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ENERGY SAVINGS POTENTIALS IN RESIDENTIAL AND SMALL COMMERCIAL THERMAL DISTRIBUTION SYSTEMS – AN UPDATE

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ABSTRACT

This is an update of a report (Andrews and Modera 1991) that quantified the amounts of energy that could be saved through better thermal distribution systems in residential and small commercial buildings. Thermal distribution systems are the ductwork, piping, or other means used to transport heat or cooling from the space-conditioning equipment to the conditioned space. This update involves no basic change in methodology relative to the 1991 report, but rather a review of the additional information available in 2003 on the energy-use patterns in residential and small commercial buildings.

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EXECUTIVE SUMMARY

This is an update of a report (Andrews and Modera 1991) that quantified the amounts of energy that could be saved through better thermal distribution systems in residential and small commercial buildings. Thermal distribution systems are the ductwork, piping, or other means used to transport heat or cooling from the space-conditioning equipment to the conditioned space.

Residential Buildings—1991 Report

The approach in 1991 involved four major steps.

1. Divide the building stock into relatively homogeneous "cells."
2. Estimate the heating and cooling energy use per building within each cell.
3. Project the building stock out to the year 2020.
4. Estimate the energy savings potentials from improved thermal distribution as percentages of the annual energy use.

The cells were defined as elements of a five-dimensional matrix covering the following categories:

Characteristic	Possible Values (Categories)
Existing building or new construction	1. Existing
	2. New
Climate zone	1. Frostbelt (Northeast and Midwest)
	2. Sunbelt (South and West)
Building type	1. Single family
	2. Mobile home
	3. Multifamily
	4. Small commercial
.Thermal distribution system type	1. Forced air
	2. Hydronic
	3. Built-in electric
	4. Other or none
Thermal distribution system location (forced-air only)	1. Unconditioned space
	2. Partly conditioned space
	3. Conditioned space

Ducts located in crawlspaces and attics were considered to be in unconditioned spaces. Basement ducts were placed in the partly-conditioned category. Ducts located between the floors of a "raised ranch" house were considered to be in the conditioned space.

When the "existing" and "new" categories were aggregated, the procedure yielded eight homogeneous groups of residential buildings that together accounted for 6.4 quads (1 quad = 10^{15} Btu) of primary energy in 2020, which was 73% of a U.S. Department of

Energy (DOE) projection for all residential buildings in 2010, the latest information available at the time.

Two levels of energy-savings potentials were presented. The lower estimate, called "current," included only technologies that were developed and reasonably well understood in 1991, at least in the buildings research community. The higher estimate, called "full," represented the ultimate energy savings that could be derived from modifications to thermal distribution systems, including those modifications for which research was still required. The sum of the "current" energy savings potentials for residential buildings was 0.9 quads, while the sum of the "full" potentials was 2.1 quads.

Multifamily and small commercial buildings were not included in these estimates, because not enough information was available to make more than a guess. When these guesses were made, they added 0.3 quads of energy savings potential, although it was recognized that the uncertainty here was very large.

Residential Buildings—This Report

This update involves no basic change in methodology relative to the 1991 report, but rather a review of the additional information available in 2003 on the energy-use patterns in residential and small commercial buildings.

The following are some major developments between 1991 and 2003 that have influenced the revised energy-use estimates and energy-savings potentials:

- Mobile homes in the Frostbelt and Sunbelt were added as two new cells in the current analysis.
- The number of housing units in cells included in the analysis increased from 59 million in the 1991 report (66% of the total number of housing units in the U.S.) to 83 million in this report (78% of all U.S. housing units). The percentage of forced-air systems in single-family houses increased from 49% to 74%.
- Space-conditioning energy use per household did not change very much between 1991 and 2003.
- Space-heating energy use in all the residential buildings included in the analysis rose by 40%, while space cooling energy use more than doubled.

The energy savings potential estimate procedure was based on a review of the 1991 report, with modifications made to the analysis as warranted by new information. The major difference was a change from the use of "current" and "full" potential estimates to a single estimate. The reason for this was that the development of new technologies to seal ducts automatically and to place ducts in the conditioned space make it possible to capture a greater fraction of the ultimate potential savings using techniques that are as advanced today as the "current" techniques were in 1991.

The energy savings potential for better thermal distribution systems in residential buildings was found to be about 1.7 quads annually by 2030. This compares with the 1991 estimate (for 2020) of about 1.0 quads annually. The difference is due in large part to the greater increase in forced-air thermal distribution systems located outside the conditioned space, as seen in the latest available data, compared with what was anticipated in 1991. A second contributor is the continuing increase in the size of new houses, which has greatly reduced energy conservation per building despite the increase in energy efficiency of space-conditioning equipment and building envelope components.

Small Commercial Buildings

The state of knowledge on small commercial buildings has advanced significantly since 1991. As a result of work by groups in California and Florida, a fairly detailed picture of the status of thermal distribution in these buildings has emerged, comparable perhaps to what was known about residential thermal distribution in 1991.

One significant change is that the upper limit of floor area, for a building to be included in the "small commercial" category, was raised from 10,000 ft^2 to 25,000 ft^2. This was done for two reasons. First, other research has tended to use a cutoff closer to the higher number. Second, it was seen that cooling technologies generally associated with large buildings, e.g., central chillers, start coming in at the 25,000 ft^2 point.

Two significant "cells" of small commercial buildings were identified, namely those using forced-air distribution and located in the Frostbelt and Sunbelt, respectively. The total space-conditioning primary energy that will be used by these buildings in 2030 was projected at 1.4 quads, up from the 1991 estimate of 1.2 quads projected to 2020. The addition of the 10,000 ft^2 to 25,000 ft^2 size range was partly offset by a reduction in the estimated energy use per unit area in the current update, relative to the 1991 report.

