Energy-Efficient Technologies

1. Buildings

1.1 Equipment and Appliances

1.2 Building Envelope

1.3 Intelligent Building Systems

1.1 EQUIPMENT AND APPLIANCES

Technology Description

All energy use in buildings depends on equipment to transform fuel or electricity into end-use services such as delivered heat or cooling, light, fresh air, vertical transport, cleaning of clothes or dishes, and information processing. There are energy-saving opportunities within individual pieces of equipment—as well as at the system level—through proper sizing, reduced distribution and standby losses, heat recovery and storage, and optimal control. Another promising opportunity lies in multifunction devices ranging from heat pumps that provide both refrigeration and hot water, to an office appliance that serves as a networked printer, copier, scanner, and paperless fax machine.

System Concepts

- Major categories of end-use equipment include heating, cooling, and hot water; ventilation and thermal distribution; lighting; home appliances; miscellaneous (process equipment and consumer products); and on-site energy and power.
- Key components vary by type of equipment, but some cross-cutting opportunities for efficiency are improved materials and applications, efficient low-emissions combustion and heat transfer, advanced refrigerants and cycles, electrodeless and solid-state lighting, smart sensors and controls, improved small-power supplies, variable-capacity systems, reduction of thermal standby losses and leaking electricity, and modular fuel cell-based micro-cogeneration.

Representative Technologies

- Residential gas-fired absorption heat pumps, desiccant pre-conditioners for treating ventilation air, proton exchange membrane (PEM) fuel cells, horizontal axis clothes washers, and low-power sulfur lamps.

Technology Status/Applications

- Technology improvements over the past 20 years—through quality engineering, new materials, and better controls—have improved efficiencies in many types of equipment by 15 to 20%. Electronic equipment is an outlier with order-of-magnitude efficiency gains, at the microchip level, every 2 to 3 years.
- Continued technical innovation, spurred by government/industry co-investment in R&D and effective, sustained market-pull policies, could at least match and potentially double these prior efficiency gains over the next 20 years.

Current Research, Development, and Demonstration

RD&D Goals

- By 2002, commercial introduction of full-size refrigerator-freezers that use as little power as a 40-W light bulb.
- By 2010, heat pumps for residential and small commercial applications with 40% improvement over conventional gas furnaces.
- By 2010, reduced standby losses, improved heat pump water heating, and application of heat recovery techniques reduce energy use for domestic water heating by 60% over conventional devices.
- By 2010, commercial introduction of hybrid lighting systems (high-efficiency centralized light sources and controlled application of daylighting).
- By 2010, fuel cells, photovoltaics, and microturbines offer cost-competitive alternatives to grid electricity. By 2020, distribution systems deliver 50% more conditioned air.
- By 2020, commercial introduction of alternative refrigeration equipment with low greenhouse warming potential (e.g., Stirling cycle, Brayton cycle, acoustic, magnetic, thermal electric).
- By 2020, prototype development of advanced cleaning technologies (e.g., electrolytic, ultrasonic, ozonated).
- By 2030, adaptation of HVAC equipment to a new generation of power sources.

R&D Challenges

- The basic RD&D needed ranges from materials science to solid-state electronics, and from a better understanding of combustion fundamentals to advances in control theory. Research is also needed on behavioral and ergonomic dimensions of the user-machine relationship.
- Building equipment and appliance efficiency will benefit from improvements in a wide range of thermal, mechanical, and electronic technologies (see System Concepts), as well as better systems integration, more cost-effective and reliable fabrication methods, and sustainable design concepts (e.g., use of recyclable and environmentally preferred materials, modular design, ecologically sound manufacturing).

RD&D Activities

- Most federal R&D on building equipment is performed by DOE.
- No systematic data have been compiled on international funding levels, although activities such as the IEA Heat Pump Centre represent a potential source of such data for selected equipment types.

