Technology Diffusion and Energy Intensity in U.S. Commercial Buildings

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Abstract

This paper analyzes the 1992 and 2003 U.S. Commercial Buildings Energy Consumption Survey microdata files to show the extent to which certain heating, cooling, lighting, and window technologies are entering use, and the resulting impacts on the intensity of energy use. Excepting the case of fluorescent lights, no technology dominates the entire market but instead each conquers a specific niche. Most of the buildings in which these technologies are installed do not have lower-than-average energy intensity, measured as annual energy use per square meter of floor space. The exceptional technology that does measurably correlate with reduced energy intensity is daylighting. These results suggest that technologies are adopted to serve comfort or quality objectives rather than to save energy, or that buildings' users confound the designers' intentions. Decision makers thus should improve operating and maintenance practices, invest in building commissioning, and rely more heavily on passive design features to save energy.

Keywords: commercial buildings, energy intensity, United States

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A tenet of the green building movement is that innovation is a win-win, because it can both reduce environmental impacts and enhance the occupant experience. Leaders in the movement make great efforts to dismantle barriers to the diffusion of innovation. Innovations that influence energy intensity—energy use per square meter—are prized because they have the potential to reduce both operating costs and greenhouse gas emissions. Many architectural, mechanical and electrical technologies are now available to influence energy intensity. Are these innovations entering widespread use? Are they actually reducing energy intensity?

Introduction

This paper examines the diffusion through the commercial building stock in the United States of technologies that influence energy use. It analyzes the 1992 and 2003 Commercial Buildings Energy Consumption Survey (CBECS) microdata for evidence on the diffusion of specific technologies and the effects on energy intensity.

Innovation Diffusion

Innovation is the introduction of something new and potentially useful, it is “fresh thinking that creates value” (Lyon 2007). Innovations must diffuse before they matter, so that scientific discoveries and technological inventions do not count as innovations until economic, social, or political actors adopt them. The key attributes determining the rate and extent of diffusion are the innovation's relative advantage over existing means, its compatibility with the existing system, and its complexity, trialability, and observability

(Rogers 1995). Microeconomic incentives, available stocks and flows of knowledge, and networking relationships also influence the processes of innovation and diffusion (von Hippel 1988, Kline 1985, Klovdahl 1985).

Innovation-oriented environmental policies—variously framed as ecological modernization, industrial ecology, or technological environmental innovation—have gained intellectual support as the first generation of regulatory controls has run its course (Huber 2004). Proponents argue over the relative merits of incremental innovations that leave the overall system unchanged, and disruptive innovations that unleash dramatic structural transformations (Koehler 2007). Regulatory policies promoting energy efficiency typically fall into the incremental innovation category, while governmental support for basic research and protection of intellectual property rights are more likely to spur disruptive innovations (Pontin 2008).

The empirical literature on innovation diffusion shows that it is a slow process. Disruptive technology substitutions such as the sequential displacement of canals by railways, roads, and air travel, or of biomass energy by coal, petroleum, and natural gas, each play out over multiple decades (Ausubel 1989). Even incremental building-sector innovations such as the introduction of compact fluorescent lights, condensing gas furnaces and low-emissivity windows require a decade or more to gain a significant market share after the research and development is done (Elliott et al 2004). The technologies discussed in this article were all invented decades before they started to enter widespread use, consider these illustrative commercialization dates: incandescent lights (1882), fluorescent lights (1938), heat pumps (1931), individual room air conditioners (1947), and variable air volume air distribution systems (1969) (Constable and Somerville 2003).

Commercial Buildings

Between 1950 and 2006, the growth in energy use allocated to the commercial end-use sector averaged 2.8% annually, most of it in buildings, reflecting both growth in the sector and a shift toward electricity (which has large associated system energy losses). Overall U.S. energy consumption increased by an average annual rate of only 1.9% (EIA 2007). The comparable rate for the residential sector was only 2.3% during the same interval (EIA 2007), and it was 3.4% for real growth in Gross Domestic Product (BEA 2007). Commercial buildings currently account for 18% of both primary energy use and greenhouse gas emissions in the United States (EIA 2007). Thus, innovations that reduce commercial building energy use are important to constrain this sector's rapidly growing energy and carbon footprints.

A 2003 snapshot of the sector shows the following (EIA 2006). Some 63% of the commercial floor space that currently exists in the United States was built from 1970 onwards. A majority of commercial buildings house a single establishment. The median building size today is 465 square meters (5,000 square feet) and the mean of this right-skewed distribution is 1366 square meters (14,700 square feet), with buildings constructed after 1970 slightly larger on average than are older structures. The Northeastern United States has 20% of today's commercial floor space, the Midwest has 25%, the South has 37%, and the West has 18%. Figure 1 shows total commercial floorspace and energy intensity (measured in annual kWh of energy entering the site per square meter of floorspace) by year built, according to the 2003 survey.

Technologies designed to improve energy efficiency began diffusing into the commercial building market following the oil price shocks of the 1970s and accompanying regulatory initiatives. Especially noteworthy have been new types of mechanical systems, lighting options, and building envelopes. In parallel with these innovations, it has become more common to cool commercial buildings. Plug loads for computers and other electronic equipment also have increased. As Figure 1 shows, on average, energy intensity in commercial buildings increased until 1990 and then began to decrease, with new buildings now performing about the same at 257 kWh/m^2 (81,600 BTU/SF) as those built before 1960 (EIA 2006: Table C3A).

Methodology

This paper shares descriptive and inferential analysis of the U.S. Commercial Buildings Energy Consumption Survey (CBECS) 1992 and 2003 microdata files developed using spreadsheet manipulations and the statistical package SPSS 16. Data from earlier survey years are sometimes shown for comparative purposes. Two analytical tasks investigate two questions, as follows.

- What are the trajectories of technology adoption within U.S. commercial buildings?
- Do these technologies influence the energy intensity of commercial buildings?

We describe trajectories of technology adoption using cohort percentages. Figures 2-8 compare, for each technology category, results from the 1992 and 2003 surveys, and for the 2003 cohorts by age of building. For easy-to-retrofit technologies such as electronic ballasts for fluorescent lights, it is also helpful to compare the 2003 data set to earlier ones, and to examine the effects of renovations; this is summarized in the text. In order to scale up from the survey sample to the full population of commercial buildings, it is necessary to multiply case variables by a weighting factor provided in CBECS. Cohort technology penetrations reported in the figures are shown as a percent of the total floor area included in that cohort.

Moving from description to inference, we next predict energy intensity in commercial buildings with ordinary least squares regression. Energy intensity is measured as the annual sum of the energy content of all fuels delivered to a building divided by the total floor area, yielding kWh/m^2 (BTU/SF). Electricity intensity in kWh/m^2 (kWh/SF) is also analyzed. Least squares regression is appropriate for modeling energy intensity y, a continuous dependent variable:

$$y = a + b_1 x_1 + b_2 x_2 + \ldots + b_\mathrm{i} x_\mathrm{i}$$

where a = the constant of the equation and, b = the coefficient of the explanatory variables x_i. To satisfy normality assumptions, right-skewed variables (energy intensity, floor area, and energy prices) are subjected to a log transformation. To make the range of regression coefficient values more comparable, variables with large values (Year built, heating degree days, cooling degree days) are divided by 1000. To allow the survey sample-based results to represent the population of U.S. commercial buildings, weighting factors are included in the calculation. Results are shown in Tables 2 and 3.

CBECS

CBECS is “a national sample survey that collects information on the stock of U.S. commercial buildings, their energy-related building characteristics, and their energy consumption and expenditures” (EIA 2006). It has been conducted on a roughly quadrennial basis since 1979, and the 2003 survey yields a usable sample of 5,215 buildings stratified satisfactorily across the nine U.S. Census geographic divisions. A microdata file consisting of individual survey responses stripped of identifiers is publicly available. Commercial buildings are defined as those that do not serve primarily residential, manufacturing/industrial, or agricultural purposes.