The energy savings potential for better thermal distribution systems in small commercial buildings was found to be about 0.4 quads annually by 2030.

The Way Forward

Two sharply contrasting pictures dominate the view of future trends in thermal distribution energy efficiency. The first picture is of the United States as a whole, for which an energy savings potential of more than 2 quads annually is equivalent in energy content to about 1,000 medium-size hydrogen bombs.[1] This would seem to be an obvious enough motivation to do something about the problem.

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[1] Medium-size is defined to be 500 kilotons TNT equivalent, roughly the typical size represented in U.S. missile deployments. At 2,000 Btu/pound, this translates to 2 X 10^{12} Btu per bomb, or 500 bombs per quad.

The other perspective, however, is quite different. This is the point of view of the building owner. In the residential sector, for example, the greatest energy savings per building are in the class of single-family forced-air distribution systems with ducts in unconditioned spaces. More than a quad of energy can be saved in these systems, but this quad is spread out over more than 50 million homes. This works out to 0.02 quads per million houses. At a primary energy cost to the user of $10 per million Btu,[2] this is a savings of just $200 per year. Even though this is enough to make duct repair cost-effective, it is not enough to get it onto the typical homeowner's "radar screen."

The situation in small commercial buildings looks a bit brighter, because here the savings potential is 0.14 quads per million buildings. This corresponds to $1400 annually. Still, compared with other cash flows in a typical small commercial building, this has to be considered "chump change."

The solution to this problem must lie in effectively demonstrating to the homeowner and the commercial building owner that dollar savings are not the only benefit from improved thermal distribution. Improvements in health, safety, and comfort need to be documented, and this information needs to be spread as widely as possible. Much has already been done along these lines, but the scope for additional effort--preferably in a partnership involving all public and private stakeholders--is immense.

Such education, combined with training of technicians who can make improved thermal distribution possible on a nationwide scale, is clearly the most pressing need that government agencies and industry associations need to address.

The second priority is research, targeted to specific areas where new technical developments could make a significant difference. The following need to be developed and validated:

- New approaches to home construction that will allow ducts to be located within conditioned spaces.
- Well-insulated, inherently leak-free duct systems that will perform adequately even if installed by poorly trained or poorly motivated personnel.
- Design and construction guidelines for small commercial buildings to eliminate losses from leaky ducts, poor management of airflows across the envelope, and suboptimal ceiling-space configurations.

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[2] This corresponds to electricity at 10 cents per kilowatt-hour, natural gas at $1 per therm, or fuel oil at $1.40 per gallon.

PART I. MARKET SEGMENTATION AND SPACE-CONDITIONING ENERGY

INTRODUCTION

This is an update of a report (Andrews and Modera 1991) that quantified the amounts of energy that could be saved through better thermal distribution systems in residential and small commercial buildings. Thermal distribution systems are the ductwork, piping, or other means used to transport heat or cooling from the space-conditioning equipment to the conditioned space.

The need for improved efficiency in thermal transport within buildings has become well recognized within the building and HVAC industries and the research community, and will not be elaborated upon here. The purpose of this report, rather, will be to provide an up-to-date estimate of the amount of energy that could be saved through better design, installation, and upkeep of thermal distribution systems in residential and small commercial buildings. For the most part this means air ducts, although hydronic systems are also included in the analysis.

In order to estimate the energy savings potential, a four-step process was performed. First, the residential and small commercial building markets were segmented into "cells" that are homogeneous with respect to characteristics that are germane to thermal distribution. Second, the energy use per building (or, for small commercial buildings, per unit floor area) were evaluated for each of these cells. Third, a reasonable and consistent means of giving relative weight to new and existing buildings was developed and applied. Fourth, specific means of conserving energy through distribution system improvements were detailed for each cell. Using this information, the potential energy savings were quantified.

The main emphasis of this update was on the first three of these tasks. For the fourth task, a complete reevaluation of the means for energy savings through improvements in thermal distribution was beyond the scope of this work. Instead, the 1991 report was evaluated to determine where changes in the set of improvements and their relative weights should be adopted, in light of a decade's additional experience. This led to at least one major change in the outlook for duct leakage repair on the basis of new technology developed since 1991, and it also led to a change in the way the results are presented.

Some elaboration on the third task in the above list may be in order. It was recognized that the energy-savings opportunities available in new construction will likely be different from those that are possible in existing buildings, both in character and magnitude. Therefore, a reasonable and consistent method of accounting for new and existing buildings needed to be devised. Following the methodology used in 1991, a period of 25 years was taken to pan an appropriate number of new buildings, for the purpose of weighing relative costs and benefits of research directed toward new construction as opposed to retrofit. In order to provide a consistent set of energy-use and energy-savings estimates, a "snapshot" of the building stock was constructed, as it is anticipated to be in 2030. Buildings constructed between 2006 and 2030 are considered "new," while those constructed in 2005 or earlier are "existing."

As in the 1991 report, a dividing line somewhat in the future was selected on the basis of a judgment of when significant advances in thermal distribution might begin to enter the market. The judgment in 1991 proved to be optimistic, since nothing special happened in or around 1995. The situation today gives somewhat more grounds for optimism. Both the housing and HVAC industries appear to have accepted the idea that thermal distribution inefficiency is a serious problem. This is bolstered by the very real health, safety, and comfort issues that go along with duct leakage.

The most important sources of information used in this update were:

1. The Residential Energy Consumption Survey (RECS 2001a, 2001b, 2001c, 2001d) published by the Energy Information Agency of the U.S. Department of Energy.

2. The Residential Gas Market Survey (AGA 2000) published by the American Gas Association.

3. The American Housing Survey of the United States (AHS 2001, 1995, 1985) published by the U.S. Department of Commerce and the U.S. Department of Housing and Urban Development.

