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AN ASSESSMENT OF ENERGY TECHNOLOGIES AND RESEARCH OPPORTUNITIES

DEPARTMENT OF ENERGY
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Chapter 5: Increasing Efficiency of Building Systems and Technologies

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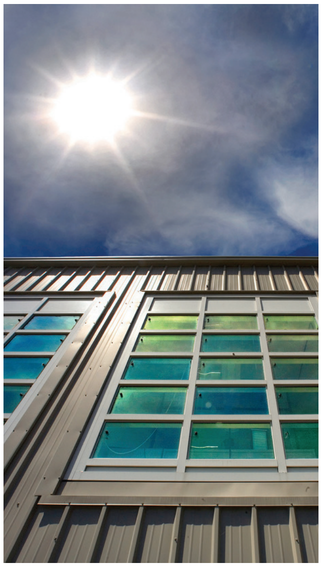


Issues and RDD&D Opportunities

The buildings sector accounts for about 76% of electricity use and 40% of all U. S. primary energy use and associated greenhouse gas (GHG) emissions, making it essential to reduce energy consumption in buildings in order to meet national energy and environmental challenges (Chapter 1) and to reduce costs to building owners and tenants. Opportunities for improved efficiency are enormous. By 2030, building energy use could be cut more than 20% using technologies known to be cost effective today and by more than 35% if research goals are met. Much higher savings are technically possible.

Building efficiency must be considered as improving the performance of a complex system designed to provide occupants with a comfortable, safe, and attractive living and work environment. This requires superior architecture and engineering designs, quality construction practices, and intelligent operation of the structures. Increasingly, operations will include integration with sophisticated electric utility grids.

The major areas of energy consumption in buildings are heating, ventilation, and air conditioning—35% of total building energy; lighting—11%; major appliances (water heating, refrigerators and freezers, dryers)—18% with the remaining 36% in miscellaneous areas including electronics. In each case there are opportunities both for improving the performance of system components (e.g., improving the efficiency of lighting devices) and improving the way they are controlled as a part of integrated building systems (e.g., sensors that adjust light levels to occupancy and daylight).

Key research opportunities include the following:

- High-efficiency heat pumps that reduce or eliminate the use of refrigerants that can lead to GHG emissions
- Thin insulating materials
- Windows and building surfaces with tunable optical properties
- High efficiency lighting devices including improved green light-emitting diodes, phosphors, and quantum dots
- Improved software for optimizing building design and operation
- Low cost, easy to install, energy harvesting sensors and controls
- Interoperable building communication systems and optimized control strategies
- Decision science issues affecting purchasing and operating choices

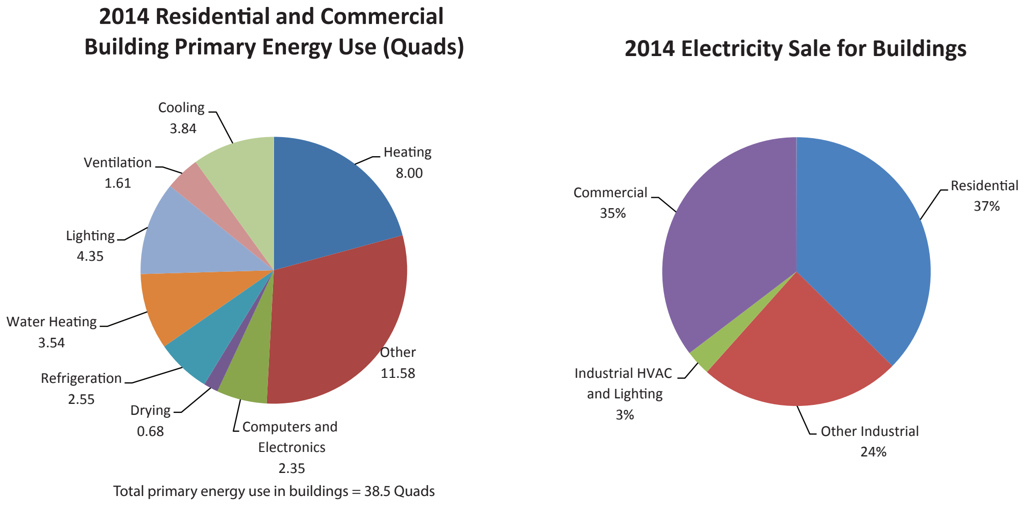
5 Increasing Efficiency of Building Systems and Technologies

5.1 Introduction

More than 76% of all U.S. electricity use and more than 40% of all U.S. energy use and associated greenhouse gas (GHG) emissions are used to provide comfortable, well-lit, residential and commercial buildings—and to provide space conditioning and lighting for industrial buildings. Successfully meeting priority technology goals for performance and cost will make it possible to significantly reduce this energy use by 2030 in spite of forecasted growth in population and business activity.

Figure 5.1 shows U.S. building energy use in 2014.[1] Space conditioning, water heating, and lighting represent well over half of the total, including energy used in outdoor lighting and cooling most data centers.

Figure 5.1 Buildings Use More Than 38% of all U.S. Energy and 76% of U.S. Electricity[1]



Key: **Quad** = quadrillion Btu; **Btu** = British thermal unit

The building sector's share of electricity use has grown dramatically in the past five decades from 25% of U.S. annual electricity consumption in the 1950s to 40% in the early 1970s to more than 76% by 2012.[2] Absent significant increases in building efficiency, total U.S. electricity demand would have grown much more rapidly than it did during this period.

Figure 5.2 Use of ENERGY STAR® technologies would reduce residential energy consumption 30%, best available technology 50%, goals of ET 52% and theoretical limits 62%. No savings are assumed for "other" technologies that become the dominant energy use in high savings scenarios. (EUI)

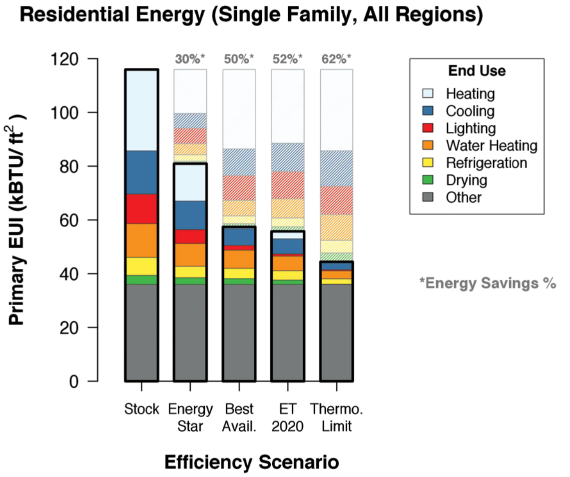


Figure 5.3 Use of ENERGY STAR® technologies would reduce commercial energy consumption 21%, best available technology 46%, goals of ET 47% and theoretical limits 59%. No savings are assumed for "other" technologies that become the dominant energy use in high savings scenarios. (EUI)

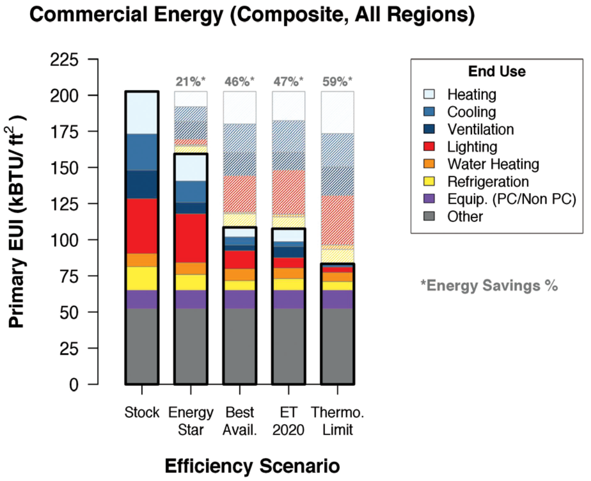


Figure 5.2 and Figure 5.3 compare residential and commercial energy use in the current building stock with buildings using ENERGY STAR® equipment, today's best available technologies, technologies meeting DOE's emerging technologies (ET 2020) cost and performance goals, and the energy used if all equipment operated at theoretical efficiency limits (e.g., perfect heat pumps). In most cases, the best available technologies have similar performance to those meeting the ET 2020 goals, but planned research advances will make those technologies cost-effective by 2020.

The cost goals represent the DOE's analysis of material costs and manufacturing methods judged plausible, including expert solicitations shown in the cited roadmaps.[3] Some of these goals are shown in Table 5.1[4] (see also the supplemental information on roadmaps for this chapter on the web).

Considering only cost-based analysis of new energy efficiency technologies has limitations. For example, features such as improving the ability to comfortably stand by a window on a cold day or changing the color of lighting reflect qualitative values that may affect consumer preferences but would be difficult to analyze quantitatively. None of the economic analysis presented here reflects the social cost of carbon, and none of them reflects services that could be provided to the electric grid (see Chapter 3). Furthermore, the savings shown in the ENERGY STAR® scenario in Figure 5.2 and Figure 5.3 include measures that are cost-effective today but are not being used because of a complex set of market failures.

Capturing the much larger, potential future savings, reflected in the best available ET 2020 and thermodynamic limit scenarios, requires a well-designed research, development, demonstration, and deployment (RDD&D) program, the focus of this chapter. It will also require market-focused programs that encourage rapid adoption of efficient technologies including credible information, standards, labels, and other policies that help consumers understand the costs and benefits of energy-purchasing decisions, and programs to ensure an adequate supply of workers with the skills needed to design, build, and operate new energy systems.

The figures show no reduction in energy used for "other" uses, which include televisions and computer monitors, computers, other electronics, and miscellaneous devices. This is not because their efficiency can't be improved but because the total is the sum of a very large number of different devices. In many cases, commercial investment in the technology is driving change so fast that federal applied research will have limited value. Rapidly increasing demand for fast information processing, for example, is facing energy-use limits, which are driving an enormous amount of private research investment. It is important to determine where and how to productively invest in RDD&D that could improve the efficiency of an electronic component used by these products, and depending on research results, private research efforts and competing priorities within budget limitations, the mix of appropriate investments is likely to change over time. As an example, the development and application of wide band gap semiconductors could reduce energy use in a number of miscellaneous devices but currently has insufficient RDD&D investment to drive this forward in a timely manner. Excluding this "other" category, Figures 5.2 and 5.3 show that building energy use can be reduced by about half.

Table 5.1 Sample ET Program 2020 Goals

	Current	2020 goal
Insulation	R-6/in and \$1.1/ft^2	R-8/in and \$0.35/ft^2
Windows (residential)	R-5.9/in and \$63/ft^2	R-10/in and \$10/ft^2
Vapor-compression heating, ventilation, and air conditioning (HVAC)	1.84 COP and 68.5 \$/kBtu/hr cost premium	2.0 Primary COP and \$23/kBtu/hr cost premium
Non-vapor compression HVAC	Not on market	2.3 Primary COP and \$20/kBtu/hr cost premium
LEDs (cool white)	166 lm/W and \$4/klm	231 lm/W and \$0.7/klm
Daylighting and controls	16% reduction in lighting for \$4/ft^2	35% reduction in lighting for \$13/ft^2
Heat pump clothes dryers	Not on market	50% savings and \$570 cost premium

Buildings last for decades (consider that more than half of all commercial buildings in operation today were built before 1970),[5] so it's important to consider technologies that can be used to retrofit existing buildings as well as new buildings. Many of the technologies assumed in Figure 5.2 and Figure 5.3 can be used in both new and existing structures (e.g., light-emitting diodes [LEDs]). Retrofits present unique challenges, and technologies focused on retrofits merit attention because of the large, existing stock and its generally lower efficiency. These include low-cost solutions such as thin, easily-installed insulation, leak detectors, devices to detect equipment and systems problems (e.g., air conditioners low on refrigerants), and better ways to collect and disseminate best practices.

Energy use in buildings depends on a combination of good architecture and energy systems design and on effective operations and maintenance once the building is occupied. Buildings should be treated as sophisticated, integrated, interrelated systems. It should also be understood that different climates probably require different designs and equipment, and that the performance and value of any component technology depends on the system in which it is embedded. Attractive lighting depends on the performance of the devices that convert electricity to visible light, as well as on window design, window and window covering controls, occupancy detectors, and other lighting controls. As the light fixture efficiency is greatly increased, lighting controls will have a reduced net impact on energy use. In addition, the thermal energy released into the room by lighting would decrease, which then affects building heating and cooling loads.

Since buildings consume a large fraction of the output of electric utilities, they can greatly impact utility operations. Specifically, buildings' ability to shift energy demand away from peak periods, such as on hot summer afternoons, can greatly reduce both cost and GHG emissions by allowing utilities to reduce the need for their least efficient and most polluting power plants. Coordinating building energy systems, on-site generation, and energy storage with other buildings and the utility can lower overall costs, decrease GHG emissions, and increase system-wide reliability.

The following discussion describes the next generation of research opportunities and priorities using three filters:

- If the research is successful, would it result in a significant increase in building energy performance?
- Is the research likely to lead to a commercially successful product in five to ten years?
- Is there evidence that private research in the field is inadequate?

