Chapter 3

Technical Potential for Improving the Energy Efficiency of Buildings in Cities

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INTRODUCTION

The building stock of U.S. cities is inherited from eras of energy use that were very different from the one that the country faces over the next two decades. Some buildings date from the mid-19th century when the only building fuel was firewood and the average home consumed 17 cords per year.[1] Many buildings still have old coal furnaces in their basements, later converted to burn oil. The shiny glass office buildings of the 1960's and early 1970's were built in the expectation of cheap electricity getting cheaper.

How well are these buildings likely to survive as energy prices continue to increase in response to the increasing scarcity of oil and gas? To be sure, those who work and live in old buildings will have the option of using them the way their ancestors did with closed off rooms and lowered temperatures in the winter, windows open, shirtsleeves, and long cool drinks in the summer.

To what extent, however, can the buildings themselves be made more energy efficient in response to higher prices? What specific changes can be made to walls, windows, and heating equipment of different kinds of city buildings to make them more efficient? At what cost compared to savings in energy? With what degree of uncertainty? Are there types of buildings that will never be even moderately frugal in their energy use and so will be prime candidates for abandonment if their energy costs become the dominant expense?

To answer these questions OTA conducted a systematic survey of physical changes that could be made to different kinds of buildings to improve their energy efficiency. For convenience, these will be called *energy retrofits* in this report. The analysis used methods of calculation of costs and savings that are somewhat more sophisticated than those of many energy auditors (see box A) but are generally simpler than calculation methods used in some elaborate computer programs. For some retrofits and some building types there have been individual

Box A.-The Energy Auditor's Work

The energy auditor's work has two components: a theoretical component and a site-specific component. In the theoretical component, the auditor takes a small number of facts about a building's walls, windows, roof, lighting, and mechanical systems and applies a series of formulas to estimate the amount of energy savings that might result from each of serveral retrofit measures. He estimates the cost of the components, also based on standard cost information.

The auditor subsequently, or simultaneously, inspects the building and discusses it with its owner in order to take into account several additional factors which are peculiar to the building and the owner's plans for it. The auditor, in this site-specific component will:

- **make a precise assessment of the efficiency of the current mechanical system components;**
- **identify any peculiar features of the building that waste energy, such as cracks around vents that release heat to the outside;**
- **identify any peculiar local variationsin the** cost of labor or materials; and
- **take into account the owner's plans for renovating or repairing such features as the roof or mechanical systems that would be affected by a retrofit.**

[1] *Energy in the American Economy, 1850- 1975: An Economic Study of Its History and Prospects,* Sam H. Schurr and Bruce Netscherf, with Vera F. Eliasberg, Joseph Lerner, Hans H. Landsberg, Resources for the Future, Inc., 1977, p. 49.

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studies that provide more detail than the comprehensive survey of retrofits described in this chapter, but these do not provide ways to compare retrofits across building types. Where applicable these studies are referenced or described i n the text and in footnotes. z

The data on actual retrofits are skimpy and do not permit any conclusions comparing savings from one category of retrofits to another or comparing one building type to another. These data are reported on later in the chapter.

The data on the nature of the building stock are also skimpy. Although much is known about the location, size, structure, and heating systems of the housing stock and the rate of new construction and demolition, until this year virtually nothing was known about the commercial building stock. Now, thanks to a survey of nonresidential (mostly commercial but a few industrial) buildings* something is known about the size, use, and heating and cooling systems of commercial buildings but still very little about their location (in central cities, suburbs, or rural areas) or the rate at which they are being constructed or demolished. This chapter, where possible, relates data on characteristics of the building stock, which are expected to affect its retrofit potential.

On the average, retrofits to existing buildings of most types are practical, feasible, and have a low capital cost compared to savings. At the same time, however, there is a large margin of uncertainty and risk about the savings achievable in a particular building. This is due both to the early stage of development and use of retrofits to buildings, and to some inherent lack of predictability for a technology applied in hundreds of thousands of buildings each with its own special characteristics. The chapter is organized to present the information to demonstrate these two overall conclusions. The first part of the chapter is devoted to the theoretical differences among buildings that systematically influence their retrofit potential. The second part of the chapter describes the reasons why energy savings for a particular building may be unpredictable.

The chapter also discusses key differences among the retrofit potential of building types that should be taken into account in designing a focused public or private retrofit program. Three of the critical differences are:

1. Which aspects of the *buildings type are most susceptible to retrofit?—The* retrofit business is still fragmented. Different businesses specialize in insulation, storm windows, improvements to the mechanical system, improvements to the hot water system, and improvements to the lighting systems. A designer of a retrofit program should know which businesses should be dealing with which building types.
2. Is *the building type capable on average of substantial/ reductions* in energy use? —This helps determine possible targets of retrofit programs. All programs, public or private, can benefit from early success and satisfied customers. Aiming a retrofit program first at those building types that are most likely to be capable of substantial reductions in energy use is one way to build the credibility of retrofits,
3. *Can a large fraction" of the potential energy savings of the building type be achieved with retrofits of low capital cost relative to savings ?—For* building types with a retrofit potential with this characteristic, financial assistance with the retrofit should not be as necessary as for building types with a large fraction of potential savings likely to come from retrofits of moderate capital cost relative to savings or a large fraction of retrofits with high capital cost relative to savings.

[2]Some examples of computer programs to assess retrofits include DOE-2 (formerly Department of Energy), E CUBE (Southern California Gas Co.) and BLDSIM (Honeywell). For more information see article and bibliography T. Kusuda "Comparison of Energy Calculation Procedures, " ASHRAE *Journal,* August 1981. Two notable studies of the retrofit potential of different categories of buildings are: 1) A *Study of Energy Conservation in Rental Housing,* prepared by Ritter, Suppes, Plantz, Architects, Ltd. for the Minnesota Housing Finance Agency, January 1979; and 2) *Energy Conservation in Existing Office* Bul/ding\, Syska and Hennessy and Tishman Research for the U.S. Department of Energy, New York, June 1977.

* Published by the Energy Information Administration of the Department of Energy in April 1981.

A FEW CHARACTERISTICS OF BUILDINGS INFLUENCE THEIR RETROFIT POTENTIAL

The variety of city buildings may seem infinite: from the small brick rowhouses of Baltimore and wooden Victorians of San Francisco to the towering offices of downtown Atlanta. To the trained eye of the energy auditor, however, there are only a few important characteristics of a city building that will determine the kinds of energy retrofit measures that should increase that building's energy efficiency. Three of these characteristics are usually visible from the outside of the building: size, wall and roof type, and building purpose (residential or commercial). A fourth, equally important but invisible to the outside, is mechanical system type. Each of these characteristics will affect the list of retrofit options as follows:

Size. –Energy retrofits that improve the tightness of the building envelope are more important for small buildings than for large buildings. Wall insulation, roof insulation, and window treatments such as storm windows save more energy for small buildings than large ones because in small buildings there is more outside surface through which heat and cooling can escape compared to the useful floor area of the building. On the other hand, certain kinds of retrofits to central heating and cooling systems or domestic hot water systems are less expensive for the same savings in large buildings than in small because of economies of scale in equipment size.

wall and roof type. –Masonry or clad walls (steel frame with brick, concrete, steel, or glass veneer) and flat roofs without attics or with very small crawl spaces are much more expensive to insulate than are wood frame walls and roofs with attics and ample crawl spaces. Many buildings characteristic of cities—cinderblock bungalows, brick rowhouses, large clad-wall apartment buildings, or stone or brick commercial strip buildings-cannot improve the energy efficiency of their structures through insulation except at great expense.

Mechanical system (HVAC) type. –Physical changes to the way space heating and cooling is produced and circulated can provide significant increases in building efficiency but vary with the type of heating, ventilation, and air-conditioning (HVAC) system used by the building. Air systems that circulate centrally heated and cooled air in various ways provide many opportunities for improved efficiency. Decentralized systems, on the other hand, use individual space heaters and air-conditioning units and generally have improved efficiency only by replacing the individual units at considerable expense. Mixed *water-based systems,* typical of older buildings that heat with circulating hot water and steam through radiators but cool with window air-conditioners, can be retrofit in the central system but share with decentralized systems the problems of retrofitting the air-conditioners. Finally complex reheat systems, typical of newer commercial buildings can have their efficiency greatly improved by changing from a very energy inefficient "reheat" way of maintaining constant temperature to a more efficient one.

Building purpose.–Most commercial buildings are used from 9 to 5 (offices) or 9 to 9 (shopping centers) and are empty outside these hours. This provides opportunities for improved energy efficiency by careful control of temperature and lighting between operating and nonoperating hours. Greater ventilation requirements and cooling loads in commercial buildings permit energy savings from careful use of outside air and opportunities also exist for more efficient and task-specific lighting in commercial buildings. Multifamily buildings on the other hand use a lot of hot water; retrofits to the hot water system can usually save energy. Since multifamily buildings must be comfortable temperatures at night, there are significant opportunities for preventing heat loss through windows at night.

The age of a building was not added to this set of four critical characteristics because by itself it does not directly influence the list of retrofits that is appropriate to the building. The age of a building is, rather, an indicator of the other characteristics of the building which will directly affect its retrofit potential. Older buildings are more likely to have solid masonry walls and central water or steam heating systems. Rather than central air-conditioning they are likely to have window air-conditioners, or none at all. An older building is also somewhat more likely to have inefficient heating systems and poorly fitting window frames subject to infiltration. However, old buildings may also be carefully maintained, and equipped with upgraded heating equipment and newly fitted windows,

AN OVERVIEW OF THE RETROFIT POTENTIAL OF DIFFERENT BUILDING TYPES

There is a List of Practical Retrofit Options for Each Distinctive Building Type. Most energy auditors prepare their work in the form of a list of retrofit options that show the cost of each option, estimated savings, and expected payback. Although retrofit lists were initially constructed for over 40 combinations of the four building characteristics described above, it was found that 13 sets of building characteristics (see table 11) were enough to explain most of the the variation among the retrofit lists. Some sample lists for some building types are presented later in the chapter (tables 15, 16, 17, and 19). The retrofit lists were constructed from a total list of almost 40 retrofits. The 13 distinct building types consist of:

- three types of small framehouses of one to four dwelling units (distinguished by their mechanical systems);
- three types of small masonry rowhouses also distinguished by their mechanical systems;
- three types of moderate or large multifamily buildings; and
- four types of moderate or large commercial buildings.

Table 11.—Thirteen Types of Buildings With Significantly Different Retrofit Options

Building type and wall type	Mechanical system type	More energy savings from: Low capital cost retrofit package[a]	More energy savings from: Moderate capital cost retrofit package[a]
Small house with frame walls (single family or 2-4 units)	Central air system	x	·
Same	Central water system[b]	x	—
Same	Decentralized system	x	—
Small rowhouse with masonry walls (single family or 2-4 units)	Central air system	—	x
Same	Central water system	—	x
Same	Decentralized system	—	x
Moderate or large multifamily building (masonry or clad walls)	Central air system	x	—
Same	Central water system	x	—
Same	Decentralized system	—	x
Moderate or large commercial building (masonry or clad walls	Central air system	x	·
Same	Central water	—	x
Same	Complex reheat system	x	—
Same	Decentralized system	x	—

[a]See app. B at the end of the report for details on retrofit packages for the different building types.
[b]OTA's assumption is that this building type has a central water system and window air-conditioners.

SOURCE: Office of Technology Assessment.

A complete listing of the full set of building types and of the full list of retrofits analyzed can be found at the end of the chapter in appendixes 3A and 3B.

For Almost All of the 13 Building Types the Retrofit Lists Contain Predominantly Retrofit Options of Low Capital Cost Compared to Savings. OTA classified retrofits on each list into low, moderate, and high capital cost compared to savings. To accommodate several common methods used by energy and housing analysts to express cost effectiveness, OTA has translated its definition of low capital cost compared to savings into three other ways of expressing cost effectiveness (see box B). The retrofit options of low capital cost on the retrofit lists are those that cost less than $14 for each annual million Btu that they save, which are expected to pay back in less than 2 years, earn an annual real return of at least 50 percent per year for 20 years, and cost less than $3.50 per million Btu saved at a capital recovery rate of **25** percent. Any way that one looks at their cost effectiveness, such retrofits are very good investments and are not likely to pose serious financing problems.

The sample retrofit lists for each of the 13 building types are shown in appendix A at the end of this report. A number of very powerful low-cost retrofits are responsible for a large share of the low-cost energy savings on each list: roof insulation for small buildings, wall insulation for frame buildings, reduction of ventilation and economizer cycles for commercial buildings with air systems, conversion from incandescent to hybrid fluorescent lamps in those commercial buildings still equipped with incandescent lights, and flow controllers and hot water system insulation in multifamily buildings.

All of the retrofit lists have on them substantial numbers of retrofits of moderate capital cost compared to savings. Such retrofits pose more serious financing difficulties for building owners no matter how the capital cost is expressed. Using OTA's definition and three other ways of expressing capital cost (see box B) moderate capital cost retrofits cost between $14 and $49 for each annual million Btu saved and would pay back in 2 to 7 years. They would earn more than 13 percent but less than 50 percent in annual real return per year over 20 years. If annualized at a capital recovery rate of 25 percent (corresponding to a 5-year loan at the fairly low interest rate of 10 percent) these retrofits would cost between $3.50 and $12,75 per annual million Btu saved. Some retrofits of moderate capital cost compared to savings include: storm windows for small buildings, shading devices for commercial buildings, and window insulation at night for multifamily buildings.

There are also a few retrofits with high capital cost compared to savings on each list but they are only important for a few building types. High capital cost retrofits pose very serious financing problems. They are not expected to payback for 7 to 15 years and are expected to earn less than 13 percent per year real return on investment. An outstanding example of a high capital cost retrofit that achieves substantial energy savings is wall insulation for masonry-walled buildings.

When Individual Retrofit Options Are Combined Into Retrofit packages, the Cumulative Savings is Significantly Less Than the Sum of the Savings From Individual Retrofits. Many of the low and moderate capital cost retrofits (which are the first that any cost-minded building owner is likely to install) reduce the potential for savings for some or all retrofits installed later. For example, storm windows reduce the amount of heat that escapes from windows. Savings from nighttime insulating window shades will be greater if installed on windows without storm windows than on those already equipped with storm windows.

For this reason savings from individual retrofits on the retrofit option lists cannot be added together. The energy savings produced when these retrofits are combined into packages is significantly less than the sum of what savings each would be expected to produce by itself. Because of the dozens of ways in which individual retrofits can be combined, each of which will produce a separate estimate of cumulative savings, most auditors generally calculate combined savings for one or a few retrofit packages.

Box B.—The Cost Effectiveness of Energy Retrofits: Four Definitions

This is an easy reference for translating the measure of retrofit cost effectiveness used by OTA (retrofit cost per annual Btu saved) into three other expressions of cost effectiveness. Each requires more assumptions than the simple cost per million Btu. The three other ways are shown below and compared to the cost per million Btu shown at left.

	OTA's method	Simple payback assuming	
Capital cost compared to savings	Total cost of retro-fit per annual million Btu saved[a]	Value of energy savings = $7 per million Btu	Value of energy savings $4.50 per million Btu
Low capital cost	$ 7.00	1 Yr.	1 ½ Yrs.
	$ 1400	2 Yrs.	3 Yrs.
Moderate capital cost	$ 2100	3 Yrs.	4 ½ Yrs.
	$ 35.00	5 Yrs.	8 Yrs.
	$ 49.00	7 Yrs.	11 Yrs.
High capital cost	$ 70.00	10 Yrs.	15½ Yrs.
	$10500	15 Yrs.	23 Yrs.

Simple payback, often used by energy auditors in dealing with their clients, is defined as the number of years for the first year's annual dollar value of energy savings to equal the cost of the retrofit. Simple payback does not take into account fuel escalation nor discount for future years. In addition to the cost per million Btu of the retrofit this measure requires an assumption about the *value of fuel savings*. In the example at the left, a low capital cost retrofit will have a simple payback of 2 years if the value of the first year savings is high because fuel oil is being saved, but will have a simple payback of 3 years if the lower cost natural gas is being saved.

	OTA's method	Real return on Investment assuming.	
Capital cost compared to savings	Total cost of retro-fit per annual million Btu saved[a]	Measure lifetime = 5 years	Measure lifetime = 20 years
		(annual percent)	
Low capital cost	$ 7.00	97%	100!%0
	$ 14.00	41%	50%
Moderate capital cost	$ 21.00	20%	33%
	$ 35.00	0	19%
	$ 49.00	Loss	13%
High capital cost	$ 7000	Loss	8 %
	$10500	Loss	3%

Real return on investment, used in business and real estate decisionmaking, takes into account the *life of the retrofit measure* and is defined as the real discount rate that equates costs and savings. In the example at left, a moderate capital cost retrofit costing $35.00 per annual million Btu saved will provide a 19 percent real return on investment if it lasts 20 years, but no return at all if it lasts only five years.

	OTA's method	Cost of conserved energy assuming	
Capital cost compared to savings	Total cost of retro-fit per annual million Btu saved[a]	Capital recovery rate of 067	Capital recovery rate of O 25
		($ per million Btu)	
Low capital cost	$ 700	$0.47	$ 175
	$ 1400	094	350
Moderate capital cost	$ 21.00	141	515
	$ 35.00	2.35	8.75
	$ 49.00	328	1225
High capital cost	$ 70.00	470	1750
	$10500	704	2625

Annualized cost of conserved energy is often used when comparing the cost of new energy supplies to the cost of conserving energy. It requires an assumption about a *capital recovery rate* in order to translate a one-time capital expenditure into annual expenses. In the example at left, the cost of conserved energy of a moderate capital cost retrofit of $49.00 per annual million Btu saved will be $3.28 per million Btu if capital is recovered at a capital recovery rate of 0.067 per year. (This corresponds to a 3 percent rate of interest over 20 years and is the assumption commonly used in lifecycle costing.) The same retrofit will cost $12.25 per annual million Btu saved at a capital recovery rate of 0.25 per year, (a rate which would amortize a 5-year loan at an annual interest rate of 10 percent).

[a]OTA assumes that all end-use Btu of electricity savings are multiplied by 2.46, in order to adjust for the differencein cost per million Btu between fuel at $1 per gallon ($7 per million Btu) and electricity at $0.06 per kWh ($17 per million Btu).

To illustrate the difference between lists of retrofit options and retrofit packages, the savings from packages of retrofits for each of the 13 distinct building types is calculated. These are shown in appendix B at the end of this report.

For Five of the Building Types the Bulk of Potential Savings is Likely to Come From Retrofits of Moderate Cost Compared to Savings. The owners of such buildings must cope with the difficulties of financing retrofits in order to achieve substantial savings. These building types and the estimate of potential savings from moderate cost retrofits are (see also table 11):

- masonry rowhouse with air system (30 percent),
- masonry rowhouse with water system and window air-conditioners (55 percent),
- masonry rowhouse with decentralized system (70 percent),
- large commercial building with water system and window air-conditioners (50 percent), and
- large multifamily building with decentralized system **(50** percent).

Only a Few Building Types Are Expected to Have Substantial Savings From Retrofits of High Capital Cost Compared to Savings. For most of the 13 building types a high-cost retrofit package would contribute less than **20** percent of the total savings. This is fortunate because, as box B makes clear, the payback on a high-cost retrofit is very slow.

However, for three building types a high-cost retrofit package compared to savings would be expected to contribute more than 20 percent of the total potential energy savings. These three building types and the expected contribution of high capital cost retrofits are:

- small masonry rowhouse *with* an air system (high-cost retrofits would contribute 40 percent of the total);
- small masonry rowhouse with a water or steam system (high-cost retrofits would contribute **25 percent of the total); and**
- **multifamily building with an air system** (high-cost retrofits would contribute **30** percent of the total).

For all these building types wall insulation is the most important element of the high capital cost retrofit package. It costs a lot but also saves a lot. For these buildings, public or private programs to facilitate the long- term financing of high-cost measures would help to realize the substantial savings available from high-cost retrofits. For the other 10 building types analyzed, high capital cost measures would contribute little enough that they can be ignored if financing is not easily avai l able.

The Total Savings Potential of Large Buildings Appears To Be Greater Than That of Small Buildings. According to OTA's analysis of total savings potential from retrofit packages, multifamily and commercial buildings have the potential to save .50 to 60 percent of their initial energy use while smaller framehouses and rowhouses have the potential to save 30 to 40 percent. For those commercial buildings still heavily dependent on incandescent lights, the savings potential from retrofit packages that include a shift to more efficient fluorescent lights may go as high as **70** percent of initial energy use.

BUILDING STOCK OF CITIES

What then are the prospects for improved energy efficiency in the building stock of U.S. cities? Each of the sections that follows describes the nature and general retrofit potential of one of the four major categories of the city building stock: small framehouses, small masonry rowhouses, moderate to large multifamily buildings, and moderate to large commercial buildings. A few additional types of buildings, e.g., freestanding masonry houses and very small commercial buildings, are also dealt with briefly.

The four categories of buildings include all 13 building types shown in table 11. Each of the four structural types (e.g., small framehouse) is further subdivided into mechanical system types because it is the mechanical system types which, especially in larger buildings, influence the retrofit potential of the building,

Small Wood Framehouses

Contrary to common perceptions about cities, the most typical building in a U.S. central city is the small wood framehouse. More than 16 million (see table 12) of the 25 million housing units in U.S. central cities are single-family detached houses (about 11 million) or are in buildings of two to four apartments (about 5 million). of these, it is estimated that a very large majority (80 to 90 percent) are buildings of wood frame construction, although there is no precise breakdown of the housing stock between wood frame and solid masonry. In four out of five of the case study cities visited—Buffalo, N. Y.; Des Moines, lowa; Tampa, Fla., and San Antonio, Tex.–the basic housing stock is of wood. only in a fifth case study, Jersey City, N. J., is masonry construction important, Half of the dwelling units in Buffalo's wooden houses are found in buildings of two to four apartments.

OTA found that the lists of retrofits applicable to such buildings is influenced by their small size (arbitrarily defined at less than **4,000 ft^2) and wall construction.** From an energy auditor's point of view the important characteristic of this type of housing is that the wood studs of the building frame provide a cavity into which wall insulation can be blown. Since the wood frame can be used to support a variety of wall types the external appearance of a wood framehouse may vary. The outer wall is most commonly of wood siding but it may also be of brick or stone veneer, or concrete blocks with and without stucco finish—a housing structure common in the South and southwest regions of the country.

The lists of retrofits most effective for such buildings are also influenced by their type of heating and cooling system. Retrofits for small wood framehouses with central air heating and cooling will differ from those with *central water or steam heat and window air-conditioners* and also differ from those with *decentralized heating and cooling systems* (electric baseboard heaters, heat pumps, gas heaters, wood stoves, or fireplaces), The likelihood of finding different types of heating and cooling systems i n different types of housing is shown in figures 10, 11, and 12. Warm air heating systems are more common in owner-occupied housing (mostly single-family detached) and in regions outside the Northeast. Water and steam systems provide the heat in more than two-thirds of the housing units of the Northeast. Room air-conditioning units are still the dominant form of cooling except in the South. More than half of all the housing units in the Northeast and West have no air-conditioning at all.