4. The Commercial Buildings Energy Consumption Survey (CBECS 1999) published by the Energy Information Agency of the U.S. Department of Energy.

5. The Buildings Energy Data Book (DOE 2002) published by the Office of Energy Efficiency and Renewable Energy of the U.S. Department of Energy.

6. The Annual Energy Outlook (EIA 2002, 2001, 2000), published by the Energy Information Agency of the U.S. Department of Energy.

7. U.S. Census data on Types of Heating Systems Used in New One-Family Houses Completed (U.S. Census 2001).

MARKET SEGMENTATION—EXISTING RESIDENTIAL BUILDINGS

The data in Table 1 of Andrews and Modera 1991 were updated by using RECS 2001 to replace the 1987 data. Table 1 shows both the old and new data. Old data are in italics and new data are in boldface Roman type.

Table 1. Breakdown of housing types by region (millions of households). Bold numbers are 2001 data (RECS 2001a), light face italics are 1987 data from Andrews and Modera 1991, Table 1.

Census Region House Type	Northeast	Midwest	South	West	All U.S.
Single-Family Detached	**9.2** *9.1*	**15.4** *14.7*	**25.5** *20.8*	**13.0** *10.5*	**63.1** *55.2*
Single-Family Attached	**2.8** *2.0*	**2.8** *0.9*	**3.1** *1.5*	**1.8** *0.9*	**10.6** *5.3*
Small Multifamily (2-4 Units)	**3.1** *3.2*	**2.2** *2.6*	**2.6** *2.2*	**1.6** *2.0*	**9.5** *10.1*
Large Multifamily (5 or More Units)	**4.5** *4.1*	**2.8** *2.8*	**4.5** *4.2*	**5.3** *3.8*	**17.0** *14.9*
Mobile Home	**0.7** *0.7*	**1.2** *1.2*	**3.3** *2.2*	**1.7** *1.0*	**6.8** *5.1*
Totals	**20.3** *19.0*	**24.5** *22.3*	**38.9** *30.9*	**23.3** *18.3*	**107.0** *90.5*

Between 1987 and 2001, the number of households increased by 16.5 million. Nearly 80% of this increase was in the South and West regions, and well over half of that was in single-family detached housing. Mobile homes (interpreted here to mean the same thing as "HUD-Code housing") are a small but growing category, especially in the Sunbelt. The term "manufactured home", which includes not only mobile homes but also some types of construction classified here as single-family, will not be used in this report.

Single-Family Housing

Andrews and Modera 1991 used some available data from the National Association of Homebuilders to break out the single-family detached housing into distribution system types. These data, from 1983, were somewhat old even in 1991. Unfortunately, comparable new data are not available in the public domain. Instead, we used U.S. Census data (U.S. Census 2001). Using the data from this source, the average numbers of new one-family houses with various heating system types were found for the years 1988-2001. These are given in Table 2. Note that these numbers do not include mobile homes, which are treated in a separate category (see below). As in the 1991 report, the "Frostbelt" is defined as the Northeast and Midwest Census Regions, while the "Sunbelt" is the South and West Regions.

Applying this average rate between 1988 and 2001, fourteen years accrual of single-family housing would be 15.3 million. For comparison, the RECS data in Table 1 show an increase of 8.6 million single-family detached units and 5.3 million single-family attached units, totaling 13.9 million during the same time period. The difference may be attributable in part to the fact that they come from two separate databases, but there is also the factor of attrition to consider. The number of new houses should exceed the increase in the number of units in place, the difference equaling the number lost by fire, flood, or general decrepitude, or taken out of use for some other reason. Not knowing how to evaluate any database differences, we chose to attribute the difference to attrition.

Table 2. Average numbers of new one-family houses by heating system type (in Thousands). Compiled from U.S. Census 2001.

Heating System Type Region	Warm-Air Furnace	Heat Pump	Hot Water or Steam	Other/ None	Total
Northeast	66	11	40	4	
Midwest	204	15	5	7	
"Frostbelt"	**270**	**26**	**45**	**11**	**352**
South	261	204	2	12	
West	210	25	10	19	
"Sunbelt"	**471**	**229**	**12**	**31**	**743**
All U.S.	741	255	57	42	1095

This was done for the Frostbelt and Sunbelt separately. In the Frostbelt, there were 26.7 million single-family housing units (attached and detached) in 1987 and 30.2 million in 2001 (Table 1). According to the Census (Table 2), 4.9 million new units were built between 1988 and 2001. The number lost, in millions, is then 26.7 + 4.9 – 30.2, or 1.4. In the Sunbelt, the comparable statistics are 33.7 million in 1987, 43.4 million in 2001, and 10.4 million built in the interim, leading to 0.7 million lost units. The percentage of units in place in 1987 that were lost in the next 14 years is therefore 5.2% in the Frostbelt and 2.1% in the Sunbelt. This assumes that none of the units lost between 1988 and 2001 were built after 1987, which is of course not quite true, but it is probably not far wrong. Based on that assumption, it is reasonable to multiply each of the 1987 cell populations by (1-0.052) in the Frostbelt and (1-0.021) in the Sunbelt before adding in the units built between 1988 and 2001.

Turning now to those more recently built units, the census data were used to develop percentages of single-family housing in the 1988-2001 vintage in each of the thermal distribution categories. Warm-air furnaces and heat pumps were identified with forced-air distribution, and hot water or steam with hydronic. Electric baseboard heat was not broken out separately, so we assume it was included in the "other or none" category. This category was quite small, motivating us to assume a negligible component of electric baseboard heat in the new housing cohort of this period.

Using this procedure, the percentages of new houses by distribution system type in the Frostbelt were: Forced Air, 84.1%; Hydronic, 12.8%; Other or None, 3.1%. The percentages in the Sunbelt were: Forced Air, 94.2%; Hydronic, 1.6%; Other or None, 4.2%.