Commercial buildings nonetheless serve a wide range of uses by firms, non-profit organizations, individuals, and governments. Principal building activities included in the CBECS data set include office, laboratory, nonrefrigerated warehouse, food sales, public order and safety, outpatient health care, refrigerated warehouse, religious worship, public assembly, education, food service, inpatient health care, nursing, lodging, strip shopping mall, enclosed mall, retail other than mall, service, other, and vacant buildings. More floor area is devoted to office, mercantile (retail), warehouse and storage, and education than to other activities (EIA 2006: Table A1). The most energy-intensive building activities are food service, inpatient health care, and food sales (EIA 2006: Table C3). Operating hours and owner-occupancy serve as parsimonious proxies for principal building activity, successfully explaining as much of the variation in energy intensity. Similarly, energy price and heating/cooling degree days serve as parsimonious proxies for geographic region.

CBECS includes several data fields that are particularly useful for the current study, as shown in Table 1. In addition to descriptors such as building age, region, size, and principal activity, the survey also indicates whether buildings incorporate specific innovations. Alternative energy sources such as renewables are not considered here because their penetration into the commercial building stock is so low. Seven categories of technologies and practices are analyzed here: window treatments, lighting technologies, lighting conservation features, heating equipment, cooling equipment, HVAC conservation features, and control strategies. Together, these items provide a strong basis for understanding the penetration of energy-related technologies within the U.S. commercial building market. It is worth noting, however, that CBECS does not include enough engineering details to model building performance precisely—it lacks such information as equipment efficiency ratings, envelope insulation u-values, and lighting power densities.

Energy-Related Building Technologies

This section briefly describes the technologies included in the study. To ensure consistency of interpretation, we use language largely identical to that in the survey and results reported in EIA (2006). Note that many of these technologies are no longer considered "cutting-edge," but we study them because they show the historical patterns of technology diffusion and the performance outcomes resulting from those innovations.

Window treatments include single-layer glass, multi-layer glass, a combination of both, tinted window glass, reflective window glass, external overhangs or awnings, and skylights or atriums. Multi-layer glass is an energy-efficient window treatment made of two or three pieces of glass with air space in between them to improve insulation against heat transfer. Reflective coatings and tinted coatings are conservation features installed on the exterior glazing of a building to reduce the rate of solar penetration into the building. External overhangs and awnings are conservation features located outside of buildings for the same purpose. Skylights or atriums designed for lighting—rather than for strictly aesthetic reasons—can reduce lighting needs by allowing occupants access to daylight.

Lighting types include incandescent, standard fluorescent, compact fluorescent, high-intensity discharge, halogen, and other. The ubiquitous incandescent light lamp produces a soft warm light by electrically heating a tungsten filament so that it glows. Because so much of the energy is lost as heat, these highly inefficient sources of light are now being phased out under federal legislation (Energy Independence and Security Act of 2007, P.L. 110-140, H.R. 6). Included in this category are the familiar type of light bulbs which screw into sockets, as well as energy-efficient incandescent lamps, such as Reflector or R-Lamps (accent and task lighting), Parabolic Aluminized Reflector (PAR) lamps (flood and spot lighting), and Ellipsoidal Reflector (ER) lamps (recessed lighting). A standard fluorescent lamp is usually a long, narrow, white tube made of glass, coated on the inside with fluorescent material that is connected to an electric fixture at both ends of the light bulb; it may also be circular or U-shaped. The lamp produces light by passing electricity through mercury vapor, causing the fluorescent coating to glow, or fluoresce. Compact fluorescent lamps are designed to replace screw-in incandescent lamps; they are often found in table lamps, wall sconces, and hall and ceiling fixtures of commercial buildings with residential type lights. They combine the efficiency of fluorescent lighting with the convenience of standard incandescent bulbs. Light is produced the same way as other fluorescent lamps. A high-intensity discharge (HID) lamp produces light by passing electricity through gas, which causes the gas to glow. Examples of HID lamps are mercury vapor lamps, metal halide lamps, and high- and low-pressure sodium lamps. HID lamps have an extremely long life and emit many more lumens per fixture than do fluorescent lights. A halogen lamp is a type of incandescent lamp that lasts much longer and is more efficient than a standard incandescent light bulb. The lamp uses a halogen gas, usually iodine or bromine, that causes the evaporating tungsten to be redeposited on the filament, thus prolonging its life. Halogen lamps produce a brighter, whiter light than standard incandescent. They are especially suited to recessed or “canned fixtures,” track lights, and outdoor lights. The “other” category includes lamp types not explicitly mentioned here.

Lighting conservation features include daylighting, daylighting sensors, specular reflectors, electronic ballasts, and control systems for lighting. Daylighting is an architectural strategy to maximize the percent of occupied floor area that can rely on natural light from windows during daylight hours. A daylighting sensor is a lighting feature that takes advantage of sunlight to cut the amount of electric lighting used in a building by varying output of the lighting system in response to variations in available daylight. They are sometimes referred to as natural lighting control sensors or photocells. A specular reflector is the mirror-like backing of a fluorescent lighting fixture designed specifically to reflect light into the room. The materials and shape of the reflector are designed to reduce absorption of light within the fixture, while delivering light in the desired angular pattern. The most common materials used are silver (highest reflectivity) and aluminum (lowest cost). An electronic ballast is a lighting conservation feature that consists of an electronic version of a conventional electromagnetic ballast. The ballast is the transformer for fluorescent and high-intensity discharge (HID) lamps and provides the necessary current, voltage, and wave-form conditions to operate the lamp. Electronic ballasts operate lamps using electronic switching power supply circuits, are lightweight, and start instantly without flickering. Specifically excluded from this category are magnetic ballasts. Control systems for lighting use microprocessors and sensors to manage the timing and intensity of lighting subject to pre-specified rules.

Heating equipment types include furnaces, boilers, packaged heating units, individual space heaters, heat pumps, district steam or hot water, and other heating equipment. A furnace is a type of space-heating equipment with an enclosed chamber where fuel is burned or electrical resistance is used to heat air directly without steam or hot water. The heated air is then distributed throughout a building, typically by air ducts. A boiler is a type of space-heating equipment consisting of a vessel or tank where heat produced from the combustion of such fuels as natural gas, fuel oil, or coal is used to generate hot water or steam. Many buildings have their own boilers, while other buildings have steam or hot water piped in from a central plant. For this survey, only boilers inside the building (or serving only that particular building) are counted as part of the building's heating system. Steam or hot water piped into a building from a central plant is considered district heat. A packaged unit is a type of heating equipment that is assembled at a factory and installed as a self-contained unit. It is useful to contrast packaged units to engineer-specified units that must be assembled from individual components (fans, heat exchangers, etc.) for use in a given building. Packaged units are generally mounted on the roof of the building, but also sometimes located on a slab outside the building. Packaged units produce warm air directly and distribute it throughout the building by ducts or a similar distribution system. An individual space heater is a type of space heating equipment that is a free-standing or a self-contained unit that generates and delivers heat to a local zone within the building. The heater may be permanently mounted in a wall or floor or may be portable. Individual space heaters are characterized by a lack of pipes or ductwork for distributing hot water, steam, or warm air through a building. A heat pump is a type of heating and/or cooling equipment that draws heat into a building from outside and, during the cooling season, ejects heat from the building to the outside. Heat pumps are vapor-compression refrigeration systems whose indoor/outdoor coils are used reversibly as condensers or evaporators, depending on the need for heating or cooling.