OTA's list of typical retrofits for wood framehouses assumes that the retrofits are applied to

Table 12.—Types of Housing Found in Central Cities

Type	Central city housing stock: Number of units (millions)	Central city housing stock: Percent of total	U.S. housing stock: Number of units (millions)	U.S. housing stock: Percent of total
Single-family detached.	10.9	43 "/0	52.4	630/o
Single-family attached	1.5	6	3.1	4
2-4 unit buildings	5.3	21	10.8	13
Buildings with five or more units	*7.2*	*29*	*12.9*	*16*
Mobile homes.	0.2	1	3.7	4
Total	25.2	100%	82.8	100 "/0

NOTE: Details may not add to total due to rounding.

SOURCE: HUD, *Annual Housing Survey,* 1978,

Photo credits: OTA staff

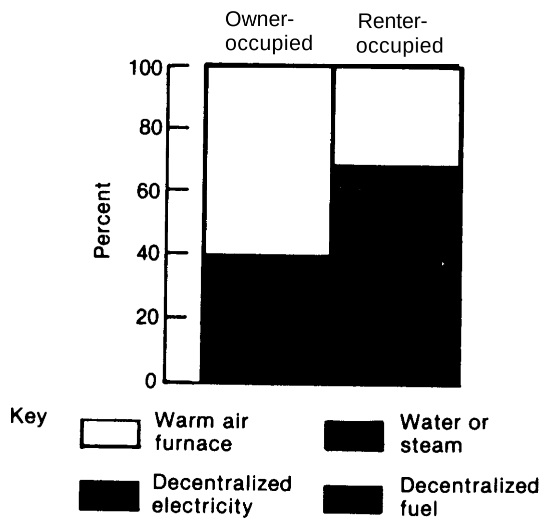
More than half of the housing stock of U.S. central cities are small detached framehouses. These come in many forms: bungalows (as in Tampa, Fla., upper left), triple-deckers (as in Waterbury, Corm., lower left), set close together (as in San Francisco, Calif., upper right) or set well apart (as in Des Moines, Iowa, lower right). Lists of retrofit options will be similar for framehouses with similar heating and cooling systems

an uninsulated house. While more than half of the housing stock as a whole has wall insulation **(50** percent), roof insulation (59 percent), and all windows covered with storm windows (41 percent), there is reason to believe that the older central city building stock is less well-insulated than the building stock as a whole. Two-thirds of the buildings with two to four units, which comprise about one-third of the Central city building stock, either don't have wall or roof insulation or don't know if they have (see tables 13 and 14).

A sample retrofit list for one type of small framehouse is shown in table 15. This type has a central water (or steam) system for supplying heat and window air-conditioners for cooling. The most powerful retrofits on this list would increase the efficiency of the building envelope. These are roof and wall insulation and storm windows. Retrofits to the mechanical system are also powerful—setback thermostat, stack heat reclaimer, vent damper, etc.

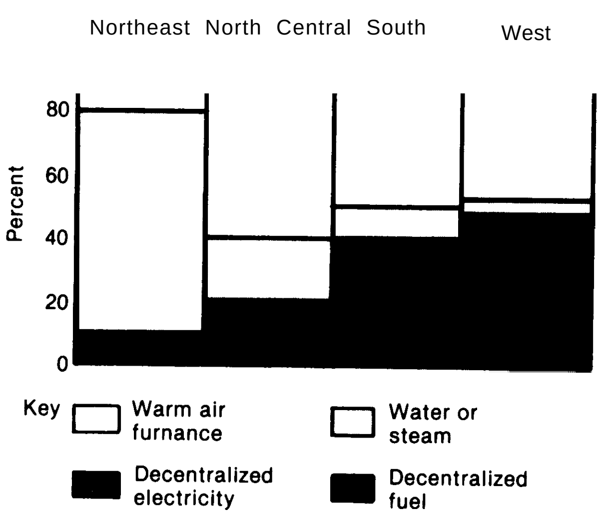
Sample retrofit lists for two other types of small framehouses—with central air system and with decentralized heating and cooling—can be found in appendix A at the end of this report. Envelope retrofits are also the most powerful retrofits on these two lists. In addition, the

Figure 10.— Heating Systems Found in Owner- and Renter-Occupied Housing Stock in U.S. Central Cities



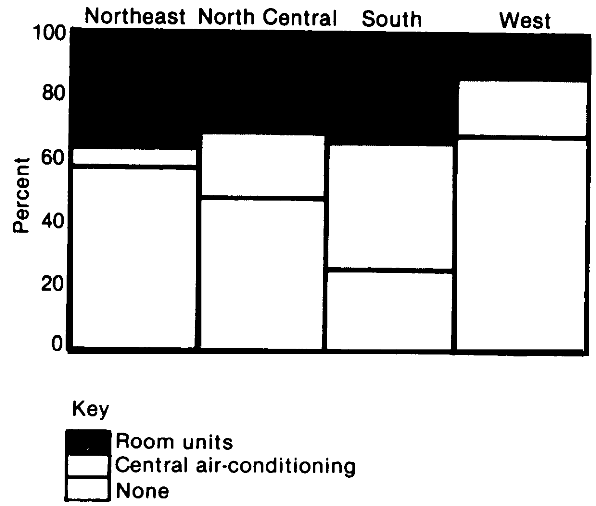
SOURCE: Energy Information Administration, ***Characteristics of the*** *Housing Stock and Households: Preliminary Findings From the National* ***In-terim*** *Energy Consumption Survey,* October 1979.

Figure 11.— Heating Systems in Central Cities Housing Stock by Region



SOURCE: Energy Information Administration, *Characteristics o/* ***the*** *Housing Stock and Households: Preliminary Findings From the National* ***In-terim*** *Energy Consumption Survey,* October 1979.

Figure 12.—Air-Conditioning in Central Cities Housing Stock by Region



SOURCE: Energy Information Administration, *Characteristics* ***of the*** *Housing Stock and Households: Preliminary Findings From the National* ***In-terim*** *Energy Consumption Survey,* October 1979.

Table 13.–Housing Stock With and Without Wall Insulation and Roof Insulation (in percent)

	Yes	No	Don't know
Building has wall insulation			
All housing units 1-4 units	50°/0	270/.	22 "/0
Single-family detached.	54		17
Single-family attached	44	28	28
Buildings with 2-4 units	28	27	44
Building has roof insulation			
Ail housing units 1-4 units	69	19	12
Single family detached. .,	77	17	6
Single family attached	53	26	21
Buildings with 2-4 units	35	29	36

SOURCE: EIA Survey of Residential Energy Consumption, February 1980.

Table 14.—Housing Stock With and Without Storm Windows (in percent)

	All windows covered	Some windows covered	No windows covered
• All housing units 1-4 units. .,	41 %	20 "/0	39 "/0
• Single-family detached	41	22	37
• Single-family attached	55	11	34
• Buildings with 2-4 units.	39	18	43

SOURCE: EIA Survey of Residential Energy Comsumption, February 1980,

Table 15.—Small Framehouse:[a] Sample List of Retrofit Options

Retrofit	Category	Total retrofit cost (dollars)	Total energy savings[b] (million Btu)	Capital cost per annual million Btu saved (dollars)
Low capital cost				
Roof insulation	Envelope	565	40	Low (13)
Wall insulation	Envelope	650	110	Low (6)
Weatherstripping	Envelope	110	9	Low (12)
Setback thermostats	Mechanical	135	25	Low (6)
Modulating aquastat	Mechanical	250	25	Low (10)
Hot water flow controls	Hot water	20	15	Low (1)
Insulate hot water storage. . .	Hot water	30	7	Low (4)
Moderate capital cost				
Storm windows	Envelope	990	40	Moderate (25)
Vent damper	Mechanical	225	10	Moderate (25)
Replace burner	Mechanical	880	20	Moderate (46)
Stack heat reclaimer	Mechanical	875	25	Moderate (36)
Replace room air-conditioners	Mechanical	890	55	Moderate (16)
Hot water vent damper.	Hot water	150	6	Moderate (25)
High capital cost				
Window insulation	Envelope	910	15	High (61)

NOTE: Savings should not be added. See app. B for estimates of cumulative savings.

a2,000 ft² building With frame walls and central *water* or steam system with window air-conditioners in the St Louis climate.
bElectricity savings are multiplied by a factor of 246 to reflect the difference between the cost Of fuel (oil) at $7 Per million Btu and the cost of electricity at $17 per million Btu for electricity priced at $0.06 Per kWh

SOURCE Office of Technology Assessment

retrofit list for the building with the air system has several retrofits suitable only to an air system (and does not include retrofits suitable to water systems). Because all retrofits to the house with decentralized (electric) heating and cooling save expensive electricity, they are each more cost effective than comparable retrofits to the other two types of small framehouses.

Because of specific assumptions used in compiling the list of retrofits for the three types, two important additional types of small framehouse are not directly covered in the above lists of retrofits. One type is the partially *insulated wood framehouse.* For most such houses it is probable that more roof insulation can be added and possible that more wall insulation can be added. In one recent estimate, adding insulation to a partially insulated roof was calculated to cost about three times as much for each annual million Btu saved as adding roof insulation to an uninsulated houses Under these conditions, adding roof insulation is a moderate capital cost retrofit rather than a low-cost retrofit compared to savings.

Another type of small framehouse not strictly covered in the lists of retrofits, is the house with *decentralized heating systems using oil or gas rather than electricity.* These are a large fraction of the housing units especially in the West and South (see fig. 11). The list of retrofit options would be similar to the list for houses with decentralized electricity but since saving oil or gas is worth less money than saving electricity, fewer retrofits for this type of building would be of low or moderate capital cost compared to savings.

‘Solar Energy Research Institute (SERI), *Report on Building a Sustainable* Future, vol. 2, published by the U.S. House of Representatives Committee on Energy and Commerce, April 1981, p. 96.

Small Solid Masonry Houses

Only about 1.5 million buildings in U.S. central cities are single-family attached houses and almost half of these are in the central cities of the Northeast.[4] Virtually all rowhouses are made of solid brick or stone walls to prevent the spread of fires. A large fraction of the buildings with two to four housing units are also masonry attached buildings; such buildings form the bulk of the building stock in the case study city, Jersey City, N.J. A much smaller fraction of the single-family detached houses are also of solid masonry walls. Brick or stone rowhouses are typical of the building stock in the Mid-Atlantic States, in such cities as Philadelphia or Reading, Pa. Both detached masonry houses and masonry rowhouses can be found i n the older cities of the Southeast and detached houses of solid cinderblock construction are common in the South and Southwest.

From an energy auditor's point of view the main characteristics of these buildings that affect the list of retrofit options available to them are their small size and the wall construction type that has *no cavity* into which wall insulation can be inserted. Furthermore, rowhouses often have flat roofs with crawl spaces that are somewhat harder to insulate than the peak roofs common in wood framehouses. The lists of retrofits are also influenced by the three types of *heating and cooling systems* that were distinguished above for small wood framehouses.

A sample list of retrofit options for a small masonry rowhouse is shown in table 16 for a building with central air heating and cooling. Several things are worth noting in this list. Envelope retrofits are still very powerful but less cost effective than similar retrofits for frame buildings. Roof insulation costs substantially more per annual million Btu saved, although it still fits within the low capital cost category. Wall insulation is a high capital cost retrofit for this type of building. Because of the relative expense of envelope retrofits, retrofits to the hot water and mechanical systems for this building look relatively more attractive.

Retrofit lists for two other types of masonry rowhouses—one with a water heating system and window air-conditioners and one with decentralized heating and cooling–are shown in appendix A, They are similar to the list in

[4] In the central cities of the Northeast there are 743,000 attached houses. Source: HUD *Annual Housing Survey*, 1978.

Table 16.—Small Masonry Rowhouse:[a] Sample List of Retrofit Options

Retrofit	Category	Total retrofit cost (dollars)	Total energy savings[b] (million Btu)	Capital cost per annual million Btu saved (dollars)
Low capital cost				
Weatherstripping	Envelope	60	7	Low (9)
Roof insulation	Envelope	690	50	Low (13)
Setback thermostats	Mechanical	135	15	Low (9)
2-speed fans	Mechanical	80	15	Low (5)
Hot water flow controls	Hot water	20	15	Low (1)
Insulate hot water storage, . .	Hot water	30	7	Low (4)
Moderate capital cost				
Storm windows	Envelope	450	20	Moderate (21)
Vent damper	Mechanical	225	6	Moderate (38)
Hot water vent damper.	Hot water	150	6	Moderate (25)
High **capital cost**				
Wall insulation	Envelope	4,700	40	High (1 14)
Window insulation	Envelope	420	8	High (53)
Insulate ducts	Mechanical	810	15	High (54)

NOTE: Savings should not be added. See app. B for estimates of cumulative savings.

[a] 2,000 ft² b,ldi ng with frame walls and central water or steam system with window alr-conditioners in the St. Louis climate.
[b] Electricity Savings are multiplied by a factor of 2,46 to reflect the difference between the cost of fuel (oil) at $7.00 per million Btu and the cost of electricity at $1700 per million Btu for electricity priced at $0.06/kWh.

SOURCE: Off Ice of Technology Assessment.

Photo credit: *OTA* staff

Masonry rowhouses can come plain (as in Lancaster, Pa.) (upper left), or fancy (as in Bridgeport, Corm.) (right), and are typical of the central city housing stock in the middle Atlantic States. One-story detached cinderblock of masonry houses (such as this one in Gainesville, Fla.) (lower left) are characteristic of cities in the South. Lists of retrofit options will be similar for small masonry houses with similar heating and cooling systems

table 16 in that wall insulation is very high capital cost and roof insulation costs more per million Btu saved than in frame buildings. The differences among the lists are similar to those explained above for the small framehouse. The list for the building with the water system and window air-conditioners has some retrofits suitable to that mechanical system type. For the building with decentralized (electric) heating and cooling, hot water retrofits are relatively more cost effective because they save electricity rather than oil or natural gas. A hot water heat pump is an especially effective retrofit for this kind of building.

These lists of retrofit options for masonry rowhouses are not precisely applicable to small detached *masonry houses* of cinderblock, stone, or brick. With four unattached walls instead of two, the energy demands for heating and cooling detached buildings will be greater. Wall insulation, however, will still be a very expensive retrofit.

Moderate= and Large-Size Multifamily Buildings

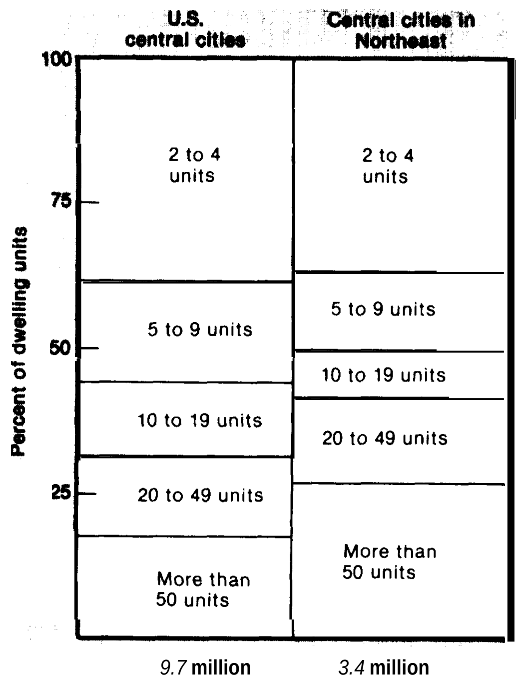
Multifamily buildings with more than 10 units provide slightly less than one-half of all central city housing in buildings with more than one family, and less than one fifth of all housing in U.S. central cities. There are no data on the size of multifamily buildings. Using data on the size of the average apartment, it is estimated that multifamily buildings of 10 to 19 units average 10,000 ft^2 and those of more than 50 units average 44,000 ft^2. There appear to be fewer very large multifamily buildings than commercial buildings. Buildings with more than 50 units provide 18 percent of all multifamily central city housing in the United States as a whole but a much greater fraction of the multifamily housing of the Northeast (27 percent) (see fig. 13).

For purposes of developing lists of retrofits, the important characteristics of multifamily buildings of this type are their size (arbitrarily defined as more than 10,000 ft^2) and *use.* Multifamily buildings compared to commercial buildings of the same size require more heating and cooling at night and use a lot more energy for hot water. Because of these characteristics, lists of retrofits for dormitories and hotels will resemble those for multifamily buildings. Lists of retrofit options for condominium buildings will be the same as lists of options for the same building types occupied by renters.

A third important characteristic is wall type. Included in this type are multifamily buildings with so/id masonry walls characteristic of the older densely settled parts of major cities such as Chicago and New York and c/ad walls (steel frame with concrete or brick veneer) characteristic of many new large high rises in the downtowns of U.S. cities (as well as the close-in suburbs).

The type of heating and cooling system is also important for developing the lists of retrofit options for multifamily buildings. There are no complete data on types of heating systems for larger multifamily buildings. More of them, however, use electricity for heat (31 percent) than do smaller buildings, as shown in figure 14. Data shown earlier (figs. 10 and 11) indicate that

Figure 13.—Small, Medium, and Large Multifamily Buildings in Central Cities: U.S. Total and Northeast



OTA's estimate of average square feet of buildings in group

2 to 4 units	2,500 ft^2
5 to 9 units	5,000 ft^2
10 to 19 units	10,500 ft^2
20 to 49 units	22,500 ft^2
More than 50 units	44,500 ft^2

SOURCE: Off Ice of Technology Assessment

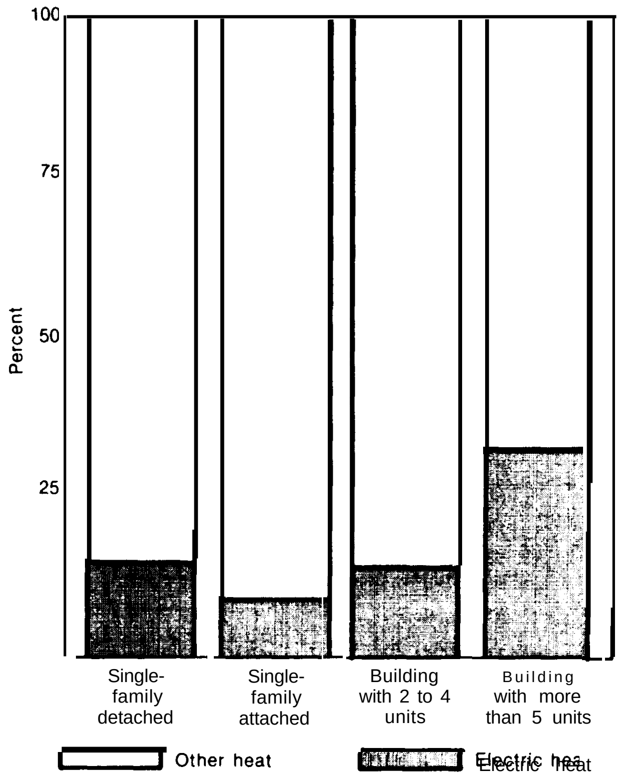
both rental units in central cities and housing in the central cities of the Northeast are much more likely to have a water or steam system. Since large multifamily buildings are a substantial fraction of both rental units and of Northeast rental housing it is estimated that at least 20 to 30 percent of large multifamily buildings have central water or steam heat.

A sample list of retrofit options for a large multifamily building with decentralized (electric) heating and cooling is shown in table 17. Such buildings are characteristic of the most recently constructed multifamily buildings in

Photo credit. OTA staff

Large multifamily buildings with masonry clad walls (such as this condominium in Tampa, Fla.) (top), or middle-sized solid masonry walkups (such as these in Hoboken, N. J.) (bottom) will have similar lists of retrofit options if they have similar heating and cooling systems

Figure 14.—Electricity Used for Heat in Single-Family and Multifamily Buildings



SOURCE: EIA Survey of Residential Energy Consumption, February 1980

U.S. cities partly because they facilitate individual metering of utilities so that electricity bills can be paid by apartment tenants rather than the building's owner (see the discussion of tenant-metered buildings in ch. 4). Because all retrofits save electricity, all savings for this building have been increased by a multiplier to reflect the higher cost of electricity. (The multiplier has been applied to electricity savings for other building types as well as is explained in the footnotes to tables 15, 16, 17, and 19.)

Owners of large buildings think of retrofit costs in cost per square foot and this list reflects that convention. Roof insulation for this building at **$\$0.30/\mathrm{ft}^2$** would actually cost about $30,000 for a building of this size (100,000 ft^2). Roof insulation is estimated to save about 7,000 $\mathrm{Btu/ft}^2$/year or about 700 million Btu per year.

Table 17.—Multifamily Building:[a] Sample List of Retrofit Options

Retrofit	Category	Total cost/ft² (dollars)	Energy savings/ft² (thousand Btu)[b]	Capital cost per annual million Btu saved (dollars)
Low capital cost				
Roof spray	Envelope	0.03	15	Low (3)
Setback thermostats	Mechanical	0.04	7	Low (6)
Flow controls	Hot water	0.02	31	Low (0.5)
Insulate hot water storage	Hot water	0.03	34	Low (1)
Hot water vent damper	Hot water	0.01	8	Low (0.5)
Hot water heat pump	Hot water	0.14	40	Low (3)
Hybrid lamps	Lighting	0.09	15	Low (6)
Moderate capital cost				
Roof insulation	Envelope	0.30	7	Moderate (41)
Weatherstripping	Envelope	0.05	1	Moderate (39)
Window insulation	Envelope	0.25	8	Moderate (31)
Install heat pumps	Mechanical	1.08	22	Moderate (50)
Replace room air-conditioners	Mechanical	0.40	15	Moderate (26)
High capital cost				
Wall insulation	Envelope	2.16	27	High (81)

NOTE: Savings should not be added.
[a]Large (100,000 ft²) multifamily building with masonry walls and decentralized system in the St. Louis climate.
[b]Electricity energy savings are multiplied by 246 to reflect the difference between the cost of fuel (011) at $7.00 per million Btu and the cost of electricity at $17.00 per million Btu for electricity at $0.06 /kWh.

SOURCE: Office of Technology Assessment.

At **$7** per million Btu that is worth about $4,900 per year.

Because hot water use is intensive in multifamily buildings and because hot water retrofits for this type of building save electricity, these are the most powerful and cost effective retrofits–all of low capital cost compared to savings.

Lists of retrofit options for the two other types of multifamily buildings—one with a water system and window air-conditioners and one with central air heating and cooling—may be found in appendix A. Hot water retrofits are also important on these lists but not as powerful because they do not save expensive electricity. Retrofits to the mechanical system (as appropriate to either air or water systems) are also very cost effective,

one category of multifamily house that the lists of retrofits does not explicitly cover are the *multifamily houses of in-between size (five to nine units).* There are about 1.7 million dwelling units in these types of buildings in U.S. central cities. Many are likely to be of wood frame construction; others are likely to be attached masonry buildings. OTA did not calculate lists of retrofits for these buildings and it is not known whether the lists of retrofit options would be dominated by retrofits to the building envelope (as with small wood frame and masonry houses) or would be dominated by retrofits to the hot water and mechanical systems (as for the large multifamily buildings). Careful analysis and/or systematic retrofitting of such buildings would be needed to make the determination.