Using the Census values of 4.9 million new units in the Frostbelt and 10.4 million new units in the Sunbelt, we obtain, in the Frostbelt, 4.1 million new forced-air systems, 0.6 million hydronic, and 0.2 million "other or none." In the Sunbelt we obtain 9.8 million new forced-air systems, 0.2 million hydronic, and 0.4 million "other or none."

Finally, dividing the forced-air units by distribution system location in the same proportion as in the 1991 report yields, in the Frostbelt, 1.8 million new forced-air systems in unconditioned spaces, 2.1 million in partly conditioned spaces, and 0.2 million in conditioned spaces. In the Sunbelt, we obtain 8.0 million new forced-air systems in unconditioned spaces, 1.5 million in partly conditioned spaces, and 0.3 million in conditioned spaces. Table 3a shows these data by distribution system type and location in the Frostbelt and Sunbelt, arranged in the same way as Table 3 in the 1991 report. In each category, the 1987 numbers are shown multiplied by their respective "survival factors" (i.e., one minus the attrition fraction), added to the 14-year increment to obtain a total for 2001. The values in Table 3a are labeled "tentative" because they do not include the effect of system conversions, which are dealt with next.

Table 3a. Distribution of existing (2001) single-family housing into categories defined in this study (millions of households). Values are before considering system conversions.

Distribution System Type	Distribution System Location	Frostbelt (Northeast and Midwest)	Sunbelt (South and West)
Forced Air	Unconditioned Space (Ducts in Attic or Crawl)	6.1 X 0.948 + 1.8 = 7.6	12.9 X 0.979 + 8.0 = 20.6
	Partly Conditioned Space (Ducts in Basement)	7.0 X 0.948 + 2.1 = 8.7	2.3 X 0.979 + 1.5 = 3.7
	Conditioned Space (Ducts in Bilevel House)	0.8 X 0.948 + 0.2 = 1.0	0.5 X 0.979 + 0.3 = 0.8
Hydronic	All	7.2 X 0.948 + 0.6 = 7.4	1.8 X 0.979 + 0.2 = 2.0
Built-In Electric	Conditioned Space	1.0 X 0.948 + 0.0 = 0.9	1.8 X 0.979 + 0.0 = 1.8
Other or None	All	4.6 X 0.948 + 0.2 = 4.6	14.4 X 0.979 + 0.2 = 14.5
Totals		30.2	43.4

Note: For each cell, the first addend is the 1987 total and the second addend is the calculated 1988-2001 increment.

We would have been tempted to use these results as found, except for the fact that there is a "reality check" in the form of information from RECS (RECS 2001b). In Table HC3-4a, "Space Heating by Type of Housing Unit," a breakdown of housing units by distribution system can be obtained for the entire country. Although there is no crosscut by census region, it is nevertheless possible to compare the totals in each category with the total Frostbelt plus Sunbelt values from Table 3a.

Of the 73.7 single-family housing units, Table 3a has a total of 42.4 million forced-air systems, 9.4 million hydronic, 2.7 million built-in electric, and 19.1 million other or none. In contrast, RECS 2001b has a total of 55.3 million forced-air systems, 6.6 million hydronic, 2.4 million built-in electric, and 9.4 million other or none. In RECS, the following categories were taken to be forced-air: central warm-air furnace (gas, electric, oil, LBG) and heat pump (electric). Also, because of the prevalence of forced air, the small number of kerosene-fired systems was allocated to this category. The following were considered hydronic: steam or hot-water system (gas, oil). Built-in electric is a single category in RECS. The remaining categories are "floor, wall, or pipeless furnace (gas)", room heater (gas, LPG), other (gas, oil, LPG, wood, and unclassified), and heating stove (wood).

We interpret the discrepancy as representing conversions of older units to forced-air from some other type of system. Direct subtraction would indicate that the numbers of conversions of each type were: hydronic to forced-air, 2.8 million or 30%; built-in electric to forced-air, 0.3 million or 11%, and other or none to forced-air, 9.7 million or 51%. The decreases in each category are summed within each climate zone and applied to an increase in forced-air systems. In the Frostbelt, the net increase in forced-air systems is 4.6 million or 27%, while in the Sunbelt the net increase in forced-air systems is 8.2 million or 33%.

Some of these "conversions" may be the result of changes in definition. For example, is a home with hydronic heating that is retrofitted with a ducted air-conditioning system reclassified as forced-air? This would not be appropriate in the Frostbelt if the hydronic system is still used for heating. Nevertheless, in the absence of any further information, we will pro-rate these indicated conversions by climate zone in proportion to the numbers in Table 3a. The results of this calculation are given in Table 3b.

Table 3b. Distribution of existing (2001) single-family housing into categories defined in this study (millions of households). Values include the effect of system conversions. Current (2001) numbers are given in bold. The 1989 values from Andrews and Modera 1991 are shown in light italic.

Distribution System Type	Distribution System Location	Frostbelt (Northeast and Midwest)	Sunbelt (South and West)
Forced Air	Unconditioned Space (Ducts in Attic or Crawl)	7.6X1.27 = **9.6** *6.1*	20.6X1.33 = **27.3** *12.9*
	Partly Conditioned Space (Ducts in Basement)	8.7X1.27 = **11.0** *7.0*	3.7X1.33 = **4.9** *2.3*
	Conditioned Space (Ducts in Bilevel House)	1.0X1.27 = **1.3** *0.8*	0.8X1.33 = **1.1** *0.5*
Hydronic	All	7.4X0.70 = **5.2** *7.2*	2.0X0.70 = **1.4** *1.8*
Built-In Electric	Conditioned Space	0.9X0.89 = **0.8** *1.0*	1.8X0.89 = **1.6** *1.8*
Other or None	All	4.6X0.49 = **2.3** *4.6*	14.5X0.49 = **7.1** *14.4*
Totals		**30.2** *26.7*	**43.4** *33.7*

Forced-air systems have increased greatly on both an absolute and relative basis as the number of houses increased while the numbers of non-forced-air systems declined. In

1987, 49% of single-family homes had forced-air distribution systems, but by 2001 this percentage had increased to 74%. Although the breakdown of these systems by climate zone and distribution system location was subject to some detailed analysis, the overall percentage increase is directly obtained from the earlier and later versions of RECS.