5.2 Thermal Comfort and Air Quality

Providing a comfortable and healthy interior environment is one of the core functions of building energy systems and accounts for about a third of total building energy use. New technologies for heating, cooling, and ventilation not only can achieve large gains in efficiency, but they can improve the way building systems meet occupant needs and preferences by providing greater control, reducing unwanted temperature variations, and improving indoor air quality. Opportunities for improvements fall into the following basic categories:

- Good building design, including passive systems and landscaping
- Improved building envelope, including roofs, walls, and windows
- Improved equipment for heating and cooling air and removing humidity
- Thermal energy storage that can be a part of the building structure or separate equipment
- Improved sensors, control systems, and control algorithms for optimizing system performance

Both building designs and the selection of equipment depend on the climate where the building operates.

5.2.1 The Building Envelope

The walls, foundation, roof, and windows of a building couple the exterior environment with the interior environment in complex ways (see Table 5.2).[6] The insulating properties of the building envelope and construction quality together control the way heat and moisture flows into or out of the building. The color of the building envelope and other optical properties govern how solar energy is reflected and how thermal energy (heat) is radiated from the building. Windows bring sunlight and the sun's energy into the building. About 50% of the heating load in residential buildings and 60% in commercial buildings results from flows through walls, foundations, and the roof (see Table 5.2).[7] Virtually the entire commercial cooling load comes from energy

Table 5.2 Energy Flows in Building Shells (Quads)

	Residential		Commercial	
Building component	Heating	Cooling	Heating	Cooling
Roofs	1.00	0.49	0.88	0.05
Walls	1.54	0.34	1.48	-0.03
Foundation	1.17	-0.22	0.79	-0.21
Infiltration	2.26	0.59	1.29	-0.15
Windows (conduction)	2.06	0.03	1.60	-0.30
Windows (solar heat gain)	-0.66	1.14	-0.97	1.38

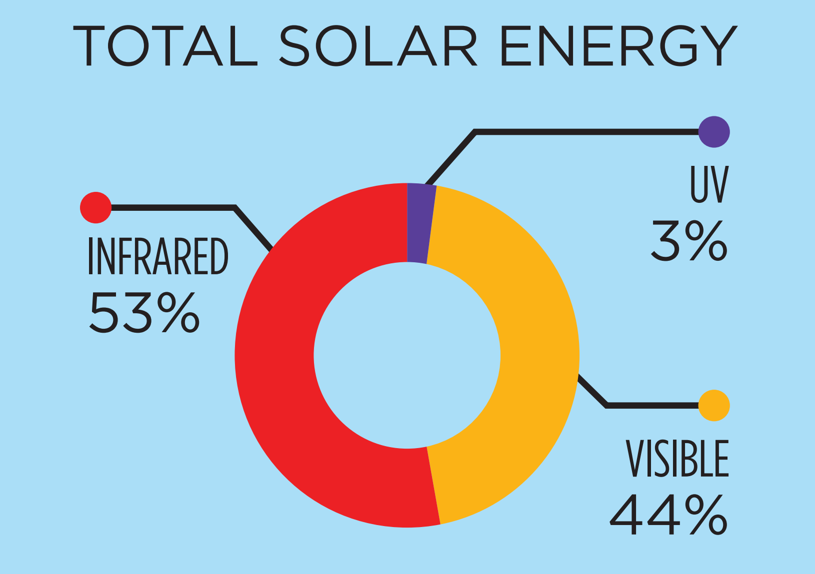
entering through the windows (i.e., solar heat gain). The bulk of residential cooling results from window heat gains although infiltration also has a significant role. Future cooling may be a larger share of total demand since U.S. regions with high population growth are largely in warmer climates.

Windows and Skylights

The quality of a window is measured by its insulating value[8] and its transparency to the sun's visible and infrared light[9] recognizing that an ideal system would allow these parameters to be controlled independently. An ideal window would provide attractive lighting levels without glare, high levels of thermal insulation, and allow infrared light to enter when it is useful for heating but block it when it would add to cooling loads (see Figure 5.4).[10] It would also block ultraviolet light that can damage skin and materials.

Figure 5.4 Only 44% of the energy in sunlight is visible light.

Credit: PPG Industries, Inc.



Windows should also be effective parts of building climate control and lighting systems. Without active control of optical properties, static window requirements will depend on the climate, orientation, and interior space use. If cooling loads dominate, windows that block the invisible (i.e., infrared) part of the solar spectrum are desirable.

Significant progress has been made in window technology over the past three decades. Thanks in large part to DOE's research investment, sealed windows (multiple panes sealed in a factory) now comprise about 95% of windows sold for residential installation and 89% of windows sold for nonresidential installation.[11] Low-emissivity ENERGY STAR® windows make up more than 80% of the market[12] and are twice as insulating as the single-glazing windows that were the default option for generations.

Innovations include glass coatings that reduce absorption and re-emission of infrared light, thermal conductivity improvements (e.g., multiple panes of glass, filling gaps between glass panes using argon, krypton, or xenon,[13] and improved frame design), and the use of low-iron glass to improve visible clarity. Commercial products are now available that provide seven times the insulation provided by single-glazing windows without compromising optical properties. A typical single-glazed window has an R value of one, but R-11 glazing materials and combined frame/glazing units with R-8.1 are commercially available.[14] The "solar heat gain coefficient" is a measure of the fraction of total sunlight energy that can pass through the window while the "visual transmittance" measures the fraction of visible sunlight that gets through. A typical single-glazed window has a solar heat gain coefficient and visual transmittance of about 0.7. Commercially available windows can come close to this with a transmittance of 0.71 and a solar heat gain coefficient that can be selected in the range 0.29–0.62.[15] Window frames transmit unwanted heat directly through rigid materials. While progress has been made both in insulating framing materials and in frame design to reduce conduction, challenges still remain. Durable edge seals remain a challenge, and stress under large temperature differences remains problematic.

The biggest challenge is providing superior performance at an affordable cost. There are also practical considerations. Windows with three or four layers of glass are too heavy and costly for most conventional installations. Using a vacuum between the panes eliminates conduction and convection completely, but it requires very small spacers or other mechanisms to keep the glass panes from touching.[16] The cost of highly insulating windows using filler gas would be reduced if the price of producing the gas can be cut (they are now made by liquefying air) or if substitutes are found.[17]

In summary, all current approaches face cost and visual quality challenges.

Building Walls, Roofs, and Foundations

The walls, roofs, and foundations of buildings also control the flow of heat, moisture, and air. Their color and other optical properties affect the way heat is absorbed and how the building radiates heat back into the atmosphere, but they must do so in ways that meet aesthetic standards and serve functions such as building stability and fire-resistance. Ideal materials are thin, light, and easy-to-install, and provide opportunities to adjust their resistance to flows of heat and moisture.

Thin materials offering high levels of insulation are valuable for all building applications but are particularly important for retrofits since space for additional insulation is often limited. Promising approaches include vacuum insulation[18] and lightweight silica aerogel.[19] Flexible insulation materials with thermal resistance of nearly R-10 per inch are available from several suppliers. Because of high costs, use of these insulating materials has been limited to industrial applications such as pipelines, although building applications have been explored.[20] More federal research here is justified only if there is evidence that there are significant opportunities to find novel materials that offer high levels of insulation in thin products that can cost-effectively meet fire, safety, and other building code requirements that the private sector is not pursuing on its own. The new materials must also be practical for construction—ideally it should be possible to cut, bend, or nail them.

More work is needed in tools and methods to measure and continuously monitor heat and moisture flows through building shells.[21] This includes analytical tools capable of converting sensor data into actionable information about the source of failures in insulation and vapor barriers.

Building shells also affect the way buildings absorb and radiate heat. Ideally, the optical properties of building materials would be adjustable to changes in the weather and other external conditions such as sunlight. Current technologies don't allow dynamic control, and designs often use a solution that optimizes annual performance even if it isn't ideal in extreme conditions. In situations where air conditioning is a significant load, roofing should reflect sunlight instead of absorbing it and be able to efficiently radiate heat from the building. New roofing materials are available that help reduce cooling loads in buildings, lengthen the life expectancy of roofing materials, and cut the "heat island" effect in which buildings and other artificial surfaces heated by the sun actually increase the ambient temperature of cities.[22]

It has proven difficult to find materials that can both reflect the sun's energy and radiate heat during the daytime (when radiative cooling would be most important). Radiating infrared is particularly difficult in areas with significant humidity since water vapor in the air blocks most infrared transmission. This problem has recently been overcome in a laboratory-scale sample. A material created from seven layers of hafnium oxide and silicon dioxide reflects 97% of the sun's shortwave energy while radiating infrared heat at such a high rate that the material was 5°C below ambient temperatures, even in strong sunlight. It achieves this by having very high emissions in the narrow range of infrared where the atmosphere is transparent to infrared (between eight and thirteen micrometers).[23]

5.2.2 Ventilation and Air Quality

Many people spend most of their time indoors, and the quality of indoor air has a significant impact on their health and comfort.[24] Inadequate ventilation can make a room stuffy and uncomfortable. Exposure to indoor pollutants such as mold, radon, secondhand smoke, pressed wood products (that may contain formaldehyde), and other materials can lead to health effects, including asthma and lung cancer. Moisture buildups can also lead to structural damage to the building.[25]

These problems can be addressed most effectively by minimizing and managing pollutant sources in the building. Problems that remain after steps have been taken to reduce pollutants can be addressed by improved building design and operations, as well as by systems bringing in filtered, outside air and exhausting contaminated interior air.[26] Fresh air may infiltrate the building unintentionally through leaks or through controlled ventilation. Standards typically require different minimum-ventilation rates for different space-use types and occupant densities. Some facilities, such as hospitals and labs, require significantly more fresh air than others.[27] However, increased ventilation increases energy consumption when unconditioned, outside air must be heated or cooled as it replaces conditioned, indoor air that is being exhausted. In 2010, unwanted residential air leaks were responsible for more than two quads of space-heating energy loss and one-half quads of space-cooling energy loss, and more than one quad of commercial heating energy loss.[28] Building codes specify maximum allowed leakage, but detecting leaks can be difficult and expensive, and compliance rates are often poor.[29] New technologies, such as the Acoustic Building Infiltration Measuring System, may improve accuracy and reduce costs.[30]

There are many ways to reduce the energy lost in ventilation systems, which include the following:

- **Reduce leaks in building shells and ducts:** While minimizing uncontrolled infiltration is a critical part of building design and construction, locating and fixing leaks in existing buildings presents a greater challenge, especially in commercial buildings where pressurization tests cannot be easily used to measure and locate leaks. DOE research led to the development of material that can be sprayed into existing ducts to seal leaks from the inside.[31]
- **Use natural ventilation where possible:** In some climates and at certain times of the year, natural ventilation can be used to introduce fresh air using natural circulation or fans. Good building design, carefully chosen orientation, windows that open, and ridge vents are some of the many strategies that can be used.[32] Economizers are devices that bring in fresh air when appropriate and can reduce cooling loads by 30% when operated by a well-designed control system. Economizer designs that minimize or eliminate failures can be important for efficiency, but a significant fraction of installed economizers may not be operative because of poor maintenance.[33] The next generation of sensors and controls can automate detection and maintenance notification to help address this issue, and economizer designs can be improved to minimize maintenance.
- **Advanced sensor and control systems provide ventilation only where and when it's needed:** Most installed systems implement fixed air-exchange rates as specified by code, but ventilation needs depend upon occupancy, building purpose and internal activities, and other factors (e.g., a hospital). Significant efficiencies could be gained if ventilation systems provided only the fresh air needed to maintain required levels of carbon dioxide (CO_2) and other compounds. Such systems are known as demand-controlled ventilation. Modern systems can use sensors to detect concentrations of CO_2 and other contaminants, and this information can be used to make appropriate adjustments to ventilation rates. However, keeping them in calibration has proven difficult. Good control systems may be able to reduce ventilation-related energy use in residences by as much as 40%.[34]

- **Use efficient, variable speed motors:** Most ventilation systems adjust flow rates only by turning motors off and on or by using dampers. Significant energy savings can be achieved using efficient, variable air volume systems with variable-speed fans along with properly designed and sealed ducts.[35] There are also major opportunities for improving the efficiency and lowering the cost of variable speed motors and motor controls.[36] Innovations that improve the performance and lower the cost of wide bandgap semiconductors are an important part of this work (see Chapter 6).
- **Use heat and moisture exchange devices:** Even greater energy savings can be achieved by using heat exchangers that allow incoming cool air to be heated by warm building air being exhausted (or the reverse if the building is cooled). Advanced systems can also exchange moisture (i.e., enthalpy exchangers). These systems are discussed in the section on heat pumps.