Recent Success

- Recent DOE-sponsored R&D, often with industry participation, has produced a prototype refrigerator that uses less than half the energy of the current best designs; an improved air-conditioning cycle to reduce oversizing and improve efficiency; high-performance insulating materials for demanding thermal applications; and a replacement for inefficient, high-temperature halogen up-lights (torchieres) which uses only 25% of the power, lasts longer, and eliminates a potential fire hazard.

Commercialization and Deployment

- Building equipment and appliances often vary in efficiency by 20 to 40% from the least efficient model on the market to the most efficient; this efficiency range is narrower where successful appliance standards have previously eliminated the least efficient models.
- The stock and energy intensity of equipment are growing faster than the building stock itself, as manufacturers introduce and consumers and businesses eagerly accept new types of equipment, more sophisticated and automated technologies, and increased levels of end-use services.
- The rapid turnover and growth of many types of building equipment—especially electronics for computing, control, communications, and entertainment—represent major growth in electricity demand and thus carbon emissions, but also an important opportunity to rapidly introduce new, efficient technologies and quickly propagate them throughout the stock.
- Provided that they are implemented without a significant reduction in amenities, the market success of most new equipment and appliance technologies is virtually ensured if the efficiency improvement has a 3-year payback; technologies with payback of 4 to 8+ years can also succeed in the market provided that they offer other customer-valued features (e.g., reliability, longer life, improved comfort or convenience, quiet operation, smaller size, lower pollution levels).
- Applications extend to every segment of the residential and nonresidential sectors. Major government, institutional, and corporate buyers represent a special target group for voluntary early deployment of the best new technologies.

Potential Benefits and Costs

Carbon Reductions

- In MtC/year for buildings overall and for this pathway

	2010	2020	2030
Buildings	25–50	50–100	75–150
Equipment and appliances	15–35	20–40	25–45

RD&D Expenditures

- Federal RD&D expenditures are required because the buildings industry does little R&D. DOE funding has been about $20M/year in recent years out of a total Buildings R&D budget of about $50M/year. A vigorous pursuit of this pathway would take an annual DOE RD&D budget of 2000–2010, $60M/year; 2010–2020, $90M/year; 2020–2030, $60M/year.

Market

- Building equipment and appliances represent an annual market in the United States alone of well over $200B, involving thousands of large and small companies. Certain technologies, such as office and home electronics, compete in global markets with little or no change in performance specifications.

Non-energy Benefits and Costs

- Major benefits, other than energy savings and reduced GHG emissions, include better control of indoor comfort conditions; improved health and productivity; potential for replacing CFC-based refrigeration equipment with efficient, non-ozone-depleting models; reduced air pollutant emissions.

Risk Factors

Technical Risk

1 2 ③ 4 5 6 7 8 9 10
Low — High

- Track record of federally funded R&D leading to commercial products.
- Small-scale units allow easier field testing, performance verification, and refinement before large-scale deployment.

Commercial Risk

1 2 ③ 4 5 6 7 8 9 10
Low — High

- Existing infrastructure for design, manufacturing, installation, and so on.
- Labeling, government procurement, and voluntary programs can reduce market risk to innovative suppliers.
- Minor dependence on foreign sources is easily overcome.

Ecological Risk

1 ② 3 4 5 6 7 8 9 10
Low — High

- Modest ecological risk from electronics and other equipment and materials manufacturing.
- Positive impact on air and water pollution.

Human Health Risk

1 ② 3 4 5 6 7 8 9 10
Low — High

- Improved indoor air quality with better ventilation and controls can reduce health risk and improve productivity.

Economic Risk

1 ② 3 4 5 6 7 8 9 10
Low — High

- Cost-effective products will encounter less market resistance, provided functional and quality/reliability requirements are met.
- Public perception is favorable to introducing advanced equipment.

Regulatory Risk

1 ② 3 4 5 6 7 8 9 10
Low — High

- Regulations on production, marketing, and installation of building products can impede new technologies.