Moderate and Large Commercial Buildings

Of the approximately 4 million commercial buildings in the country as a whole, less than 25 percent are 10,000 ft² or larger but these contain more than 60 percent of all the commercial building square footage (see fig. 15). Commercial buildings used for education or lodging tend to run bigger than the average (see fig. 16) while buildings used for retail or services, or food sales tend to run smaller. Office buildings follow the size distribution of all commercial buildings.

The number and relative size of commercial buildings located in central cities is not known (see ch. 2). It is possible to speculate that larger commercial buildings can be found inside cen-

Photo credit: OTA staff

Lists of retrofit options will be similar for diverse types of moderate- and large-sized commercial buildings with similar heating and cooling systems, including: large curtain-wall office buildings (such as these in Wilmington, Del.) (left and top right), middle-sized masonry retail buildings typical of older shopping areas in U.S. cities, or large commercial buildings converted from solid masonry factories and warehouses (such as this shopping center converted from a cigar factory in Tampa, Fla.) (bottom right)

tral cities, Most metropolitan areas have a distinct downtown area of large office buildings, hotels, retail buildings, and government buildi rigs. Large buildings are somewhat more common i n the Northeast which has only 17 percent of all commercial buildings but almost 30 percent of the buildings of more than 100,000 ft^2. OTA identified one survey of commercial buildings i n downtown Baltimore, that showed that commercial buildings come in all sizes and for many types of buildings the characteristic size is small (less than 5,000 ft^2) (see table 18).

From the energy auditor's point of view the characteristics of commercial buildings that affect the list of retrofit options available to them are:

1. moderate *or large size* which diminishes the importance of measures to improve the building envelope;
2. *commercial use* which means the building uses a lot of energy for lighting and *is* not normally occupied at night; and
3. wall *type.*

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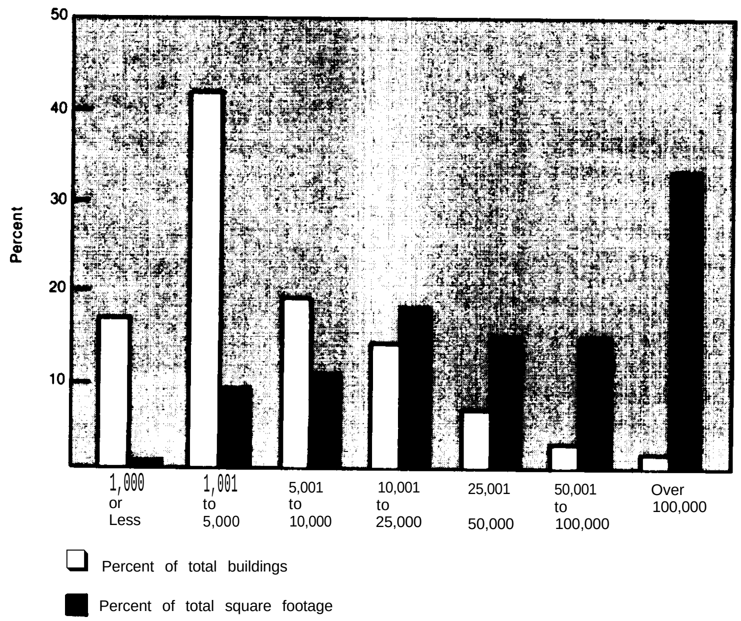
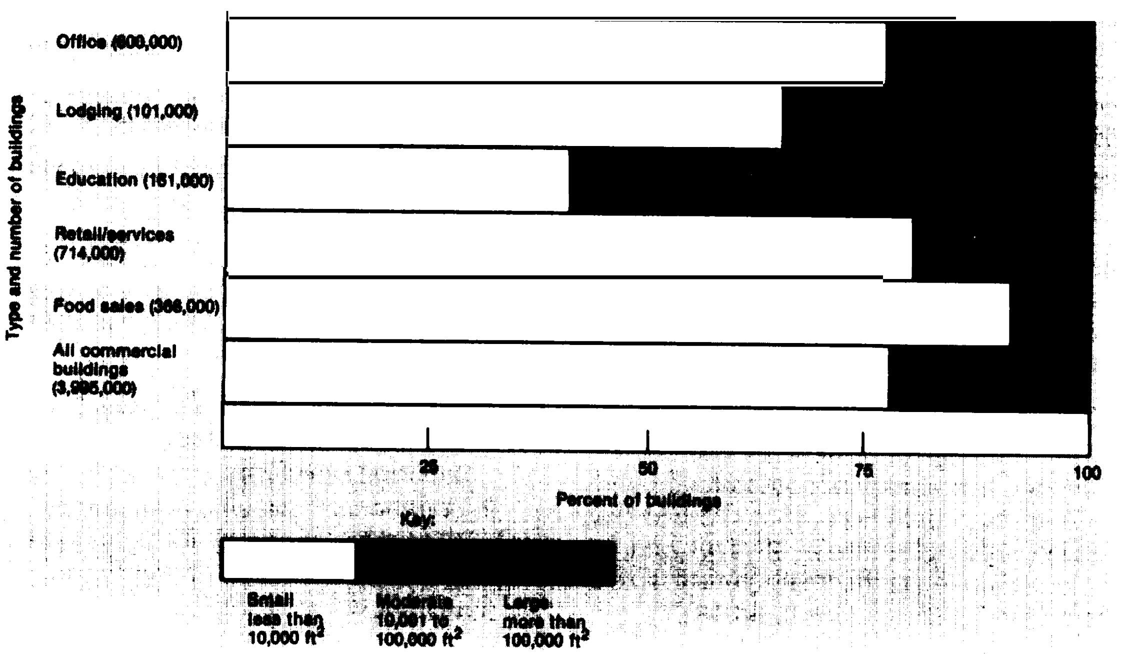
Figure 15.—Square Footage of Commercial Buildings



NOTE: Includes about 250,000 industrial buildings out of 4,2 million nonresidential buildings, All the rest are commercial buildings.

SOURCE: Energy Information Administration, Nonresidential Buildings Energy Consumption Survey, Fuel Characteristics and Conservation Practices, June 1981,

Figure 16.—The Relative Sizes of Various Types of Commercial Buildings



SOURCE: Energy Information Administration, Survey of Nonresidential Buildings: Building Characteristics, and the Office of Technology Assessment

Table 18.—The Characteristic Sizes of Commercial Buildings in Downtown Baltimore

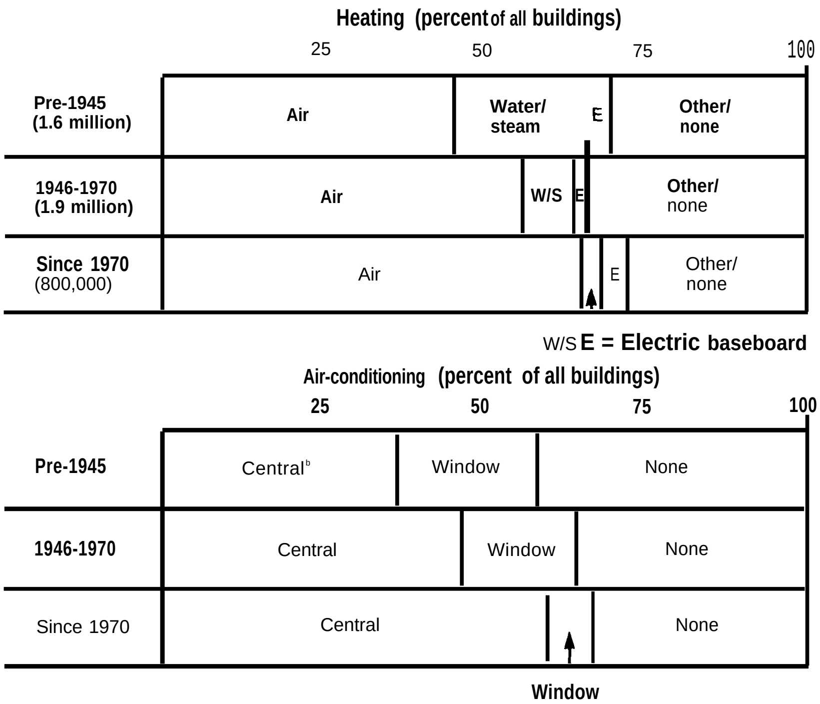
Categories	Total range (ft²)	Characteristic size: Range (ft²)	Characteristic size: Percent in range
Office buildings.	500-552,200	500-4,000	49
Motels/hotels	1,000-235,000	None	—
Theaters.	500- 13,500	None	—
Small (general) stores. . .	500- 26,000	500-4,000	85
Department stores	500-142,000	None	—
Drug stores	1,000- 19,500	1,000-3,500	72
Food stores	500- 10,000	500,1,500	90
Restaurants	500- 14,500	500-4,000	82
Banks	500- 31,500	500-3,500	61
Personal	500- 8,000	500-2,000	66

SOURCE. Hittman Associates, "Physical Characteristics, Energy Consumptions and Related Institutional Factors in the Commercial Sector " A report for the Federal Energy Administration, February 1977, p. 51

Although there are no good data available on the structure of commercial buildings, it is concluded from observation that there are very few wood frame commercial buildings of moderate or large size. Virtually all of the moderate- and large-size commercial buildings are of solid masonry wall *construction* (typical of low-rise attached commercial buildings in older parts of U.S. cities) or of clad wall construction (steel or concrete frame with a brick, concrete, steel, or glass veneer).

For commercial buildings, the lists of retrofits options are influenced most decisively by the type of *heating and cooling system in the building*. Retrofits options will differ substantially for commercial buildings with: *central air heating and* cooling *systems, complex* reheat systems, central water *or steam heat with window air-conditioners, or decentralized heating and cooling systems.* The distribution of heating and cooling systems among commercial buildings built in different eras is shown in figure 17. Central air systems are used in more than half the commercial buildings built since 1946. Central

Figure 17.— Heating and Air-Conditioning Systems for Commercial Buildings[a] by Year of Construction



[a]Includes about 250,000 mixed commercial/industrial buildings
[b]Includes custom-made central, package and combination/other

SOURCE Energy Information Administration, Survey of Nonresidential Buildings Energy Consumption: Building Characteristics; and the Off Ice of Technology Assessment water or steam systems are likely to be found only in buildings built before 1945 where they provide heat to 23 percent of the buildings. Decentralized electric systems are rare among commercial buildings as a group but can be found in 4 percent of the buildings built since 1970. The data do not explicitly show complex reheat systems. It is concluded from discussions with energy auditors that these systems are used in large commercial buildings built since 1960. Figure 17 also shows that the share of central air-conditioning has increased to over so percent in buildings built since 1970. Window air-conditioning provides cooling to 25 percent of the buildings built before 1945 but only 10 percent of the buildings built since 1970.

A sample list of retrofit options for a large commercial building with a complex reheat type of mechanical system is shown in table 19.

Compared to the other sample lists this list is a long one. There are a large number of low capital cost retrofits to the mechanical system. The most powerful of these is a conversion from the energy wasteful terminal reheat form of controlling the temperature of a multizone building to the variable air-volume method. (Both of these systems are explained in fig. 23, pp. 70-71.) If this building is still equipped with incandescent lights, conversion of fluorescent lights is the most powerful retrofit of all. It saves expensive electricity both for lighting and for cooling. If the building is already equipped with fluorescent lights, a shift to high-efficiency fluorescent lights is cost effective but not nearly as powerful as the shift from incandescent. For commercial buildings the most effective envelope retrofits are those which improve the energy efficiency of the windows. Hot water retrofits are of low capital cost but are insignificant i n impact.

Table 19.—Large Commercial Building:[a] Sample List of Retrofit Options

Retrofit	Category	Total retrofit cost (dollars/ft²)	Total energy savings[b] (thousand Btu/ft²)	Capital cost per annual million Btu saved (dollars)
Low capital cost				
Roof spray	Envelope	0.04	10	Low (4)
Replace burner	Mechanical	0.05	20	Low (2)
Vent damper	Mechanical	0.02	8	Low (3)
Stack heat reclaimer	Mechanical	0.05	28	Low (2)
Boiler turbolators	Mechanical	0.09	9	Low (10)
Setback thermostats	Mechanical	0.04	9	Low (10)
Convert reheat to variable air volume	Mechanical	0.14	45	Low (3)
Hot water flow controls	Hot water	0.01	1	Low (0.5)
Hot water vent damper	Hot water	0.01	2	Low (1)
Fluorescent hybrid lamps	Lighting	0.76	132	Low (6)
High-efficiency fluorescent	Lighting	0.13	10	Low (13)
Moderate capital cost				
Weatherstripping	Envelope	0.06	1	Moderate (44)
Double glazing	Envelope	0.65	13	Moderate (48)
Window insulation	Envelope	0.38	11	Moderate (36)
Shading devices	Envelope	0.25	15	Moderate (17)
Insulate ducts	Mechanical	0.50	15	Moderate (23)
Insulate hot water storage	Hot water	0.01	1	Moderate (17)
High capital cost				
Roof insulation	Envelope	0.30	4	High (73)
Water-cooled condenser	Mechanical	0.32	4	High (86)
Task lighting	Lighting	0.68	13	High (52)

NOTE: Savings should not be added. See app. B for estimates of cumulative savings.

[a] 100,000 ft² commercial building with clad walls and a complex reheat central heating and cooling system in the St. Lou Is climate zone.

[b] Electricity energy savings are multiplied by 246 to reflect the difference between the cost of fuel (oil) at $7.00 per million Btu and the cost of electricity at $17.00 per million Btu for electricity at $0.06/kWh.

SOURCE: Off Ice of Technology Assessment.

Three other sample retrofit lists for other types of commercial buildings—with air systems, with water systems and window air-conditioners, and with decentralized heating and cooling —are shown in appendix A. The retrofit lists for commercial buildings with air or water systems also have large numbers of retrofit options to the mechanical systems although the specific retrofits differ from system to system. For a commercial building with a decentralized system on the other hand, the only cost-effective retrofit to the mechanical system is the moderate cost retrofit of replacing all the window air-conditioners with more efficient models. Improvements to the energy efficiency of windows are more cost effective for commercial buildings with decentralized systems because the electricity saved is so expensive. The lists for all four commercial buildings include the very powerful option of shifting from incandescent to fluorescent lights (for the relatively few commercial buildings with incandescent lights) as well as less powerful and less cost-effective lighting measures.

OTA did not specifically develop a list of retrofits for the **40** percent of commercial building square footage in small commercial *buildings* (less than 10,000 ft^2). Based on discussions with energy auditors, OTA concludes that a list of retrofits for such buildings would also stress lighting retrofits and retrofits to the mechanical systems (differing by type of system) but would also include storm windows and roof insulation because such measures are feasible and effective in small buildings. Among smaller commercial buildings, a substantial (but unknown) percentage are wood frame construction, for which wall insulation should be of low or moderate capital cost compared to savings.

EFFECTIVENESS OF INDIVIDUAL RETROFITS FOR DIFFERENT BUILDING TYPES

From the analysis of the effectiveness of specific retrofits for different building types in four climate zones, there are several general observations about the extent to which some retrofit measures are effective in almost all buildings, some measures are only physically applicable to some building types and not to others, and some measures, while physically applicable to all building types are far more effective for some building types than to others. These observations are discussed in this section.

In the analysis that follows, the costs and measures *of cost effectiveness* are approximate and should be used as *rough guides only to distinguish* among *measures that are very cost effective and those that are not.* For any given building, detailed analysis of costs, estimated savings, and cost effectiveness of measures may differ substantially from these, based on local conditions, building conditions, and more detailed methods of estimating. Appendix C, at the end of the report, gives a brief description of each retrofit and the caution that must be exercised in estimating its savings potential and cost. The full lists of building types and retrofits analyzed and some of the critical assumptions about structural and mechanical system types are listed in appendix tables 3A through 30 at the end of the chapter. The sources for costs and savings estimates for each retrofit are listed in appendix D. Finally, a full set of assumptions is to be published separately in a working paper as a second volume to this report.

The observations about the relative effectiveness of retrofits for different building types based on the calculations and occasional other studies are summarized below in four sections:

- Retrofits to the building envelope.
- Retrofits to the mechanical systems.
- Retrofits to the domestic hot water system.
- Retrofits to the lighting systems.

Retrofits to the Building Envelope

Wall Insulation for All Masonry-Bearing and Clad-Wall Buildings Can Be More Than 10

Times as Expensive for the Same Energy Savings as Wall Insulation in Cavity Wall Buildings. Cavity wall structures can be retrofitted with blown-in insulation at relatively low cost, and with no materials other than the insulation itself and a small amount of material for patching and replacing interior or exterior wall covering, to cover up the holes through which the insulation is blown in (see fig. 18). Masonry-bearing and clad-wall buildings, by contrast, seldom if ever have any available cavity through which to add insulation. The contractor must either create cavities through the addition of a stud wall inside the existing wall, which can receive blown or batt insulation, or must add rigid insulation outside or inside the wall, and pay the cost of completely new exterior or interior wall covering, with corresponding window and door trim.

The calculations of the costs and savings of wall insulation for a wood framehouse and a masonry wall rowhouse are shown below (see fig. 19). The particular calculations are not strictly applicable to detached masonry houses since both costs of wall insulation and savings would be greater in a building with four exposed walls, but the relative cost effectiveness should be the same. Similar results in calculations of the cost effectiveness of wall insulation for moderate-sized buildings were obtained.

Roof Insulation is Several Times More Expensive for Buildings With Flat Roofs and No Attics or Crawl Spaces Than It is for Buildings With Pitched Roofs That Enclose Attics. Although insulation of approximately the same thermal qualities is added to all building types, the estimates of cost effectiveness vary significantly. The retrofit cost per annual million Btu saved is lowest for the insulation work done in attics beneath pitched roofs because of the ease of accessibility. For the cost estimates described here, it was assumed that the attics were unfinished, either with no floor or, at most, with rough floorboards; access to these is relatively straightforward. Costs increase slightly for single-family homes typical of rowhouses in cities, with flat roofs that still have an accessible crawl space between the roof decking and the ceiling of the room below. Costs are higher for the other roof types, typical of all multifamily and commercial structures, because there is almost never an available cavity. Therefore, the only practical way to add insulation is to reroof, adding rigid insulation beneath the new layer of roofing material.

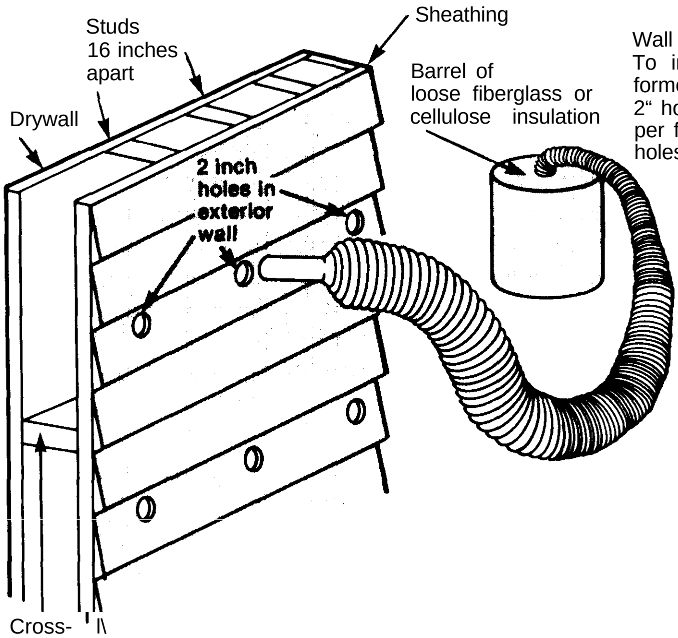
A sample of the calculations of the costs of roof insulation are shown below (fig. 20). The costs for insulating the concrete slab roofs include the cost of a new roof. It was assumed that the flat roofs already had a thin slab of roof deck insulation. It was also assumed that the peaked roof attic of the small house was insulated–an assumption that excludes the large share of partially insulated houses in the housing stock (see previous section). If the same insulation were added, for example, to an attic equipped already with 2 inches of somewhat compacted rock wool insulation, it is estimated that savings would be only about **60** percent of those in the uninsulated attic,

Storm Windows and Double Glazing (Replacing Existing Single Pane Glass With New Double-Glazed Units) are Applicable and Cost Effective for Different Window Types. Storm windows can be used with wood or metal frame double-hung windows and cannot be used with commercial or residential casement windows. Double-glazing, on the other hand, costs less than half as much for commercial casement windows ($6/ft^2 of window area) as it does for double-hung wood frame windows ($13.50/ft2 of window area). Storm windows are generally cost-effective retrofits for small single-family and multifamily buildings while double glazing is cost effective for commercial buildings and large clad-wall multifamily buildings.

Most Window Treatments are Cost Effective in Cold Climates and Prohibitively Expensive in Hot Climates. Storm windows, double glazing, and night insulation reduce the thermal transmission of windows and are most effective when there is a big differential between inside and outside temperature, especially in cold climates in the winter. Sunscreens and reflective films (see fig. 21) are designed to block the solar gain through windows. Some types are also designed to reduce thermal transmission in the winter.

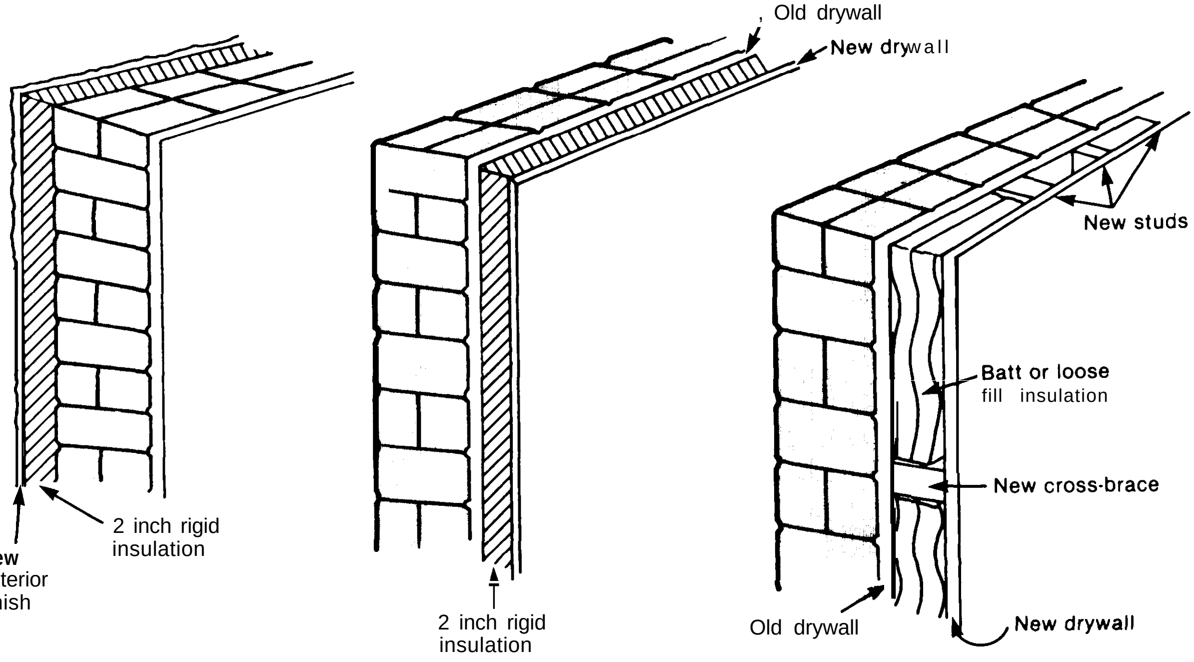
Figure 18.—Adding Wall Insulation to Existing Frame Walls and Existing Masonry Walls

The illustrations below compare the relatively inexpensive technique for adding wall insulation to a frame building (blown-in insulation) with three different, and relatively expensive, techniques for adding wall insulation to solid masonry walls. Similar techniques would also be required for adding insulation to clad walls.