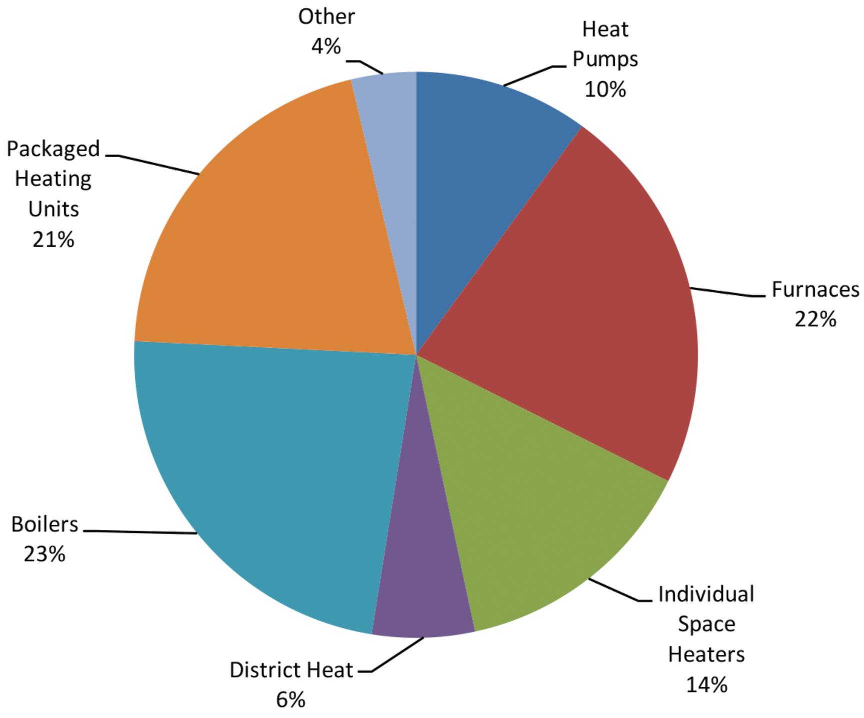
It has been particularly difficult to get advanced systems into smaller buildings. More than half of buildings larger than 10,000 square feet use economizers and variable air volume systems, but less than 10% of buildings smaller than 10,000 square feet use them.[37] Technologies that are inexpensive and easy to use in smaller buildings would be particularly useful.

5.2.3 Space Conditioning Equipment

Although well-designed building envelopes can dramatically reduce heating and cooling loads, there will always be a need for mechanical systems to condition air. Fresh outdoor air will need to be brought into the building and conditioned to replace exhaust air and the heat and moisture generated by occupants and building equipment will need to be removed.

Space conditioning involves two distinct operations: 1) increasing or decreasing air temperature (i.e., adding or removing "sensible heat"), and 2) humidifying or dehumidifying air (i.e., adding or removing "latent heat").

Figure 5.5 Types of Building Heating Equipment



Because warmer air can also contain more moisture (water vapor), heating usually needs to be coupled with humidification and cooling with dehumidification. Traditional air-heating equipment includes furnaces and heat pumps (see Figure 5.5).[38] About half of the floor space is heated with systems that burn fuels and produce CO_2 that cannot practically be captured or sequestered with conventional technology. In large commercial buildings, space heating typically uses boilers to heat water, piping the hot water to spaces (i.e., offices and other rooms), and then blowing air over compact hot water coils or running the coils through the floor or wall and radiating heat into the space. These systems require a separate, dedicated outdoor air system to bring in fresh air. The combination of water pipes/pumps and small air ducts/efficient fans not only requires less energy than large air ducts, it also needs less space between floors.

Air conditioning involves both cooling the air and removing moisture. The traditional approach does both using vapor-compression heat pumps. Smaller systems, including most residential systems, move conditioned air while most large commercial buildings use central chillers to cool water and transfer heat from water to air closer to the occupied spaces. Dehumidification is the process of taking water out of air, and it accounts for nearly 3% of all U.S. energy use. It is typically achieved by inefficiently cooling moist air until the water vapor condenses out and then re-heating the air to a comfortable temperature, which is an inefficient process. Efficiency improvements in heating, ventilation, and air conditioning (HVAC) systems will involve efforts to improve the efficiency of heating or cooling air and technology that can efficiently remove moisture from air.

Heat pump systems are often used for heating in regions where natural gas[39] is not available. Next-generation cold weather heat pumps can be cost effective in a wide range of climates. Current heat pumps lose 60% of their capacity and operate at half the efficiency when operating at -13°F. Work is underway to develop a heat pump capable of achieving a Coefficient of Performance (COP)[40] of 3.0 for residential applications at that temperature (compared with a COP of 3.6 for an ENERGY STAR® heat pump operating with no more than a 25% reduction in capacity).[41] Work is also underway to improve the performance of cold-weather gas furnaces.[42] Heat pumps have the advantage of providing both heating and cooling with a single unit offering an opportunity to lower initial costs.

Vapor-compression heat pumps and air conditioners rely on refrigerants (working fluids) such as hydrofluorocarbons that have a significantly higher global warming potential (GWP) than CO_2 when they are released to the atmosphere. The search for substitutes has proven difficult since alternatives present challenges in toxicity, flammability, lower efficiency, and/or increased equipment cost. It is an area of active, ongoing research by the National Institute of Standards and Technology (NIST) and others.[43] See Table 5.3 for more information.[44]

Table 5.3 Non-Vapor Compression Heat Pump Technologies

Magnetocaloric: Certain paramagnetic materials undergo temperature changes when placed in magnetic fields. Specifically, they undergo heating when a magnetic field aligns the magnetic dipoles of their atoms and cooling when the field is removed and dipole directions randomize.

Thermoelectric: Current flowing through two different semiconductors can either add or remove heat at the junction.

Thermoelastic: Shape-memory alloys heat up when physically stressed and cool down when stress is removed.

Electrochemical: This device uses a membrane that allows protons but not electrons to pass through. When a voltage is applied across the membrane, protons (hydrogen nuclei) accumulate at pressure on one side of the membrane. This leads to compressed hydrogen on one side of the membrane which can create cooling when expanded.

Electrocaloric: This device uses a dielectric that is heated when exposed to an electric field and gives off heat when the field is removed.

There is a number of promising heat-pump technologies that have the potential to increase system efficiency and eliminate refrigerants with high GWP.[45] Some use vapor-compression with CO_2, ionic liquids, water, and various combinations as working fluids. Heat pumps can also be built that do not require vapor compression (see Table 5.3). There are also opportunities to improve thermally driven technologies using adsorption and absorption devices and duplex-Stirling heat pumps.

While a key interest in developing these new approaches is to reduce GHG emissions, some can exceed the efficiency of current vapor-compression units.

5.2.4 Moisture Removal

Well-designed building shells and foundations can greatly reduce moisture infiltration, but residual moisture transfer coupled with moisture generated by people and building operations will continue to make moisture removal a priority in building energy systems. A number of new approaches do not require heat pumps and could lead to major gains in efficiency. Membrane technologies allow water vapor to pass but block the passage of dry air or can be used to separate moisture from air using only the difference in vapor pressure, passing thermal energy from outgoing to incoming air. Alternatively, these systems may develop a vacuum on one side of the membrane and then compress and exhaust the water vapor removed. These systems can be combined with evaporative cooling stages to provide both dehumidification and chilling.[46]

5.2.5 Heat Exchangers

Heating and cooling systems depend on devices called "heat exchangers" that transfer heat from the surfaces of the equipment, usually metal surfaces, to air. Efficient heat exchangers are typically large and expensive. It may be possible to greatly improve heat exchange efficiency through improved designs such as microchannel devices[47] or the rotating heat exchanger.[48] New manufacturing methods as discussed in Chapter 6, including additive manufacturing, may allow production of heat exchange designs not possible with traditional approaches, which could increase the efficiency of commercial air conditioners by as much as 20%.[49]

5.2.6 Thermal Storage

The performance of building heating and cooling systems and the electric grid system serving the building can be enhanced by systems that store thermal energy, particularly cooling capacity. Thermal storage can be provided with a number of different technologies and a number of commercial products are available.[50] Approaches include the following:

- Designing buildings to store and remove thermal energy in the mass of the building itself (i.e., floors, support columns, etc.)
- Using ice and other phase change materials

Since chillers are more efficient when outdoor air is coolest, systems that pre-cool buildings in the early morning can result in energy savings. Chillers can also store cooling capacity by pre-cooling chilled water or ice during night hours and then shutting off the vapor compression systems during peak cooling demand periods in the afternoon. This can yield small site energy savings through chiller efficiency improvements during the cooler nighttime hours, but the largest site benefit of thermal energy storage lies in reducing the site peak demand and peak energy usage. Shifting energy demand away from peak periods could improve electric utility operations by requiring fewer generation plants to be brought on line and reducing the need to build new plants and distribution systems.[51] Thermal storage could also be a dispatchable asset, mitigating problems associated with the intermittent output of wind and solar energy systems. Such systems must be operated as part of an integrated building control system (this is discussed in a subsequent section of this report).

5.2.7 Integrated System Analysis

Taken together, the technologies described above can achieve major improvements in efficiency. Figure 5.6 through Figure 5.9 summarize some of the cost and performance goals for key technologies and estimate the associated energy savings if they fully penetrate potential markets.[52] Figure 5.6 shows that a new residence, built using the best available technology today, could reduce its cooling energy needs by 61% while systems operating at the thermodynamic limit would see an 82% reduction.

This analysis assumes that improvements in windows and the opaque envelope were applied first, since they are passive approaches, and the remaining cooling demand was then met with more efficient equipment. As a result, envelope improvements are shown as contributing more to the overall primary energy use intensity reductions in both cases.

The savings potential of residential heating is even greater since the occupants and household appliances and other devices generate enough heat to meet a large fraction of the home's heating needs given high quality insulation, windows, and controlled ventilation (Figure 5.7).

Figure 5.6 Use of the most efficient wall, window, and HVAC equipment now available could reduce residential cooling 61%. The theoretical limit is an 82% reduction.

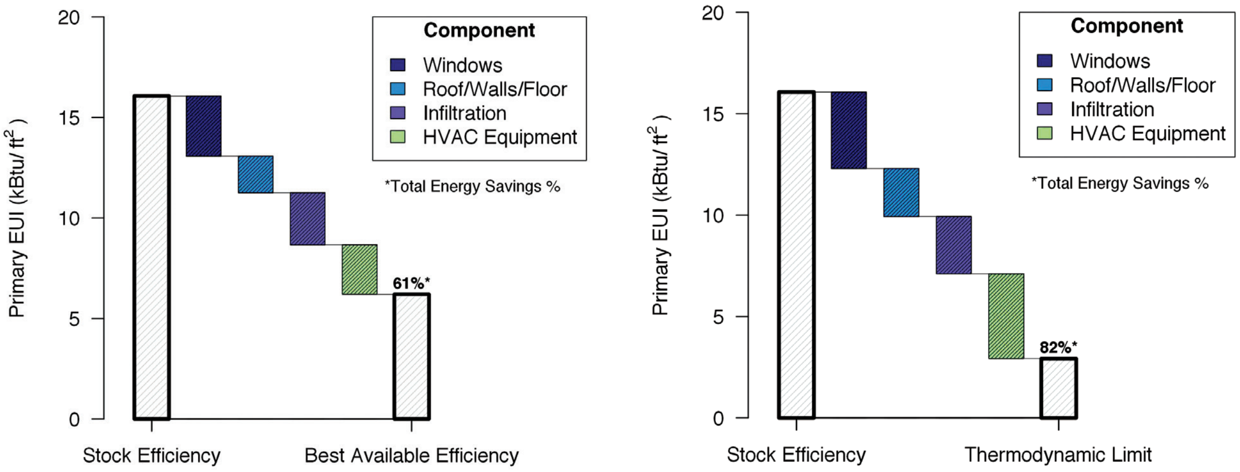
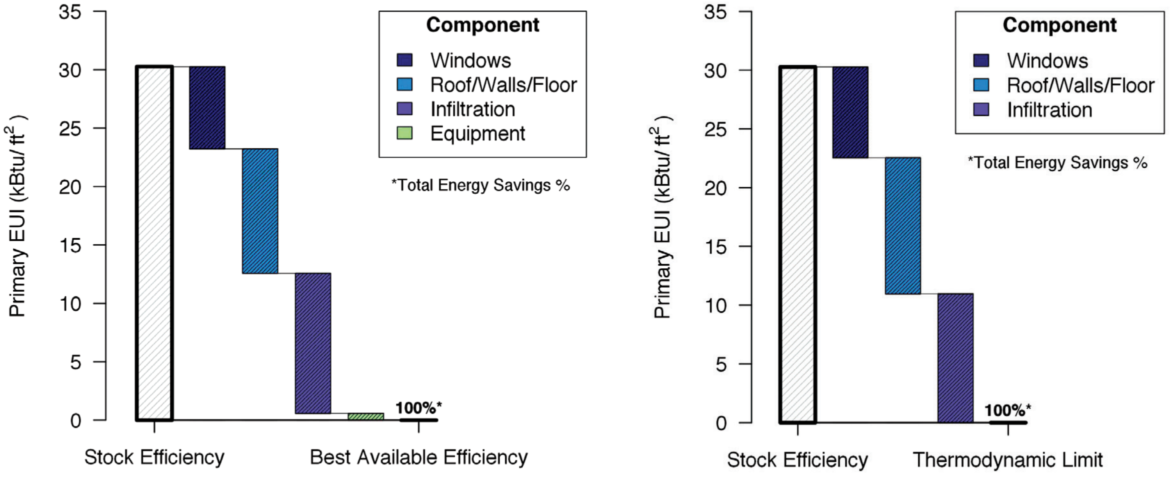


Figure 5.7 Use of the most efficient wall, window, and HVAC equipment now available could eliminate residential heating.