Multifamily and Mobile Homes

Multifamily housing was treated in the same manner as in Andrews and Modera 1991, that is, by subtracting single-family data from total housing data. It is important to note that "non-single-family" includes mobile homes. The term "multifamily" will be used after mobile homes are subtracted out. The calculations are summarized in Table 4.

Three minor discrepancies in the data should be noted. Probably most important, subtracting the single-family forced-air cases from the total forced-air cases gives a number that is greater than the total of non-single-family residences. Since the number of non-single-family forced-air residences can't exceed the number of non-single-family residences with any type of distribution system, the result was reduced from 20.9 million to 19.0 million, the largest number consistent with all other data. The other two occur in the hydronic systems, and are relatively small compared with the total number of households in the U.S. The adjustments indicated in the notes to Table 4 result in zero residuals for the "other/none" category. Probably these numbers are not exactly zero, but rather are relatively small, i.e., less than a few hundred thousand units.

Table 4. Distribution system characteristics of existing (2001) non-single-family residential households, including mobile homes (in millions of households). Bold numbers are 2001 data obtained as indicated. Light italics are corresponding values from Andrews and Modera 1991, Table 4.

Building Set Description	How Obtained	Frostbelt (North-east and Midwest)	Sunbelt (South and West)
1. Total Non-Single-Family	Table 1	**14.5** *14.6*	**19.0** *15.4*
2. Total Forced Air	RECS 2001a	**28.7** *21.1*	**46.0** *28.4*
3. Single-Family Forced Air	Table 3	**21.9** *13.9*	**33.3** *15.7*
4. Non-Single-Family Forced Air	(2) – (3)	**6.8** *7.2*	**12.7** *12.7*
5. Total Hydronic	RECS 2001a	**10.8** *13.6*	**1.5** *1.9*
6. Single-Family Hydronic	Table 3	**5.2** *7.2*	**1.4** *1.8*
7. Non-Single-Family Hydronic	(5) – (6)	**5.6** *6.4*	**0.1** *0.1*
8. Non-Single-Family Other/none (includes built-in electric)	(1) – (4) – (7)	**2.1** *1.0*	**6.2** *2.6*

Comparison of the 2001 and 1987 values in Table 4 indicates, for the most part, a "non-surprising" set of changes, with the possible exception of the increase in non-single-family other or none. An important point is that no negative residuals were obtained, whereas if the data of Table 3a are used to develop Table 4, three negative results are obtained in the subtraction steps. This may lend some credibility to our choice of procedure here.

The next step is to separate mobile homes from multifamily housing. The overwhelming majority of mobile homes have forced-air distribution systems. RECS 2001b shows a total of 6.8 million mobile homes nationwide, of which 1.9 million were in the Frostbelt and 4.9 million in the Sunbelt. Of the national total 6.0 million or 88% had forced-air distribution systems (RECS 2001b). Pro-rating these by climate zone yielded 1.7 million forced-air mobile homes in the Frostbelt and 4.3 million in the Sunbelt. No significant numbers of hydronic or systems were reported for mobile homes. The estimated populations by category are given in Table 5.

Table 5. Mobile homes by distribution category (millions). Populations in 2001 are in bold, while the 1989 values from Andrews and Modera 1991 Table 5 are in light italics.

System Type	Frostbelt	Sunbelt
Forced Air	**1.7** *1.1*	**4.3** *1.8*
Hydronic	**0.0** *0.4*	**0.0** *0.0*
Other or none (includes built-in electric)	**0.2** *0.4*	**0.6** *1.4*
Totals	**1.9** *1.9*	**4.9** *3.2*

As was done in the 1991 report, we now subtract out the mobile homes from the non-single-family category to obtain multifamily populations. This is shown in Table 6 Noteworthy is the apparent decline in multifamily forced-air systems. This may be real, but it could easily be the result of a change in definition of what is multifamily and what is single-family attached. If a significant number of units were reclassified from the former to the latter category between 1987 and 2001, this might help in understanding the tremendous increase in single-family forced-air systems. Instead of a 111% increase in the single-family forced-air sunbelt category, from 12.9 to 27.3 million units, it might be more reasonable to think about the 50% increase, from 23.8 to 35.7 million, in a combined single-family/ multifamily forced-air sunbelt category. The possibility of such changes in definition must be kept in mind when interpreting these trends.

Table 6. Distribution system characteristics of existing (2001) multifamily units. Bold numbers are 2001 data obtained as indicated. Light italics are corresponding values from Andrews and Modera 1991, Table 4.

Building Set Description	How Obtained	Frostbelt (North-east and Midwest)	Sunbelt (South and West)
1. Non-Single-Family Forced Air	Table 4	**6.8** *7.2*	**12.7** *12.7*
2. Mobile Homes w/ Forced Air	Table 5	**1.7** *1.1*	**4.3** *1.8*
3. Multifamily Forced Air	(1) – (2)	**5.1** *6.1*	**8.4** *10.9*
4. Non-Single-Family Hydronic	Table 4	**5.6** *6.4*	**0.1** *0.1*
5. Mobile Homes with Hydronic	Table 5	**0.0** *0.4*	**0.0** *0.0*
6. Multifamily Hydronic	(4) – (5)	**5.6** *6.0*	**0.1** *0.1*
7. Non-Single-Family Other/none (includes built-in electric)	Table 4	**2.1** *1.0*	**6.2** *2.6*
8. Mobile Homes, Other/none	Table 5	**0.2** *0.4*	**0.6** *1.4*
9, Multifamily Other/none	(7) – (8)	**1.9** *0.6*	**5.6** *1.2*

Existing Buildings Summary

We can now update the existing building summary from Andrews and Modera 1991. The purpose of this is to pull out those "cells" that have large populations of housing units, and also have identifiable types of distribution systems, i.e., are not classified as "other or none." These are shown in Table 7.