Key Federal Actions

- Deployment programs to leverage the RD&D investment.
- Equipment and appliance standards developed with industry.
- Federal procurement to create demand.

1.2 BUILDING ENVELOPE

Technology Description

The building envelope is the interface between the interior of a building and the outdoor environment. In most buildings, the envelope—along with the outdoor weather—is the primary determinant of the amount of energy used to heat, cool, and ventilate. A more energy-efficient envelope means lower energy usage in a building and lower GHG emissions. Advances in materials research and fenestration systems, better building practices, and increased use of renewable technologies promise to significantly lower the energy required to maintain high-quality building interior climate conditions.

System Concepts

- Control of envelope characteristics provides control over the flow of heat, air, moisture, and light into the building. These flows and the interior energy and environmental loads determine the size and energy usage of HVAC and distribution systems.
- Materials for exterior walls, roofs, foundations, windows, doors, interior partition walls, ceilings, and floors that can impact future energy use include insulation, with innovative formula foams and vacuum panels; optical control coatings for windows and roofs; and thermal storage materials, including lightweight heat storage systems.

Representative Technologies

- *Superinsulation:* Vacuum powder-filled, gas-filled, and vacuum fiber-filled panels; structurally reinforced beaded vacuum panels; and switchable evacuated panels with insulating values over four times those of the best currently available materials will soon be available for niche markets. High-thermal-resistance foam insulations with acceptable ozone depletion and global warming characteristics will allow for continued use of this highly desirable thermal insulation.
- *Advanced window systems*: Krypton-filled triple-glazed low-E windows and electrochromic glazing and hybrid electrochromic/PV films and coatings will provide improved lighting and thermal control of fenestration systems. Advanced techniques for integration, control, and distribution of daylight will significantly reduce the need for electric lighting in buildings. Self-drying wall and roof designs will allow for improved insulation levels and increase the lifetimes for these components. More durable high-reflectance coatings will allow better control of solar heat on building surfaces.
- *Advanced thermal storage materials:* Dry phase-change materials and encapsulated materials will allow significant load distribution over the full diurnal cycle and significant load reduction when used with passive solar systems.

Technology Status/Applications

- Building insulations have progressed from the 2–4 °F·h·ft^2/Btu/in. fibrous materials available before 1970 to foams reaching 7 °F·h·ft^2/Btu/in. Superinsulations of over 25 °F·h·ft^2/Btu/in. will be available for niche markets soon. It is critical to find acceptable replacements for HCFCs in foams in order not to backslide in the use of this insulation in buildings. Improvements in window performance have been even more spectacular. In the 1970s, window thermal resistance was 1 to 2 °F·h·ft^2/Btu. Now, new windows have thermal resistance of up to 6 °F·h·ft^2/Btu (whole window performance). Windows are now widely available with selective coatings that reduce infrared transmittance without reducing visible transmittance. In addition, variable-transmittance windows under development will allow optimal control to minimize heating, cooling, and lighting loads.

Current Research, Development, and Demonstration

RD&D Goals

- 30/30 (R/30 insulation and 30-year life) low-slope roof options.
- Windows with 70% of adjacent wall thermal resistance and variable, controllable light transmittance.
- Mass-produced (factory-built) customized buildings with integrated envelope and equipment systems designed and sized for specific sites and climates.
- Vacuum insulations dominating several niche markets (mobile homes and freezer walls).
- On-site renewables replacing 15% of purchased energy [see photovoltaics pathway].
- 50% of building materials containing 50% recyclable materials.
- A 30% decrease in the average envelope thermal load of existing residential buildings and a 66% decrease in the average thermal load of new buildings.

