as efficiency approaches the thermodynamic limit. While some end uses, such as refrigeration, have limited room for improvement, overall EUI is reduced by 59% at the thermodynamic limit.



Despite these differences, at the thermodynamic limit, the percentage improvement in total EUI is comparable between the two building types shown in Figures 2 and 3. As in residential buildings, the "Other" category of commercial building energy use comprises a growing fraction of EUI as the thermodynamic limit is approached. Furthermore, Table 1 shows that for both residential and commercial buildings, Miscellaneous Electric Loads (MELs) are the largest "Other" subcategory of energy end-use that can be broken out, with Kitchen Ventilation and Dry Transformers appearing as the most prominent MELs for the commercial sector. While focusing on this "Other" category and its composition is again important going forward, the task will be complicated for commercial buildings by the large portion of the "Other" category of energy end-use that remains uncategorized (see "Other [all fuels]" in Table 1b), as well as the highly differentiated nature of the subcategories that can be broken out. Moreover, attempting to track the contribution of such loads to overall energy use is difficult because they tend to change over time.[3]

Table 1 Breakdown of the "Other" end-use categories for (a) Figure 2 (Residential) and (b) Figure 3 (Commercial). Numbers for each sector are consistent with the census division and building type assumptions described in the "Analytical Assumptions and Limitations" section, and represent AEO 2014 data for the year 2010. Of the subcategories that can be pulled out of "Other", Miscellaneous Electric Loads (MELs) comprise the largest EUI fraction for both residential and commercial buildings. In commercial buildings, a further breakdown of MELs shows Kitchen Ventilation and Dry Transformers to be the largest EUI contributors (breakdown not available for residential buildings). Note that non-building commercial MELs such as water distribution and street lighting are not included in Table 1b. In residential buildings, TV, Cooking, Ceiling Fan and Furnace Fans/Boiler Pumps subcategories each comprise greater than 5% of the "Other" end-use EUI in Figure 2.

(a) **Residential "Other" End Use Breakdown QTR North/South Divisions*, Single Family**

	kBtu/sq.ft.**	% of "Other"
Misc. Electric Loads (MELs)	15.1	40.6%
TV	3.0	8.2%
Cooking	2.5	6.8%
Ceiling Fan	2.2	5.9%
Furnace Fans/Boiler Pumps	2.0	5.4%
Pool Heater/Pumps	1.5	3.9%
Dishwashers	1.5	3.9%
Freezer	1.5	3.9%
Set Top Boxes	1.4	3.8%
Other Appliances	1.3	3.4%
Desktop PC	0.8	2.1%
Dehumidifiers	0.7	1.9%
Microwaves	0.7	1.8%
Spas	0.5	1.3%
Clothes Washers	0.5	1.3%
Monitors	0.4	1.2%
Network Equip.	0.4	1.0%
Laptops	0.3	0.8%
DVD Players	0.2	0.6%
Coffee Makers	0.2	0.6%
Rechargeable Batteries	0.2	0.6%
Home Theater	0.1	0.3%
Video Game Consoles	0.1	0.3%
Security Systems	0.1	0.2%
Total	**37.2**	**100.0%**

*New England, E/W S Central, S Atlantic
**Primary energy, using 109,064 sq.ft. floor space from AEO 2014

(b) **Commercial "Other" End Use Breakdown QTR North/South Divisions*, All Bldg. Types**

	kBtu/sq.ft.**	% of "Other"
Other (All fuels)	33.8	64.8%
Cooking	3.2	6.2%
Misc. Electric Loads (MELs)	-	-
Kitchen Ventilation	5.5	10.5%
Dry Transformers	5.0	9.6%
Fume Hoods	0.9	1.8%
Security Systems	0.9	1.8%
Lab Fridges	0.6	1.2%
Electric Vehicles	0.6	1.1%
Elevators	0.4	0.7%
Coffee Brewers	0.3	0.7%
Medical Imaging	0.3	0.6%
Video Displays	0.3	0.6%
Laundry	0.2	0.4%
Escalators	0.1	0.1%
Large Video Boards	0.0	0.0%
Total	**52.3**	**100.0%**

*New England, E/W S Central, S Atlantic
**Primary energy, using 55,108 sq.ft. floor space from AEO 2014

Analytical Assumptions and Limitations

Several important assumptions were made to facilitate this modeling effort, including the treatment of climate zones, fuel types, building types, and interactive effects. Also discussed are the techno-economic and time-based limitations of the analysis, and specific assumptions related to two of the scenarios.

Climate Zones

The analysis uses general "north" and "south" climatic groupings, where the northern group is comprised of the New England and East/West North Central U.S. census divisions, and the southern group is comprised of the South Atlantic and East/West South Central census divisions.[4] This climatic grouping allows the analysis to incorporate both AEO data, which breaks energy use down by census division, and to incorporate thermal load components data from two studies by LBNL,[5] which uses a similar "north" and "south" climatic breakdown.