Cooling equipment types include residential-type central air conditioners, heat pumps, individual air conditioners, district chilled water, central chillers, packaged air conditioning units, swamp coolers, and other. A residential-type central air conditioner is like the standard system in a home. An individual air conditioner is the familiar window- or wall-mounted unit. A central chiller is a type of cooling equipment that is centrally located and that produces chilled water in order to cool air. The chilled water or cold air is then distributed throughout the building by use of pipes or air ducts, or both. Chillers are generally located in, or just outside, the building they serve. Chillers located at central plants to serve multi-building systems are included in “District Chilled Water.” Like a packaged heating unit, a packaged cooling unit is a type of equipment that is assembled at a factory and installed on the roof or on an exterior pad as a self-contained unit. Some types of electric packaged units are also called “Direct Expansion,” or DX, units. A swamp cooler, or evaporative cooler, is a type of cooling equipment that turns air into moist, cool air by spraying cool water into ducts and cooling the air as the spray evaporates. It does not cool air by use of a refrigeration unit. This type of equipment is commonly used in warm, dry climates.

HVAC conservation features tracked in CBECS include variable-air-volume (VAV) systems, economizer cycles, HVAC maintenance, and control systems, discussed separately. A VAV system is an HVAC conservation feature that supplies varying quantities of conditioned (heated or cooled) air to different parts of a building according to the heating and cooling needs of those specific areas, essentially maintaining the desired room temperature by adjusting the airflow. An economizer cycle is a HVAC conservation feature consisting of indoor and outdoor temperature and humidity sensors, dampers, motors, and motor controls for the ventilation system to reduce the air-conditioning load. Wherever the temperature and humidity of the outdoor air are more favorable (lower heat content) than the temperature and humidity of the return air, more outdoor air is brought into the building. HVAC maintenance is a conservation feature consisting of a program of routine inspection and service for heating and/or cooling equipment. The inspection is performed on a regular basis, even if there are no apparent problems.

Control strategies include manually-reset thermostats, time-clock thermostats, and energy management and control systems (EMCS). Manually-reset thermostats are the simplest form of temperature control for HVAC systems, requiring the user to adjust the temperature setpoint at the beginning and end of every day. Time-clock thermostats provide a simple means of automatic control based on schedule, and they are commonly used with smaller, packaged HVAC equipment. An EMCS is an energy management feature that uses microcomputers, instrumentation, control equipment, and software to manage a building’s use of energy for heating, ventilation, air conditioning, lighting, and/or business-related processes. These systems may also manage fire control, safety, and security.

Results

The results are organized according to the two major questions and their associated analytical tasks. Figures 2-8 and Tables 2-3 show the results, summarized below.

What are the trajectories of technology adoption within U.S. commercial buildings?

Figures 2 through 8 show the penetration of various technologies in the U.S. commercial building stock. These column charts first show the overall penetration from the 1992 and 2003 CBECS (in the first two columns), and then the vintage penetrations from the most recent CBECS (in the remaining columns). The data set is thus divided into two sets of cohorts, first by survey year, and second, by when the building was built. Earlier survey years and older buildings should have a lower penetration of newer technologies. Old buildings will still have some usage of the new technologies because it is frequently possible to perform retrofits, especially items such as lighting equipment. Analysis of renovated buildings, not shown, supports the technology penetration trends discussed here. Penetration is measured as a percent of total floor area within the cohort.

It is important to note that the comparisons between CBECS survey years do not constitute a panel study because the 2003 survey utilizes an entirely new sample frame from that in 1992. Thus the standard errors associated with the inter-survey comparisons of column heights may be quite large.

Window treatments in U.S. commercial buildings have changed in several ways over time (see Figure 2). Usage of plain, single-layer glass has dropped, and double-layer, tinted, or reflective glass that reduces heating and cooling loads has become ubiquitous. Warehouse buildings that lack windows entirely are an increasing fraction of the total. Reliance on external overhangs or awnings, skylights, and atriums has remained relatively constant over the decades.

Lighting technologies of several types are competing for market share within commercial buildings (see Figure 3). Incandescent bulbs and traditional fluorescent tubes are being replaced not only by energy-efficient compact fluorescents but also by higher-performance high-intensity discharge lamps and halogen lamps. Since lights are so easy to retrofit, we also compare the overall 1992 and 2003 CBECS surveys to confirm the pattern of technology substitutions. Comparing 1992 and 2003 survey sample totals, usage of incandescent lamps dropped from 58% to 54% of floor area respectively, fluorescent lamps dropped from 91% to 83%, compact fluorescent lamps increased from 12% to 38%, and high-intensity discharge lamps increased from 26% to 29%. Halogen lamps were not tracked in the 1992 survey.

Lighting conservation features (see Figure 4) show a rather different pattern. Technologies associated with the installation of fluorescent lights are now in widespread use in all building age cohorts. That was not the case in 1992. Comparing the 1992 and 2003 survey sample totals, usage of specular reflectors jumps from 22% to 36% of commercial floorspace, respectively, and use of electronic ballasts soars from 5% to 65%. Use of lighting sensors and control systems is advancing much more slowly, and it remains in single digits in both the 1992 and 2003 surveys. Reliance on daylighting has not changed much in recent decades, hovering around 14%.

Innovation in space heating fundamentals has progressed very slowly in recent decades (see Figure 5). More important is the development of new packaged products that can be quickly and inexpensively installed in buildings, new and old. Custom-assembled boilers are giving way to packaged heating units and heat pumps. District heating had a heyday in the inter-war years but its market share has not grown in recent decades even though there have been technological advances.

Widespread provision of space cooling is a relatively recent advance (see Figure 6). Small-scale approaches such residential-type central air conditioners and individual room units are giving way to alternatives. Central chiller systems peaked in popularity during the 1970s but still play a significant role. District chilled water systems have entered use mainly on campuses (college, military, healthcare) in the United States. Packaged systems are especially popular and have captured over one half of the commercial building market. Heat pump systems, another packaged technology, have established a significant niche.

HVAC conservation features are enjoying widespread use (see Figure 7). VAV systems, economizer cycles, and energy management and control systems are being installed in almost half of new buildings. Regular HVAC maintenance is a standard practice in most commercial buildings.

Control technologies have evolved significantly in recent decades (see Figure 8). Manual thermostats have been displaced by computerized energy management and control systems in many applications. But the advent of packaged HVAC units has limited their spread, because these systems allow the use of simpler approaches such as time clocks.

In sum, it is clear that new technologies are very slowly displacing old ones, and their levels and rates of penetration vary substantially. Many of the technologies are now in widespread use within specific categories of commercial buildings. This begs the following question.

Do these technologies influence the energy intensity of commercial buildings?

About a decade ago, the Energy Information Administration (1997) proudly proclaimed that energy conservation measures were widespread, and it named most of the technologies studied here. Many of these technologies are currently identified as energy conservation measures in local statutes (see, e.g., Section 19.72.090 of the Berkeley, CA, Municipal Code) and are recommended by energy efficiency experts (ACEEE 2004). Engineering analyses predict that many of the innovations discussed in this paper can save energy because of their superior efficiency (EnergyStar 2008, Koomey et al 1998, Mortimer et al 1998). This section looks for evidence that buildings that have adopted these innovations are less energy- or electricity-intensive. The results are surprising, even counter-intuitive. In the CBECS 2003 data set, buildings that employ innovative HVAC technologies, window treatments, and lighting technologies are likely to be more, not less energy intensive. They are also likely to be more electricity intensive.

The columns of Table 2 show a set of ordinary least squares regression models predicting overall energy intensity of U.S. commercial buildings (that is, the total annual kWh/m^2 or BTUs per square foot of floor area of combined electricity, natural gas, fuel oil, and other energy usage). Variables with right-skewed distributions (energy intensity, floor area, and energy prices) are all subject to log transformations to prevent them from violating the standard normality assumptions of regression analysis. To test for nonmonotonic relationships, a squared term for building age was added to initial regressions but it was not significant so it was removed. Since air-conditioned buildings are significantly more energy-intensive than those without, and since most of the innovations studied here are intended for use in such buildings, cases without cooling systems are deleted from the data set prior to running this set of regressions.