The results for commercial buildings differ in part because lighting plays a large role in energy use. Improved lighting efficiency decreases the heat energy released into the building by the lighting systems and thus reduces the demand for cooling (Figure 5.8). In the heating season, increasing lighting efficiency actually increases the demand for heating energy. This can be offset by improved insulation and heating equipment (Figure 5.9). These summary figures cover all building types and U.S. climate regions; actual building loads will depend heavily on climate region, size, and other design features.

Figure 5.8 Use of the most efficient wall, window, and HVAC equipment now available could reduce commercial cooling 78%. The theoretical limit is a 92% reduction.

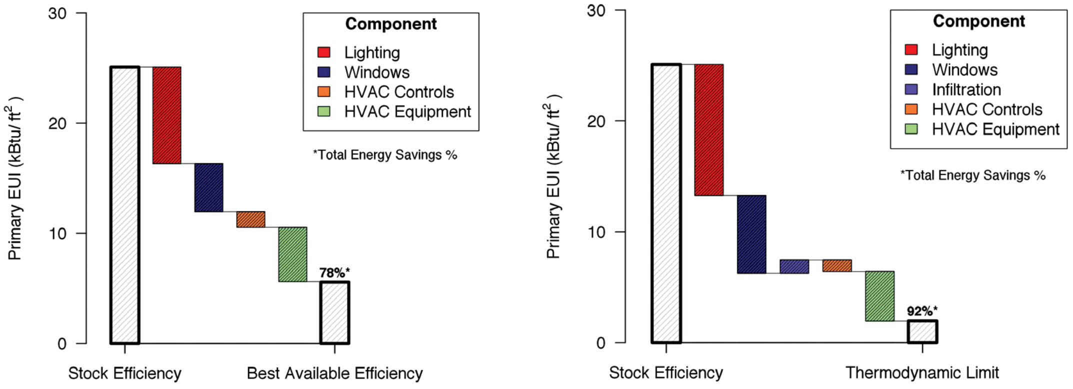
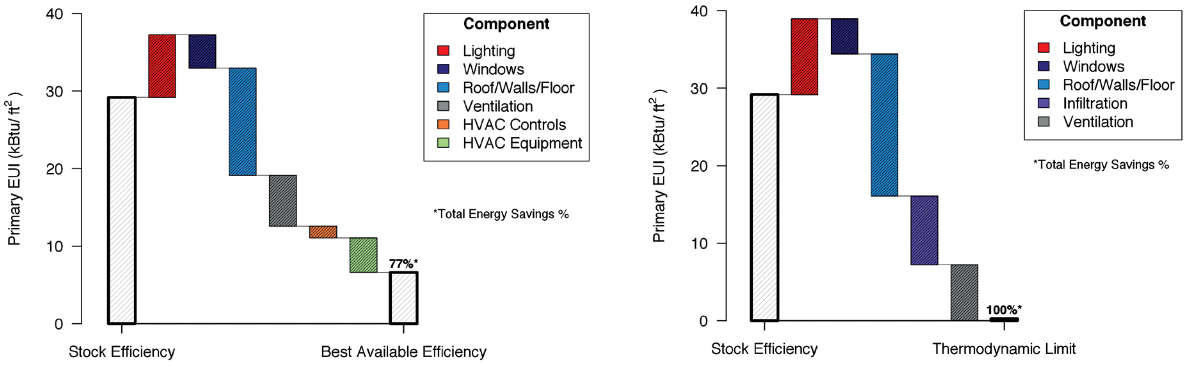


Figure 5.9 Use of the most efficient wall, window, and HVAC equipment now available could reduce commercial heating 77%. Increased lighting efficiency increases the load met by heating systems.



5.2.8 Research Opportunities

Primary areas for improving the efficiency and quality of building thermal comfort are the following:

- Materials that facilitate deep retrofits of existing buildings (e.g., thin insulating materials)
- Improved low-GWP heat-pumping systems
- Improved tools for diagnosing heat flows over the lifetime of a building
- Clear metrics for the performance of building shells in heat management and air flows

A detailed discussion of research opportunities for windows and wall materials can be found in a DOE report on windows and buildings envelope RDD&D,[53] and a detailed discussion of advanced non-vapor compression heat pumps can be found in a report on that topic.[54] In brief, areas where fundamental research problems remain unresolved include the following:

- Glazing materials with tunable optical properties (transmissivity and emissivity adjustable by wavelength) including materials that could be applied to existing windows
- Materials that are thin and provide tunable insulating and vapor permeability and materials that could be used in next-generation enthalpy exchange devices
- Technologies that could lower the cost of producing noble gases and identifying transparent, low-conductivity gases that could substitute for noble gases
- Strategies for using vacuum as a window insulation
- Innovative heat exchanger designs for heat pumps and other uses (variety of scales) that reduce the volume and weight of heat exchangers
- New ways to enhance ventilation and health that are cost-effective, energy-efficient, and practical to implement
- Improved ways to control moisture transfer into and out of buildings
- Components for non-GHG heat pumps including magnetocaloric, thermoelastic, thermoelectric, electrochemical, and electrocaloric systems

In a number of cases, the technology for achieving needed system performance is known but products are too expensive. In most cases, costs will decline as production volumes increase. Emphasis should also be placed on lowering manufacturing costs. In some cases, finding inexpensive materials is also important. Areas with opportunities include electrochromic windows, variable speed motors, vacuum insulation/advanced insulation (e.g., aerogel), sensors, and controls.

Continuing research brings the goal of creating a “net-zero energy façade or envelope” within reach. A window could reduce a building’s need for external energy sources more than a highly-insulated opaque wall. While the specifics vary with location and orientation, the opportunities to do this include: 1) reduce thermal losses by a factor of two to three below current code requirements; 2) provide active control of solar gain and daylight over a wide range; 3) introduce sufficient daylight to adequately light the outer thirty-foot depth of floor space; and 4) use natural ventilation when it can offset HVAC use. These systems require careful integration with other building systems to be effective and to provide the required levels of thermal and visual comfort.

5.3 Lighting

Lighting quality plays an essential role in the appeal and safety of interior and exterior spaces. Well-designed lighting systems can enhance productivity while glare and other harsh lighting features can decrease it.[55] Light quality also affects sleep patterns and health[56] and can shape the mood of any space. About 18% of U.S. electricity consumption and 6% of all U.S. energy consumption is used to provide indoor and outdoor lighting.

The goal of the DOE lighting research is to give designers the strategies and the devices that can provide optimal lighting performance while minimizing energy use. The new technologies can do much more than match existing lighting system performance with far less energy use. They can improve the quality of lighting by allowing greater user control including an ability to select color as well as intensity. The new lighting systems may be able to operate for decades without replacement or maintenance.

The key strategies for improving the efficiency and quality of lighting are good building and lighting design, window and window covering technologies (such as blinds and diffusers), lighting sensors and controls (including occupancy sensors and light sensors), and lighting devices (LEDs and others). Good lighting design can ensure that light levels are adjusted to user requirements. Intense task lighting may be needed for detailed work while much lower levels are needed in hallways.

Since each of these elements is influenced by the others, it is important to evaluate each as a part of an integrated system. It must also be recognized that lighting, whether provided by daylight or by artificial light, can have a significant impact on heating and cooling loads. The energy and environmental impacts of lighting systems must always be considered as a part of integrated building performance.

While 71% of all lamps in the United States are installed in residential units (Figure 5.10), commercial building lighting is by far the largest consumer of energy and lumens (lm).[58] Although only 29% of lamps are installed in commercial buildings, these buildings make significantly heavier use of fluorescent lighting fixtures—which on average use four times less electricity to produce a lumen than a typical residential incandescent lighting fixture.

The market for efficient lamps, driven in part by regulations, is rapidly changing the lighting market. Electricity used for lighting fell 9% between 2001 and 2010 even though the number of installed lamps increased by 18%.[59] The efficiency of a lighting unit is best measured by the lumens produced for each unit of electricity consumed, lumens per watt (lm/W). Lumens are a measure of light the human eye actually perceives. A candle produces about 12.6 lm and a traditional 100W incandescent light bulb produces about 1700 lm. The human eye is much more efficient at processing green light than it is processing deep reds or blues, and we are completely blind to infrared and ultraviolet (see Figure 5.11). The efficiency of incandescent bulbs is about 17 lm/W while a good fluorescent bulb can achieve 92 lm/W.[60]

Figure 5.10 Most light fixtures are in residences, but the bulk of lighting energy is in commercial buildings. The average commercial device is 3.6 times as efficient but is in use more than six times (in hours) as much per day.[57]

Credit: Navigant Consulting

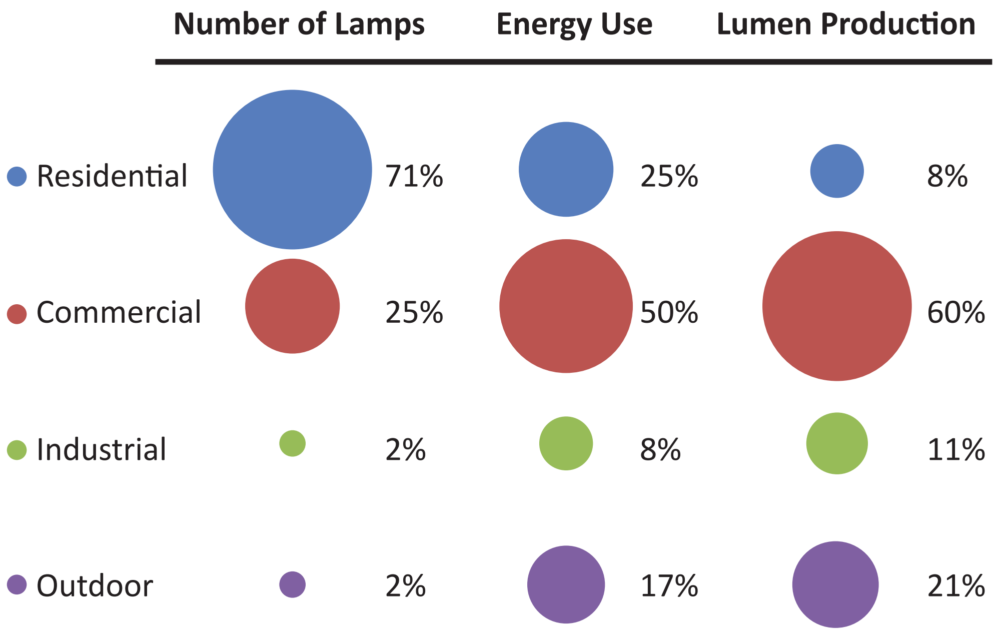


Figure 5.11 The efficiency of the human eye is highest for green light at 683 lumens per watt.

Credit: E. Fred Schubert, Light Emitting Diodes. Second Edition. Cambridge University Press (2006).

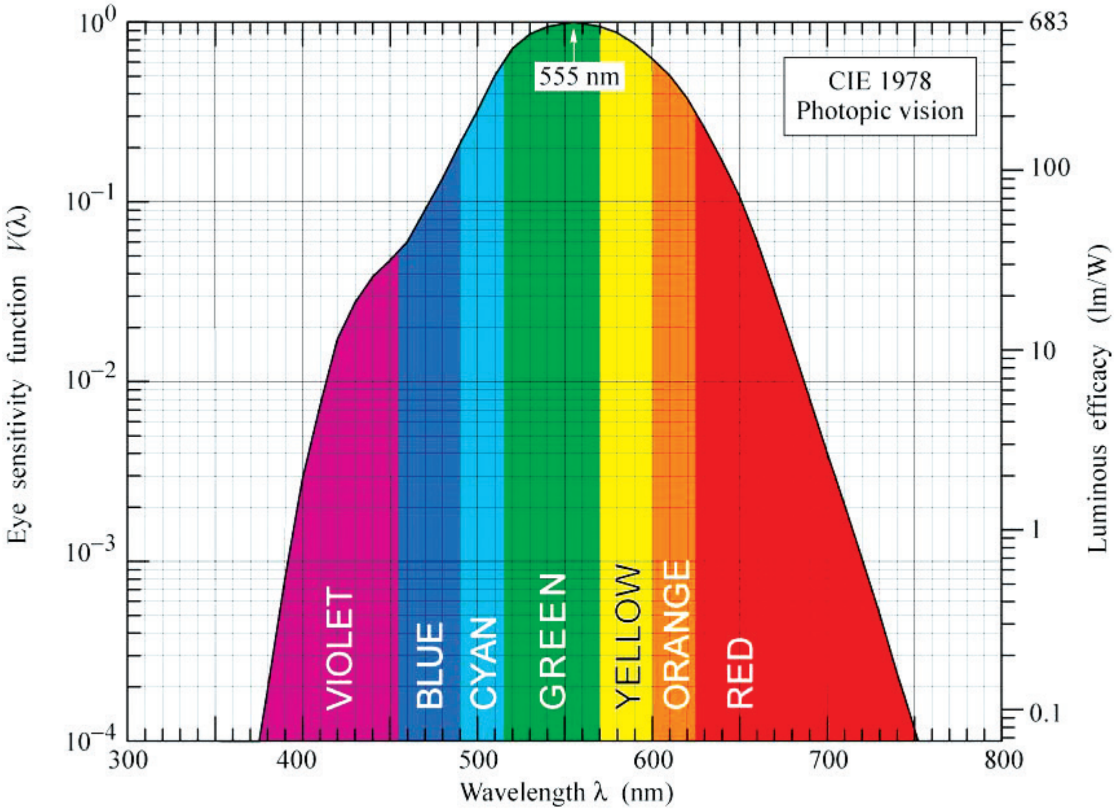


Figure 5.11 shows that one watt of energy in the form of green light results in 683 lm. This means that the absolute limit of a light device's efficiency is 683 lm/W. White, of course, is a mixture of many different colors and therefore seeing it requires eye receptors that are much less efficient than the green peak (Figure 5.11). There has been extensive analysis of what qualifies as an acceptable "white light."[61] The "white" that is acceptable depends on what is being illuminated (i.e., food, living areas, or streets), and there may be cultural differences.[62] Preferences for "warm" colors with more red or preferences for "cool" colors, which more closely match sunlight on a clear day, depend on a range of individual tastes.[63] New lighting technology, which allows a range of color and even an ability to adjust light color, will allow this diversity to be expressed in the marketplace.[64]

Taken together, the potential of daylighting, controls, and more efficient devices can be enormous. And the impact could be rapid if lighting devices, lighting sensors, and lighting controls were easily retrofit without major renovations.