The cells are the same as in 1991, except that mobile homes have been added to the list of cells for consideration. They are listed in order of population in 2001.

In the earlier analysis, a third of housing units could not be included, either because they were in cells that were too small or because they were in the "other or none" category. Now, only one unit in eight is missed, largely because of the increase in forced-air systems and the decrease in "other or none."

Table 7. Cell populations, existing (2001) housing. Bold numbers are 2001 data. Light italics are corresponding values from Andrews and Modera 1991, Table 7.

Cell Description				Number of Units (Millions)	
Building Occupancy	Dist. System Type	Dist. System Location	Climate Zone	2001	1987
Single Family	Forced Air	Unconditioned	Sunbelt	**27.3**	*12.9*
Single Family	Forced Air	Partly Conditioned	Frostbelt	**11.0**	*7.0*
Single Family	Forced Air	Unconditioned	Frostbelt	**9.6**	*6.1*
Multifamily	Forced Air	All	Sunbelt	**8.4**	*10.9*
Multifamily	Hydronic	All	Frostbelt	**5.6**	*6.9*
Single Family	Hydronic	All	Frostbelt	**5.2**	*7.2*
Multifamily	Forced Air	All	Frostbelt	**5.1**	*6.1*
Single Family	Forced Air	Partly Conditioned	Sunbelt	**4.9**	*2.3*
Mobile Homes	Forced Air	All	Sunbelt	**4.3**	N/A
Mobile Homes	Forced Air	All	Frostbelt	**1.7**	N/A
Total of Cells Included in Analysis				**83.1**	*59.4*
Included Cells as Percentage of Housing Units				**78%**	*66%*

ENERGY USE PER HOUSEHOLD—EXISTING RESIDENTIAL BUILDINGS

The second step in estimating energy savings potential, after market segmentation, is estimating per-household energy use. As in Andrews and Modera 1991, a cross-check procedure was used, in which data from the Gas Market Survey (AGA 2000) was used to project total space-heating energy use across the United States. This was then compared with information in the U.S. Department of Energy's Buildings Energy Data Book (DOE 2001). The evaluation of space-cooling energy use was carried out using DOE 2001 and RECS 2001c.

Space Heating—Natural Gas

AGA 2000, p. 14, gives average fuel use for gas-heat households, for each of the nine census divisions, with furnaces broken out separately from other appliances. In order to aggregate these data into the four census regions, weighted averages were calculated using the populations of gas heating customers in AGA 2000, p. 11. These numbers of customers were usually somewhat lower than the number of gas-heat households reported in RECS 2001b. The AGA numbers were used here for consistency within one source and because the resulting total gas use for heating was closer to the DOE 2002 value.

The values obtained are shown in the middle column of Table 8. They are not very different from the earlier numbers reported in Andrews and Modera 1991, except for the West region, where there is an apparent doubling of gas use for heating per household. Such a jump is probably not real, but whether the earlier or later numbers are more accurate is not known. Intuitively, the earlier value, being less than that for the South, seems low, but on the other hand the later value seems high, given that more than half of the gas heating households in the West are in California. We have no choice here but to use the data as given.

In the 1991 study, the total of 3.15 quads was compared with a value of 2.87 quads as reported by the U.S. Department of Energy. The difference of 9% was seen as being within the expected margin of error for such studies. The value of 3.44 quads as given by DOE 2001 is 24% less than the value calculated here.

Perhaps the problem is that the per-household gas heat usages reported by AGA 2000 are too high. They are, after all, higher than the corresponding 1987 values, especially in the West. This is in the face of new standards for furnace efficiency that were not in effect in 1987. If the older values are used instead of the new ones, the total calculated gas usage for space heating works out to 3.68 quads, which differs from the DOE value by only 7%. Another choice would be to use the average of the old and new values. In this case the total calculated gas usage for space heating would be 4.10 quads, a 16% difference from the DOE 2002 value.

Table 8. Annual U.S. natural gas usage for space heating in residential buildings. Bold numbers are 2001 data. Light italics are corresponding values from Andrews and Modera 1991, Table 8.

U.S. Census Region	Number of Gas-Heated Housholds (Millions)	Average Space-Heat Gas Use per Household (Million Btu)	Total Space-Heat Gas Use in Region (Quads or 10^{15} Btu)
Northeast	**10.6** *8.1*	**89.6** *86.5*	**0.95** *0.70*
Midwest	**18.8** *16.6*	**89.2** *87.9*	**1.68** *1.46*
South	**15.4** *13.6*	**53.7** *46.1*	**0.83** *0.63*
West	**13.7** *11.8*	**78.2** *30.1*	**1.07** *0.36*
Total	**58.5** 50.1		**4.53** *3.15*

In the end, we have opted for the last of these options as being a way to avoid gross error. The result of this choice is reflected in the modification of Table 8 given below as Table 8a.

Table 8a. Annual U.S. natural gas usage for space heating in residential buildings, adjusted computation. Bold numbers are 2001 data, with the exception of the middle column, where an average of 2001 and 1991 values are used. (See text for explanation.) Light italics are corresponding values from Andrews and Modera 1991, Table 8.