RD&D Challenges

- Foam insulations that retain high thermal resistance while using blowing agents with zero ozone depletion potential and negligible global warming effect.
- Self-drying wall and roof designs to avoid moisture problems such as materials degradation.
- Electrochromic window films and electrochromic/PV hybrid window films to control energy flows and generate electricity on site.
- Techniques to distribute and control daylight to reduce electrical energy use for artificial lighting.
- Advanced durable cost-effective superinsulations to reduce heating/cooling loads.
- Advanced building simulation tools to permit better design, construction, commissioning, and operation.
- Self-calibrating multi-function micro-sensors for in situ performance and air quality monitoring.
- Thermal storage materials: typically, thermal storage in building components is achieved with heavyweight materials such as masonry. Advanced thermal storage materials need to be lightweight to integrate with elements similar to drywall, floor, and ceiling panels.

RD&D Activities

- Key agencies doing R&D on building envelopes are DOE, NIST, and several state agencies such as the Florida Solar Energy Center and the Iowa Ames Laboratory.
- DOE funding has been about $8M/year in recent years. Funding from other agencies has been significantly less. No attempt has been made to estimate funding for private sector R&D, although it is thought to be considerably more than that of agencies and is typically directed toward specific products and problems. Total international support is also significant. Most developed countries have one to several laboratories doing research, often more fundamental than that in U.S. labs. International participants typically are 20% or more of those attending U.S. conferences on envelope research.

Recent Success

- A DOE-sponsored RD&D partnership with the Polyisocyanurate Insulation Manufacturers Association, the National Roofing Contractors Association, the Society of the Plastics Industry, and EPA helped the industry find a replacement for CFCs in polyisocyanurate foam insulation. This effort enabled the buildings industry to transition from CFC-11 to HCFC-141b by the deadline required by the Montreal protocol.

Commercialization and Deployment

- The market potential is significant for building owners taking some actions to improve building envelopes. Currently, 40% of residences are well insulated, 40% are adequately insulated, and 20% are poorly insulated. Over 40% of new window sales are of advanced types (low-E and gas-filled). In commercial buildings, over 17% of all windows are advanced types. Over 70% of commercial buildings have roof insulation; somewhat fewer have insulated walls.
- Building products are mostly commodity products. A number of companies produce them; and each has a diverse distribution system, including direct sales, contractors, retailers, and discount stores.
- A critical challenge is improving the efficiency of retrofits of existing buildings. Retrofitting is seldom cost-effective on a stand-alone basis. New materials and techniques are required.
- Many advanced envelope products are cost-competitive now, and new technologies will become so on an ongoing basis. There will be modest cost reductions over time as manufacturers compete.

Potential Benefits and Costs

Carbon Reductions

- In MtC/year for buildings overall and this pathway

	2010	2020	2030
Buildings	25–50	50–100	75–150
Envelopes	5–10	15–30	30–60

RD&D Expenditures

- Federal RD&D expenditures are required because the buildings industry does little R&D. DOE funding has been about $8M/year in recent years out of a total Buildings R&D budget of about $50M/year. A vigorous pursuit of this pathway would take about an annual DOE RD&D budget of 2000–2010, $30M/year; 2010–2020, $45M/year; 2020–2030, $30M/year.

Market

- Building structures represent an annual market in the United States of over $70B/year and involve thousands of large and small product manufacturers and a large, diverse distribution system that plays a crucial role in product marketing. Exporting is not an important factor in the sales of most building structure products.

Nonenergy Benefits and Costs

- Major benefits, other than energy savings and reduced GHG emission, include more affordable housing; improved comfort, health, and productivity; a significant increase in recycled materials; reduced ozone depletion potential with non-CFC/HCFC foam insulations; reduced air pollutant emissions.

Risk Factors

Technical Risk

1 ② 3 4 5 6 7 8 9 10

Low — High

- Track record of federally funded R&D leading to commercial products.
- Materials and concepts typically are tested in other areas.

Commercial Risk

1 2 ③ 4 5 6 7 8 9 10

Low — High

- Existing infrastructure for design, components, construction, and so on.
- Conservative industry can impede new technologies.
- Minor dependence on foreign sources easily overcome.