The base model, shown in the second column of Table 2, includes explanatory factors associated with location (degree days, energy price), the building itself (floor area, year built, percent of external wall area in windows), and operations (operating hours, owner occupancy). Expectations are that energy intensity increases with higher degree days, year built, external glass, and operating hours, and that it decreases with higher energy prices, floor area, and owner occupancy. The base model is significant based on a robust *F* statistic, and it explains 43% of the variation in the dependent variable. Floor area, year built, percent glass, operating hours, energy price, and owner occupancy show the expected relationships with energy intensity. Both heating and cooling degree days show significant coefficients but run counter to expectations, with more extreme climate conditions associated with lower energy intensity. However, because building codes vary with climate, they may mitigate the effects of heating and cooling degree days in this cross-sectional analysis. Comparing standardized regression coefficients for the significant variables (Betas, not shown), the price effect is most important, with operating hours the next most influential. Floor area and percent glass are somewhat less important, and degree days and owner-occupancy matter even less.

The heating model, shown in the third column of Table 2, adds heating technology choices to the base model. Boilers, packaged heating units, and district heating systems are associated with higher energy intensity, whereas individual space heaters are associated with lower energy intensity. Standardized regression coefficients show that these technology choices are more influential than owner-occupancy, climate conditions, and year built, but less influential than energy price, operating hours, floor area, and percent glass.

The HVAC conservation model, shown in the fourth column of Table 2, adds conservation technology adoptions to the base model. VAV systems, economizer cycles, and preventative maintenance are all significantly associated with higher energy intensity, although their influence based on standardized regression coefficients is smaller than that of energy price, operating hours, floor area, and percent glass.

The HVAC controls model, another extension of the base model, is shown in the final column of Table 2. Thermostatic control based on manual re-sets shows a significant negative correlation with energy intensity, whereas EMCS and, to a lesser extent, time-clocks correlate positively. Based on standardized regression coefficients, control system choices are less influential than energy price, operating hours, and floor area, but more important than building age and climate.

Factors affecting electricity intensity are modeled in Table 3. The base model, not shown, is quite similar in absolute performance and in relation to its extensions to the energy intensity base model from Table 2 except that the year built is no longer significant and the number of heating degree days is significant. The second column models the effects of cooling technology choice on electricity intensity. Low-cost technologies, including individual room air conditioners and swamp coolers, correlate with low electricity intensity. Capital-intensive district chilled water and central chillers correlate strongly with higher electricity intensity. Standardized regression coefficients show that operating hours, floor area, percent glass, and electricity price are the most influential factors, followed by heating degree days. Cooling technology choices and owner occupancy have a relatively minor influence on electricity intensity.

The windows model, shown in the third column of Table 3, reveals that only a couple of choices are significant. Both tinted windows and awnings/overhangs correlate with higher electricity intensity. However, they explain a relatively small amount of the variation in electricity intensity, according to their standardized regression coefficients.

The lights model, shown in the fourth column of Table 3, strongly correlates fluorescent, compact fluorescent, high-intensity discharge, and halogen lamps with higher electricity intensity.

The final column of Table 3 shows the effects of lighting conservation choices on electricity intensity. Unlike the other models in the two tables, this model includes only buildings that are both cooled and use fluorescent lights. Specular reflectors, electronic ballasts, and auto sensors all correlate with higher electricity intensity. Only the percent of floor area that is daylight correlates negatively. Standardized regression coefficients indicate that percent daylit is a relatively influential factor in explaining electricity intensity, tied with electricity price.

These results regarding explanatory factors for energy and electricity intensity are robust across a number of model specifications and tests. Similar results appear whether the dependent variable is energy or electricity intensity, whether log transformations are applied or not, and whether outliers are deleted or not. Models limited to specific building activities (e.g., offices) and regions (e.g., South Atlantic) show a similar pattern.

Comparisons of means tests between cohorts with and without specific energy efficiency features also support the same basic findings. Summaries of previous CBECS surveys report similar results (EIA 2003).

Discussion

Discussion of the results follows the two questions posed at the outset. The patterns revealed by these analyses support some expectations and not others.

Our first question is: What are the trajectories of technology adoption with in U.S. commercial buildings? New technologies have penetrated the U.S. commercial building sector, but only a few, such as fluorescent lights, have become dominant. It is more common for technologies to achieve plurality status after several decades, becoming dominant within particular submarkets. Attractive new technologies find usage in existing buildings by means of retrofits.

The next question is: Do these technologies reduce the energy intensity of commercial buildings? The answer must be highly qualified but is “no” in most of the cases examined here. Causality could well go in the other direction. Energy intensity in U.S. commercial buildings is a strong function of the price of energy, the required operating schedule, and amount of exterior glass. Scale economies are also evident, such that larger buildings are often less energy intensive, in part due to a lower surface area-to-volume ratio, and in part due to improved technological opportunities, although this relationship does not appear to be strictly monotonic. Climatic conditions are not particularly influential, reflecting the core-dominated cooling loads of commercial buildings and the fact that building codes are more stringent in the more extreme climates. With the exception of daylighting, the so-called innovative HVAC, window, and lighting efficiency technology adoptions are associated with higher—not lower—energy intensity.

The counter-intuitive finding that the presence of innovative, energy-saving technologies correlates with higher energy intensities deserves further discussion, although we do not resolve it here. One possible explanation is that CBECS is too blunt an instrument to measure the impacts of these technologies accurately. Indeed, the 1995 CBECS rather heroically includes engineering model-based estimates of energy consumption by end-use category that Katipamula and Gaines (2003) use to make the claim that most of the efficiency technologies *do* save energy, but the 1995 methodology has been abandoned in subsequent years because of its unreliability (EIA 2003). The 2003 CBECS data set is more robust because it only reports actual billing data. However, any regression analysis using the CBECS data ignores a host of physical and operating characteristics of buildings and their occupants that influence energy use, and the models do not explain more than a fraction of the variation in the dependent variable. The unexplained variation could swamp the effects of energy efficient technology choices.

Alternatively, the rebound effect, whereby efficiency improvements encourage more intensive use of building systems, could play a role (Hertwich 2005). A modest rebound effect on the order of 10-30% has been identified in many energy markets, including U.S. buildings (Greening, Green & Difiglio 2000), although there is less scope for this behavior in commercial buildings compared to residences.

In a secular shift, increasing plug loads (office equipment, appliances) may be offsetting the savings from innovative HVAC, window, and lighting technologies. HVAC and lighting are shrinking as a percent of total energy use within U.S. commercial buildings and plug loads are growing, thereby reducing the potential impact of the efficiency technologies investigated (EIA 2003). However, there is no significant correlation in the (cross-sectional) 2003 CBECS data set between proxies for plug loads (e.g., counts of computers and copy machines) and the use of the innovative technologies studied here. A comparison of the seven CBECS survey waves from 1983 to 2003 shows that during that period there have been no statistically significant changes in national-average aggregate energy intensity, given confidence intervals associated with the survey data. However, there is an upward drift in aggregated electricity intensities and a decline in fossil fuel intensities that is consistent with higher plug loads.

Perhaps innovative energy-efficiency technologies are being adopted more often in circumstances where they make the most economic sense. In other words, these innovations are adopted specifically in commercial buildings with higher-than-average energy-intensities. Efficiency investments are more valuable in such circumstances.

An income effect might play a role. Higher-end commercial buildings, whose more affluent occupants tend to demand greater comfort and use more energy, are adopting these technologies as a de facto design standard. Conversely, low-end buildings have less affluent occupants who are less willing to invest in premium equipment, are more willing to endure discomfort, and who simply operate their buildings in a thrifty manner.

It is also likely that some of these technologies do not work well in actual use. For example, economizer cycles are notorious for poor operational performance, with post-construction investigations often revealing dampers jammed in the open position, thereby wasting instead of saving energy (Lunneberg 1999). Similarly, energy management and control systems, VAV systems, and other complex technologies often fail to operate as expected (Lupinacci 2001). By contrast, daylighting is a passive technology that does not depend on the building operator or occupant to work correctly. These findings suggest that complexity is not as big a barrier to technology diffusion in commercial buildings as it ought to be.