U.S. Census Region	Number of Gas-Heated Housholds (Millions)	Average Space-Heat Gas Use per Household (Million Btu)	Total Space-Heat Gas Use in Region (Quads or 10^{15} Btu)
Northeast	**10.6** *8.1*	**88.0** *86.5*	**0.93** *0.70*
Midwest	**18.8** *16.6*	**88.5** *87.9*	**1.66** *1.46*
South	**15.4** *13.6*	**49.9** *46.1*	**0.77** *0.63*
West	**13.7** *11.8*	**54.2** *30.1*	**0.74** *0.36*
Total	**58.5** *50.1*		**4.10** *3.15*

Space Heating—Other Fuels

As in Andrews and Modera 1991, we treated fuel oil and liquefied petroleum gas (LPG) by assuming that their fuel energy use per household is the same as for natural gas. The numbers of households for each census region were taken from RECS 2002b, and tables similar to Table 8a were then developed. The results for oil are shown in Table 9 and those for LPG are given in Table 10.

Table 9. Annual U.S. fuel oil usage for space heating in residential buildings. Bold numbers are 2001 data, with the exception of the middle column, where an average of 2001 and 1991 values are used. (See text for explanation.) Light italics are corresponding values from Andrews and Modera 1991, Table 9.

U.S. Census Region	Number of Oil-Heated Housholds (Millions)	Average Space-Heat Oil Use per Household (Million Btu)	Total Space-Heat Oil Use in Region (Quads or 10^{15} Btu)
Northeast	**6.3** *7.7*	**88.0** *86.5*	**0.55** *0.67*
Midwest	**0.8** *1.5*	**88.5** *87.9*	**0.07** *0.13*
South	**0.8** *1.3*	**49.9** *46.1*	**0.04** *0.06*
West	**0.2** *0.4*	**54.2** *30.1*	**0.01** *0.01*
Total	**8.1** *10.9*		**0.67** *0.87*

Table 10. Annual U.S. LPG usage for space heating in residential buildings. Bold numbers are 2001 data, with the exception of the middle column, where an average of 2001 and 1991 values are used. (See text for explanation.) Light italics are corresponding values from Andrews and Modera 1991, Table 10.

U.S. Census Region	Number of LPG-Heated Housholds (Millions)	Average Space-Heat LPG per House-hold (Million Btu)	Total Space-Heat LPG Use in Region (Quads or 10^{15} Btu)
Northeast	**0.4** *0.2*	**88.0** *86.5*	**0.04** *0.02*
Midwest	**1.8** *1.3*	**88.5** *87.9*	**0.16** *0.16*
South	**2.0** *2.1*	**49.9** *46.1*	**0.10** *0.10*
West	**0.7** *0.6*	**54.2** *30.1*	**0.04** *0.04*
Total	**4.9** *4.2*		**0.34** *0.25*

The totals for these two fuels agree well with the values given by DOE. For oil, the calculated value of 0.67 quads differs insignificantly from the DOE 2002 value of 0.70 quads. For LPG, the calculated value of 0.34 quads compares with 0.33 quads as given by DOE 2002. For the three fossil fuels overall, the calculated space-heat energy use is 5.11 while the sum of the values from DOE 2002 is 4.47 quads. The difference is 13%.

Space Heating—Electric

As explained in Andrews and Modera 1991, some adjustments are needed for electric heat that are not required for fossil fuels. Electric heating differs from fossil-fuel heating in several important respects. First, no heat is lost through an on-site chimney. Therefore, stack losses from furnaces need to be subtracted out in order to obtain a "base heating load" for the housing unit. The 1991 report used a factor of 0.7 for the average efficiency of existing gas heating systems. One would have hoped that the furnaces would show improved efficiencies by now, but the data from AGA 2000 do not seem to bear this out. Of course, to some extent the increases in energy use that seem to have occurred may be due in part to newer houses being larger, on average, than existing ones. In any event, the 0.7 furnace efficiency factor has been retained for use in this study.

The second difference is that many electric heating systems do not use furnaces. Some use heat pumps. For these systems a correction is needed to account for the "free" energy imported from the outside ambient. As in the 1991 report, an average coefficient of performance (COP) will be used to account for this fact. In 1991, a COP of 2 was used for all regions, but in this report the COP for the South has been raised to 3 to account for higher seasonal performance ratings at warmer temperatures. It is assumed that the duct losses for heat pumps and furnaces are the same. Although this is probably not exactly true (heat pumps may have greater duct losses), the assumption will probably not skew the results in any important way.

On the other hand, some electric heating systems use direct resistance elements within the rooms. These are like electric furnaces in that they do not "amplify" the heat, but on the other hand they don't have duct losses to contend with. This effect was not included in the 1991 report, but it seems appropriate to do so here. A conservative assumption of 25% duct loss will be made, which means that the electric baseboard systems can be given a "comparative" COP of 1.0/0.75 or 1.3.

The unnumbered table below summarizes the calculation of an effective overall COP for each census region. Data on the populations of electric furnaces, heat pumps, and in-space electric heat are taken from RECS 2001b. The "effective COP" is measured using an electric resistance furnace with duct losses as the baseline.

Populations (millions) of electric heating equipment, by type and census region.				
Unit Type and Effective COP	Northeast	Midwest	South	West
Furnaces (1.0)	0.3	0.9	9.5	2.2
Heat Pumps (2.0; in South, 2.5)	0.4	0.5	8.0	1.7
In-Space (1.3)	1.6	1.3	2.1	3.1
Average Effective COP				
All units combined	1.4	1.3	1.8	1.4

The third consideration is the difference between end-use electricity and the primary energy needed to run a central power plant. In the 1991 report, a site-to-primary energy conversion factor of 3.37 was used. DOE 2002 indicates an improvement in electric generation and transmission efficiency, in that it uses a conversion factor of 3.16. This equals a reduction in the heat rate for delivered power from 11,500 to 10,800 Btu/kWh.