Ecological Risk

1 ② 3 4 5 6 7 8 9 10

Low — High

- Materials and concepts have been studied in other areas.
- Positive impact on air and water pollution.

Human Health Risk

1 ② 3 4 5 6 7 8 9 10

Low — High

- Much installation is do-it-yourself and entails a higher risk than professional handling.
- Small risk from outgassing from materials.

Economic Risk

1 ② 3 4 5 6 7 8 9 10

Low — High

- Commodity market will drive out products that are not economical.
- Public perception is very favorable to implementation of advanced envelopes.

Regulatory Risk

1 ② 3 4 5 6 7 8 9 10

Low — High

- Regulations on production, marketing, and installation of building products can impede new technologies.

Key Federal Actions

- Deployment programs to leverage the RD&D investment.
- Building standards developed with industry.
- Federal procurement to create demand.

1.3 INTELLIGENT BUILDING SYSTEMS

Technology Description

Intelligent building systems (IBSs) would use data from design, together with sensed data, to automatically configure controls and commission (i.e., start up and check out) and operate buildings. Control systems would use advanced, robust techniques and would be based on smaller, cheaper, and more abundant sensors. These data would ensure optimal building performance by controlling building systems and continuously recommissioning them using automated tools that detect and diagnose performance anomalies and degradation. IBSs would optimize operation across building systems, inform and implement energy purchasing, guide maintenance activities, and report building performance, while ensuring that occupant needs for comfort, health, and safety were met at the lowest possible cost.

System Concepts

- The system would consists of design tools, automated diagnostics, interoperable control systems, and sensors.
- These components would work together to collect data, configure controls, monitor operations, and correct out-of-range conditions that contribute to poor building performance.
- IBSs would ensure that essential information, especially the design intent and construction implementation data, would be preserved and shared across many applications throughout the lifetime of the building.
- Equipment and system performance records would be stored as part of a networked building performance knowledge base that would grow over time and provide feedback to designers, equipment manufacturers, and building operators and owners.

Representative Technologies

- DOE is developing computer-based building commissioning and operation tools to improve the energy efficiency of *existing* buildings. It is also investing in the next generation of building simulation programs that could be integrated into design tools.

Technology Status/Applications

- Savings from improved operation and maintenance procedures could save more than 30% of the annual energy costs of existing commercial buildings, even in many of those buildings thought to be working properly by their owners/operators. These technologies would have very short paybacks because they would ensure that technologies were performing as promised, for a fraction of the cost of the installed technology.

Current Research, Development, and Demonstration

RD&D Goals

- Design environments with fully and seamlessly integrated building design tools that support all aspects of design and provide rapid analysis; design suggestions; quick and easily understood data interpretation; automatic generation of all design documents; and a building electronic data structure that supports start-up, operation, maintenance, and renovation of the building by IBS.
- Automatic operation of buildings by automatically sensing installed equipment, checking for proper installation, generating control algorithms, implementing optimal adaptive control, diagnosing and correcting operating episodes that produce inefficient or uncomfortable conditions, managing maintenance, and providing performance data in usable forms for operators of new and existing buildings, facility managers, and owners.

RD&D Challenges

- Design tools: enhanced analytical capabilities, integration with the design environment, automated design and analysis capability, design databases, visualization, and high-level monitoring and reporting tools.
- Automated diagnostics: diagnosticians, plug and play capabilities, automated real-time purchasing, and advanced data visualization.
- System interoperability and controls: integrated control networks; adaptive, optimized, self-generating control algorithms; and advanced control techniques.
- Sensors: materials properties, microscale sensors, microelectronic sensors, multiple-sensor arrays, protocols for using new sensors, and new sensing technologies.
- Visualization: use of supercomputers, advanced computational methods, and virtual reality systems to permit real-time visualization of designs and design changes, including lighting, thermal flows, and air quality.
- Early priorities include enhancing design tool integration, developing automated diagnosticians, implementing remote data collection and visualization, and developing sensors.