Conclusions

This work has described the diffusion of key technologies affecting the energy intensity of U.S. commercial buildings. Many of these technologies are quite mature, having entered widespread use years or even decades ago. Future research should examine emerging, cutting-edge innovations that are now entering widespread adoption. Study of clusters of technologies and their adoption within specific building niches would also be worthwhile.

This work further shows that, excepting the case of fluorescent lights, no technology dominates the entire U.S. commercial building market. Instead, each successful technology conquers a specific niche. Future research should examine the specific determinants of technology adoptions in commercial buildings.

This work has also shown that the adoption of several so-called “energy saving” technologies is actually correlated with higher energy intensity. Future work should attempt to explain more completely the inconsistency between engineering studies showing that energy-efficient technologies reduce energy intensity, and econometric studies such as this one that fail to find much supporting evidence. Ongoing efforts to run building-level simulations for all of the building types in the 2003 CBECS (Torcellini et al, 2008) and to develop end-use consumption estimates for the 2003 CBECS are definitely steps in the right direction.

The U.S. commercial building market is beset with market failures that discourage the adoption of energy-saving technologies. Yet most of the buildings in which these technologies are deployed do not have lower energy intensities. The exception that does measurably correlate with reduced energy intensity is daylighting. These results suggest that decision makers also should improve operating and maintenance practices, invest in building commissioning, and rely more heavily on passive design features to save energy.

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Note: Estimates are presented in metric units, although the CBECS survey uses customary U.S. units. Floorspace estimates are converted to metric units by using the relationship: 1 square foot is approximately equal to 0.0929 square meters. Energy estimates are converted to metric units by using the relationship: 1 Btu is approximately equal to 1,055 joules; one kilowatthour is exactly equal to 3,600,000 joules; and one gigajoule (109 joules) is approximately 278 kilowatthours (kWh).

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Table 1: Summary Statistics for CBECS Variables

Continuous Variables	**N**	**Minimum**	**Maximum**	**Mean**	**Std. Deviation**
Weighting factor	5215	1	6374	932	1016
Floor area (enclosed sq.meters)	5215	93	148645	9308	21485
Daylit (% of floor area)	4631	0	100	15	24
Heating Degree Days (annual, C)	5215	0	6144	2472	1268
Cooling Degree Days (annual, C)	5215	11	3280	768	584
Energy Price (Multi-fuel, $/kWh)	5108	0.003	0.409	0.068	0.034
Electricity Price (electricity only, $/kWh)	5104	0.018	0.564	0.092	0.038
Year built	5215	1771	2003	1969	30
Operating hours (weekly)	4820	0	168	77	51
Energy Intensity (kWh/sq.m.)	5111	0.24	5013.28	344.64	391.07
Electricity Intensity (kWh/sq.m.)	5107	0.05	3790.73	184.49	215.06
Discrete Variables	**N**			**Discrete Variables**	**N**
Window Type	4820			Percent glass	4362
Single layer	1824			10% or less	1881
Multi-layer	1942			11% to 25%	1345
Combination	865			26% to 50%	759
No windows	189			51% to 75%	295
				76% to 100%	82
Main Heating System	5215				
Furnace	1295			Main Cooling System	5215
Boiler	1145			Packaged unit	1768
Packaged unit	937			Residential-type central	681
Indiv. Space htr.	292			Indiv. Room unit	450
Heat pump	359			Heat pump	413
District heat	285			District chilled water	179
Other	145			Central chiller	637
				Evaporative cooler	70
Controls (for cooling systems)	5215			Other	39
Time clock thermostat	847				
Manual thermostat	1421				
Energy management & control system	898				
Binary variables	**N**	**No (0)**	**Yes (1)**		
Variable Air Volume	4447	3173	1274		
Economizer	3890	2508	1382		
Maintenance	4447	853	3594		
Energy management & control system	3523	2548	975		
Incandescent bulbs	4622	1857	2765		
Fluorescent bulbs	4622	199	4423		
Compact fluorescent bulbs	4622	2757	1865		

High-intensity Discharge bulbs	4622	3423	1199		
Halogen bulbs	4622	3474	1148		
Other bulbs	4622	4602	20		
Specular reflectors	4423	2741	1682		
Electronic ballasts	4455	1079	3376		
Tinted glass	4631	2626	2005		
Reflective glass	4631	4047	584		
Awnings	4631	3291	1340		
Skylights	4631	3844	787		
Auto sensors	4631	4436	195		
Owner Occupied	4820	2029	2791		

Table 2: Factors Affecting Multi-fuel Energy Intensity in Air-Conditioned U.S. Commercial Buildings

	Base Model	Heating Model	HVAC Conservation Model	HVAC Controls Model
Dependent Variable:	kWh/m^2	kWh/m^2	kWh/m^2	kWh/m^2
Explanatory Variables:	Coeff. (S.E.)	Coeff. (S.E.)	Coeff. (S.E.)	Coeff. (S.E.)
Constant	6.055 (0.942)***	5.320 (0.934)***	8.727 (1.008)	8.191 (0.926)
Floor area	-0.263 (0.012)***	-0.308 (0.012)***	-0.315 (0.012)***	-0.313 (0.012)***
Year built	2.567 (0.479)***	2.898 (0.473)***	1.099 (0.514)*	1.731 (0.468)***
Percent glass	0.226 (0.015)***	0.201 (0.014)***	0.190 (0.015)***	0.204 (0.015)***
Operating hours	0.010 (0.000)***	0.010 (0.000)***	0.010 (0.000)***	0.009 (0.000)***
Energy price	-1.165 (0.035)***	-1.102 (0.035)***	-1.079 (0.036)***	-1.164 (0.034)***
Heating degree days	-0.064 (0.018)***	-0.043 (0.017)*	-0.039 (0.018)*	-0.065 (0.017)***
Cooling degree days	-0.107 (0.036)**	-0.103 (0.035)**	-0.067 (0.036)	-0.100 (0.035)**
Owner Occupied	-0.078 (0.026)**	-0.101 (0.025)***	-0.125 (0.026)***	-0.091 (0.026)***
Furnace		0.000 (0.054)		
Boiler		0.404 (0.066)***		
Packaged unit		0.312 (0.055)***		
Space heater		-0.309 (0.066)***		
Heat pump		0.073 (0.062)		
District heat		1.076 (0.117)***		
VAV			0.251 (0.040)***	
Economizer			0.261 (0.039)***	
Maintenance			0.190 (0.030)***	
Time-clock				0.066 (0.039)*
Manual				-0.312 (0.032)***
EMCS				0.337 (0.057)***

Number of cases	3823	3823	3505	3823
F (df)	359 (8)***	243 (14)***	279 (11)***	299 (11)***
Adjusted R^2	0.43	0.47	0.47	0.46

Notes:
Ordinary least squares regression analysis. The equation predicts the log of energy (or electricity) intensity. Observations are weighted to reflect their prevalence in the population of U.S. commercial buildings. Only buildings with cooling systems are included.
Energy intensity, floor area, and energy price are subjected to a log transformation to enhance the normality of their distributions. Year built, heating degree days, and cooling degree days are divided by 1000 to improve the readability of the coefficients.