5.3.1 Windows, Daylighting, and Lighting Controls

Daylight provided by windows can make a major contribution not only to the ambiance of indoor environments but to reducing a building's demand for artificial light. Windows account for about four quads of energy in terms of their thermal impacts and can influence another one quad. This complex connection to other building energy systems means that windows and daylighting sensors and controls can only be understood as a part of an integrated building system analysis. This integrated design impact will be considered later in this report.

Invisible sunlight (most of it in the near infrared) is important for building heating and cooling—and possibly can be used as a source of energy using photovoltaic (PV) cells designed to transmit visible daylight and use the remaining infrared light energy to generate electricity.[65]

From a lighting perspective, an optimal window would provide attractive light levels throughout the day while avoiding glare and unpleasantly intense light on surfaces such as computer screens. It would allow the user to control the amount of visible daylight transmitted through the window—possibly altering the direction of the transmitted light and adjusting transmission by color. Windows with varying optical properties can be built using mechanical systems such as adjustable blinds or louvers. Glazing can have adjustable optical properties such as thermochromic windows that automatically change transmissivity in response to temperature and electrochromic windows that change with electronic controls.[66] Light pipes, light shelves, and skylights to direct sunlight from roofs deep into buildings can lead to large savings, but these will depend on effective building designs. Advances in optics and manufacturing of dynamically-controlled windows make it possible to redirect light into the window material itself.[67]

The energy needed to control an active window device is generally small compared to the available sunlight, so window and lighting control systems can harvest energy for their own operations from sunlight, greatly simplifying installation. Several self-powered systems are commercially available today.

The challenge for all advanced window control systems has been cost, controls integration, and in some cases, durability. It has proven difficult, for example, to develop electrochromic films with variable optical properties that transmit a high fraction of the incoming daylight (e.g., 60% or more) when set to be fully transparent, switch to a very low level in the dark state, are color neutral, switch rapidly, and operate for approximately 50,000 cycles.[68]

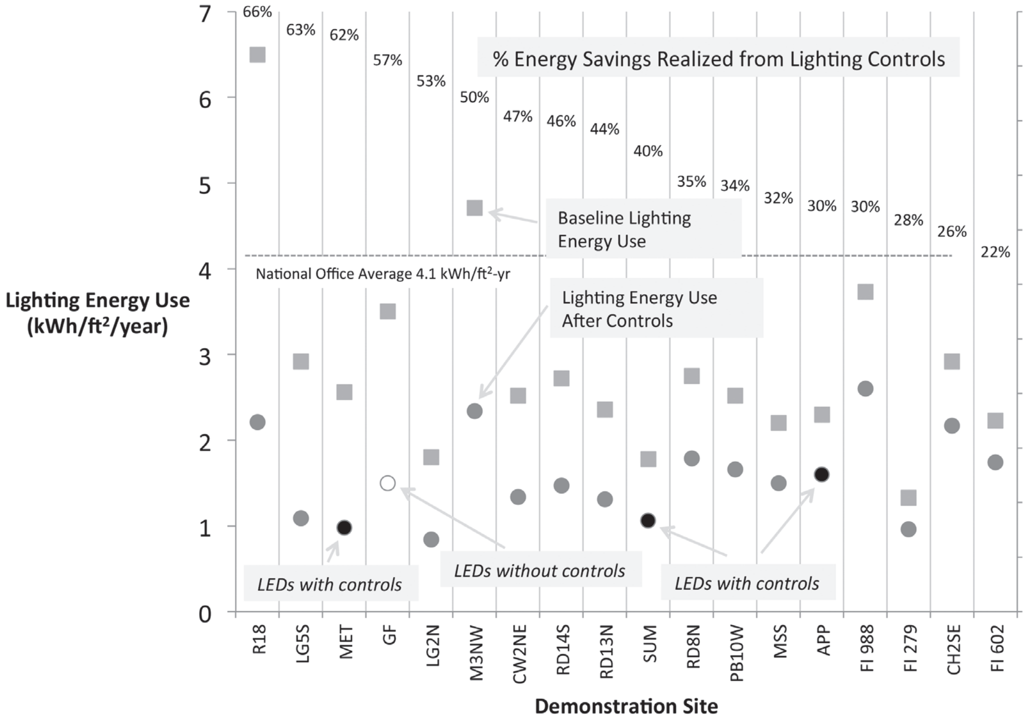
High-cost systems have found markets in specialty applications. A case in point is Boeing's 787 aircraft with tunable windows that can be controlled by the crew and individual passengers. At least two manufacturers in the United States have now invested in state-of-the-art manufacturing facilities to produce large-area, high-performance electrochromic coatings. The final price to end users is still too high for widespread adoption although they are being installed by early adopters and some costs can be offset by certain techniques, e.g., reduced chiller size for a reliable smart coating that reduces solar heat gain. Promising research using novel materials with low cost manufacturing processes (e.g., solution based) may also have potential to dramatically reduce costs.

Good lighting systems also depend on inexpensive sensors and controls. These include detecting when people enter a space and measuring light and color levels of key surfaces. It has proven difficult to build reliable, inexpensive occupancy sensors but steady improvements are being made. Further progress is needed in areas such as the quality of the sensors, system commissioning and continuous monitoring of system performance, combining sensor information with other information that can indicate occupancy (e.g., electricity consumption or computer use), and improved algorithms to extract information from multiple data streams (some of which may contain errors).[69]

While it is difficult to assign a precise value to good design, recent studies indicate that good designs can achieve impressive results. A meta-study of daylighting and control systems showed a wide range of savings without using new high-efficiency lighting devices (see Figure 5.12).[70] Savings range from an average of 30% using only occupancy sensors to an average of 45% when daylighting and more sophisticated controls were used. The U.S. Department of Defense also examined the performance of three advanced lighting systems and was able to achieve savings above 40% using only improved sensors, lighting design, and control systems.[71]

Figure 5.12 Energy Savings from Lighting Retrofits

Credit: Lawrence Berkeley National Laboratory



5.3.2 Lighting Devices

While many lighting technologies are commercially available, the technology most likely to dominate the future is the LED. There are two major classes of LEDs: crystalline semiconductor devices LEDs that have many of the characteristics of silicon-based computer chips, and organic LEDs (OLEDs), which use organic materials that have the characteristics of semiconductors.[72] Laboratory LED devices have been demonstrated that approach 300 lm/W,[73] which is beginning to approach the 400 lm/W theoretical maximum efficiency for an acceptable white light. The most efficient commercial products today have efficiencies between 120 and 160 lm/W. Remaining research challenges include efficiency improvements, cost reduction, reliability, color consistency, and compatibility with dimmers and other controls.

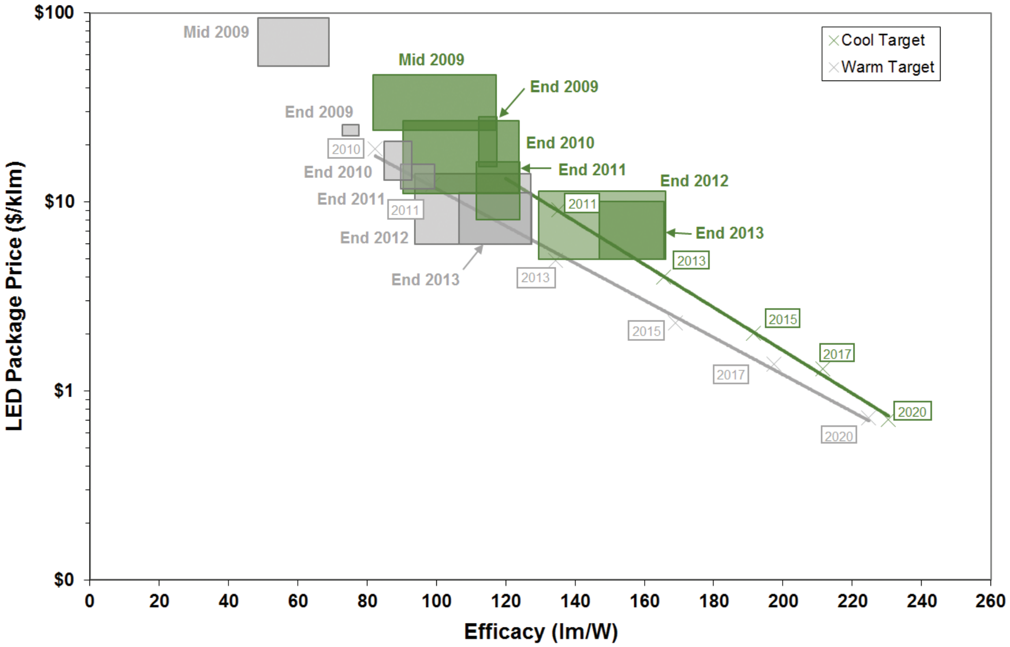
The combination of federal and private research has driven rapid increases in LED efficiencies and driven down the cost per lm of LED products (see Figure 5.13).[74]

Three approaches have been taken to produce a LED with high efficiency and acceptable light quality. These include the following:

- Combining three or four single-color LEDs to produce an acceptable approximation to an incandescent light source. These are chosen to match at red, green, and blue eye receptors. Amber LEDs are sometimes added to achieve better color quality. One advantage of this approach is that the different LED devices can be dimmed separately allowing users to control the color.
- Use of high efficiency blue LEDs to illuminate a phosphor, which then re-radiates the light over a broad range of colors.
- Hybrid approaches that use LED colors with comparatively high efficiency and produce green or other colors using a phosphor.

Figure 5.13 The price and performance of LEDs have steadily improved since 2009.

Credit: Navigant Consulting



One of the challenges in using multiple LEDs has been the low efficiency of green LEDs. Table 5.4 shows the performance challenges facing LEDs that use phosphors to convert blue LED output into other colors.[75] Significant improvements are needed in both green and red phosphors.[76]

Quantum dots, which are nanoscale semiconductor structures, can substitute for phosphors, but challenges remain in achieving high efficiency without use of cadmium.[77] Innovations are also needed to improve the fraction of light that actually leaves the device (as opposed to being absorbed internally) and the electronic subsystems that provide dimming and convert alternating current (AC) plug power into the direct current (DC) required by the lights. Color reliability and guaranteed lifetimes are also a challenge.

Research teams have been attempting to achieve efficiency, reliability, and other targets that would make them convincing competitors to other LEDs. While progress has been steady, major challenges remain.

Table 5.4 LED Efficiencies

	LED efficiency in percent (Light energy out/electric energy in)				Effective phosphor conversion efficiency in percent		
	Blue	Green	Amber	Red		Green phosphor	Red phosphor
Current efficiency	55	22	8	44	Current efficiency	44	37
2025 goal	80	35	20	55	2025 goal	67	56

Other Advanced Technologies

A variety of innovative strategies have been proposed for bringing natural light into interior spaces. They include the following:

- Internally reflective light conduits that bring light from roof collectors into interior spaces
- PV devices that are transparent to visible light but convert infrared and other portions of the sunlight into electricity (these devices may cut installation costs for self-powered window and window shading devices)
- Combined systems that generate electricity in rooftop PV units and transmit visible light through fiber optic systems to interior spaces

5.3.3 Integrated System Analysis

Taken together, use of efficient lighting devices, daylighting, sensors and controls, and good design can reduce the energy used for lighting by an order of magnitude. Potential savings from integrated systems is shown in Figure 5.14 and Figure 5.15. The order in which measures are considered shapes the magnitude of savings for subsequent measures. Least expensive measures were considered first, therefore sensors and controls were considered first.

Figure 5.14 A combination of improved lighting devices and controls meeting 2020 program goals (ET) can reduce residential lighting energy 93% of the theoretical limit.