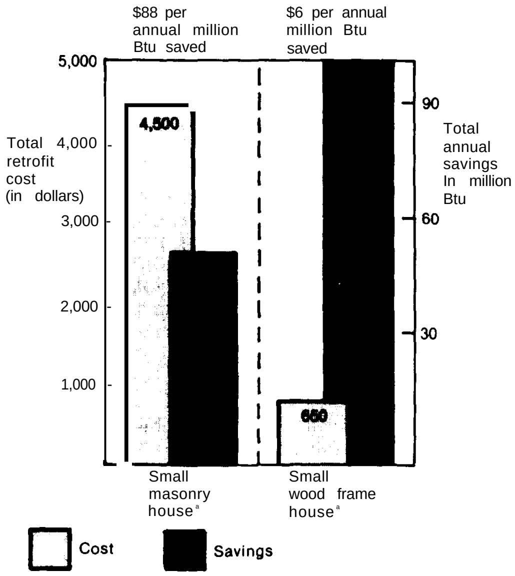
Wall insulation for frame walls (left)
To insulate existing frame walls with substantial cavities formed by studs, cross-braces, exterior and interior walls, 2" holes are drilled in each cavity (approximately 2 per stud per floor) and loose fiberglass or cellulose fill is blown. The holes are then plugged with wooden plugs.

Wall insulation for masonry walls (below)
There are three ways to add insulation to masonry walls, all of which are expensive. The first way (shown at left) is to add 2 inches of rigid insulation (usually a polystyrene compound with insulation value of R10 to R14) to the outside of the wall and cover it with some acceptable exterior wall finish such as a cement compound with a stucco-like appearance. The second way (middle illustration) is to add 2 inches of rigid insulation on the inside and cover it with drywall. The third way (shown at the right) is to construct an interior wall with 3-5 inch cavities into which batt or loose fill insulation can be placed.



SOURCE. Office of Technology Assessment

Figure 19.—Calculated Costs and Savings:[b] Wall Insulation



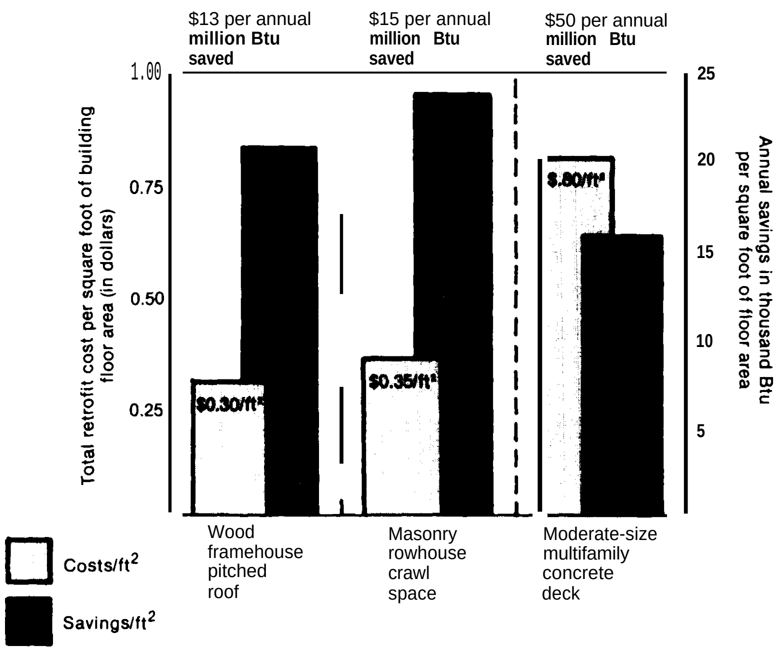
[a]Small houses with water systems In St Louis climate
[b]All electricity energy savings have been multiplied by 246 to reflect the difference between the cost of fuel (011) at $7 00 per million Btu and the cost of electricity at $1700 per million Btu ror electricity at $0 06/kWh

SOURCE: Office of Technology Assessment. Detailed sources for retrofits in app. G.

The calculations of the cost effectiveness of various window treatments for multifamily and commercial buildings in Buffalo and Tampa are shown in table 20. The particular models of shading device and reflective film analyzed were only applicable to commercial buildings and did block thermal transmission as well as reduce solar gain. The shading device analyzed is a fiberglass screen that acts as a storm window on the window (see fig. 21). It is installed on all windows in the summer and on all windows except those on the south in the winter, and is more cost effective in Buffalo than Tampa. Shading devices that only reduce solar gain were not analyzed, but are likely to be less cost effective in Buffalo than Tampa. Similarly the particular reflective films analyzed are more cost effective i n cold climates than hot because they are designed to block thermal transmission as well as solar gain.

For All Active and Passive Solar Retrofits to All Types of Buildings There are Retrofits to the Building Envelope With Comparable Savings at

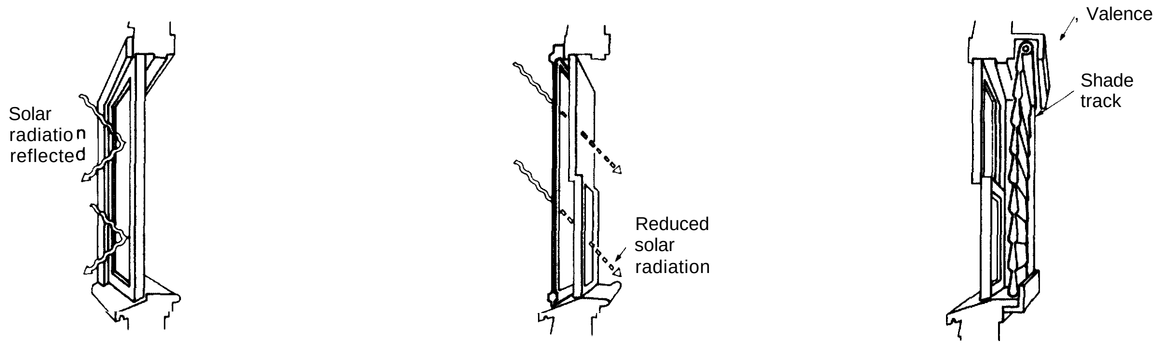
Figure 20.—Calculated Costs and Savings: Roof Insulation



NOTE: Buildings w!th water systems. St Louis climate

SOURCE: See app. G.

Figure 21.—Three Window Retrofits



Reflecting film
Semitransparent plastic film with a very thin reflective layer reflects solar radiation out to reduce cooling requirements and also reflects thermal radiation back into the room to reduce heating requirements.

Sunscreen
A solid sheet of tinted fiberglass is fitted outside, reducing conductive heat loss in winter and solar gain in summer.

Thermal shade
Quilted, polyester fiber-fill lined window shade with a track or magnetic fastening system to maintain a good air seal between the shade and the window.

SOURCE: Office of Technology Assessment.

Table 20.—Calculated Capital Cost of Window Retrofits in Buffalo and Tampa (approximate investment cost per annual million Btu saved is shown in parentheses)[c]

	Buffalo	Tampa
Retrofits for a moderate-sized multifamily building[a]		
Weatherstripping	**Moderate ($20)**	**High ($60)**
Storm windows	**Moderate ($20)**	**High ($75)**
Window insulation	**Moderate ($35)**	**Not cost effective ($300)**
Double glazing	**High ($70)**	**Not cost effective ($140)**
Retrofits for a moderate-sized commercial building[b]		
Shading device (see illustration)	**Moderate ($15)**	**Moderate ($20)**
Reflective film (designed to also block thermal transmission)	**Moderate ($25)**	**High ($40)**
Double glazing	**Moderate ($40)**	**High ($60)**

a 15,000 ft² masonry building with air system
b 15,000 ft² clad wall building with air Systems
c All electricity savings have been multiplied by 2.46 to reflect the greater expense of electricity

SOURCE Office of Technology Assessment.

the Same or Less Cost. Passive solar retrofits are retrofits designed to use the heat of the Sun (solar gain) through windows or glazed walls to provide heat to a building. By definition they are systems that have no moving parts and as such are simpler and usually less expensive than active solar systems (which must use pumps or fans to transfer heat from liquids or air heated by the Sun–see fig. 22).[5] OTA did some simple calculations to compare the cost effectiveness of several passive solar and active solar retrofit measures with the cost effectiveness of wall insulation, roof insulation, and various conservation retrofit measures for windows. The results (shown in table 21) are only suggestive, but they are consistent with several other studies.

For a wood frame single-family house, under OTA's assumptions, wall insulation is by far the most cost-effective retrofit and has much lower capital cost than any solar retrofits. Two passive solar retrofits, however, are of moderate capital cost and comparable to roof insulation or storm windows for such a house. One of these retrofits is very simple. It would add 100 ft² of glazing on the south side of the house and provide insulation for this area at night. In a variation of this retrofit, glazing would also be added but water wall storage would be used behind part of it to store the heat to provide heat at night.[6]

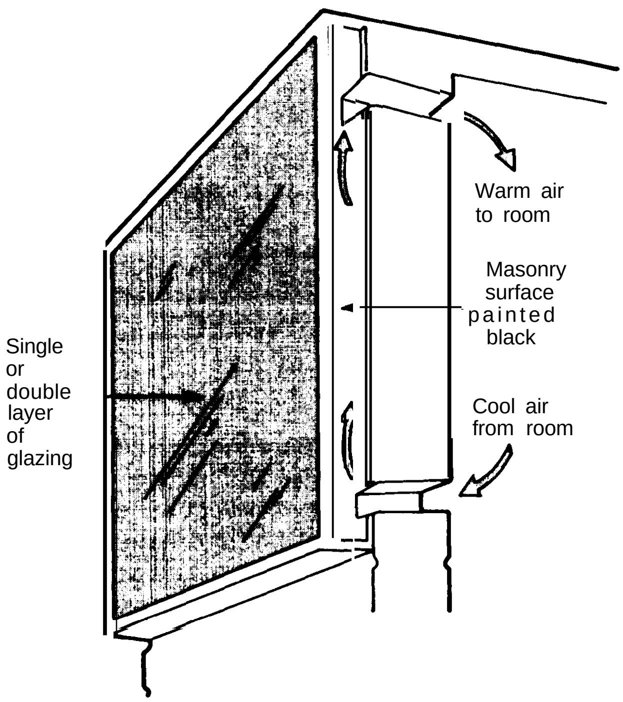
For a masonry wall rowhouse, adding glazing (with insulation) is far less expensive than wall insulation and comparable to roof insulation and storm windows. It is also substantially less expensive for the savings than another passive solar retrofit considered suitable to masonry buildings–the Trombe Wall (see fig. 22). For this retrofit, the wall is painted black and

[5] For further discussion of active and passive solar systems see two previous OTA studies: *Application of Solar Technology to Today's Energy Needs*, vol. 1, OTA-E-66, June 1978; *Residential Energy Conservation*, vol. I, OTA-E-92, July 1979.

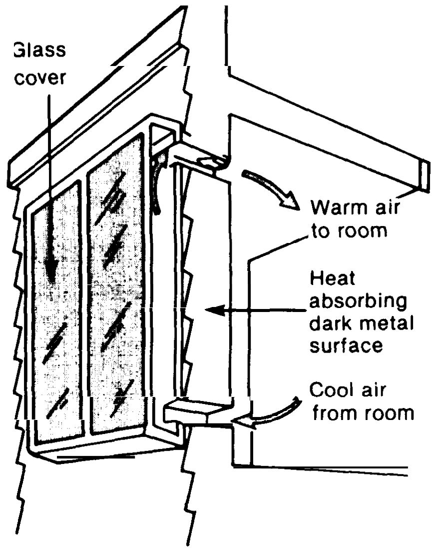
[6] OTA's calculations did not include the cost of savings for night insulation in addition to the storage. Night insulation would increase both the cost and savings with an indeterminate impact on cost effectiveness.

Figure 22.—One Active and Two Passive Solar Devices for Heating Buildings

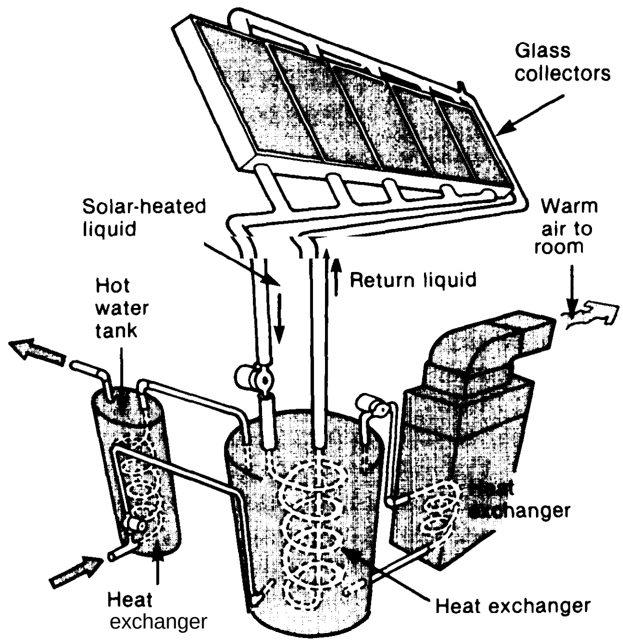
The illustrations below show two passive solar devices for providing space heat to buildings—a *thermosiphoning air panel* and a *Trombe wall.* Also shown is an *active solar collector* which provides *both* hot water and space heat.



Trombe wall (above)
For this retrofit. a south-facing masonry wall is painted a dark color and covered with glazing to minimize heat loss. Thermocirculation vents at the top and bottom provide a flow of air that draws hot air into the room at the top and draws cold air out of the room at the bottom. Dampers are closed at night to prevent backdraft losses.



Thermosiphoning air panel (above)
Where masonry walls do not exist, metal panels painted black and covered with glazing can be attached to the south wall. As for the Trombe wall, there are thermocircula-tion vents at the top and the bottom of the panel.



Active solar space and domestic hot water heater
Flat plate collectors are installed in the roof. The solar-heated liquid circulates through a heat exchanger in a central tank of hot water. This water in turn runs through a heat exchanger into the domestic hot water tank and through another heat exchanger into an air handling unit for space heat.

SOURCE' Office of Technology Assessment.

Table 21.— Calculated Capital Costs of Energy Efficiency Retrofits Compared to Active and Passive Solar Retrofits

	Estimated total annual energy savings[a]		Capital cost category (dollars per annual million Btu of savings)	
	Energy efficiency retrofit	Solar retrofit	Energy efficiency retrofit	Solar retrofit
	(million Btu)			
Small wood framehouse[b]				
Roof insulation	42		Moderate (15)	
Wall insulation	108		Low (6)	
Storm windows	31		Moderate (30)	
Add 100 ft^2 of glazing with night insulation		30		Moderate (20)
Add glazing with thermal storage		35		Moderate (40)
Add thermosiphoning wall panel		17		Not cost effective (120)
Moderate masonry rowhouse[b]				
Roof insulation	47		Moderate (15)	
Wall insulation	53		High (1 10)	
Add glazing with night insulation		30		Moderate (20)
Glaze masonry wall (Trombe wall)		43		High (65)
Large masonry multifamily building[b]				
Roof insulation	637		High (50)	
Night insulation on all windows	631		Moderate (40)	
Flat plate collectors for space heat and hot water		1,480		High (80)
Add glazing with thermal storage		480		High (70)
Add glazing with night insulation		520		Moderate (30)

NOTE: Savings should not be added. For detailed sources see app. D.

[a] All savings of electricity have been multiplied by 2.46 to reflect the greater expense of electricity.

[b] 2,000 ft^2, 15,000 ft^2, and 100,000 ft^2 buildings with water systems in the St. Louis climate zone.

SOURCE: Office of Technology Assessment

glazed. Ventilation openings cut in the wall allow heated air to rise in the space between metal panel and glazing and flow into the room. By OTA's calculations, this retrofit is of **high** capital cost for the savings.

For a large multifamily building, roof insulation is high capital cost (compared to savings) and wall insulation is not cost effective at all. The calculated high capital cost of an active flat *plate system for providing space heat and hot water (see* fig. 22) is at least comparable to these measures. The only envelope retrofits of moderate capital cost are adding night insulation on all windows (conservation retrofit) or adding glazing on the south side equipped with night insulation (passive solar retrofit). As was pointed out in the preceding section, however, retrofits to the building envelope in general are less cost effective for large multifamily buildings than are retrofits to the domestic hot water system and to the mechanical system.

The results are consistent with the results of several other studies of solar retrofits and solar features in cities. A careful architectural analysis of the optimum balance of insulation, passive and active solar features for rehabilitated and retrofitted buildings in the low-income Manchester neighborhood of Pittsburgh came to a preliminary conclusion that the best combination is likely to be either thorough insulation and blocking of infiltration alone or a combination of thorough insulation and large windows on the south side for increased solar gain. '

An analysis of low-cost solar options in the Boston area concluded that many passive solar retrofits (such as solar porches, sunspaces and greenhouses, wall collectors, thermsiphoning wall panels—see fig. 22—and night insulation applied to increased window size) are only competitive with the costs of conventional fuels if labor is contributed free or at reduced cost, if the retrofit cost is amortized over the life of the measure and if a tax credit or other subsidy is provided. These are very stringent criteria in light of the impact of financing difficulties and high interest rates described in chapter 4. of all the measures analyzed, only homemade insulating shades provide a payback that would categorize the measure as of moderate capital cost .[8]

For climates that are more favorable than those of Boston, the cost effectiveness of passive solar retrofits appears greater although very variable. In a survey by the Tennessee Valley Authority (TVA) of costs and savings of passive solar retrofits, the retrofit cost per annual million Btu saved ranges from $14 per annual million Btu saved to $140 for a Trombe Wall, from $28 to $190 for south windows, and from $27 to $360 for a solar greenhouse.[9]

Retrofits to the Mechanical System

For many building types, especially larger building types, retrofits to the mechanical system are likely to be the most effective of all retrofits, although specific retrofits and their relative cost effectiveness differ substantially among the four mechanical systems analyzed for this report. OTA developed lists of retrofits for each mechanical system type for each size and use of building. In a few cases the precise list of retrofits is more applicable to the specific system modeled than it is to other systems of the same general type. Appendix table D to this chapter describes the basic mechanical systems modeled for each type and identifies the most important differences i n the lists of retrofits for other systems of the same type. The general conclusions from the analysis are described below.

The Most Effective Retrofit to a Building With a Complex Reheat System is to Convert the Reheat System to a Variable Air Volume System. (See fig. **23** for diagrams of a terminal reheat system, variable air volume system, and three other mechanical systems suitable for large commercial buildings with several zones,) Complex systems with terminal reheat features are extremely wasteful; their name derives from the fact that they operate by centrally cooling all air to be used in the building to a single temperature, typically around 55° F. This chilled air is then distributed to the various zones of the building through ducts, and just before being introduced into the conditioned space, the air is reheated to the desired temperature, Used almost solely in commercial buildings, a terminal reheat system provides very precise temperature control. In addition, it neatly handles the conditioning problem that occurs in commercial buildings with large "core" areas, i.e., interior areas of the building, where, because of the amount of heat generated by people, lights, and office equipment, air-conditioning is required year round. On a cold day in January, in this type of building, a terminal reheat system can send cooled air without reheat to the core areas of the building, and send cooled air which is then reheated at the perimeter areas near the windows, where relatively heated air is needed. This type of system uses energy twice to achieve a single desired temperature; first using energy to cool, then to heat air. As a result, the total heating load of commercial buildings with complex systems is more than twice that of comparable buildings with air or water systems. Reheat mechanical systems can generally be converted to variable air volume systems, a type of air system, with little difficulty. Variable air volume

[7] *Energy Guidelines for* an *Inner-City* Neighborhood, Travis O. Price III & Partners and Volker Hartkoff, Naomi Yoran, and Lawrence Hoffman of Carnegie Mellon University. *Proceedings of the* Fifth *National Passive Solar* Conference. Published by the American Section of the International Solar Energy Society, Inc., a workbook based on this analysis is due to be published in 1981.

[8] *Boston* Solar *Retrofits: Studies of* Solar Access and Economics. Michael Shapiro (with Shauna Doyle), Kennedy School of Government, December 1980.

[9] *Building* a *Sustainable* Future, vol. 2, SE RI, published by the House Committee on Energy and Commerce, April 1981, p. 171.

systems supply air at constant temperatures for each set of hot air and cool air requirements and satisfies the needs for different zones by varying the volume of air supplied. Such systems require central air-handling controls which are usually already installed for reheat systems. Installing such controls is estimated to add about 30 percent to the cost. Some temperature control is sacrificed, but the savings are so great that they equal the cost of the retrofit very quickly. In the particular calculation done for a building of 100,000 ft^2, the retrofit would cost about $0.14 ft^2 ($1 4,000 total) and save about 45,000 Btu/ft^2 which would be worth about $0.32 ft^2 for heating oil at $1 /gal. The savings in this case would equal the cost of the retrofit in less than a year (see table 19).

Lists of Retrofits are Different for Air Systems and Water Systems But They Perform Similar Functions. Some retrofits to improve the efficiency of air (including reheat systems converted to variable air volume systems) and water mechanical systems are described in figures **24** and 25. The calculations of costs and savings for some of them are shown in table 22. Some retrofits improve the combustion efficiency of the central heat source: replacing the burner for both air and water systems (see fig. 25 for a description of the source of improved efficiency), replacing the *entire boiler* for a water-based system or replacing the furnace for an air system. [n the particular set of calculations shown in table 22, it was assumed that an old boiler of slightly over 50-percent combustion efficiency (the ratio of Btu of usable heat to Btu of fuel) was replaced by a new boiler of almost 75-percent combustion efficiency. The costs of a new boiler are estimated to be large but savings are great enough that it falls into the category of moderate capital cost compared to savings.