*** Significant at 0.001 level
** Significant at 0.01 level
* Significant at 0.05 level

Table 3: Factors Affecting Electricity Intensity in Air-Conditioned U.S. Commercial Buildings

	Cooling Model	Windows Model	Lights Model	Lighting Conservation Model
Dependent Variable:	kWh/m^2	kWh/m^2	kWh/m^2	kWh/m^2
Explanatory Variables:	Coeff. (S.E.)	Coeff. (S.E.)	Coeff. (S.E.)	Coeff. (S.E.)
Constant	7.647 (1.052)***	6.238 (1.091)***	5.717 (1.046)***	6.086 (1.042)***
Floor area	-0.255 (0.013)***	-0.212 (0.013)***	-0.247 (0.013)***	-0.226 (0.013)***
Year built	-0.938 (0.529)	-0.478 (0.556)	-0.297 (0.533)	-0.227 (0.531)
Percent glass	0.210 (0.016)***	0.209 (0.016)***	0.216 (0.016)***	0.232 (0.017)***
Operating hours	0.010 (0.000)***	0.010 (0.000)***	0.009 (0.000)***	0.010 (0.000)***
Electricity price	-0.494 (0.044)***	-0.545 (0.045)***	-0.532 (0.044)***	-0.495 (0.045)***
Heating degree days	0.108 (0.019)***	0.093 (0.020)***	0.077 (0.019)***	0.077 (0.019)***
Cooling degree days	-0.053 (0.040)	-0.040 (0.041)	-0.056 (0.040)	-0.027 (0.041)
Owner Occupied	-0.082 (0.028)**	-0.070 (0.029)*	-0.075 (0.029)**	-0.063 (0.029)*
Packaged unit	0.157 (0.164)			
Residential central unit	-0.112 (0.165)			
Individual room unit	-0.360 (0.167)*			
Heat pump	-0.154 (0.167)			
District chilled water	1.024 (0.217)***			
Central chiller	0.667 (0.183)***			
Swamp cooler	-0.142 (0.186)			
Double glazing		0.026 (0.034)		
Combination windows		0.076 (0.044)		
Tinted windows		0.181 (0.031)***		

Reflective windows		-0.017 (0.052)		
Awnings/Overhangs		0.128 (0.031)***		
Skylights/Atriums		0.073 (0.053)		
Incandescent bulbs			-0.033 (0.029)	
Fluorescent bulbs			0.521 (0.064)***	
Compact fluorescents			0.221 (0.035)***	
High-intensity dischargebulbs			0.149 (0.048)**	
Halogen bulbs			0.291 (0.042)***	
Specular reflectors				0.174 (0.034)***
Electronic ballasts				0.071 (0.031)*
Auto sensors				0.241 (0.095)*
Percent daylit				-0.007 (0.001)***
Number of cases	3822	3762	3798	3623
F (df)	129 (15)***	118 (14)***	139 (13)***	143 (12)***
Adjusted R^2	0.34	0.30	0.32	0.32

Notes:
Ordinary least squares regression analysis. The equation predicts the log of electricity intensity. Observations are weighted to reflect their prevalence in the population of U.S. commercial buildings. Only buildings with cooling systems are included.
Electricity intensity, floor area, and electricity price are subjected to a log transformation to enhance the normality of their distributions. Year built, heating degree days, and cooling degree days are divided by 1000 to improve the readability of the coefficients.
The lighting conservation model only includes buildings with both cooling systems and fluorescent lights. EMCS for lighting is not included because there are too few cases.

***	Significant at 0.001 level
**	Significant at 0.01 level
*	Significant at 0.05 level

Figure 1: Energy Intensity and Floorspace of U.S. Commercial Buildings by Year Built

Note that energy intensity is measured at the site boundary and does not include the losses of primary energy associated with electricity production.

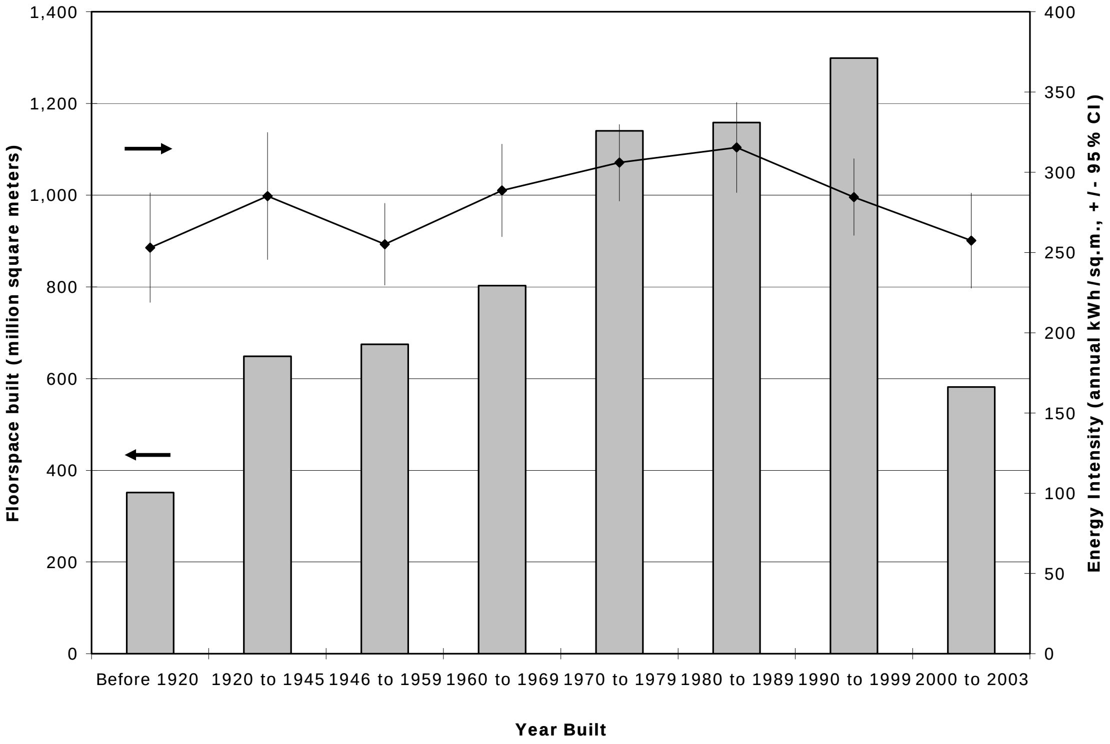

Figure 2: Penetration of Window Treatments in U.S. Commercial Buildings

Notes:
Data sources are the CBECS 1992 and 2003 Public Use Microdata files.
Penetration is shown as a percent of total floor area built in that time period.
1992 data are missing for single-layer glass, no windows, and percent daylit.

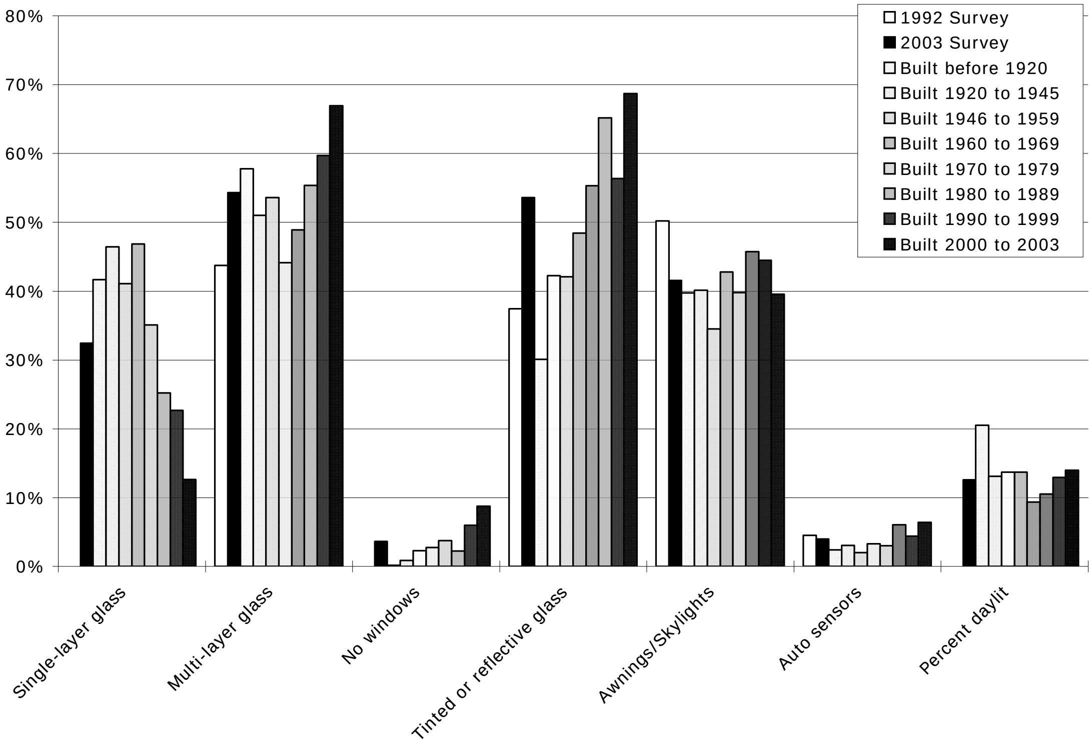

Figure 3: Penetration of Lighting Technologies in U.S. Commercial Buildings

Notes:
Data sources are the CBECS 1992 and 2003 Public Use Microdata files.
Penetration is shown as a percent of total floor area built in that time period.
Since lighting technologies are easy to retrofit, many older buildings have adopted new technologies.
Column totals do not sum to 100% because multiple technologies may be use in each building.
1992 data are missing for halogen bulbs.