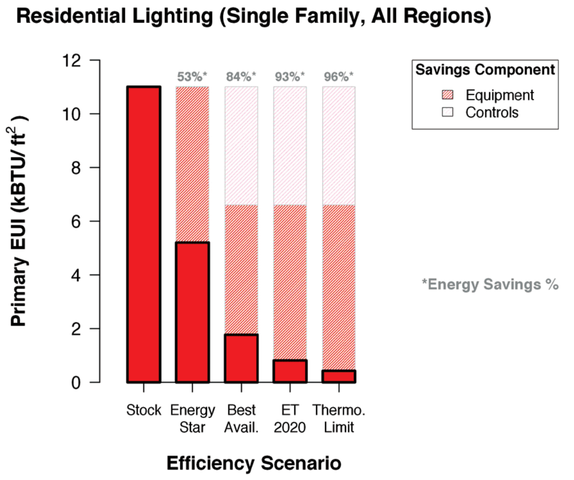
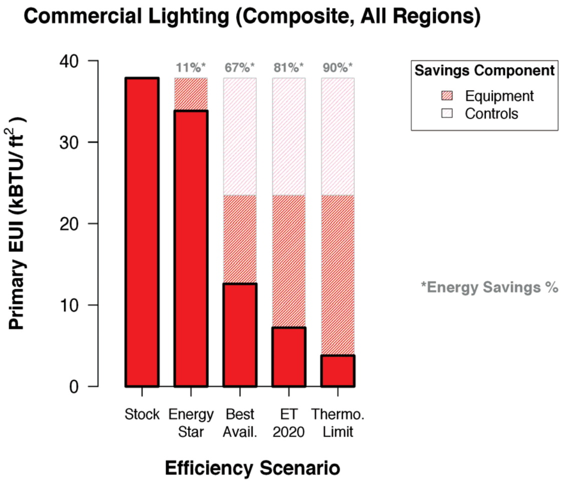


Figure 5.15 A combination of improved lighting devices and controls meeting 2020 program goals (ET) can reduce commercial lighting energy 81% of the theoretical limit.



5.3.4 Research Opportunities

Innovators ranging from large global glass companies to small venture-supported firms are making significant investments in new window and window control systems. Federal research investment focused on devices should be limited to high-risk innovations such as novel optical materials and new manufacturing methods. There is a clear and continuing need for federal support of testing protocols for advanced glazing and fenestration systems, and the development of voluntary interoperability specifications for building controls that integrate and optimize dynamic envelope components, lighting, and HVAC. There is also a continuing role for the development of performance databases and simulation tools with open and validated algorithms and models. Detailed research priorities are laid out in recent roadmaps.[78]

One fundamental need is the development of test procedures for reliably determining the expected lifetime of commercial products. LEDs can last for decades but there are no data on long-lifetime units. A standard method for accelerated lifetime testing is essential.

Opportunities for fundamental research also include the following:

- Understanding why LED efficiency decreases at high power densities
- High-efficiency green LEDs
- Efficient quantum dot materials
- Glazing with tunable optical properties (also needed for thermal load management)
- Efficient, durable, low-cost OLEDs

Opportunities for reducing costs through improved design and manufacturing and other mechanisms include the following:

- Sensors and controls
- Lowering retrofit costs of new light fixtures

5.4 Major Energy Consuming Appliances: Hot Water Heaters, Refrigerators, and Clothes Dryers

Water heaters, refrigerators, and clothes dryers are major energy consumers and are responsible for about 18% of all building energy use. Many of the technologies designed to improve whole building energy performance discussed earlier can also be used to increase the efficiency of these appliances. For example, water heating efficiency can be improved using advanced heat pumps, low-cost variable-speed motors, thin insulation, and other improved designs. Improved insulation and other strategies can reduce the losses from lengthy hot water distribution systems in commercial buildings and large homes. Water heaters with storage tanks are good candidates for load shifting and providing other services important for optimizing electric utility performance with the help of improved controls and communications technologies. Work is often needed to ensure that these approaches are designed for the size ranges needed for appliances.

Significant gains have been made in refrigerator performance over the past decades but these gains have been partially offset by the increasing number of refrigerators and freezers used per household.[79] Improvement in heat pumps, advanced thermal cycles, heat exchangers, and thin, highly-insulating materials (e.g., vacuum insulation) can lead to major performance gains. Further gains are possible by using separate compressors optimized for freezers and refrigerator compartments and using variable speed drives and new sensors and controls to reflect ambient temperatures and react to signals from utilities.

Until recently, clothes dryers were untouched by the technical advances transforming markets for other building equipment, but this is changing rapidly. New clothes dryers now on the market use heat pumps to circulate heated air over clothing in a drum, pass the air over a heat exchanger cooled by the heat pump, condense the water out of the air, and then reheat and recycle the air. Since air is recycled, there is no need for an air vent. These appliances operate at lower temperatures (thus are gentler to clothes) and reduce utility peaks since their peak electric demands are one-fifth of conventional dryers'. The technology is attractive for designs that provide washing and drying in the same front-loading unit.[80]

U.S. sales have been limited because of their comparatively high cost and longer cycle times (typically double current times). American consumers, used to doing multiple loads of laundry, demand dryers that have roughly the same cycle time as washing machines. However, improved heat pumps, insulation, heat exchange, variable speed motors, and other innovations promise further gains in performance and lowered costs.[81] There are also some potentially game-changing technologies on the horizon including the use of ultrasound to shake moisture out at ambient temperatures and technologies embedding thermoelectric heat pumps in the lining of the rotating drum.[82]

5.5 Electronics and Other Building Energy Loads

About 36% of building energy use is distributed across a wide range of systems, the majority of them electric. These include a variety of electronic devices such as computers, televisions, imaging equipment (e.g., printers and multifunction devices), audio/video equipment other than displays, telephony devices, and network equipment. Kitchen and household devices are also included, as are application-specific commercial building systems. Electric vehicle chargers are also included in this category. They are now small, but their importance may grow rapidly in coming years (see Chapter 8).

5.5.1 Computers and Other Electronic Devices

Computers and other electronic devices account for about 6% of all building energy use, and the U.S. Energy Information Administration forecasts that energy use in data center servers will increase five-fold by 2040, while energy use in other information technology equipment will more than double.[83] Table 5.5 contains additional information on the number of selected electronic devices in the United States and the total energy usage (in quads) associated with them.[84]

Federal research investments have played a major role in creating the fundamental innovations in devices and software that has driven the explosive growth of computers and other electronic equipment.[85] However, most applied research work has been supported by corporate research investments. This has driven both continuous improvements in the capabilities and cost reductions of computers, displays, communications devices (e.g., network equipment, telephony, and set-top boxes), imaging equipment (e.g., printers), and other audio/video equipment. There are still many opportunities for further improvement (see Table 5.6).

Table 5.5 Computers and Electronic Devices

	Quads	Units (millions)
Residential	1.38	1363.3
TV and related equipment	**1.02**	**895.1**
TV	0.53	302.8
Set top boxes	0.39	327.1
Home theater	0.03	34.1
Video game consoles	0.02	60.1
DVD players	0.04	170.9
PC and related equipment	**0.36**	**468.2**
Monitors	0.07	84.1
Desktop PC	0.14	69.9
Network equipment	0.06	128.8
Laptops	0.10	185.3
Commercial	0.97	N/A
PC equipment	0.30	N/A
Non-PC equipment	0.67	N/A

While most research has focused on improving product speed and quality, the large energy requirements of computational facilities have led to increased interest in improving energy efficiency and finding ways to reduce their peak power consumption.

Concern about the battery life of mobile devices and the huge energy use of modern data centers has driven major innovation in efficient chip design.[86] Despite this, it is clear that society is far from the physical limits of energy efficient computing. Consider that a mouse brain can be 9,000 times faster than a personal computer simulation of its function, but the computer performing the simulation uses 40,000 times more power. Research is beginning to make this "neural networking" approach to information processing available in practical devices, which can reduce computing energy use. Recently a number of groups have attempted to imitate the way biological brains process data.[87]

Table 5.6 Efficiencies of Electrical Devices

	Current stock (kWh/yr)	Best available (kWh/yr)	Max tech (kWh/yr)
TVs	213	63	24
Residential computers	158	34	N/A
Commercial computers	336	34	N/A
Set-top boxes	142	86	65

The best measure of merit for computational facilities would be based on the functions performed by the computers (e.g., data searched and images rendered) per unit of energy used. It would also provide a measure of inefficiencies owing to poorly written code or systems where servers are powered up but aren't doing any work. These metrics are inherently specific to the particular type of computation or "workload" being performed; efforts to create a generic metric have thus far been unsuccessful.

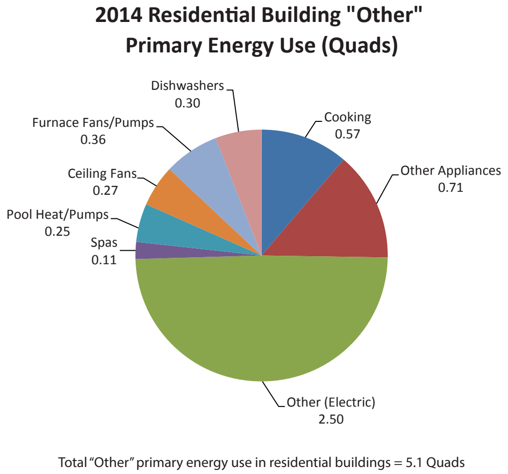
Buildings that house and cool large computer centers are also major energy consumers.[88] A commonly used measure of the efficiency of data centers is the power usage effectiveness (PUE). This is the ratio of the total energy used by the center to the energy used just by the computers. Older centers often used more energy for cooling than they did for the computers (i.e., PUE > 2). Better cooling designs have made it possible to greatly reduce this demand. The National Renewable Energy Laboratory's recently completed center has a PUE of 1.06.[89] DOE and the U.S. Environmental Protection Agency have been active in encouraging much greater efficiency in these systems, and DOE recently partnered with a number of companies in a "data center challenge."[90]

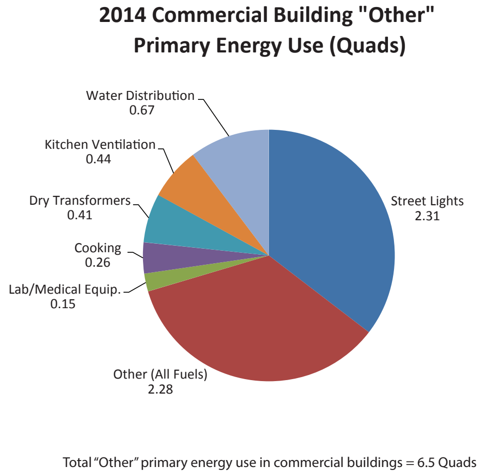
Computer screens, televisions, and other display devices can be major electricity users and the technology of these devices is changing very rapidly. Table 5.6 shows a large difference between the efficiency of the average televisions in use and the best available technologies.[91] This evolution has occurred even though new screens are often much larger and offer higher resolution and refresh rates than the ones they replace. Display technologies have rapidly become more energy efficient per unit of display area over the last decade. The increasing size, number, and hours of usage of displays are making this a topic of ongoing concern, and it increases the need for effective controls. The energy needed to operate network equipment was 20 terawatt-hours per year (TWh/year) in 2008 and continues to grow rapidly.[92]

5.5.2 Other Building Energy Loads

About 30% of all building energy consumption is not included in any of the technologies covered in earlier sections. Figure 5.16 shows that in the residential sector, the most prominent of these "other" building energy loads are cooking, household appliances, and various fans/pumps, while in the commercial sector the most prominent "other" loads come from non-building uses (e.g., street lighting, water distribution, etc.) and from kitchen ventilation and dry transformers.[93] It is notable that in both the residential and commercial sectors, a significant portion of the "other" loads remain unclassified with the unclassified portion limited to electric loads in the residential sector and stretching across all fuel types in the commercial sector.

Figure 5.16 The "other" category of demand in buildings is created by a huge variety of devices—many of which are miscellaneous electric loads.





5.5.3 Research Opportunities

The diversity in these electronic and other building energy loads is so great that it has proven difficult to devise research strategies for addressing them; yet, the large amounts of energy they use becomes increasingly significant as other end uses become more energy efficient. An important part of the strategy will involve finding technologies that could address efficiency issues across a wide range of these miscellaneous end uses. Such technologies include more efficient circuitry, more flexible power management (though hardware and software solutions), and standardized communications protocols. Wide bandgap semiconductors (discussed in Chapter 6) can improve controls, and highly efficient motors, next-generation heat exchangers, and thin-insulation can improve the performance of a wide range of devices.

In the case of computers, basic research in materials, algorithms, and other work funded by the National Science Foundation, DOE's Office of Science, and other federal agencies has been the foundation of this rapid growth. Building on this basic research foundation, the pace of change in the "computer and electronic products" industries has been extremely rapid because of high levels of commercial investment in innovation. This sector invested nearly 10% of their sales to research and development in 2007 in comparison to the national average of 3.8%.[94] While energy use has become a priority in areas like large server systems, where energy dissipation is becoming a barrier to progress, energy efficiency in a diverse set of other products is often neglected in the race to bring innovations to the market.