Fuel Type

Residential buildings used ten types of fuel: electricity, natural gas, distillate, liquefied propane gas, kerosene, coal, solar, geothermal, natural gas, and wood. Commercial buildings used three fuel types: electricity, natural gas, and distillate. Improvements in end-use technologies were only applied to electricity and natural gas fuel types in both residential and commercial buildings. Envelope improvements, which modified the demand for heating or cooling services, affected all fuel types used in space heating or cooling applications in residential buildings. No fuel switching was assumed.

Representative Buildings

Residential buildings are represented by single-family homes because multi-family dwellings generally have different thermal load characteristics and use different equipment to provide major building services, such as heating, cooling, and hot water. Commercial buildings are modeled using the 11 representative building types used in the EIA AEO,[6] with the "composite" building type again representing a floor area weighted average of the energy use calculated for each of the various building types. While there are likely differences in the possible efficiency improvement levels for each of these commercial building types, performance levels for each scenario were applied uniformly across all commercial buildings.

Interactions

Interactions between the building shell, insulation, and windows, and heating and cooling systems were considered by reducing or increasing the HVAC load to reflect changes in this load resulting from envelope improvements. Similarly, interactions between lighting and HVAC equipment improvements were considered by modifying the HVAC load to reflect changes resulting from improved lighting equipment (with lower waste heat). Implicit in this handling of interactions is an assumption about the ordering in which end-use improvements occur, with both envelope and lighting equipment improvements carried out before HVAC equipment improvements. Such assumptions extend to the consideration of lighting and HVAC controls measures, which are also assumed to occur before improvements in the performance of the lighting and/or HVAC equipment itself.

Technical Potential

This analysis does not consider the possible market uptake of energy-efficient technologies over time or related changes in the size of the building stock and efficient technology performance and cost levels. Accordingly, the results represent only a snapshot of the technical potential of end-use performance improvements represented by the efficiency scenarios considered. Cost-effectiveness was also not directly considered; however, it is indirectly represented in efficiency scenarios that use cost-effective performance targets, such as Energy Star and ET 2020.

Special Considerations—Energy Star

In the Energy Star scenario, Energy Star specifications are used only where the program includes the applicable products. For building components that do not have Energy Star specifications, either the relevant Federal Minimum Standard or ASHRAE Standard 90.1-2010 is used.

Special Considerations—Thermodynamic Limit

The Thermodynamic limit scenario presented some unique challenges. In some cases in the northern climates during the heating season, the efficiency levels tighten the envelope to the point that cooling is required to reject internal heat generation. In these cases, it was assumed that the added cooling load is met without energy use by introducing cool outdoor air.

Approaches to evaluating performance levels for the thermodynamic limit were straightforward for certain end-use categories; for example, the limits for heating and cooling were developed assuming a heat pump with a fixed-speed Carnot Cycle efficiency. Walls were assumed to be perfectly sealed and insulating. In categories where the physical limits were less straightforward to determine, values were drawn from relevant literature (for example, the maximum luminous efficacy of a red, green, blue (RGB) white LED[7]). Finally, in cases where relevant literature was not available, theoretical efficiency performance was derived from consultation with technology experts who provided their assessment and first-principles calculation of the maximum technologically feasible performance of that component.

Endnotes

1 http://www.energystar.gov/buildings/facility-owners-and-managers/existing-buildings/use-portfolio-manager/understand-metrics/difference

2 Huang, J.; Hanford, J.; Yang, F., “Residential Heating and Cooling Loads Component Analysis.” LBNL-44636. Berkeley, CA: Lawrence Berkeley National Laboratory, 1999.

Huang, J.; Franconi, E., “Commercial Heating and Cooling Loads Component Analysis.” LBNL-37208. Berkeley, CA: Lawrence Berkeley National Laboratory, 1999.

3 U.S. Energy Information Administration, “Analysis and Representation of Miscellaneous Electric Loads in NEMS, December 2013. http://www.eia.gov/analysis/studies/demand/miscelectric/pdf/miscelectric.pdf

4 Note that the Mid-Atlantic, Mountain, and Pacific census divisions were omitted from the analysis because they cannot be considered geographically “north” or “south” but rather span across both regions.

5 Huang, J.; Hanford, J.; Yang, F., “Residential Heating and Cooling Loads Component Analysis.” LBNL-44636. Berkeley, CA: Lawrence Berkeley National Laboratory, 1999.

Huang, J.; Franconi, E., “Commercial Heating and Cooling Loads Component Analysis.” LBNL-37208. Berkeley, CA: Lawrence Berkeley National Laboratory, 1999.

6 U.S. Energy Information Administration, “Annual Energy Outlook 2014”, DOE/EIA-0383(2014), April 2014. http://www.eia.gov/forecasts/aeo/pdf/0383(2014).pdf

7 Ohno, Y., “Spectral Design Considerations for White LED Color Rendering.” Optical Engineering (44:11), 2005; p. 111302.