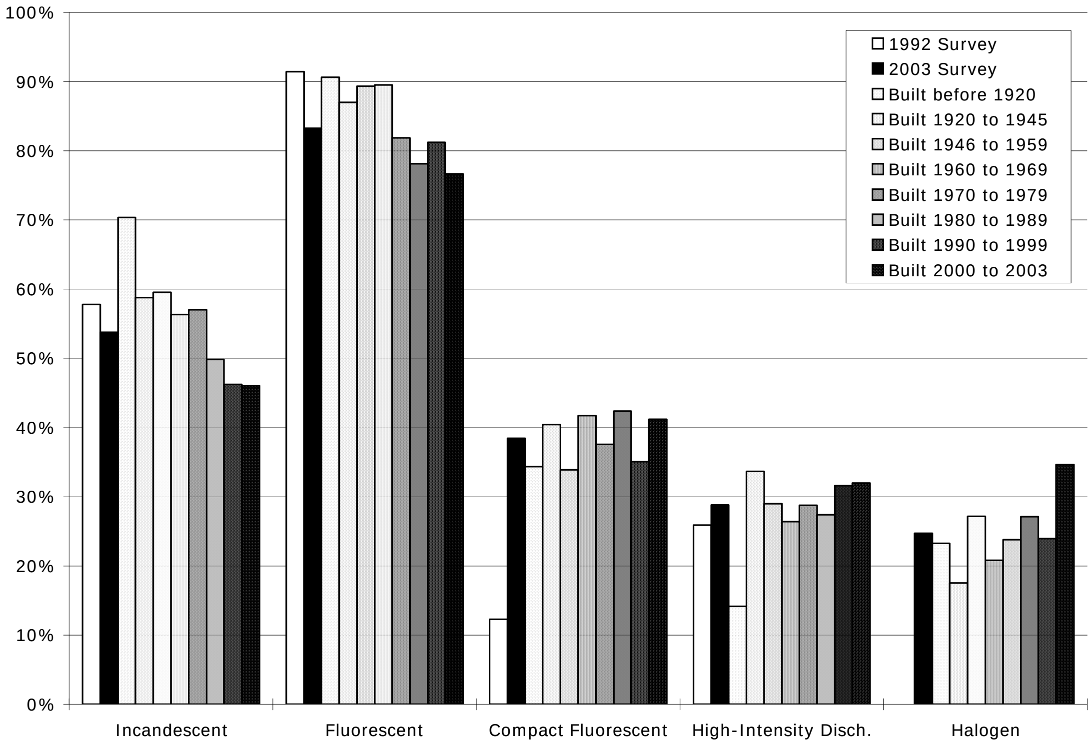

Figure 4: Penetration of Lighting Conservation Features in U.S. Commercial Buildings

Notes:
Data sources are the CBECS 1992 and 2003 Public Use Microdata files.
Penetration is shown as a percent of total floor area built in that time period.
Since lighting technologies are easy to retrofit, many older buildings have adopted new technologies.
Column totals do not sum to 100% because multiple technologies may be use in each building.
1992 data are missing for electronic ballasts and percent daylit.

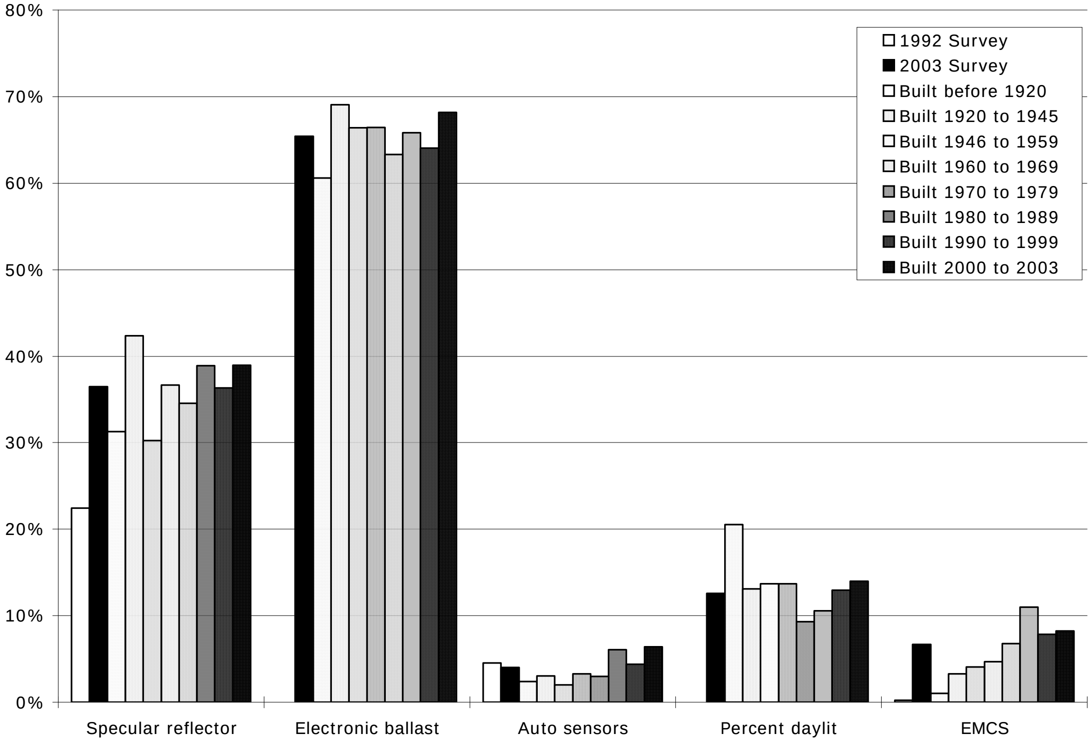

Figure 5: Penetration of Space Heating Technologies in U.S. Commercial Buildings

Notes:
Data sources are the CBECS 1992 and 2003 Public Use Microdata files.
Penetration is shown as a percent of total heated floor area built in that time period.
Column totals do not sum to 100% because multiple technologies may be use in each building.