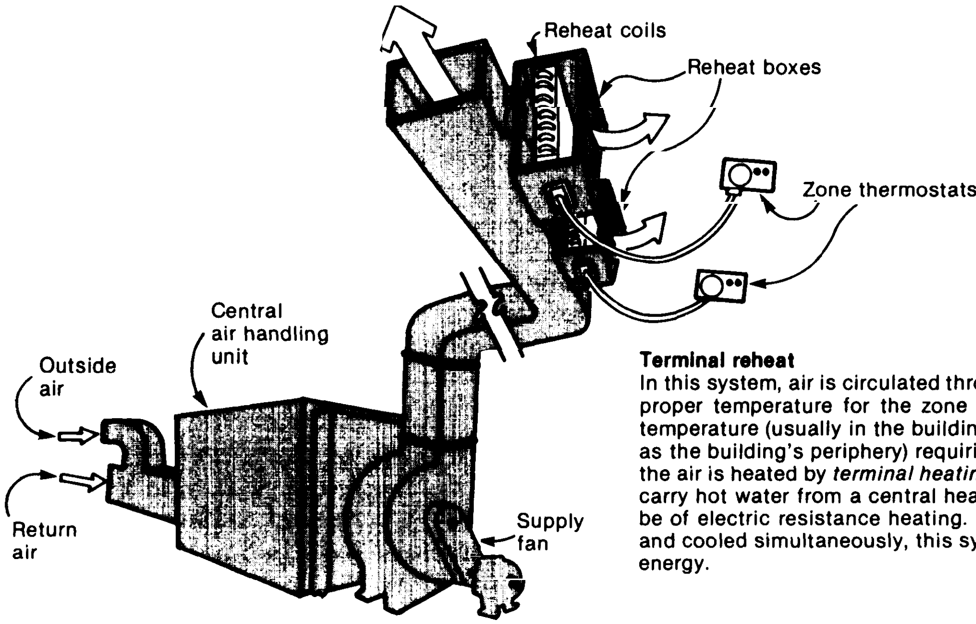
Vent dampers improve the efficiency of both water and air systems by preventing heat from escaping up the flue when the burner is not firing. An electrically activated damper automatically closes when the burner is cycled off. A stack heat *reclaimer* is a device for water systems that uses the heat that escapes up the stack from a boiler to preheat the water that passes through the boiler. A *boiler* turbolator reduces stack heat losses before heat goes up the stack by improving the exchange of heat between the hot combustion gases and the water to be heated.

Several devices improve efficiency by taking better advantage of variations in outside temperature with the change of seasons. For water systems, a *modulating aquastat* regulates the temperature of the water in the boiler according to the outdoor temperature. On very cold days, the boiler temperature is allowed to rise. On milder days, it is kept lower. For air systems with central air-conditioning a similar retrofit varies the temperature of chilled water according to the outside temperature, setting it coldest on the hottest days. Also for air systems a *two-speed fan motor* sets the fan to blow faster for the peak cooling load and slower for the heating load which usually requires a smaller air volume. An *economizer damper control,* also for air systems, makes possible the automatic use of outside air for cooling when outside air is cooler than that inside, Most of these retrofits are low or moderate capital cost compared to savings.

Many Retrofits to Mechanical Systems Benefit From Economies of Scale and Cost Significantly Less per Annual Million Btu Saved in Large Buildings Than in Small Ones. The cost of many retrofits to mechanical systems is only somewhat greater for large buildings than small, but the savings can be many times greater. This point can be illustrated with the calculations of the costs and savings for a modulating aquastat (the device that increases boiler water temperature when the outside air is colder, and vice versa). As shown in figure 26, the cost of the modulating aquastat for a 100,000 ft^2 multifamily building is about double the cost of one for a small 2,000 ft^2 rowhouse, but the savings are 40 times as great. Figure **27** illustrates the same phenomenon for four other retrofits to mechanical systems. Replacing a boiler, for example, at $50 per annual million Btu saved would be a high capital cost retrofit for a small rowhouse in Buffalo, but is a low capital cost retrofit (at $12 per annual million Btu saved) for a large multifamily building.

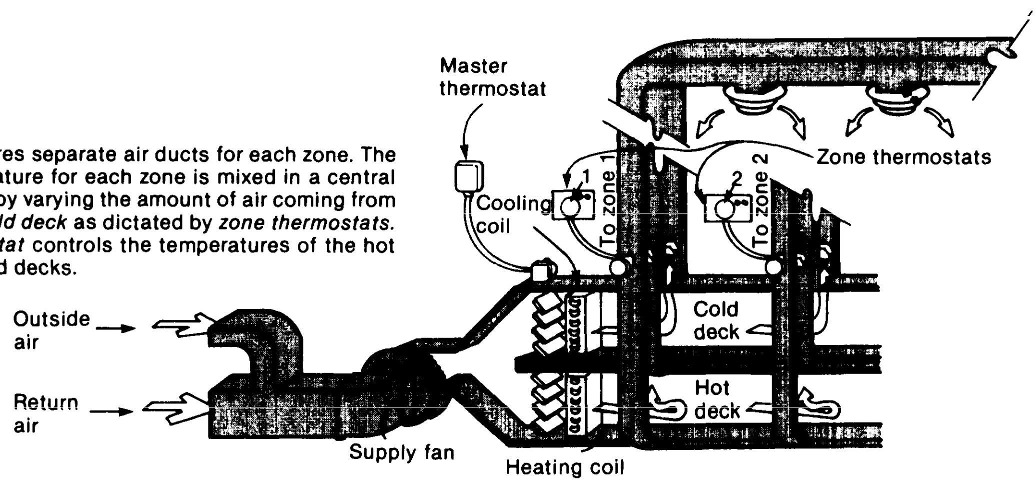
Figure 23.—Five Systems for Adjusting the Amount of Heat and Cooling to Different Zones in a Commercial Building

The illustrations below and next page show five different heating and cooling systems designed to handle the complex requirements of large commercial buildings. In such buildings, core areas and machine rooms with high heat loads require less heat and more cooling than peripheral areas of the building. An effective but energy-inefficient way to handle these mixed requirements is using any of a number of systems with reheat features: *terminal reheat* or *rnultizone* or *variable air volume* which may or may not include reheat. In reheat systems the air may be cooled below the temperature needed and then reheated for purposes of dehumidification as well as zone control. A *variable air volume* system with no reheat feature is far more energy efficient than any of the systems with reheat. *Induction* and *fan-coil* systems also eliminate simultaneous heating and cooling. In OTA's classification, terminal reheat and multizone are classified as *water systems. (See* app. table 3D for a more comprehensive list of systems in each type.) Retrofits which are appropriate to such systems are generally determined by their general type.



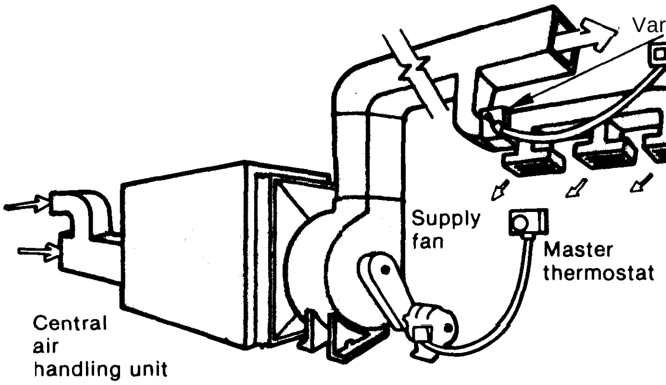
Terminal reheat
In this system, air is circulated through a single duct at the proper temperature for the zone requiring the lowest air temperature (usually in the building's core). In zones (such as the building's periphery) requiring higher temperatures, the air is heated by ***terminal heating coils***. These coils may carry hot water from a central heating source or they may be of electric resistance heating. Since air is both heated and cooled simultaneously, this system is very wasteful of energy.

Multizone
This system requires separate air ducts for each zone. The proper air temperature for each zone is mixed in a central mechanical room by varying the amount of air coming from a ***hot deck*** or a ***cold deck*** as dictated by ***zone thermostats***. A ***master thermostat*** controls the temperatures of the hot decks and the cold decks.



SOURCE: Office of Technology Assessment.

Figure 23.—Five Systems for Adjusting the Amount of Heat and Cooling to Different Zones in a Commercial Building (Continued)

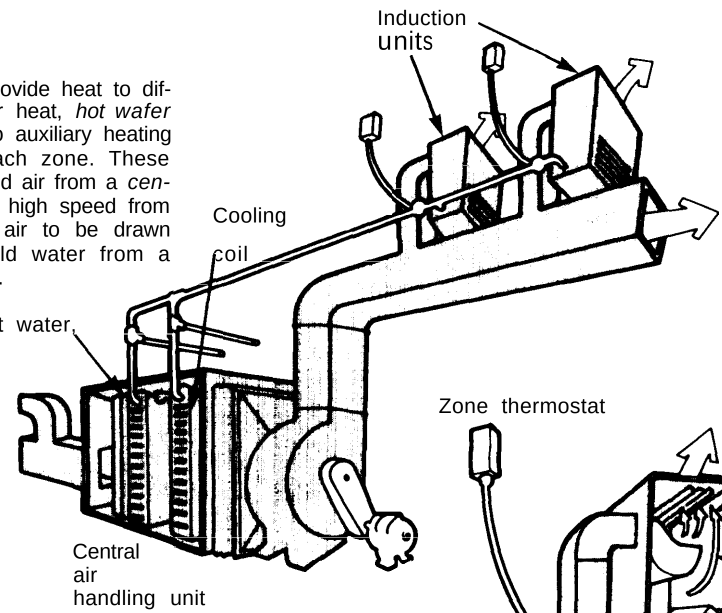


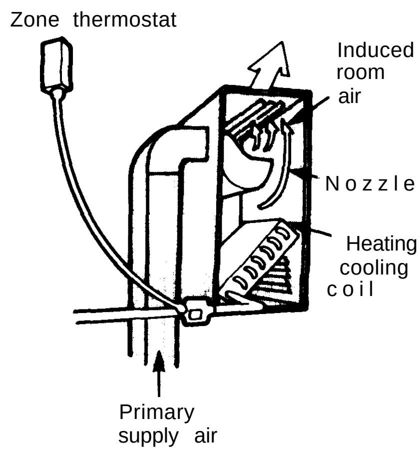
Variable air volume

In a variable air volume system, either heated air or cooled air is circulated through a single duct to each zone. The zone temperature is adjusted by adjusting the size of the orifice in the variable air volume box. Terminal reheat systems can usually be converted to variable air volume systems for low to moderate capital cost compared to savings.

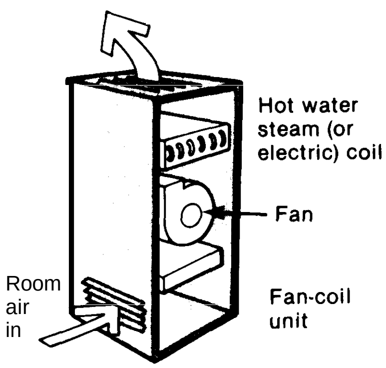
Induction system

This system uses both water and air to provide heat to different zones in a commercial building. For heat, *hot wafer* is circulated through pipes from a boiler to auxiliary heating cooling coils inside *induction units* in each zone. These units are also supplied with heated or cooled air from a *central air handling unit.* The air is ejected at high speed from *nozzles* within each unit, inducing room air to be drawn across the *heating coil.* For cooling, cold water from a chiller is circulated to the induction units.





Induction unit



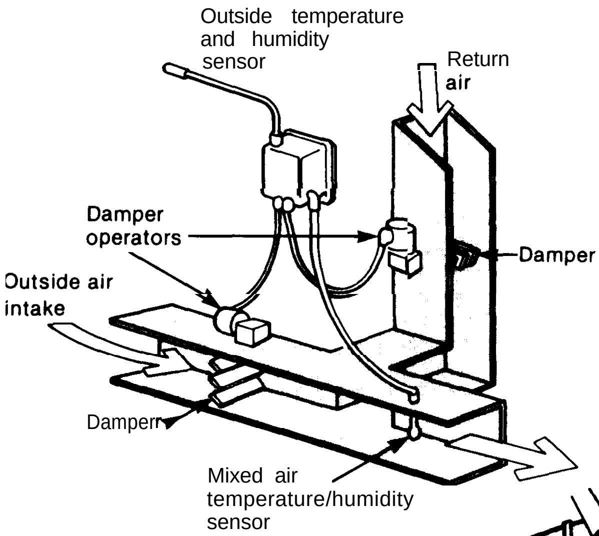
Fan-coil system

In a fan-coil system, the hot or cool water is circulated from a central source to the coils in a fan-coil unit in each zone. Within each unit, a fan propels air over the hot coil (for heat) and out into the room while cooler air from the room is drawn into the fan coil unit to be warmed. For cooling, air from the room is cooled by a similar process.

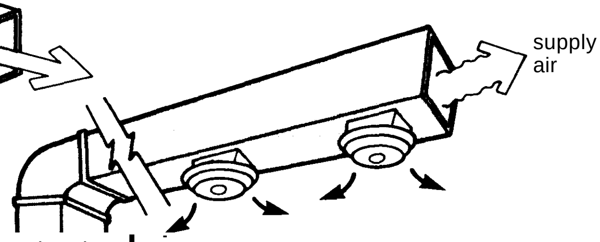
SOURCE: Office of Technology Assessment

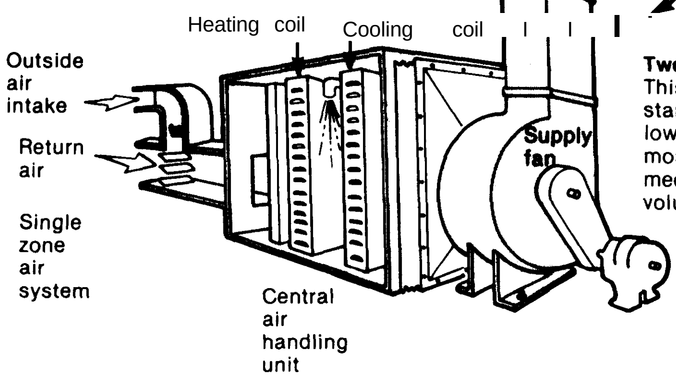
Figure 24.—Sample Retrofits to Central Air Heating and Cooling Systems

The illustration below shows a single-zone air heating and cooling system and several of the retrofits that might be applicable to such a system.

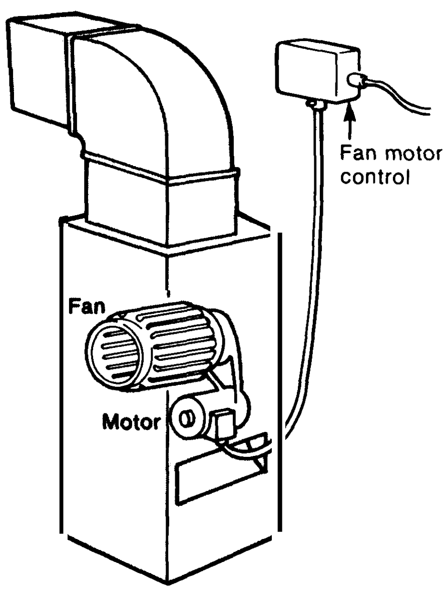


Enthalpy control (left)
This retrofit consists of a *sensor* that measures the temperature and the humidity of the outside air. When the outside air is sufficiently cool to help meet the cooling demand of a building (usually a commercial building) with high internal heat loads, an automatic *damper* reduces the opening in the *return air duct* and another *damper* opens the *outside air intake.* Another *sensor* in the ducts measures and regulated the temperature and humidity of the mixed air going into the building.





Two-speed fan motor (below)
This retrofit provides for a slower fan speed in addition to a standard speed. A slow fan speed is a better match to the lower demands for air volume during the heating season. In most buildings, fans and air handling systems are sized to meet demands during the cooling season when more volume of air is needed.



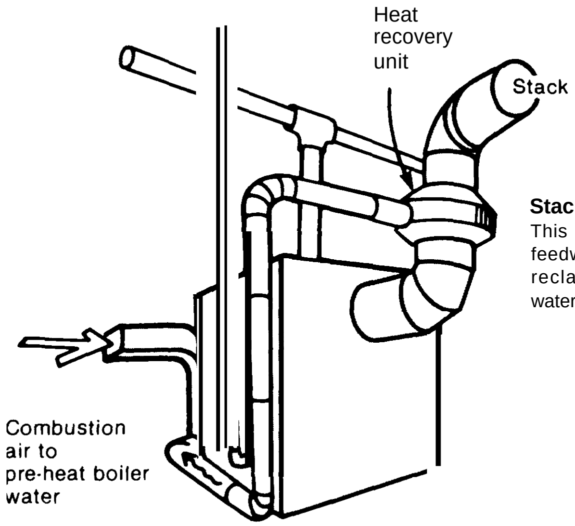
Reduce ventilation volume (not shown)
This retrofit installs leak-proof dampers in the *outside air intake* and damper controllers set to an intake volume of 5 cubic feet per minute per occupant. Recent changes in building and sanitation codes have allowed a reduction from the former design standards of 7.5 or 10 cubic feet per minute per occupant.

Replace burner (not shown)
This retrofit replaces an old inefficient burner on either a furnace that heats air or a boiler that heats water or steam for the heating coil in the air handling unit shown above. Improved burner efficiency is due to more efficient fuel dispersion and fuel-air mixing.

SOURCE: Off Ice of Technology Assessment.

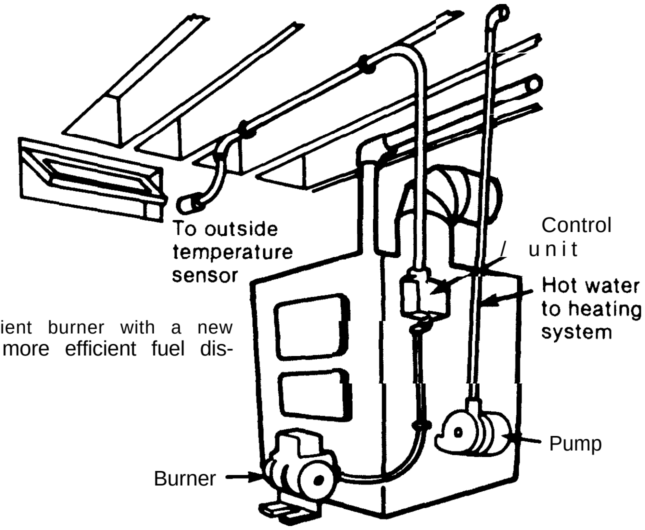
Figure 25.—Sample Retrofits to Water-Based Heating Systems

The illustrations below show five different retrofits appropriate to water systems. All three heating sources shown are boilers.

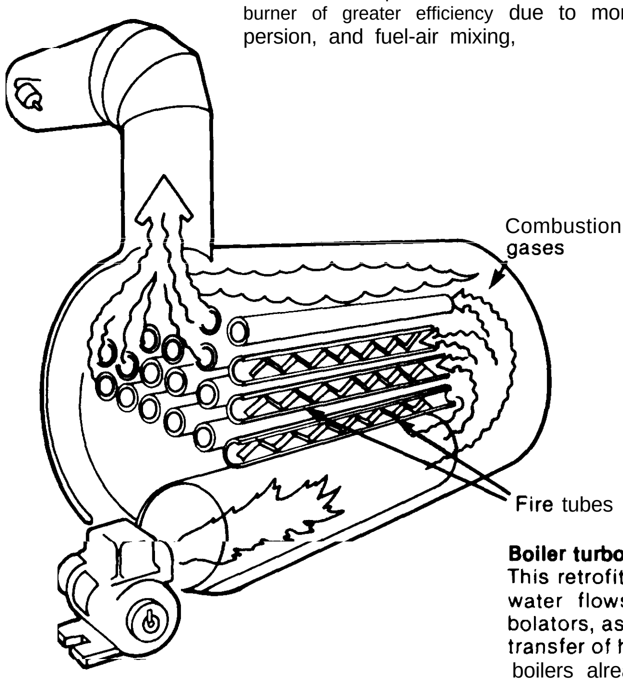


Vent damper (not shown)
An electronically-controlled vent damper closes the stack when the burner is not firing in order to reduce the loss of heat up the stack.

Stack heat reclaimer (left)
This device recaptures heat by circulating water (for boiler feedwater) or air (for combustion air) through the stack heat reclaimer, thus transferring heat from the flue gas to the water or air.



Replace burner
This retrofit replaces an old inefficient burner with a new burner of greater efficiency due to more efficient fuel dispersion, and fuel-air mixing,



Modulating aquastat (above)
This device consists of an outside temperature sensor and a control system that automatically resets boiler water temperature to match the outside temperature: hotter water for colder outside temperatures and vice versa.

Boiler turbolators
This retrofit only applies to fire tube boilers (in which the water flows around tubes filled with hot gases). Turbolators, as shown , slow the gases down and improve the transfer of heat between hot gas and water. Many fire-tube boilers already have turbolators.