5.6 Systems-Level Opportunities

5.6.1 Sensors, Controls, and Networks

Lighting, windows, HVAC equipment, water heaters, and other building equipment are starting to be equipped with smart controllers and often wireless communications capabilities. These systems open many opportunities for improving building efficiency, managing peak loads, and providing services valuable to controlling the cost of large utility systems. They also offer many non-energy benefits that may be of greater interest to building owners and occupants than just energy usage. These include improved security, access control, fire and other emergency detection and management, and identification of maintenance issues before they lead to serious problems. Low-cost sensors and controls also expand opportunities for individuals to have greater control of the thermal and lighting conditions, and if they power themselves using available light, vibrations, or fields generated by AC lines, it simplifies installation.

More than 40% of all commercial buildings more than 100,000 square feet had some kind of "energy management control" system but less than 7% of buildings smaller than 10,000 square feet used them in 2003.[95] Data on the type of controls and the way they are used (or misused) are very poor. A recent study of controls for packaged air units in California showed that 4.75% used manual controls while 35.7% employed a programmable thermostat.[96] Only 4% were part of an energy management system. Innovations that greatly lower the cost and simplify the installation and operation of control systems will be particularly valuable for expanding markets for advanced control systems in smaller commercial buildings and residences.

While individual subsystems such as lighting require their own control, the building as a whole will perform most efficiently if all the building systems are controlled as a part of an integrated system. Well-designed control systems can increase building efficiency up to 30% without the need to upgrade existing appliances.[97]

Figure 5.17 demonstrates the wide range of actors and interactions that characterizes the integrated building and grid system. Additional needs of the integrated electric grid are discussed in Chapter 3. Systems should be able to do the following:

- Control room temperatures, humidity, ventilation rates, tunable windows, variable louvers, and dimmable lights
- Control major appliances—most devices are controlled by turning them off or on, but the new generation of appliances allows more sophisticated adjustment of operation
- Use weather forecasts to develop optimum strategies for preheating or cooling the structure
- Detect and identify component failures and look for signs that equipment is about to fail
- Adapt performance in response to communications from utilities using new rate structures to minimize overall system costs
- Learn and anticipate user behaviors including adjusting for holidays and integrate user preferences dynamically

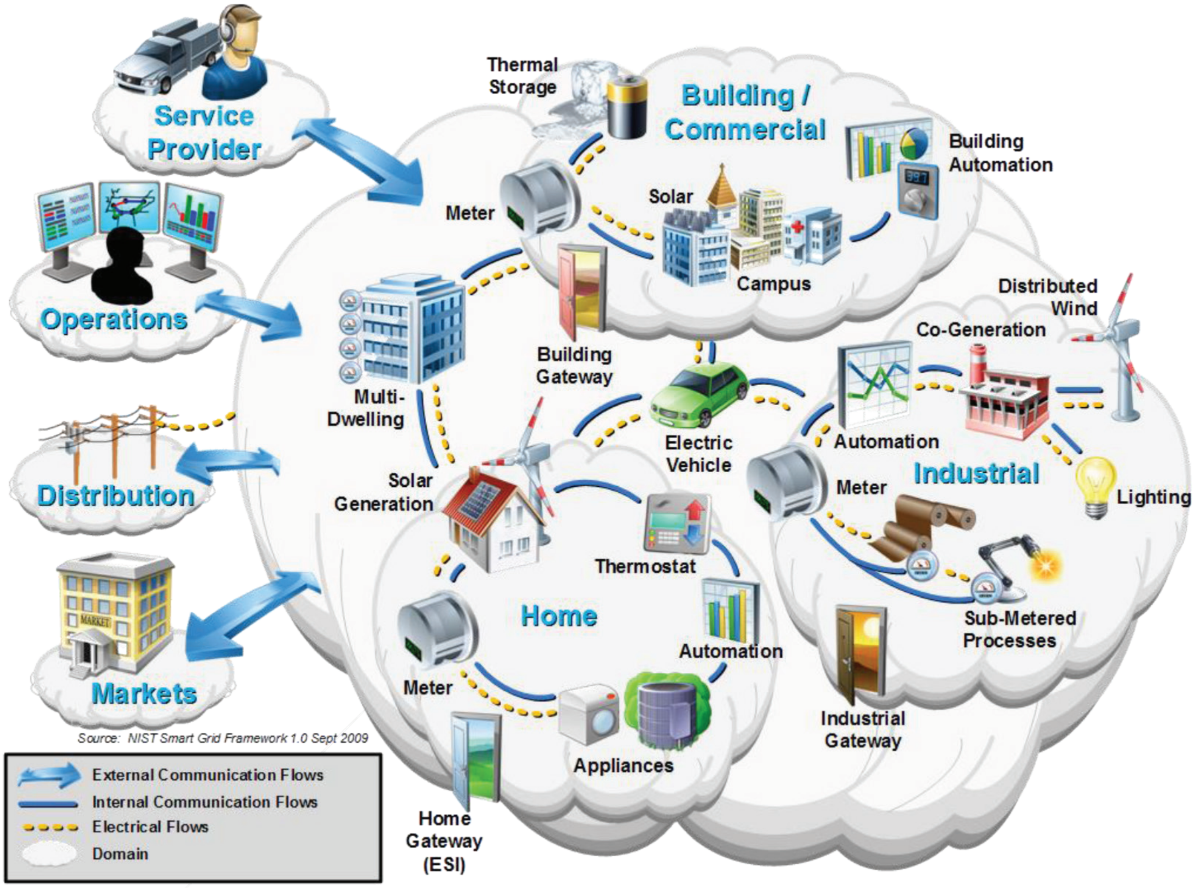
Cost has been a major barrier to the use of self-powered sensors and controls connected by wireless communication systems. Advances in designs and production technologies can cut the cost of lighting, temperature, occupancy, current, and other sensors from the $150–$300 per node to $1–$10 per node using printed electronic substrates for circuits, sensors, antennas, PVs, and batteries.[98]

Since buildings are responsible for more than 76% of all electric demand, control systems in buildings can also play a major role in optimizing the performance of the next-generation electric grid. Advanced building controls and control strategies can provide a portfolio of services ranging from helping maintain utility sixty-cycle frequency over periods of seconds, to short-term load shedding by controlling water heaters and other appliances, to longer-term load shifting using the thermal mass of the building or storage systems. PVs are rapidly entering the market in some regions, and the inverters that connect them to building loads and the electric grid can also provide services to the building and the electric grid.[99]

Control strategies can be designed for small grids internal to a building, micro-grids serving clusters of buildings, and large utility-scale "smart" grids. Benefits to the grid include improved frequency control, reduced spinning reserve, deferred expansion of transmission and distribution systems, and smoother reaction to unplanned outages. Early estimates suggest that intelligent building controls could potentially be worth $59 billion (in 2009 dollars) annually in the United States by 2019.[100] These savings require major innovations in the financial incentives provided to customers for these services. Capturing these benefits requires building

Figure 5.17 Future grid systems and smart building controls can communicate in ways that improve overall system efficiency and reliability.

Credit: National Institute of Standards and Technology



Source: NIST Smart Grid Framework 1.0 Sept 2009

communications networks allowing the components to interoperate and respond to facility-wide control systems for both functionality and power distribution. Inverters connecting distributed PV systems can create problems if not effectively managed as a part of a grid system, but if properly managed, they, like other building control systems, can make significant contributions in the form of frequency regulation and in other areas.

Today, there is a lack of agreement on comprehensive communications and data standards. Competing, proprietary systems inhibit the widespread adoption of technologies and control strategies and drive up the cost of deployment. The absence of dynamic price incentives for customer grid services in most areas is a major barrier to development and commercialization of sophisticated systems.

Two major challenges in developing widely affordable building sensor and control systems include the high labor cost for retrofitting new lighting and lighting control systems and for getting complex control systems to work correctly. It takes many hours of expensive, highly-skilled system designer/operators to adjust schedules and ensure that building lighting and comfort levels actually reflect user needs.

There is growing concern that building communications systems need cybersecurity and privacy protection as an integral part of their design. Security concerns are particularly important in hospitals and other sites where life and safety are at risk.[101] Finding ways to update the software embedded in low cost devices is a new challenge.

5.6.2 Building Design and Operation

Well-designed buildings, systems, and control strategies can improve comfort levels, increase reliability, and reduce costs by optimizing use of component technologies. Often these low-energy buildings can be built with little or no extra cost. Advanced software that models buildings as integrated systems provides a powerful set of tools for ensuring effective building design and operations. These systems can predict building energy use given a description of its geometry, construction, systems, operations, occupancy, and local weather conditions. Whole-building energy modeling allows architects, engineers, and energy consultants to design a building's envelope, systems, and operation schemes to match its anticipated use profile and local conditions and to maximize energy-efficiency or return on investment while subject to constraints such as first cost. Innovations in the process of construction itself, such as greater use of modular components that could minimize air leaks and other problems associated with site-construction, might make this easier to accomplish.

A 2013 study of 1,112 design projects submitted to the American Institute of Architects 2030 Commitment program shows that buildings designed using energy modeling have a design energy consumption that is 44% lower than the 2003 stock. Buildings designed using prescriptive one-system-at-a-time rules outperform stock by only 29%.[102]

Unfortunately, only 55% of commercial building projects used modeling anywhere in the design process, including for either code compliance or green certification after the design had been finalized. However, thanks in part to DOE investments in the open-source modeling engine EnergyPlus and in the testing and long-term support for the validation of energy simulation engines, whole-building energy modeling has become more capable, robust, and consistent. DOE's open-source energy simulation software development platform OpenStudio is helping make energy modeling easier to use.[103] Nevertheless, more work remains to be done. Integrative design must also fit gracefully into existing relationships between owners, architects, engineers, and other stakeholders.

In addition to supporting system-level design, whole-building energy modeling can also be used to maintain, diagnose, and improve building energy performance during occupancy. Comparing modeled operations to actual operations supports detection and diagnosis of equipment and control faults, and, more generally, any divergences from design intent. Model-predictive control uses energy modeling, as well as real-time weather forecasts and (price) signals from the grid to tailor short-term control strategies for energy reduction, peak demand reduction, or other objectives—energy reductions of 15%–40% have been demonstrated.[104] Energy models can act as an intelligent interface for a building's on-site generation, energy storage, and thermal storage capabilities, and can be an integral part of systems that provide services to the utility grid.

Technical challenges and RDD&D opportunities for building energy modeling include the following:

- Continued improvements to open-source modeling tools to make them faster, more accurate, and easier to use while keeping up with emerging building technologies, especially in HVAC components, systems, and controls.
- Empirical validation and calibration of energy modeling engines including new strategies for benchmarking model results against large numbers of well-monitored buildings (facilitated by low cost sensors, controls, and communications capabilities). This will require measured information about temperature, equipment usage, occupancy, infiltration rates, and other critical variables. This could include a more detailed database of existing U.S. buildings than is possible with traditional survey methods. Interoperability standards are essential to convey data to and from the modeling system.[105]
- Use of the same control specification for energy simulation, control design, testing, and implementation. This unification would greatly streamline control design and eliminate interpretation and re-implementation errors.

- Development of system designs that minimize the risk of poor designs and installation and that detect and diagnose equipment faults. Models should be able to include estimates of stochastic behavior, uncertainty, and faults. Modeling should account for these conditions and provide ranges of expected outcomes given reasonable distributions of inputs.[106]
- Improved software for integrating smart distribution grids and advanced building controls.

5.6.3 Decision Science

The actual impact of new building technologies depends on how they are used by building occupants and operators, purchasing decisions, and many other factors that depend on aspects of human decision making. Building systems must be designed with the clearest possible understanding of user needs and preferences and the way they choose to interact with the technology.[107] Savings of five to nine quads per year appear possible.[108] Examples of areas where decision science and associated social and behavioral research can have a measurable impact include the following:

- The consumer "rebound effect" whereby efficiency investments lower the cost of energy services and thus could encourage wasteful behavior, (e.g., reduced incentives to turn out the lights).[109] Greater understanding of this effect would contribute to equipment and interface designs and forecasting.
- Many utilities are experimenting with approaches to customer communication that can actually influence their decisions and potentially have a lasting effect. These include strategies for helping consumers compare their energy use with their peers and neighbors and notifications that alert customers to anomalies that might need to be remedied. Modern communications and big-data analytics tools can personalize communication to provide clear and credible information when it's most likely to be useful. Persistent savings of at least 3% and a peak demand reduction of 5% appear to be possible.[110]
- There are many examples of misuse or non-use of energy efficient equipment. As an example, less than 5% of housing units equipped with programmable thermostats use them properly.[111] Research to develop human interface designs that make controls transparent and easy to use is essential for capturing the potential of many technologies.
- There are several ways to provide information to consumers and users about their energy consumption. Well-designed energy labels can positively influence consumer decisions when they're purchasing energy-intensive equipment, but care must be taken in their design.[112]
- The task of labeling increases as ET increase the complexity of purchasing decisions. Examples include: lighting devices that must be labeled for output in lumens rather than input in watts; lights with a wide range of color characteristics; and networking equipment with different kinds of communications, interoperability, cybersecurity, privacy, and other features.
- New technologies need to be introduced with consumer desires and needs clearly presented. When "smart" utility meters were initially introduced, there was often poor communication over the benefits and concerns. As a result, privacy and health concerns led to a backlash and low participation rates in some areas.
- Many energy-efficiency technologies that appear to be highly cost-effective have not found large markets. It's important to understand how these markets operate to design effective programs to encourage more rapid adoption.