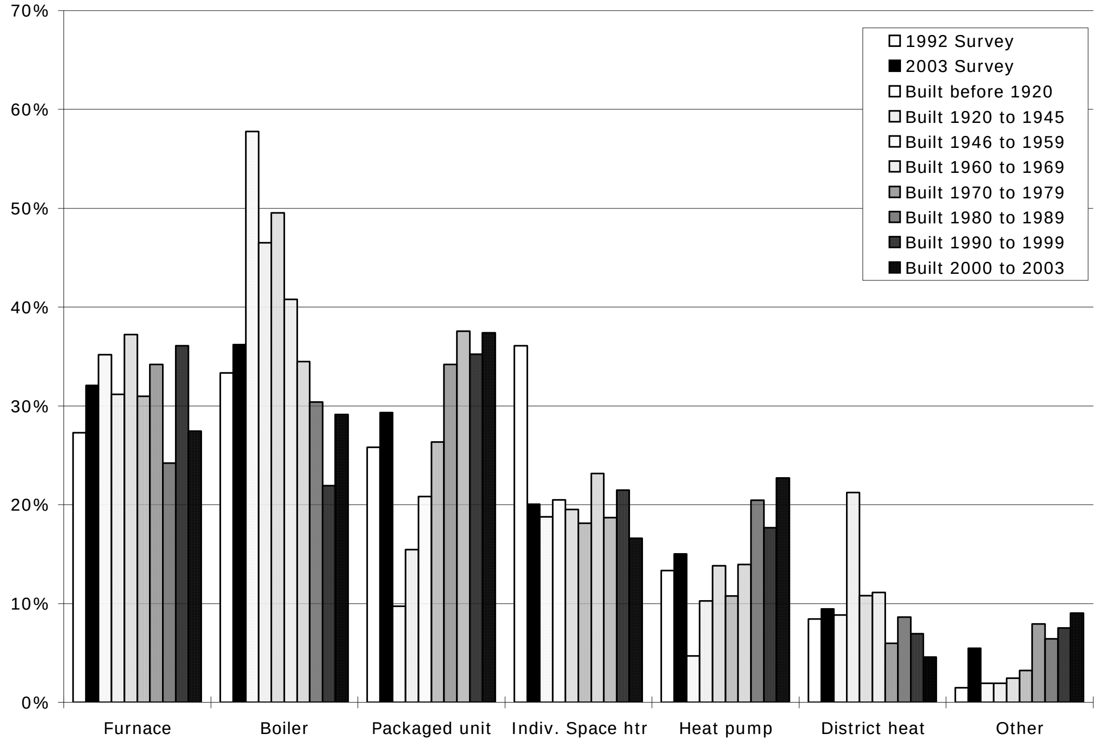

Figure 6: Penetration of Space Cooling Technologies in U.S. Commercial Buildings

Notes:
Data sources are the CBECS 1992 and 2003 Public Use Microdata files.
Penetration is shown as a percent of total cooled floor area built in that time period.
Column totals do not sum to 100% because multiple technologies may be use in each building.

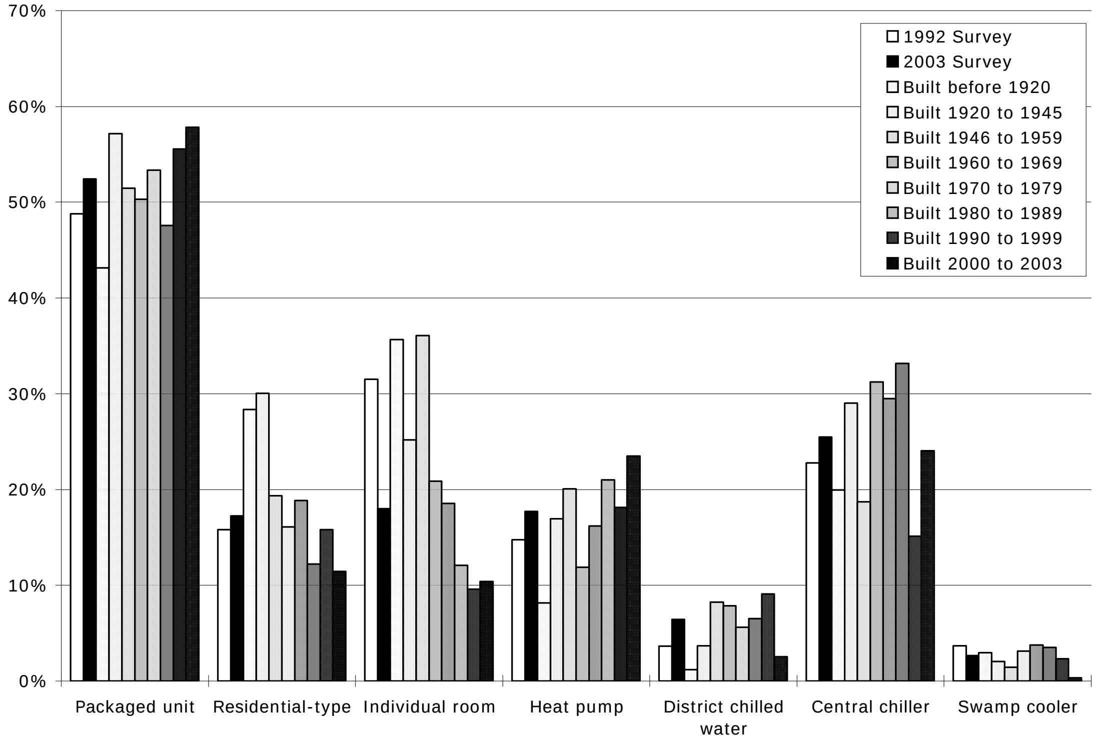

Figure 7: Penetration of HVAC Conservation Technologies in U.S. Commercial Buildings

Notes:
Data sources are the CBECS 2003 Public Use Microdata files.
Penetration is shown as a percent of total cooled floor area built in that time period.
Since maintenance is an operating practice, many older buildings have adopted it.
Column totals do not sum to 100% because multiple technologies may be use in each building.

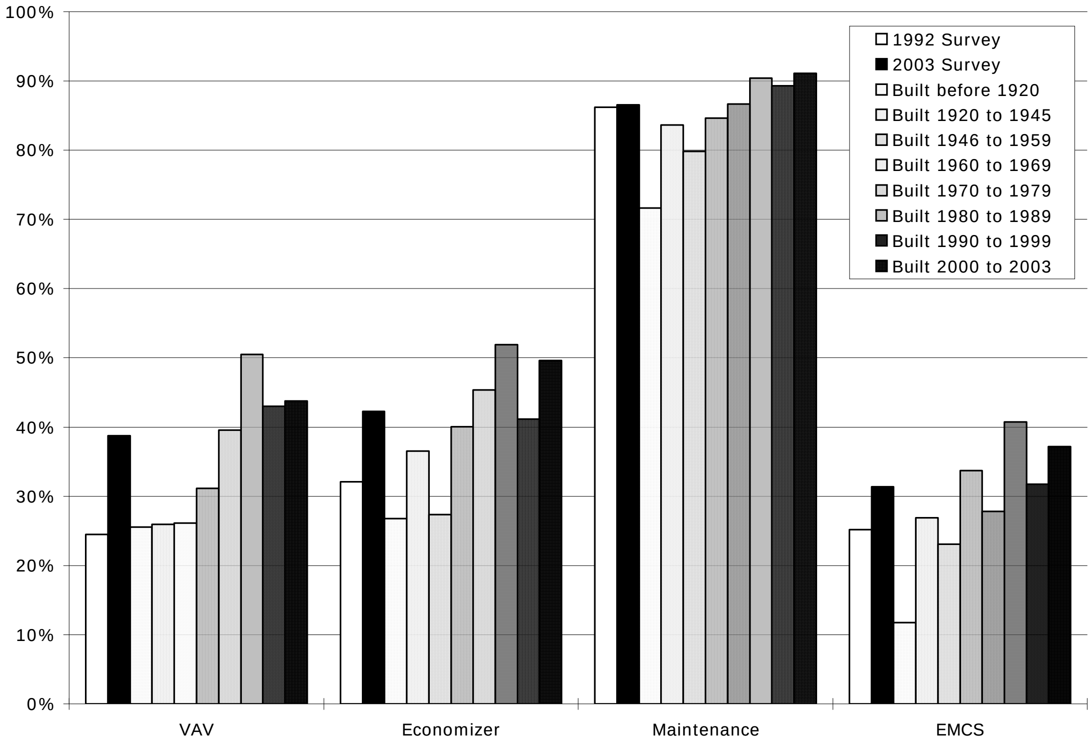

Figure 8: Penetration of HVAC Control Technologies in U.S. Commercial Buildings

Notes:
Data sources are the CBECS 2003 Public Use Microdata files.
Penetration is shown as a percent of total cooled floor area built in that time period.
Since maintenance is an operating practice, many older buildings have adopted it.
Column totals do not sum to 100% because multiple technologies may be use in each building.
1992 data are missing for time clock and manual thermostatic controls.