SOURCE. Off Ice of Technology Assessment

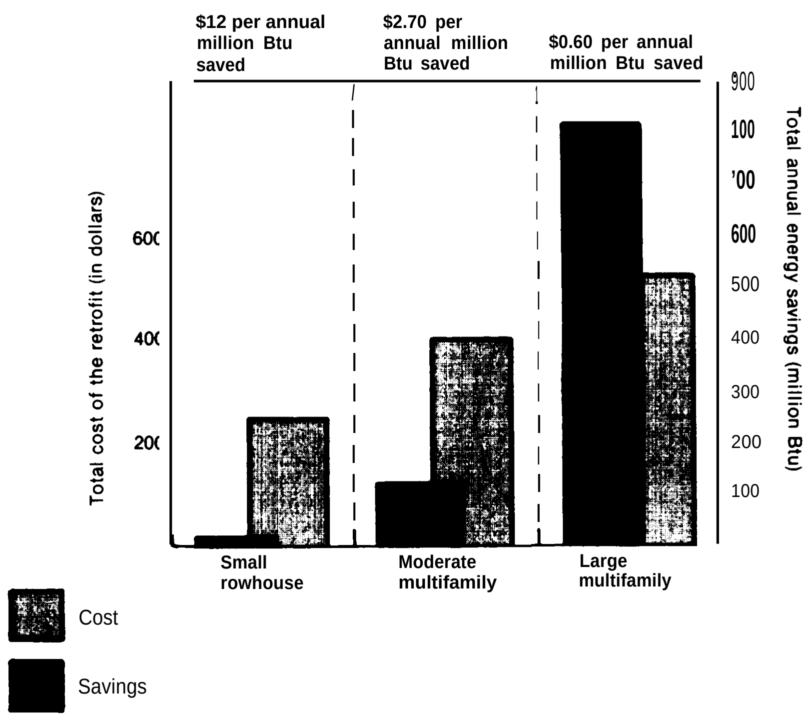
Table 22.—Calculated Capital Costs of Retrofits to Air and Water Mechanical Systems

Retrofit	Total cost per installation	Relative capital cost (number in parentheses is retrofit cost per annual million Btu saved)
Applicable to both air and water systems		
—Vent damper	$1,300	Low ($7)
—Replace burner	2,900	Moderate ($35)
Applicable to air systems only		
— Economizer damper control (to use temperate outside air)	2,000	Low ($2)
—2 speed fan motor	500	Low ($4)
—Vary temperature of chilled water	2,200	Moderate ($24)
—Replace furnace	(Not estimated)	
Applicable to water systems only		
—Stack heat reclaimer (to pre-heat boiler water)	1,200	Low ($12)
—Modulating aquastat	400	Low ($5)
—Replace boiler	4,500	Moderate ($35)
—Boiler turbolator	1,800	High ($90)

NOTES: Calculations were done for a hypothetical 15,000 ft^2 multifamily building in St. Louis. See app. C for a description of each measure and app. D for sources on costs and savings,

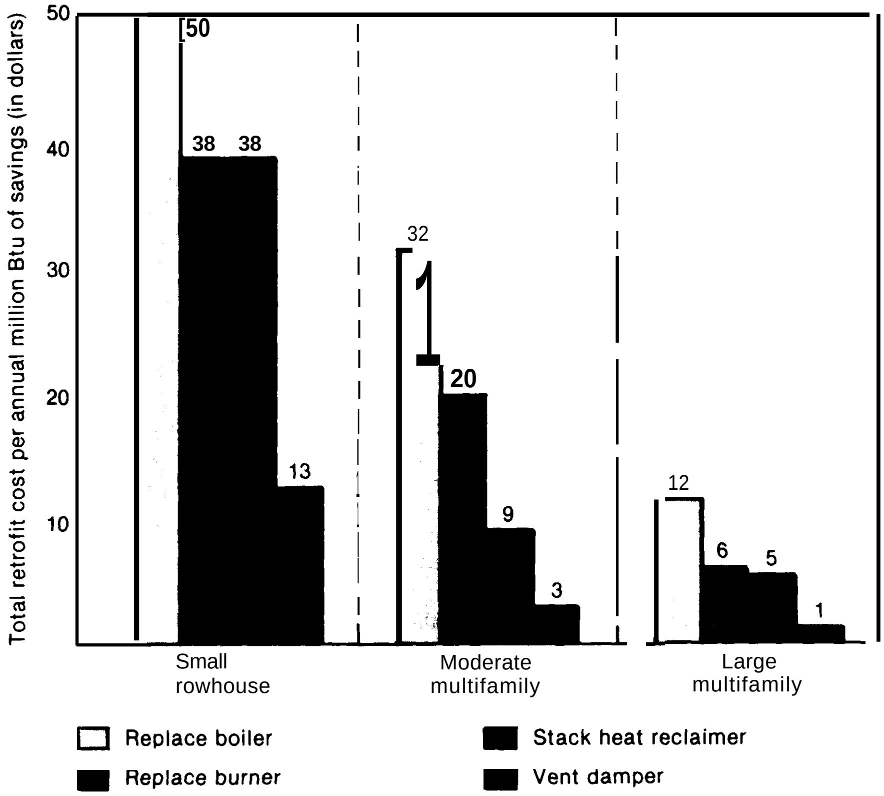
SOURCE: Office of Technology Assessment.

Figure 26.—Calculated Capital Costs of a Modulating Aquastat—Three Building Sizes



SOURCE: Office of Technology Assessment, See app. D for detailed sources on retrofits.

Figure 27.—Calculated Capital Costs of Four Mechanical System Retrofits-Three Building Sizes



NOTE: Buildings of 2,000 ft², 15,000 ft², and 100,000 ft² with water systems in Buffalo climate.
SOURCE Office of Technology Assessment See app D for detailed sources for individual retrofits

The Installation of Setback Thermostats is Very Cost Effective, If Used Properly, in All Building Types and All Climate Zones Except the Very Warmest. This retrofit measure, by now well-known and well-documented, is adaptable both to small family homes and large commercial buildings. At its simplest, it reduces the temperature of specific rooms or zones overnight or when unoccupied. Timers lower the temperature automatically and may be set to raise it again before the room or zone will be occupied in the morning. The savings estimated for this analysis assume that the daytime temperature is 65° and nighttime temperature is 55°, and that the daytime temperature was maintained around the clock before the setback thermostat was installed. There will be no savi rigs, except in labor costs, if maintenance crews already performed the setback function manually.

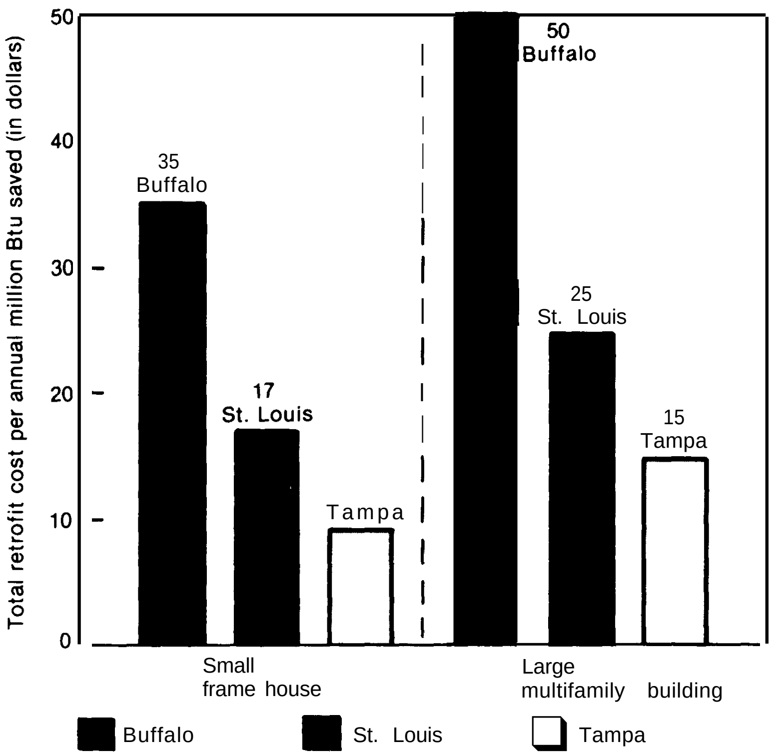
Setback thermostats can also reduce cooling loads, but it was assumed for this analysis that the cooling load is already kept to a minimum by maintaining the daytime temperature at 78° and turning off the cooling system in commercial buildings at night. OTA did not analyze the substantial benefits of more complex energy management systems that are being successfully installed in many commercial buildings. Such systems, using central or microcomputers, can manage lighting systems, ventilation, and the temperature of circulating water as well as space thermostat settings.

The estimates of the retrofit cost per annual million Btu saved range from low ($5) for setback thermostats installed in a large multifamily building in Buffalo, to moderate ($25) for the same building in Tampa.

For Buildings With Decentralized Systems, There are Few Cost Effective Retrofits to the Mechanical Systems. Decentralized systems heat and cool with individual air-conditioners, individual gas heaters, or occasionally with individual heat pumps. By definition, there are no ducts or pipes, nor is there complex interaction among ventilation, heating, and cooling. Efficiency improvements cannot be achieved by modifications to a single central plant. In most cases, efficiency can only be improved by replacing all less efficient individual units with more efficient individual units.

Under some circumstances, savings can be considerable by replacing *all air-conditioners in a building with more efficient air-conditioners.* The calculations of the costs and savings from such a retrofit are shown in figure 28. For both a small framehouse and a large multifamily building, it is assumed that room air-conditioners with a seasonal efficiency of 1.5 (coefficient of performance–the ratios of Btu of cooling to Btu of input electricity) were replaced with new air-conditioners with a seasonal efficiency of 2.3. Savings are greatest in hot climates and thus the retrofit has a much lower capital cost (per annual million Btu saved) in Tampa than it does in Buffalo. It is assumed that the cost of each unit air-conditioner is the same for large buildings as for small and that the cooling load per square foot is somewhat lower. So under these assumptions, replacing the air-conditioners has a higher capital cost in a larger building than in a small one. If a discount were available for a bulk purchase of new air-conditioners for a large building, however, this retrofit might be equally cost effective in large buildings,

Figure 28.—Calculated Capital Cost of Replacing Window Air-Conditioners in Tampa, St. Louis, and Buffalo



NOTES: The original ratios of cost to savings in end-use Btu are multiplied by 0.4 to reflect the difference between the cost of fuel (oil) at $7,00 per million Btu and the cost of electricity at $1700 per million Btu (equals $0.06 per kWh).

SOURCE: Off Ice of Technology Assessment.

OTA also estimated costs and savings for replacing both the electric resistance heaters and air-conditioners with heat pumps that perform both heating and cooling. Heat pumps currently on the market tend to be more efficient at heating than electric resistance heaters but less efficient at cooling than conventional window air-conditioners. The calculations reflect this assumption. Installing heat pumps is a retrofit of moderate capital cost, compared to savings, for a large multifamily building in Buffalo, St. Louis and Memphis, but actually uses more energy in Tampa where the cooling load is far more important than the heating load. Newer heat pump technology with higher efficiencies for both heating and air-conditioning should prove to be an effective retrofit in Tampa as well as in colder climates. Further improvements in air-conditioning technology could also increase the cost effectiveness of replacing existing air-conditioners with more efficient ones. '"

Retrofits to the Domestic Hot Water System

Many Retrofits to Improve Hot Water System Efficiency are Very Cost Effective in All Types of Residential Buildings in All Climates. The energy used for domestic hot water is a significant fraction of single-family and multifamily energy use and a much smaller fraction of the energy use of most commercial buildings. This can be illustrated with the calculations of the fraction of energy for domestic hot water used for several types of buildings in Buffalo and Tampa.

	Hot water as a percent of total bullding energy use
Small framehouse	7
Small rowhouse	11
Large multifamily buildlng	25
Large commercial bulldlng	6

Furthermore domestic hot water is a bigger fraction of the energy use of all buildings, residential and commercial, in warmer climates (since a smaller fraction of energy goes for heat).

Several retrofits to the hot water system are very cost effective in all climates and to all residential building types. The most cost effective are also cost effective for commercial buildings. A vent damper that shuts automatically when the heater is off reduces heat losses when the hot water heater is not heating. Flow control devices on faucets and shower heads use the available water pressure more efficiently to disperse the water better and create a higher apparent pressure for less actual water use. insulating the hot water storage tank with a 1 ½ inch thick insulation blanket reduces heat losses from the storage tank.

All three retrofits benefit from economies of scale and should cost less for the savings they achieve in a bigger building than in a small building. A hot water heater vent damper, for example, costs only 25 percent more in a moderate multifamily building than it does in a single-family house (according to OTA's calculations), but it saves more than 10 times as much energy. The calculations of retrofit costs per annual Btu saved are shown in figure 29.

There are two other much more expensive retrofits to the hot water system which each save about as much energy (under OTA's assumptions) as installing water flow controllers. The active *solar hot water heater* according to OTA's calculations would be a retrofit of high capital cost (compared to savings) for both a single-family detached house and a multifamily building in Buffalo, if it were used to save energy in the form of fuel (see fig. 29).

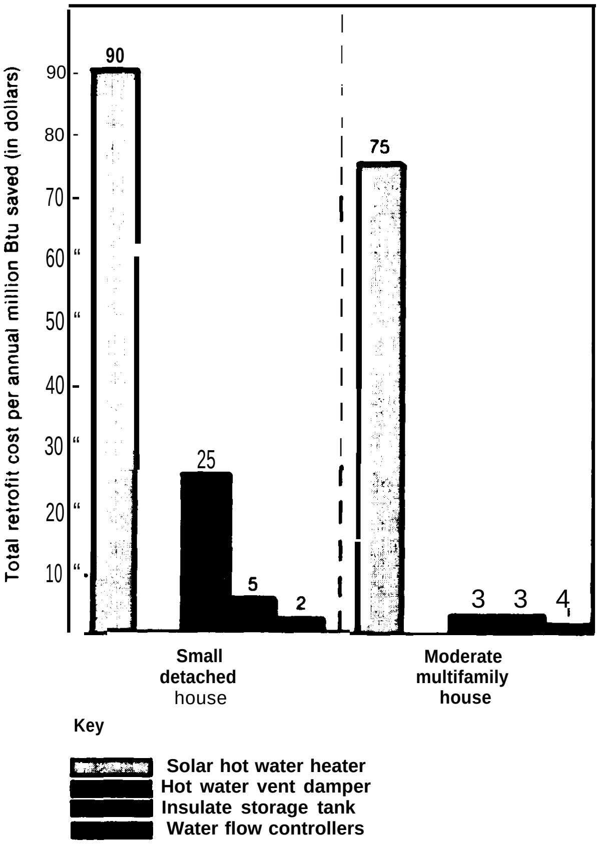
When used to save electricity, however, both the solar hot water heater and another retrofit, the air-to-water heat pump (see fig. 30) fall into the category of moderate capital cost retrofits. The air-to-water heat pump is now available in small and medium sizes. OTA assumed that a set of them (five medium and one small) could be used to heat hot water for a large multifamily building. Because medium-sized heat pumps cost somewhat less per unit of heat produced, there would probably be some economies of scale i n using heat pump hot water heaters for

[10] OTA's assumptions about relative seasonal efficiencies were as follows:

a. Heat pump cooling efficiency: 85 percent of conventional window air-conditioner—1.5 instead of 1.8 Instantaneous coefficient of performance (COP) and 1.3 Instead of 1.5 seasonal COP.

b. Heat pump heat/rig efficiency: Seasonal COP: Buffalo , 1.3; St. Louis 1.55; Memphis 1.8; Tampa 2.15.

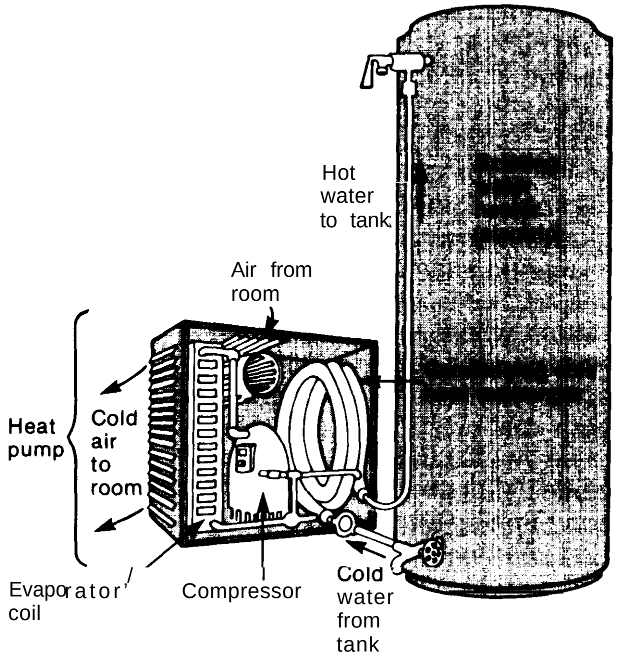
Figure 29.–Calculated Capital Costs of Solar Hot Water Heaters and Three Other Hot Water Retrofits



NOTE: 2,000 ft² and 15,000 ft² building with water systems in Buffalo

SOURCE: Office of Technology Assessment. See app. D for sources for individual retrofits,

Figure 30.—Diagram of a Heat Pump Hot Water Heater



SOURCE: Office of Technology Assessment.

larger buildings than for a small house. Further technical developments that produced large-sized heat pump hot water heaters should increase the potential for economies of scale. Solar hot water heaters are most cost effective in areas of greatest insolation. By OTA's calculations, a solar hot water heater would cost about 30 percent less per unit of heat produced in Tampa than in Buffalo.

Retrofits to the Lighting Systems

Lighting absorbs a large share of the energy used by commercial buildings in the form of electricity—the most expensive form of energy. For buildings built in 1975-76, and sampled in the Department of Energy survey in preparation for developing building energy performance standards, offices had an average of 2.8 W/ft^2 of installed lighting while multifamily buildings had only 1.6 W/ft^2. The sample also demonstrated the variation in lighting practice in office buildings. Thirteen percent had less than 2 W/ft^2 installed capacity while 17 percent had over 4 W/ft^2.[11]

Many Types of Lighting System Retrofits for Commercial Buildings are Expensive, But are Included in the Low or Moderate Capital Cost Category Because They Save Expensive Electricity. The most powerful of these would replace incandescent lights with far more energy-efficient fluorescent lights. Since much of the energy used for incandescent lights is used (and wasted) as heat rather than light, this category of retrofit has two important side effects—it greatly reduces cooling requirements in a commercial building and increases heating requirements. OTA found no information on the number of commercial buildings that still use incandescent lights; from observation, it appears that most

[11] Results from the BEPS phase I analysis of sample buildings were reported in SERI, op. cit., VOI. 2, p. 365.

use fluorescent lights already. For multifamily buildings and single-family houses, however, a shift to fluorescent lighting could still produce substantial savings. For completeness, OTA has included this category of retrofits in its list of retrofit options for commercial buildings, but it has not been included in the estimates of cumulative savings from retrofit packages.

Lighting retrofits will have an impact on the interior appearance of a building more than any other kind of retrofit except passive solar retrofits, sunscreens, or reflective film (all of which affect daylighting). The tone, intensity and form of the light can all be changed. For this reason, planning a lighting retrofit can require some assistance from an interior designer. Four lighting retrofits analyzed are described briefly below. Their costs and savings are compared in table 23. (Other types of lighting retrofits—such as sodium vapor lights (for gymnasiums) or installations to maximize daylighting—can be very effective in particular buildings but their general cost effectiveness cannot be analyzed.)

Change *incandescent fixtures to fluorescent fixtures.* Fluorescent lights use only about one-third as much energy as incandescent lights, but they normally come in different shapes and have a cooler light. This retrofit will generally change the shape of fixtures from round to rectangular and lighting tone from warm to cool. Cooling savings are added to lighting savings in table **23 and requirements for increased heating are subtracted from the total.**

Install *fluorescent* hybrid lamps (see fig. 31). In this variation on the same retrofit, any of several makes of fluorescent lights that fit into incandescent sockets are substituted for incandescent lights. Calculating the costs and benefits of this retrofit is tricky. OTA assumed an initial cost of installing the lamps at 15 times the cost of incandescent bulbs, and savings of about 55 percent for the same brightness. The lamps are estimated to last 7,500 hours, or about 10 times as long as conventional lamps (more than 3 years for 45 hours a week use). Using these assumptions over a 10-year period (assuming electricity at an average of $0. 10/kWh over the period) the 10-year savings (net of lamp replacement cost) from a 100-W lamp installation would be $121 per lamp.

Use *high-efficiency fluorescent lamps.* In this retrofit 40-w fluorescent lamps are replaced with lamps of 32 to 35 W. The capital cost is assumed to be the cost of changing all the lamps at once. The cost can be spread out over a period of time by replacing original fluorescent lights as they burn out.

Use low wattage task *lighting.* This retrofit reduces overall wattage per square foot by installing fixtures designed for each task area. This saves energy in two ways. It permits lower watt-

Table 23.—Calculated Capital Costs of Four Retrofits to Commercial Lighting Systems (large commercial building[a])

	Costs and savings from the retrofit/ft²		Capital cost category
Retrofits	costs (dollars/ft²)	Savings (thousand Btu/ft²)	Dollars per annual million Btu of energy[b]
Replace incandescent fixtures with fluorescent	$2.30	214	Low ($1 1)
Install fluorescent hybrid lamps	0.75	205	Low ($4)
Install task lighting	0.70	26	Moderate ($26)
Install high-efficiency fluorescent lights	$0.15	16	Low ($0)

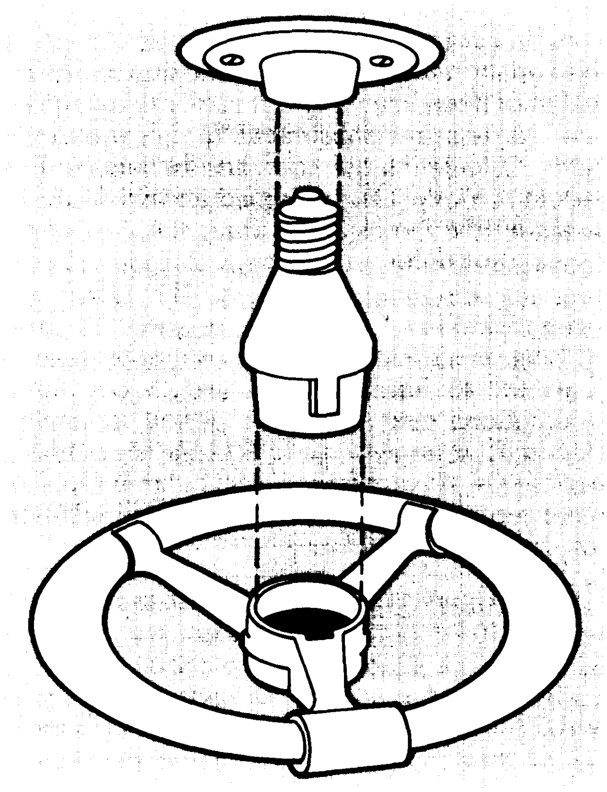
NOTE: Savings should not be added,

[a]Estimates are for a clad-wall commercial building with an air system in the St. Louis climate

[b]Retrofit cost per annual million Btu of energy saved is adjusted by a fuel factor 0,46 times end-use Btu to reflect the difference between fuel 011 at $7 per million Btu and electricity at $17 per million Btu for electricity at $006 per kWh

SOURCE Off Ice of Technology Assessment

Figure 31.– Hybrid Lamps Are Fluorescent Bulbs That Fit in Incandescent Sockets



SOURCE: Energy works and Office of Technology Assessment.

age for the same illumination in the task areas since the fixture usually brings the light closer to the work being done, and it permits lower levels of general illumination outside the task area. This retrofit probably requires the most careful design work in order to retain the maximum flexibility for future changes in the arrangement of task locations.

Conclusion—Variation in Retrofit Applicability by Building Type

This long section of the report has laid out OTA's assessment of the variation in the retrofit potential of different building types. The analysis has shown that a relatively small number of building characteristics systematically affect the likelihood that a particular retrofit will be generally effective. The next section of the report describes the site-specific nature of building retrofit, i e., those aspects of particular buildings which affect their individual potential for energy savings.

ENERGY SAVINGS FOR PARTICULAR BUILDINGS MAY BE BOTH SITE SPECIFIC AND UNPREDICTABLE

This section of the report describes two interrelated characteristics of building retrofits. The first is that, for many reasons, the site-specific aspects of a building's susceptibility to retrofit may outweigh the systematic aspects derived from its structure, size, use, and mechanical system type. The second characteristic of building retrofit is that energy savings are difficult to prediet now and because of the site-specific nature of much effective retrofit, there is a limit to the future predictability of building retrofits even with far better data on retrofit performance than exists now.

The Site-Specific Nature of Building Retrofit

Many aspects of a building will affect its energy use and prospects for retrofit–its regional location, orientation to the Sun and wind, condition of structure and equipment, intensity of occupancy, carefulness of management, and many other factors. Compared to the small number of factors that affect the energy performance of an automobile, many more factors must be taken into account in assessing the energy performance of a building.

one of the few surveys to date of energy use in different kinds of commercial buildings, in the Baltimore central business district, found that energy use varied strikingly for buildings used for similar purposes. As can be seen from table **24,** office energy use ranged from a low of 21,000 Btu/ft^2 to a high of 432,000 Btu/ft^2 (more than 20 times as much). The most energy-extravagant banks use five times as much energy as the least extravagant; the most energy-extravagant department stores use six times as much energy as the least. In this survey only some of the variation could be explained by general characteristics such as glass area, type of heating and cooling, or building height.