RD&D Activities

- DOE is funding work along with the California Institute for Energy Efficiency, Honeywell, Johnson Controls, Landis and Staefa, EPRI, and Pacific Gas and Electric Company. International efforts include a European Union–funded effort to develop adaptive control techniques for improving the thermal environment for JOULE III—SEC.

Recent Success

- Energy 10: models passive solar systems in buildings.
- DOE 2: international standard for whole building energy performance simulation has thousands of users worldwide.
- The International Alliance for Interoperability is setting international standards for interoperability of computer tools and components for buildings.

Commercialization and Deployment

- Design tools for energy efficiency are used by less than 2% of the professionals involved in the design, construction, and operation of commercial buildings in the United States. A larger fraction of commercial buildings have central building control systems. Few diagnostic tools are available beyond those used for air balancing or integrated into equipment (Trane Intellipack System). About 12 software vendors develop, support, and maintain energy design tools; most are small businesses. Another 15 to 20 building automation and control vendors exist in the marketplace; the major players include Johnson Controls, Honeywell, and Landis and Staefa.
- Deployment involves two major aspects: seamless integration into existing building design and operation platforms, and a focus on benefits that are desirable in the marketplace (not only energy efficiency).

Potential Benefits and Costs

Carbon Reductions

- In MtC/year for buildings overall and this pathway

	2010	2020	2030
Buildings	25–50	50–100	75–150
Intelligent building systems	~5	10–20	20–45

RD&D Expenditures

- Federal RD&D expenditures are required because the buildings industry does little R&D. DOE funding for building systems R&D has been about $20M/year in recent years out of a total buildings R&D budget of about $50M/year. A vigorous pursuit of this pathway would take an annual DOE RD&D budget of 2000–2010, $60M/year; 2010–2020, $90M/year; 2020–2030, $60M/year. In addition to funding RD&D on IBSs, this budget would support RD&D on human factors and community systems.

Market

- These technologies would apply to all buildings, but especially to existing commercial buildings and new buildings. In addition, new technologies would be integrated into the building design process using this technology.

Nonenergy Benefits and Costs

- Human health, safety, and comfort would be greatly enhanced using these technologies. In addition, major growth markets in India, Southeast Asia, and Latin American could use these technologies to develop their next-generation buildings.

Risk Factors

Technical Risk

1 ② 3 4 5 6 7 8 9 10

Low — High

- Track record of federally funded R&D leading to products used by the design community.
- Much of the needed technology exists in other sectors.

Commercial Risk

1 2 ③ 4 5 6 7 8 9 10

Low — High

- Amenable to design community, but requires integration into existing construction practices.
- Increase in design fees, but could be offset by lower construction costs.

Ecological Risk

① 2 3 4 5 6 7 8 9 10

Low — High

- Positive impact on air and water pollution.

Human Health Risk

1 ② 3 4 5 6 7 8 9 10

Low — High

- Improved indoor air quality with better sensors and controls can reduce health risk and improve productivity.

Economic Risk

1 ② 3 4 5 6 7 8 9 10

Low — High

- Would be cost-effective in reducing labor and energy costs.
- Public perception is favorable to introducing intelligent systems.

Regulatory Risk

1 ② 3 4 5 6 7 8 9 10

Low — High

- Would not require changes to existing buildings regulations.

Key Federal Actions

- The focus of the building design, control, and operation industry is service, not research. In its quest to serve its customers, it does not perform R&D. The federal government could provide this industry with the R&D necessary to demonstrate the viability of this system and work with the industry to transfer the technology to its markets.
- The government could also work with voluntary standards organizations to require energy analysis, building commissioning, and proof of operation in conjunction with building energy codes. Federal buildings could also be showcase facilities for the demonstration of these new technologies.