New information technologies open up opportunities to collect and evaluate large amounts of information at very low cost. This makes it possible to conduct statistically significant samples of different strategies for influencing consumer decisions. The federal government faces significant constraints in collecting this kind of information, but it could work on methodologies and analytical tools that facilitate research sponsored by utilities and others.

5.6.4 Embodied Energy

There is great variation in the energy needed to produce construction materials and build a structure (embodied energy). Analysis shows that this “embodied energy” is 5% of total building energy use for single-family residential building[113] and 16%–45% for office buildings.[114] NIST has recently introduced a powerful set of tools for evaluating the embodied energy of buildings.[115] The greatest potential for reducing the embodied energy of building materials involves strategies such as increasing recycling and the use of recycled materials, reducing process yield losses, substituting with less energy-intensive materials, and optimizing product design for minimal material use.

5.6.5 DC Systems

LED lights, computers, TVs and computer monitors, and many other modern devices operating in buildings now use relatively low-voltage DC instead of the AC available at wall plugs. The ubiquitous Universal Serial Bus connectors operate at five volts DC. PV devices and associated battery systems, as well as electric vehicles, operate on DC. Recent analysis suggests that a typical house using a PV system could reduce its electric demand by 14% if it was equipped with energy storage and 5% if there was no storage.[116] While AC to DC and DC to AC converters are becoming very efficient (typically greater than 90%) and are designed to go into hibernation modes when not in use, the large number of conversions leads to significant losses.

There may also be a growing market for distributed electrical storage to provide a variety of grid support services in future electric grid and microgrid systems. The best location and size of electric storage systems in any region will require a careful analysis of the value of increased reliability, economies of scale, diversity, and many other factors (see Chapter 3).

5.6.6 Thermal Energy Distribution and Reuse

Refrigeration equipment, clothes dryers, washing machines, and many other building energy systems generate heat that is typically dumped into the ambient air. It is clearly possible, however, to capture and circulate this heat so that it can be reused (possibly after its temperature is increased). Waste heat from refrigeration could be used to help heat hot water. Waste heat may also be available from combined heat and power systems and possibly from rooftop solar devices. In high-density areas, it might even be reasonable to share heat or cooling between buildings. The core of large buildings in most climates require air conditioning even in cold weather and improved strategies for moving heat from the core could contribute to system efficiency. Very little work has been done to explore low cost approaches to such energy sharing systems.

5.6.7 Research Opportunities

Many research topics exist covering a wide variety of areas. Among the priority areas are the following:

- Reducing the cost of sensors and controls for electrical current, temperature, CO_2 emissions and other airborne chemicals and materials, occupancy, and many others
- Developing energy harvesting systems to provide power for wireless sensors and controls
- Improving the design of sensor and control systems including cybersecurity and improved methods for installing and commissioning these systems
- Developing easy-to-use, fast, accurate software tools to design highly-efficient buildings and to assist operations
- Improving support for co-simulation with other modeling engines using a widely used interface standard
- Developing algorithms that allow building sensor and control systems to automatically optimize system performance without large inputs from skilled designers

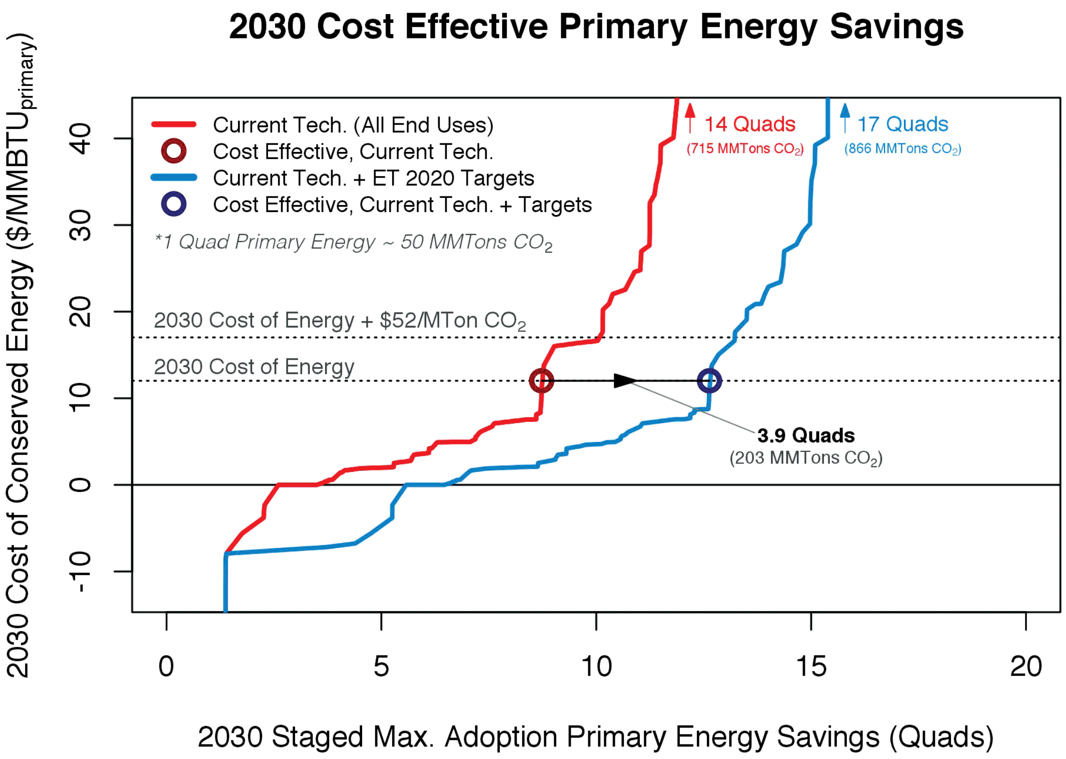
- Developing open-source software modules that can be combined to form sophisticated commercial control systems to enable flexible and dynamic buildings that provide value on both sides of the utility meter (DOE is encouraging the use of interoperable communications protocols for all building control and sensor systems and open-source system integration tools that will encourage creative commercial algorithms using both open-source and proprietary components.)
- Developing accurate, reliable sensors with low-installed costs, including occupancy sensors that can provide real-time occupancy counts
- Incorporating more decision science research while protecting the privacy of individuals and businesses
- Developing components and system designs that allow building devices to share waste heat

5.7 The Potential for Building Efficiency

Taken together, the technologies that can result from successful completion of the research topics discussed in this chapter have the potential to make significant reductions in building energy use at costs lower than forecast energy prices (Figure 5.18).[117] For reference, Figure 5.18 also shows energy prices that include the cost of GHG emissions now used to establish federal appliance standards; it is not intended to reflect a new analysis of the actual cost of these emissions.

In Figure 5.18, the red "Current Tech" curve shows the costs of efficiency measures now on the market. All the measures below the "2030 cost of energy" line—roughly nine quads—could be saved if all cost effective measures were purchased.[118] This would reduce building consumption by about 23%. If the 2020 goals described

Figure 5.18 More than seven quads of energy could be saved in buildings by cost effective technologies by 2030. Meeting program goals would increase this by 3.9 quads. A carbon price would increase savings further.



earlier in this chapter for major technology categories are met, the cost-effective savings potential increases to nearly thirteen quads or about 34% of all building energy use. The additional four quads of energy savings represent an associated CO_2 emissions reduction of 203 million metric tons.[119]

This estimate is conservative for several reasons. For example, it does not address opportunities for reductions in miscellaneous electric loads that contribute significantly to building energy consumption. The analysis also doesn't place a value on increased amenities associated with an efficiency measure (such as increased comfort and safety), or on the ability of these measures to provide valuable services to electric grids (such as frequency regulation and load shifting). It is also highly likely that currently unknown innovations will lead to further cost reductions and performance improvements.

5.8 Conclusion

While there has been spectacular progress in building energy efficiency over the past few decades, it is clear that major opportunities remain. In many areas there are still large gaps separating the performance of commercial equipment and theoretical limits. In some cases our understanding of the nature of theoretical limits has changed because some novel mechanism has been discovered, such as membranes used to separate water from air or use of ultrasound to dry clothes. The limits have also changed because of better understanding of the way building technologies can take advantage of the external environment (e.g., daylighting and use of natural ventilation), and they should reflect the opportunity to reuse waste heat generated by building equipment. Reaching the potential will require ingenious product designs, advanced manufacturing methods that can lower costs and improve product quality, and advances in basic science—particularly in areas of materials science where novel approaches are needed on optical and thermal properties, magnetic materials, and on heat exchange and enthalpy exchange. The problems lead to a number of fundamental research challenges (see Table 5.7).

It is DOE's hope that this discussion effectively outlines the breadth, complexity, and importance of building energy technologies and help the nation's innovators understand where they can make critical contributions; those RDD&D opportunities presented in this chapter are summarized in Table 5.8.

Table 5.7 Fundamental Research Challenges

- Materials with tunable optical properties (adjust transmissivity and absorptivity by wavelength)
- Materials for efficient LEDs
- Materials for efficient motors and controls (magnets and wide bandgap semiconductors)
- Enthalpy exchange materials
- Materials for low-cost krypton/xenon replacement
- Materials for non-vapor compression heat pumps (e.g., thermoelectric, magnetocaloric, and electrocaloric)
- Big-data management for large networks of building controls and next-generation grid systems
- Ultra-efficient computation (neural networks)
- Decision science research

Table 5.8 Increasing Efficiency of Building Systems and Technologies

Area	RDD&D opportunities
Building thermal comfort and appliances	■ Materials that facilitate deep retrofits of existing buildings (e.g., thin insulating materials) ■ Low/no GWP heat pump systems ■ Improved tools for diagnosing heat flows over the lifetime of a building ■ Clear metrics for the performance of building shells in heat management and air flows
Lighting	■ Test procedures for reliably determining the expected lifetime of commercial LED and OLED products ■ Understanding why LED efficiency decreases at high power densities ■ High-efficiency green LEDs ■ Efficient quantum dot materials ■ Advanced sensors and controls for lighting ■ Glazing with tunable optical properties (also needed for thermal load management) ■ Efficient, durable, low-cost OLEDs ■ Lower cost retrofit solutions for lighting fixtures
Electronics and miscellaneous building energy loads	■ More efficient circuitry (hardware and software) ■ More flexible power management (hardware and software) ■ Standardized communications protocols ■ Wide-band-gap semiconductors for power supplies
Systems-level opportunities	■ Accurate, reliable, low installed cost sensors (including continuous occupancy sensors) ■ Energy harvesting to power wireless sensors and controls ■ Improved control systems (cybersecurity, install/commissioning) ■ Control algorithms to automatically optimize building system performance ■ Open source software modules supporting interoperability for commercial control systems ■ Easy-to-use, fast, accurate software tools to design and operate highly efficient buildings ■ Co-simulation modeling with a widely used interface standard ■ Decision science research incorporating personal information security ■ Components and systems that allow building devices to share waste heat

Supplemental Information

Building Energy Technology Roadmaps

Building Technologies Office Potential Energy Savings Analysis

[See online version.]

Endnotes

[1] Energy Information Administration (EIA). *Annual Energy Review 2014*. Washington, DC: U.S. Department of Energy, 2014. Available at: http://www.eia.gov/forecasts/archive/aeo14/. Note that total building energy use, as described here, includes residential and commercial energy use and also the similar HVAC and lighting energy use of industrial buildings. This changes the values presented slightly from those of chapter 1, which strictly separated residential and commercial building energy use from all industrial energy use.

[2] Energy Information Administration (EIA). *Manufacturing Energy Consumption Survey 2010*. Washington DC: EIA, 2013. Because more recent data is not available, the figure assumes that the ratio of industrial electricity used for HVAC and lighting is the same as that found in the 2006 MECS survey.

[3] This figure assumes that the price and performance goals described throughout this chapter are met and all cost-effective technologies are adopted. See the Appendix for detailed assumptions. A technology is assumed to be cost effective if the cost of saved energy (in dollars per million BTU or equivalent units) is lower than the cost of conventional energy (i.e., electricity or natural gas). The cost of saved energy is the discounted value of incremental costs divided by the discounted value of savings. A nominal discount rate of 6% is used. See Farese, P.; Gelman, R.; Robert, H. (2012). “A Tool to Prioritize Energy Efficiency Investments.” Golden, CO: National Renewable Energy Laboratory (NREL), 2012. Available at: http://www.nrel.gov/docs/fy12osti/54799.pdf. The social cost of carbon and other externality costs are not included in this analysis.

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[7] Ibid.

[8] The insulating value is a measure of the rate at which heat passes through the window, typically specified by an R-value. A typical single-glazed window has an R-value of 1, but R-11 glazing materials and combined frame/glazing units with R-8.1 are commercially available. Zola European Windows. (n.d.). Zola European Windows: http://www.zolawindows.com/.

[9] The “solar heat gain coefficient” is a measure of the fraction of total sunlight energy that can pass through the window, while the “visual transmittance” measures the fraction of visible sunlight that gets through. A typical single-glazed window has a solar heat gain coefficient and visual transmittance of about 0.7. Commercially available windows can come close to this, with a transmittance of 0.71 and a solar heat gain coefficient that can be selected in the range 0.29–0.62.

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