There are several effective retrofits that are highly dependent on individual characteristics of buildings and are so site specific that their applicability cannot be easily predicted by type of building. Some of these retrofits are described below.

Blocking Thermal Leaks and Thermal Bypasses. Techniques developed at Princeton and elsewhere have proved effective in locating such leaks as warm air leaking into unheated attics and cold air leaking into basements. Such leaks are found typically in single-family detached houses. Instruments that have proved helpful in locating such leaks include a blower to be installed in the door or window of a house to pressurize it to find the leaks and an infrared scanner to identify differences in temperature where air is leaking. For other building types, warm air may be wasted as it flows up in spaces along party walls of attached buildings or in spaces created by later additions to buildings. Such thermal bypasses can often be identified by careful three-dimensional analysis of buildings, taking note of dead space and passages from floor to floor. If significant leaks or bypasses are blocked, savings can be significant and cost low.

Table 24.— Energy Use per Square Foot in Buildings of Downtown Baltimore

	Thousand Btu/ft^2	
	Median	Range minimum to maximum
Offices	90	20-430
Department stores	70	55-360
Hotels/motels	145	100-235
Small stores	90	15-725
Banks	130	50-250
Restaurants	340	65-900

SOURCE: Hittman Associates, February 1977. "Physical Characteristics, Energy Consumption, and Related Institutional Factors in the Commercial Sector" (fig 16), p. 73.

Energy Management System Controls. Computerized controls can go well beyond thermostat setbacks and can be used to 'manage ventilation dampers, heating system pressure valves, and temperature settings. These controls take advantage of existing equipment. Savings will depend on the specific nature of existing equipment and may also include labor savings as well as energy savings. Such computerized systems are often designed to include security and fire-safety features.

Cogeneration. For certain very large commercial and multifamily buildings in cities with high electricity rates, it may make sense to produce both heat and electricity using any of several types of building-size cogenerators. Several large buildings in New York City, where electricity rates are the highest in the country, have taken this step. The economic and technical feasibility of cogeneration for a variety of uses is to be analyzed in detail in a forthcoming OTA report *Industrial and* Commercial Cogeneration, to be published by the summer of 1982.

Daylighting. There are several devices available to increase the use of daylight as a substitute for electric lighting. "Lighting shelves" installed in or near windows can reflect light up to reflective panels on the ceiling and reflect daylight deep into a building. Outside reflecting panels can also be used to increase daylighting. The savings from such retrofits may be considerable but are highly dependent on the availability of light outside the building, the configuration of windows, the configuration of walls inside the building and the nature of computerized or other controls that control switching between daylighting and electric lighting.

Adjustable Radiator Vents. Steam systems in older buildings frequently have problems with overheating on floors away from the space thermostat that controls the flow of steam to the radiator. Adjustable air vents can be installed to control this problem. The amount of savings may be considerable if the overheating is considerable and if the adjustable vents are actually used to control radiator heat (rather than the more typical method in such buildings of **opening the windows). A somewhat** more expensive retrofit adds thermostats to the adjustable valves and controls the radiator temperature automatically.

Whole House Fans. A powerful fan installed in the attic or upper floor of a small building is designed to ventilate the whole house by drawing cooler air in from the outside. Such a fan permits air-conditioning systems to be turned off when outside air is cool enough. The effectiveness of this retrofit is dependent on the location of the building in terms of the likelihood of cooler outside temperatures and is also dependent on the tolerance of the occupants for the higher humidity of unconditioned air.

Reducing **Orific (Nozzle) Sizes. Boilers and furnaces often have firing rates well in excess of the peak heating load requirement, and therefore operate inefficiently all of the time, with increased flue and standby losses. This can be a particular problem** where building envelope conservation measures have greatly reduced the heating requirements. The firing rate can be reduced by adjusting the fuel/air mixture and reducing the fuel orifice or nozzle size to reduce the overall fuel volume. This problem was very evident in a recent survey of the retrofit options for multifamily buildings in Minneapolis. Out of six buildings, four had oversized furnaces. For these buildings downsizing was a top priority retrofit.[12]

Refrigeration Heat Reclaim To Heat Hot Water. Special heat exchangers can be installed on the condenser side of an air-conditioning system to extract condenser heat for heating hot water. This measure can also be used to extract heat from freezers and refrigerators and is thus useful in supermarkets and restaurants. There are two sources of savings. Energy is saved that would otherwise be used to heat the water and the cooling system works more efficiently because the temperature of the condensor is lowered. The potential for such a retrofit in a particular building depends on the relative locations of cooling equipment and water-heating equipment and the cost of transporting heat from one to another.

In addition to these particular retrofit measures that are site specific, there are two general categories of steps that are often very important in determining energy savings.

Operations and Maintenance Steps. For some buildings there is a lot of wasted energy that could be eliminated, before any retrofit investments are made, simply by careful maintenance of equipment. There are several convenient lists and explanations of such steps.[13] Some examples of them are: clean air-conditioning condenser coils, clean and repair steam traps, remove excess lamps (delamp), repair steam and water leaks, and repair ventilation dampers. Energy savings will be greatest from such measures when the building and its equipment have been least well managed. Prospects for savings, however, depend on the prospects for better management of the equipment in the future. in some cases this may require a change in staffing or supervision of maintenance crews.

Auxiliary Repairs. Many smaller buildings that lack energy efficiency features such as storm windows and roof and wall insulation, also have more basic problems such as structural weaknesses in roof or floor or poorly fitting basic windows. Although the data on specific problems that affect energy use is poor, the extent of the problem can be judged by the fact

[12] "Final Report on Energy Conservation Modifications: Buildings 2-8, 2-9, 2-10, 2-181, 2-18B and 2-22" Chasney Associates, presented to the Minneapolis Housing and Redevelopment Authority, May 15, 1979.

[13] Recommended operations and maintenance steps can be found in: *Total* Energy Management: A *Practical* Handbook on Energy Conservation and Management, National Electrical Contractors Association (NECA) and National Electric Manufacturers' Association (NEMA) 1976, 2d cd., 1979. An evaluation of operations and maintenance steps recommended in hospital audits can be found in: Eric Hirst, et al., *Analysis of Energy* Audits in 48 *Hospitals,* Oak Ridge National Laboratory, July 1981. (Both reports also assess capital investments in energy efficiency.)

that more than half of all detached houses lacking roof insulation, storm windows, and storm doors, also are substandard, while substandard housing is only 3 percent of all housing.[14] This problem is discussed in more detail in chapter 7 because it greatly affects the implementation of the weatherization program. For buildings with basic deficiencies these must often be corrected before or during a basic energy retrofit. Primary windows must be repaired or replaced before storm windows will perform the function of creating an air barrier to block heat transfer. The roof may be repaired as it is being insulated.

Interactive Effects Among Retrofits Are Site Specific

Savings from individual retrofits can be estimated by careful testing of retrofits one-at-a-time, When combined into packages, however, the savings from the package will be different from the sum of the savings from the individual retrofits. If retrofits are installed as a series the savings contributed by each will depend on how many retrofits have been already installed. For these reasons, cumulative savings for an individual building must be estimated for that particular building taking into account the package of retrofits or series of packages of retrofits that the owner wishes to install. An auditor cannot possibly compute in advance cumulative savings from all the possible combinations of retrofits so that the owner may choose among them, but must get some input from the owner on his preferences first.

Some of the most important interactive effects are described below. In a few cases interactive effects may actually increase energy savings from a package of retrofits over what savings are available from individual retrofits. More often, the impact of interactive effects is to reduce savings below the simple sum of the individual retrofits in the package.

Measures That Act on the Same Feature of the Building Envelope Will Combine To Save Less Than the Sum of Each Alone. For example, window insulation will save less if storm windows are already reducing heat loss through a building's windows. Wall insulation, attic insulation, and storm windows, on the other hand, all improve resistance to heat loss (and cooling loss) of different features of a building envelope and savings of these should be additive.

Measures To Improve Mechanical System Efficiency May Have a Mutually Reducing Effect. Replacing the burner, for example, with a more efficient burner will increase combustion efficiency and reduce the amount of heat going up the stack. If a stack heat reclaimer is installed after the increase i n burner efficiency it will save less because there will be less stack heat to reclaim. A vent damper on the other hand should not be so affected by an increase in burner efficiency because it prevents heat loss up the line when the burner is not firing.

Improving the Building Envelope Efficiency May Decrease the Seasonal Efficiency of the Heating System. If better insulation reduces the heating load of the building, the boiler or furnace will operate less time each day in order to heat the building. This reduces the overall efficiency of the heating system because of heat loss while the system is off and because more fuel must be used to fire up a cold boiler or furnace than a hot one. A combined retrofit package that can achieve more savings than the sum of individual retrofits would downsize a heating system to match the new more efficient load. If the heating system was oversized before (as is frequently the case) this package will both reduce the load and increase the efficiency of the equipment,

Domestic Hot Water Measures May Reduce Each Others' Effects. Flow controls and storage insulation reduce the hot water load which in turn reduces the effect of an efficiency improving measure like a vent damper.

Improved Lighting Efficiency May Increase the Heating Load and Reduce the Cooling Load of a Building, Inefficient lighting due to either excessive illumination for the tasks involved or excessive wattage for the illumination required (such as happens when incandescent lights are used instead of fluorescent lights) will give off more heat than efficient lighting.

[14]Andreassi, et al., The *Impact of Residential Energy Consumption on Households*, the Urban Institute, Washington, D. C., June 1980. A more complete discussion of this data can be found in ch. 5.

A careful energy audit will take all these factors into account when recommending an optimum package of retrofits. An audit that does not, may recommend acceptable retrofits but not a package that will produce the most savings for the money as a group.

Unpredictability of Savings From Building Retrofits

There is ample evidence that energy savings from retrofits to buildings on average are likely to be significant and cost effective, However, savings are unpredictable for particular buildings. This characteristic of building retrofit concerned many building owners interviewed for the analysis of building owner motivation in chapter 4. While this situation should improve with the maturity of retrofit technology and practice, the site-specific nature of building retrofit described above will make it difficult, for example, to achieve the predictability of gas mileage performance for different models of automobile. The reasons for this situation are described below.

Poor Documentation of Retrofit Results. Despite considerable theoretical analyses and thousands of audits, there is still very little documented information on the results of actual retrofits on different types of buildings. In the biggest survey of documented retrofits to date, Howard Ross and Sue Whalen collected energy savings and retrofit information on 222 buildings.[15] Only 65 of these buildings had complete information to allow a full cost benefit analysis. The distribution of building types is scarcely representative of urban building types. Over half the buildings are schools, and about a fifth are large office buildings. There is only one shopping center, one multifamily building, one small office building, and four hotels. There are no small stores or department stores (see table 25).

Individual private retrofit efforts for such buildings as restaurants, retail store chains, and supermarkets have also been documented but the results are considered proprietary and are not available for use by other building owners. Data beyond the Ross and Whalen survey have also been assembled by Lawrence Berkeley Laboratory and by a group analyzing 40 building reporting retrofit results in the Energy User *News.* Data from these sources also are very skimpy on retrofits to multifamily buildings and to small office buildings and stores.[16]

Available Data on Retrofits Show Energy Savings are Variable and Unpredictable, The Ross and Whalen data confirm the general predictions of theoretical analyses of energy retrofits to buildings as a group. The results of their survey are shown in table 26. The survey also shows, however, that savings vary greatly from building to building including a significant prob-

[15] The 19 smaller surveys of buildings from which data was compiled for this study included: 1) 21 public schools retrofitted for the Maine Advancement Programs; 2) 14 office buildings included in the total Energy Management Research Report by NECA and NEMA; 3) 11 office buildings for which data was provided by Hagler, Bailly & Co.; 4) 15 buildings owned by the State of New York; 5) 7 office buildings for which data was provided by Flack and Kurtz of New York City; 6) 9 buildings for which data was provided by EBASCO Services, Inc. of New York City; 7) 10 buildings owned by Ohio State University; 8) 10 school buildings analyzed in *Saving School House Energy* sponsored by the American Assn. of Schools Administration; 9) 10 buildings owned by the State of New Jersey; 10) 80 schools monitored by the Buffalo Board of Education; 11) 24 community buildings for which data was collected by the Columbia Association of Columbia, Md.; several other reports on individual buildings. From: "Conservation progress in Commercial Buildings. " *Building Energy Use Compilation and Analysis:* Part C. Howard Ross and Sue Whalen, unpublished report. May 1981 (revised August 1981) to be published in *Energy* and *Buildings* Magazine, Lansanne, Switzerland.

[16] H. P. Misuriello and R. M. Bily, Jr., "A Study of Actual Metered Energy Savings for Energy Conservation Retrofit Measures Reported for Commercial Buildings., ' April 1981, cited in Hirst, op. cit., A. H. Rosenfeld, et al,, *Commercial Bu//dlng Retrofit Survey* draft September 1980.

Table 25.—Documented Energy Savings by Type of Commercial Building

Building category	Site: Average percent of savings	Site: Sample size	Source: Average percent of savings	Source: Sample size
Elementary	24°/0	72	21 %	72
Secondary	30	38	28	37
Large office	23	37	21	24
Hospital	21	13	17	10
Community center	56	3	23	18
Hotel	25	4	24	4
Corrections	7	4	5	4
Small office	33	1	30	1
Shopping center	11	1	11	1
Multifamily apartment	44	1	43	1

SOURCE: Ross and Whalen, "Building Energy Use Compilation and Analysis—part C: Conservation Progress in Commercial Building," draft, May 1981 (revised August 1981),

Table 26.-Summary of Findings From Survey of Commercial Building Retrofits

	Average	Range[a]	Sample size
Savings[b] including 22 failed retrofits	190/0	1.5-36,5%	195[c]
Savings excluding failed retrofits	22 %	7-37%	173
Electricity savings	80/0		156
Fossil fuel savings.	28°/0		151
Average cost of retrofit	$0.65/ft²	$0.13-$1.17/ft²	77

[a]Within one standard deviation
[b]Primary energy including energy used to generate electricity.
[c]Excludes buildings for which primary energy savings could not be estimated

SOURCE "Building Energy Use Compilation and Analysis—Part C, Conservation Progress in Commercial Buildings " Draft Howard Ross and Sue Whalen May 1981. and Office of Technology Assessment

ability of *increased* energy use. Further the survey shows that savings also vary substantially from what was predicted for those buildings for which predictions are available. The specific findings of the study are as follows:

On average, retrofits saved considerable *energy and were low in* capital cost. —Savings for 173 buildings out of a subsample of 195 buildings with decreases in energy use following the retrofit averaged 22 percent of preretrofit energy use. For almost 90 percent of the retrofits, the cost of the retrofit could be recovered in a 3-year payback or less[17] (see fig. 32).

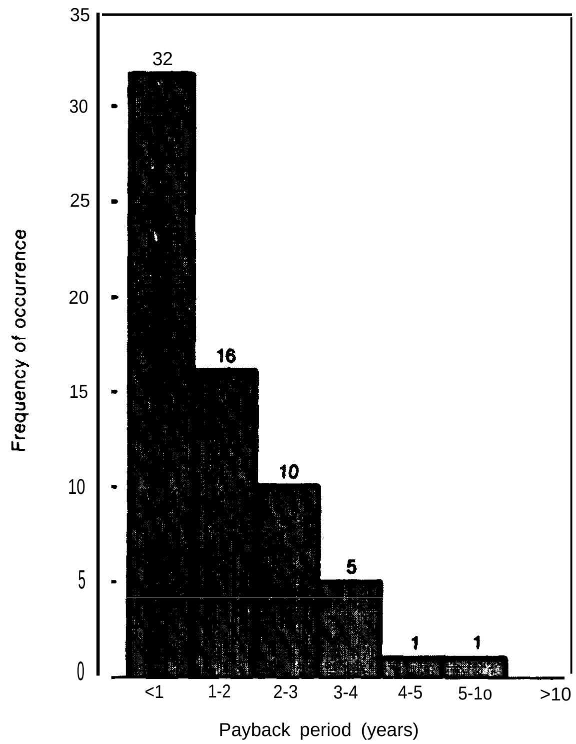
On the *other hand,* savings *were very variable.* Twenty-two of the 195 buildings failed to save any energy at all following a retrofit and some actually *increased* their energy use. The experience of the buildings that did save energy ranged from a low of 7-percent savings to a high of 37-percent savings.

*Actual savings differed considerably from pre*dicted savings. A set of 60 buildings out of the full sample had some information on predicted savings as well as actual savings. One group within the 60—a set of 18 community centers from Columbia, Md.–illustrates the variation from predicted to actual savings. For this group actual savings on average were only 85 percent of predicted savings. Six buildings had higher savings than predicted while 12 had lower savings. Savings ranged (within one standard deviation) from 80 percent less than predicted to 50 percent *more* than predicted. Several other groups described by Ross and Whalen experienced equal or more savings than predicted. A group of Maine schools had predicted 5-year paybacks, for example, and achieved 3-year paybacks. On the other hand, actual savings for the nine school buildings retrofitted by the American Association of Schools Administration were far less than predicted by computer simulation. An analysis of the poor retrofit performance was done for each school, and identified errors in selecting retrofits, installing them and maintaining them afterward. In one school, for example, maintenance personnel allowed a blown steam trap to remain in service, although a new one would have paid off in weeks. Apart from these 60 buildings reported on by Ross and Whalen, OTA found no study comparing actual to predicted savings.

Many buildings gradually increased their sav*ings in the years following the retrofit, but some*

Figure 32.—Simple Payback Period

N = 65 (does not include 3 buildings which failed to save)



SOURCE Ross and Whalen, "Building Energy Use Compilation and Analysis— Part C: Conservation Progress in Commercial Building, " draft, May 1981.

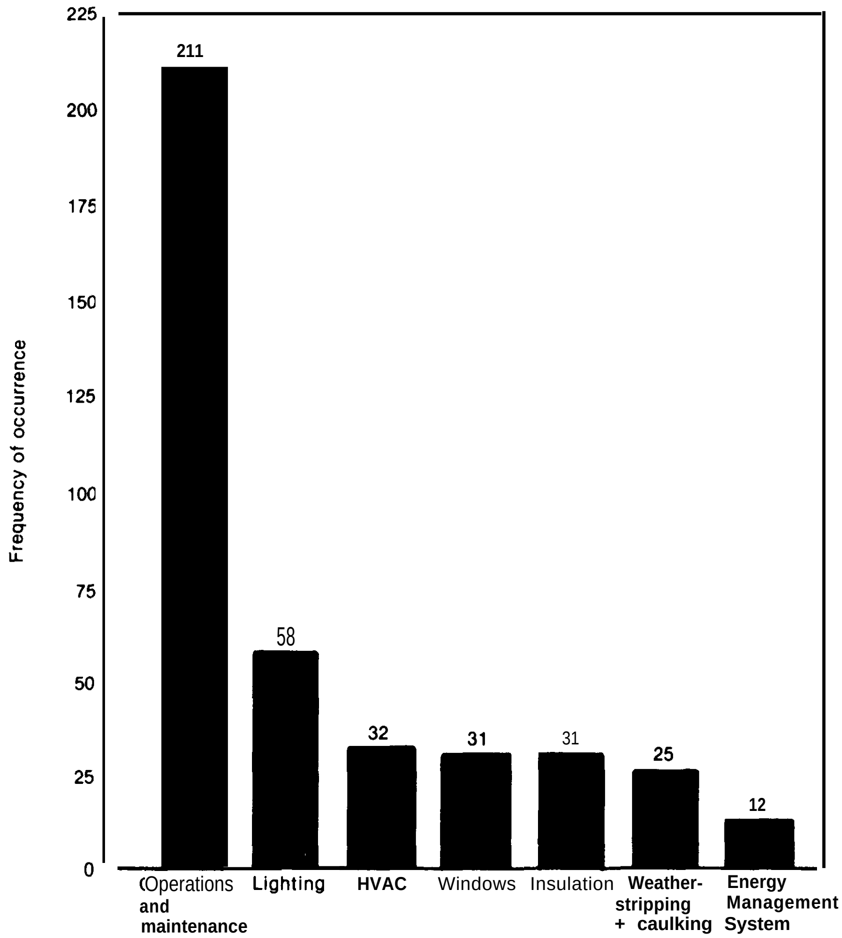
[17]The Ross and Whalen results are reported for different sample sizes out of the 222 buildings in order to get consistency of data.

decreased their savings. Out of 15 **buildings with** more than 1 year of data on energy savings following the retrofit, **9** buildings increased their savings following the retrofit, but **6** buildings decreased their energy savings over time.

Retrofits were limited to simple, cheap and we//-known measures. Improvements in operations and maintenance and lighting measures (including delamping) were the most frequent retrofits (see fig. 33). Only 76 buildings or about one third of the total installed more complex and expensive retrofits to the mechanical system or windows, or installed insulation or energy management systems. No buildings in the survey had installed some of the more "innovative" retrofits described earlier in the chapter—night insulation, passive solar additions, waste heat recovery systems or automatic daylighting control systems. It was not possible to draw any conclusions on the relative effectiveness of individual measures from the survey. It is evident that owners are cautious in their choice of retrofits and are sticking to those that are both inexpensive and well known.

Improved Data Should Increase the predictability of Building Retrofit Up to a Point. Im-

Figure 33.—Categories of Completed Retrofits: Summary of Commercial Building Retrofits



SOURCE: Ross and Whalen, "Building Energy Use Compilation and Analysis—Part C: Conservation Progress in Commercial Building," draft, May 1981, " proved data of several kinds would certainly improve the predictability of savings from building ret refits.

improved data on *the results of individual retrofits.* While there are now substantial data on savings from installing the more common retrofits such as energy management systems, there are still very little data on actual installations of some of the most effective retrofits identified in testing and computer simulation such as: night insulation for multifamily buildings or heat pump hot water heaters replacing electric resistance hot water heaters.

Improved data on the *results of retrofit packages.* These data would result from systematic retrofit of categories of buildings with similar uses, sizes and mechanical systems. Multifamily buildings are one category of buildings for which there are almost no data on systematic retrofits. Technical data could be obtained from retrofits of condominiums, which appear to be more likely than other multifamily types to be retrofit.

Data on actual savings *compared to predicted.* Systematic studies of actual savings compared to savings predicted in an energy audit should be able to identify categories of retrofits for which savings tend to be overestimated and those for which savings are usually underestimated. A careful examination of the reasons for differences in actual savings could identify categories of retrofits which are particularly susceptible to errors in installation or subsequent maintenance.

There is a limit, however, on the precision with which data can be gathered to improve the predictability of energy savings for particular buildings. The limit arises out of the site-specific nature of building retrofit described above. In collecting data on retrofit results for a group of buildings an analyst must:

- Allow for differences in the combinations of retrofits which will affect the behavior of individual retrofits due to the interactive effects described above.
- Allow for differences in hours of occupancy and vacancy among the buildings.
- Allow for weather conditions if the data are from several years. This is especially true for any solar retrofits for which hour-by-hour data are often necessary.
- Take into account the impact of very site-specific retrofits described above, such as blocking thermal bypasses or recovering waste heat from cooling equipment.

By the time these factors have been taken into consideration the analysis has become very complex and the power of generalization from large numbers has been reduced.

OTA's conclusion is that predictability of building retrofit could certainly be increased through improved data beyond the fragmentary data available in 1981. However, a certain amount of variation in actual savings from that predicted by a retrofit will probably always be characteristic of building retrofit, and this variability will have an impact on the motivation of those building owners, especially smaller building owners whose financial situation does not allow them to absorb risk. (These are discussed in ch. 4.)

IMPLICATIONS FOR RETROFIT OF BUILDINGS IN CITIES

This analysis of the systematic and site-specific nature of the retrofit of buildings has some implacations for the actual practice of building retrofit in cities through private enterprise and public programs. This section summarizes some observations about the nature of large-scale retrofit in cities, some of which is also applicable to buildings in general, wherever they may be located,

Energy Retrofit Business

One of the reasons why actual building retrofits have lagged behind the identification of ample opportunities for retrofit (as described earlier in the chapter) is that the energy retrofit business, as a business, is still in the process of organization. Although some parts of the business—such as home insulation and energy management systems for large buildings—have considerable track records by now, it still is difficult to find a single place for the owner of an existing building to go to for advice and action. There has been a lot of talk about a "one-stop" type of organization that would serve such a need in the private sector. Why are there so few now? A partial answer is that retrofit of a building is complex. A building's energy ailments must be diagnosed first, then cost-effective solutions proposed, then the retrofit work must be performed. Retrofits may affect almost every aspect of a building: structure, hot water, lighting, and mechanical system. Such a task may require a set of building services that is almost as complex as that used to construct the original building.

For small *buildings,* especially frame buildings, the most cost-effective retrofits will be insulation and improvements in window efficiency. This requires little more than light carpentry skill but is demanding work to organize and maintain of high quality. Insulation crews often work in semiaccessible places; it takes care to see that gaps in insulation are avoided and peculiar structural features in the walls are taken care of. Such work is difficult to streamline; it is exceedingly labor intensive. Separate companies often specialize in window retrofits and insulation.

A separate specialty is developing in the retrofit of small buildings—solar specialist. Active solar domestic hot water heating is an enterprise requiring carpentry, and licensed plumbing and electrical work. passive solar retrofit requires carpentry skills that are upward extensions of the skills currently in use by insulation and storm window contractors, but which are not typically in the portfolio of those organizations. The current trend has been toward further disaggregation of the small building retrofit industry as contractors specializing in renewable retrofit start up practices without regard to the lower technology conservation work. This may change as more people come to understand the benefits of combining conservation retrofits with active or passive solar retrofits.

Many retrofits to the mechanical systems are cost effective even in small buildings and these cannot usually be performed by insulation contractors with carpentry skills. A retrofit contractor usually must subcontract out the installation of a new burner, hot water heat pump, vent damper, or modulating aquastat. Some natural gas utilities and larger fuel oil dealers maintain service departments which perform these functions. otherwise, they are carried out by mechanical system specialists in furnaces, boilers, and air-conditioners. A few retrofits can be done directly by the small building owner, such as installing a clock thermostat or faucet and shower flow controllers.

In the *retrofit of larger buildings,* the full range of building trades (including sprinkler system specialists for roof sprays), gets involved. With the higher intensities of lighting and inherent wastefulness of many of the HVAC systems installed on larger buildings, this study has shown the tremendous cost effectiveness of a much broader range of retrofits on larger buildings than on smaller ones. Large buildings have more complex central plants, and require more highly trained and experienced people to retrofit them. In addition, retrofit of the distribution portion of the heating and cooling system is limited to insulation of pipes and ducts for small buildings, whereas specialists are needed in large buildings who can change ventilation settings, install outside air controls, or make the switch from a terminal reheat system to a variable air volume distribution system. Work on the lighting system is much more intense in larger buildings, and electricians are required to make the shift to task lighting, or change over incandescent fixtures to fluorescent or sodium vapor. Large buildings often have engineers or maintenance personnel with skills enough to perform the simpler retrofits themselves.

Offsetting all this large building complexity is the fact that envelope retrofit plays a much smaller role except in major renovations. In addition, the construction industry which caters to the large building is as a whole much more used to packaging diverse construction operations under a single general contract. Therefore, the large building is much more likely to be systematically retrofitted than the small one, even though the job requires higher skill levels.

Problems and Opportunities of Urban Retrofit

The construction business in urban areas has always operated differently than in rural areas. What particularly is different about retrofitting in the city?

Because of *the high proportion of relatively old buildings* in urban areas, a *lot of retrofit cannot occur at all without a certain amount of restorative work occurring first.* For instance, people working in weatherization programs in our cities are familiar with having to patch holes in walls before performing the wall insulation itself. This characteristic of urban buildings (discussed more extensively in ch. 5) tends to increase costs of retrofit above those presented in this report, which consider only the costs of the retrofit itself, not those of any repair which may be necessary beforehand.

What makes a city a city is its density. *Urban density can result* in economies of scale, but high density a/ways drives up construction costs associated *with access problems.* The kinds of economies of scale that can result from high density include reduced travel time to any given retrofit site, an important cost consideration for many small retrofit jobs, for which travel is a large percentage of total job costs. For any step prior to retrofit, such as a sales call, an estimating visit, or an onsite energy audit, costs of travel are an even larger fraction of the total cost of the activity. Access problems associated with urban construction sites include increased travel times and parking fines caused by streets congested with either traffic or snow, difficult ladder access because ladders must rest on an adjacent property or a public sidewalk, and tremendously increased costs associated with accessing any kind of exterior retrofit location above ladder access level. The retrofitter installing storm sash, calking, replacement sash, wall insulation, or any other envelope retrofit measure above the third floor has the choice of erecting scaffolding or disturbing the occupants of the building. Either tactic adds cost to the job.

The opportunity *for* renewable retrofit *is* different *in cities.* There are plenty of masonry-walled structures appropriate for passive solar retrofit strategies, and acres of flat roofs available for the mounting of active solar collectors or small wind energy conversion devices. On the other hand, urban buildings may be so close together that they shade one another's sun or obstruct one another's wind.[18] In addition, urban particulate pollution degrades collector efficiency more rapidly than in relatively unpolluted locations. Vandalism, or the threat of vandalism, discourages any solar retrofit that will place a breakable panel, passive or active, within stone's throw of the street.

There *is more crime* in urban areas. This increases the cost of doing retrofit business by raising insurance costs, both for retrofit vehicles and equipment and for the business location itself. In addition, vandalism can degrade the performance of more than just solar collectors. Heating and air-conditioning thermostats, storm windows, and reflecting trim are also subject to intentional damage, with the resultant elimination of the energy savings these improvements were designed to cause.

Urban Retrofit: Mass Production or Custom Work?

Based on the results of this report, can a general set of retrofit measures be confidently recommended for a given building type without further site analysis of actual individual buildings? The results suggest that it would be tempting to do this, but a poor risk.

It is attractive to consider that retrofit could be performed without site-specific consideration in the form of an energy audit. The total cost of retrofitting urban buildings is not just the cost of

[18] An analysis of hours of exposure to sunlight for buildings of different heights in Boston is described in Shapiro, op. cit.

the construction service itself, but also the cost of the energy audit. Depending on how close the energy audit comes to being a construction estimate that the retrofitter can work from, the energy audit can make up 2 to 10 percent of the typical cost of retrofit. Avoiding some of this cost would help. Some "class action" retrofit occurs now in the form of two Federal programs, "no cost/low cost" and the Residential Conservation Service (RCS). "No Cost/Low Cost" recommends a set of conservation measures without hesitation in a brochure that uniformly recommends the same action to a homeowner in Minneapolis as it does to a homeowner in Los Angeles. This is possible because the improvements recommended, such as flow restrictors for shower heads and faucet aerators are so cheap that it is practically impossible for a poor recommendation to be made. Domestic hot water usage is almost completely independent of climate, and even if a homeowner doesn't heat the home's domestic hot water at all, water bill savings are sufficient to pay for flow restrictors in less than a year. Besides, the first flow restrictor comes with the "No Cost/Low Cost" brochure anyway. This is not to say that "No Cost/Low Cost" is completely incapable of causing a homeowner to make a mistake, that is to invest money foolishly. For example, the program recommends that the temperature cutoff on hot air furnaces be adjusted downward to make the most of the heat contained in the furnace itself. A certain number of people are going to pay a serviceperson to come to their homes to make the temperature adjustment only to discover that the adjustment has been made. The designers of "No Cost/Low Cost" find this an acceptable risk, and rightly so. Far more money would be wasted having energy auditors tell people whether their hot air furnaces needed adjustment than just going ahead and adjusting them.

RCS is a partial "class action" program. Under RCS, energy auditors visit homes, collect site-specific data, and then make projections of cost and fuel savings that may accrue from the implementation of a variety of individual measures, from small wind energy conversion systems to weatherstripping. This makes sense, because it is foolish to make a blanket recommendation of window weatherstripping, regardless of the severity of the heating or cooling climate, unless the condition of the existing prime window and storm window (if any) is known. But RCS is by no means a program customized to each home. The regulations that have governed RCS specify that the auditor shall make estimates of cost and savings for a limited set of energy-conserving measures.[19] Flame retention oil burners are included, but modulating aquastats are not. Under the original RCS regulations, as long as a home audited under RCS has an oil burner that is not of the flame retention variety, the auditor must make an estimate. No matter how appropriate the home is for installation of a modulating aquastat on the hot water space heating system, the auditor may not take any recommendations for it (unless the particular state in which a home is located has applied for, and secured approval to consider that energy-conserving improvement). So for RCS, some judgments were made in advance of the promulgation of the program as to which energy-conserving improvements were sufficiently applicable to make their consideration a cost-effective use of the energy auditor's time. Implicit criteria included commercialization of the measure (it had to exist in the marketplace, and there had to be evidence that a fair number of people were in business who could reliably install the measure), as well as evidence of energy-conserving performance. Under regulations proposed in the winter of 1981 which would extend the RCS concept to a Commercial and Apartment Conservation Service it was recognized that commercial buildings and apartment buildings are far more varied than small houses. The regulations required only five measures to be evaluated for every building and a much longer list of measures to be considered for evaluation if appropriate.[20]

There is sufficient predictability of applicable measures by building type to support a RCS-type program (whether Federal, State, or utility directed) for buildings other than single-family

[19]The rigidity of these regulations was reviewed by the Reagan administration and new more flexible regulations have now been issued (see ch. 9).

[20]Proposed Regulations for Commercial and Apartment Conservation Service, February 1981.

houses in which onsite auditors are asked to consider certain kinds of measures for certain building types. The predictability of retrofits, on the other hand, is not universal or consistent enough to justify a "No Cost/Low Cost" style program for larger buildings. For instance, for climates in cities like Buffalo, nearly half of the energy-conserving measures considered fall into the category of low capital cost under the assumptions used for these calculations. But variations specific to individual buildings will be sufficient to cause some of these measures to be of moderate capital cost compared to savings.

There are other powerful reasons for making onsite judgments even after a particular set of retrofit measures have been identified as usually physically applicable and potentially cost effective when applied to a particular building type. The advantages of onsite auditing are that the auditor can properly account for the special conditions of use and of building condition when considering a measure or measures for recommendations, and also when making estimates of costs and savings. Trained auditors are able, in their examination of the building itself and of the way in which the building is used, to account for:

- Special conditions of *use.* —These include unusual hours of operation, portions of the building unused during particular times of day or season, portions of the building which can be zoned to different temperature ranges, and usage patterns allowing cutoff of domestic hot water to lavatories.
- Long-term *strategy for the building.* —Many retrofit strategies often depend on what future remodeling plans are in the works and certainly influence the owners' level of spending.
- Esthetic *consideration.* —Many envelope, lighting, and renewable retrofit measures have major effects on the appearance of the building. Only an auditor at the site can tell if the owners are willing to live with a passive solar wall collector on the front of their building.
- *Site-specific conditions affecting costs and* savings. —There is no such thing, even for a given building type in a given location, as a standard per square foot price for attic insulation. Many RCS audit procedures currently mislead building owners by presenting relatively uniform costs for attic insulation, whereas site-specific conditions such as required access and ventilation can influence cost by a factor of 50 percent, and site-specific conditions such as air leakage into the attic or amount of ventilation proposed can influence projected savings by a similar amount. only an onsite auditor has the ability to make the judgment calls that are essential to deliver a responsible level of accuracy to the owner.
- *Optimum package of retrofits.* –Taking into account the interaction among retrofits, an auditor can come up with an optimum package for that building which might include, for example, recommendations on down-sizing of equipment to accommodate a better insulated building envelope.

Thus, this report does lay some important groundwork for anyone considering a retrofit program for a single building or entire group of buildings by providing concrete lists of retrofit measures worth consideration for particular combinations of building types and climates.

Beyond this, however, "class action" retrofit, or retrofit without detailed site analysis, is to be avoided because of the individual variation, both in costs and in savings, that occurs as the result of site-specific conditions. Lastly, if audits are to be performed at the site, their computation methods must make fewer approximations than those made in the algorithms in this report in order to be marginally more accurate than the projections given here.

Retrofit, Rehab, or Demolish?

Each prospective building owner or developer picks one of four strategies when considering a property for acquisition: do nothing, repair, rehab, or demolish. With the addition of energy costs to the factors to take into account in this strategic decision, the question is changed only slightly: do nothing, retrofit, rehab, or demolish?

The advantages of retaining the basic structure of an urban building are increasing, and range from historical significance to architectural quality to the avoidance of skyrocketing new construction costs. The financial factor is a key to all development decisions, and, from the energy point of view, the developer must examine the energy element of the projected operating statement of a building with new respect, and must attempt to answer two difficult questions: 1) How low can energy costs be brought before major rehab is required? 2) How low can energy costs be brought, even after major rehab?

This report shows that some buildings in some climates have far higher potential than others. Consider, for example, a developer in a city with a climate like Buffalo's who is looking at two small commercial properties that are equal except that one is of frame (cavity) wall construction, the other of clad-wall construction. The buildings are roughly similar in energy efficiency; neither is insulated to begin with, but the developer must rehab the clad wall at far greater cost than he can retrofit the frame (cavity) wall to achieve the same improvement in energy efficiency. Sooner or later, if the only buildings available to developers can be made energy efficient only at very high costs, demolition will occur more frequently.

This report cannot consider a critical factor in the decision to demolish or rehab, which is the energy efficient qualities given a building at the time it was built, which no amount of retrofit or rehab can change. Those "hereditary" qualities can change drastically on the same site according to the structure's built-in characteristics, notably, surface-to-volume ratio and orientation. Buildings that can profitably absorb large amounts of retrofit, but which were poorly sited and which have very complicated shapes, may never approach the low levels of energy consumption which are possible with reasonable investment in new construction. And on the other hand, buildings that are well sited and whose shape approaches that of a cube may well be capable of being retrofitted to lower levels of energy consumption at far less total cost, than a building constructed from scratch on the site.

Table 3A.—43 Building Types for Which Retrofit Lists Were Developed

Size and use	Wall type	Mechanical system type
Small residential (2,000 ft²)	Cavity	• Air • Water • Decentralized
	Masonry	• Air • Water • Decentralized
Moderate residential (15,000 ft²)	Cavity	• Air • Water • Decentralized
	Masonry	• Air • Water • Decentralized
	Clad	• Air • Water • Decentralized
Moderate commercial (15,000 ft²)	Cavity	• Air • Water • Decentralized • Complex reheat
	Masonry	• Air • Water • Decentralized • Complex reheat
	Clad	• Air • Water • Decentralized • Complex reheat
Large commercial (100,000 ft²)	Masonry	• Air • Water • Decentralized • Complex reheat
	Clad	• Air • Water • Decentralized • Complex reheat
Large residential (100,000 ft²)	Masonry	• Air • Water • Decentralized
	Clad	• Air • Water • Decentralized

SOURCE: Office of Technology Assessment.

Table 3B.—Retrofits Assessed by Office of Technology Assessment[a]

	Retrofit applies only to:	Costs and savings of retrofit not specifically analyzed by OTA
Envelope retrofits		
Roof/attic insulation		
Wall insulation		
Storm Windows		
Replacement double glazing		
Window and door weatherstripping		
Window insulation		
Reflective insulation		
Shading devices		
Roof sprays		
Mechanical system retrofits		
Replace burner and controls		
Replace boiler/furnace		
Install vent damper		
Stack heat reclaimer	Water systems	
Replace electric resistance heater with heat pumps	Decentralized	
Boiler turbolator	Water systems	
Modulating aquastat	Water systems	
Setback thermostats		
Enthalpy control/economizer	Air systems	
Replace room air conditioners	Decentralized	
Replace central air conditioning	Air systems	
Vary chilled water temperature		
Convert terminal reheat to variable air volume	Complex reheat	
Reduce ventilation volume	Air systems	
Evaporative cooling system		
Replace air-cooled condenser with water cooled		
Fog cooling (evaporator coil spray)		
Insulate ducts	Air systems	
Insulate pipes	Water systems	
Two-speed fan motors	Air systems	
Adjustable radiator vents	Water systems	X
Reduce orifice size on furnace/boiler		X
Install multifuel boiler		X
Whole house fan		X
Condenser coil spray		X
Chiller bypass system		X
Hot Water Retrofits		
Summer domestic hot water boiler		
Flow control devices		
Insulate hot water storage		
Vent damper on heater		
Hot water heat pump		
Refrigeration heat reclaim for hot water		X
Lighting retrofits		
Replace incandescent light with fluorescent		
Install fluorescent hybrid lamps		
Use low wattage task lighting		
Use high-efficiency fluorescent lamps		
Maximize use of daylighting		X
Solar retrofits		
Solar hot water heater		
Active solar combined space and hot water		
Sunspace/greenhouse		
Glaze masonry wall (trombe)		
Add wall panel without storage		
Add glazing without storage but with night insulation		
Add glazing with storage but without night insulation		

[a]Each retrofit IS described In appendix

SOURCE Off Ice of Technology Assessment

Table 3C.—Characteristics of the 12 Building Types
(as determined for analysis of retrofit measures)

Building type	Size	Walls	Roof	Windows
Single-family detached	2,000 ft² 2 stories	"Cavity" wood frame with wood or brick siding	Wooden, peaked roof with attic	Wooden, double hung
Single-family masonry rowhouse	2,000 ft² 2 stories	Brick or stone bearing walls, two walls attached	Flat or slightly pitched with crawl space	Wooden, double hung
Small frame apartment house	15,000 ft² 18 apartment units, 3 stories	Wood frame with wood or brick siding	Flat wooden roof	Wooden, double hung
Small masonry apartment house	15,000 ft² 18 apartment units, 3 stories	Brick or stone bearing wall	Concrete slab roof	Wooden, double hung
Small clad wall apartment house	15,000 ft² 18 apartment units, 3 stories	Prefabricated masonry panels attached to metal frames	Concrete slab	Metal frame, double hung
Small clad wall commercial building	15,000 ft² 3 stories	Wood frame with wood or brick siding	Flat wooden roof	Wood frame, double hung
Small masonry commercial building	15,000 ft² 3 stories	Brick or stone bearing wall	Concrete slab	Metal frame, double hung
Small clad wall commercial building	15,000 ft² 3 stories	Prefabricated masonry panels attached to metal frames	Concrete slab	Metal frame, commercial casement windows
Large masonry commerical building	100,000 ft² 8 stories	Brick or stone bearing wall	Concrete slab	Metal frame, double hung
Large clad wall commercial building	100,000 ft² 8 stories	Prefabricated masonry panels attached to metal frames	Concrete slab	Metal frame, commercial casement
Large masonry apartment house	100,000 ft² 8 stories, 150 apartments	Brick or stone bearing wall	Concrete slab	Metal frame, residential casement
Large masonry clad apartment house	100,000 ft² 8 stories, 150 apartments	Prefabricated masonry panels attached to metal frame	Concrete slab	Metal frame, residential casement

SOURCE: Office of Technology Assessment,

Table 3D.—Assumptions About the Mechanical System Types Used in OTA's Analysis of Retrofit Cost Effectiveness (see illustrations of mechanical systems in chapter text)

Basic system modeled	Variations in retrofit options for other systems
Air systems	
Heat Single zone without reheat. Oil-fired burner cycles in response to single thermostat. Cooling For small and moderate size buildings a direct expansion (DX) split system. For large buildings a reciprocating chiller making chilled water. Outside air is used for cooling and ventilation only for commercial buildings.	• For gas-fired burners. Some retrofits save fewer Btus (vent dampers) because less heat escapes up the flue. • Variable air volume (VAV). Systems without reheat are somewhat more energy efficient. Some retrofits save fewer Btus on VAV systems than on single zone system.
Complex reheat systems	*Variations in retrofit options for other reheat systems*
Heat Single duct terminal reheat system. Air is circulated to all zones at the temperature required by the zone with the least heat requirements and then heated at zones with higher heat requirements by a terminal coil with hot water or steam from a central oil-fired boiler. Outside air is used to cool the return air (at room temperature) down to temperature required by the zone with the least heat requirement. Cooling Air is circulated at the temperature required by the zone with the most cooling requirement and then reheated to meet the temperature requirements of other zones.	• For gas-fired boilers. No difference in retrofit cost effectiveness except that resulting from lower fuel cost. • Dual-duct systems. Hot and cool air are carried in different ducts and duct insulation might be more effective. • Multizone and variable air volume (VAV). Are more efficient. Thus, the same retrofits to these systems would be somewhat less cost effective. • Terminal reheat provided by electric resistance heater. Converting to variable air volume would be even more cost effective.
Water/steam systems	
Heat Single zone hot-water baseboard radiation with single water temperature setpoint. Boiler cycles in response to single space thermostat and circulation pump responds to system water temperature. Cooling Window or wall air conditioners controlled room-by-room (coefficient of performance 1.8).	• Systems with steam radiators. Pipe insulation would be more important for the higher temperatures. A steam pressure reset would be used instead of a modulating aquastat to relate temperatures inside the boiler to those outside (hotter temperatures inside for colder temperatures outside). • Two-pipe fan coil and induction systems. Use various methods to heat air in each zone from the centrally-heated water or steam. If each zone has a thermostat multizone setback thermostats may be appropriate. • Four-pipe fan coil and induction systems. Circulate centrally-chilled water as well as hot water or steam. The heating retrofits identified by Office of Technology Assessment would apply to the heating system.
Decentralized systems	
Heat Electric resistance baseboard radiation which cycles in response to room thermostats, Cooling Window or wall air conditioners (coefficient of performance 1.8).	• Systems with all-electric wall units provialing heating and cooling. Retrofits will be the same in cost effectiveness for a combination window unit with the same coefficient of performance as the room air conditioner. If the wall unit takes in a large amount of outside air retrofits will be more cost effective. • Gas space heaters. No difference in building envelope retrofits except for that resulting from lower fuel cost. A retrofit to improve the efficiency of the space heaters (e.g., by installing high-efficiency room-sized pulse boilers) would substitute for retrofits to improve the efficiency of electrical systems.