Table 11. Annual U.S. primary energy usage for electric space heating in residential buildings. Bold numbers are 2001 data. Light italics are corresponding values from Andrews and Modera 1991, Table 11.

Census Region	Number of Electric-Heat Households (Millions)	Average Base Heating Load[1] (Million Btu)	Electric Energy per Household[2] (Million Btu)	Primary Energy per Household[3] (Million Btu)	Total Primary Energy (10^{15} Btu)
Northeast	**2.3** *2.1*	**61.6** *60.6*	**44.0** *48.4*	**139** *134*	**0.32** *0.34*
Midwest	**2.7** *1.4*	**62.0** *61.5*	**47.7** *49.2*	**151** *166*	**0.41** *0.23*
South	**19.6** *10.6*	**34.9** *32.2*	**19.4** *25.8*	**61** *87*	**1.20** *0.92*
West	**7.0** *3.8*	**37.9** *31.1*	**27.1** *16.9*	**86** *57*	**0.60** *0.22*
Totals	**31.6** *17.9*				**2.53** *1.71*

Note 1: Table 8a gas usage multiplied by 75% furnace efficiency.
Note 2: Previous column divided by effective COP from unnumbered table above.
Note 3: Previous column multiplied by site-to-primary energy conversion factor.

In Andrews and Modera 1991, the calculated total primary energy of 1.71 quads compared with a DOE value of 1.81 quads, a 6% difference. Now, DOE 2002 quotes a total primary energy use of 2.23 quads, which differs from the calculated value here by 12%.

The following unnumbered table summarizes the primary energy use for space heating calculated from the sources on individual fuels and reported by DOE, in both the 1991 report and the present volume.

	This Report		Andrews and Modera 1991	
Energy Source	Calculated	DOE	Calculated	DOE 2002
Gas	**4.10**	**3.44**	*3.15*	*2.87*
Oil	**0.67**	**0.70**	*0.87*	*1.00*
LPG	**0.34**	**0.33**	*0.25*	*0.39**
Electricity	**2.53**	**2.23**	*1.71*	*1.81*
Totals	**7.64**	**6.70**	*5.98*	*6.07*

*Included coal

In contrast to 1991, when the agreement between the two methods was nearly perfect, we now have a discrepancy of nearly one quad. It may be worth noting that the calculated numbers represent an annual growth of 1.7%, whereas the DOE numbers reflect an annual growth rate of just 0.7%. The latter would appear, perhaps, to be on the low side, given the housing boom and the overall growth rate of energy use of ~2% annually.

Primary Energy Ratio—Space Heating

This section, like its counterpart in Andrews and Modera 1991, considers how the mix of energy sources for each thermal-distribution system type will affect the estimate of that system's primary energy requirements as a function of climate zone. The basic assumption is that each housing unit uses a number of Btu's for space heat as given in AGA 2000, modified to reflect the amount of electricity in the mix of end uses. In the 1991 report, the corresponding gas industry source broke out single-family and multifamily housing, with the ratio of gas use for the former to that for the latter being ~0.6 in both the Sunbelt and Frostbelt. AGA 2000 does not give a similar breakout. To get around this difficulty, it was noted that single-family housing comprised ~70% of the total in both climate zones. If a ratio of 0.6 is assumed for the ratio of energy use in single-family homes to that in multifamily and mobile homes, this implies that the gas use in single-family homes will be 114% of the overall average, whereas that in multifamily and mobile homes will be 68% of the overall average. These assumptions, together with the average per-unit gas usages from Table 8a, lead to the values in the first row of Table 12.

The next step was to bring in the impact of electricity use on primary energy. For forced-air systems, a primary energy ratio (PER) was defined for each climate zone as:

PER = fraction fossil + fraction electric X electric primary / average gas use where "fraction fossil" is the fraction of housing units heated by gas, oil, or LPG; "fraction electric" is the fraction heated by electricity; "electric primary" is the average primary energy use implicit in the operation of the electrically heated units, taken from Table 11, and "average gas use" is the average gas use for the climate zone, from Table 8a. Noting that "fraction fossil" + "fraction electric" = 1.0 and that "electric primary" > "average gas use", it is necessarily true that PER must be greater than or equal to unity. The values of PER resulting from this equation are 1.07 in the Frostbelt and 1.19 in the Sunbelt.

The values of PER calculated as described above were used directly for forced-air systems, even though some error is introduced by the inclusion of hydronic and electric baseboard systems in the data base. The justification is the prevalence of forced air, making any errors relatively small. For hydronic systems, on the other hand, a PER of 1.0 was used, since very few hydronic systems use electricity as their energy source. This value matters only in the Frostbelt, since hydronic systems are not significant in the Sunbelt. All these numbers are shown in row 2 of Table 12.

Table 12. Space-heating primary energy, by building type, distribution system type, and climate zone. Bold numbers are 2001 data. Light italics are corresponding values from Andrews and Modera 1991, Table 12.

Climate Zone	Frostbelt		Sunbelt	
Building Type	Single-Family	Multifamily	Single-Family	Multfamily
Average Gas Use* (million Btu)	**101** *107*	**60** *67*	**59** *52*	**35** *31*
Primary Energy Ratio				
Forced Air	**1.07** *1.05*		**1.19** *1.32*	
Hydronic	**1.00** *1.00*		Not significant	
Primary Energy Use Per Household, Space Heating (million Btu)				
Forced Air	**108** *112*	**64** *70*	**70** *69*	**42** *41*
Hydronic	**101** *107*	**60** *67*	Not significant	

*From AGA 2000 with calculations as explained in text.

Space Cooling

The method used in Andrews and Modera 1991 for assigning cooling energy use into climate zones and house types was continued here. That is, each category of house type was related to the single category expected to have the highest per-unit cooling energy use. Single-family homes are expected to use more cooling energy than multifamily or mobile homes. Sunbelt homes are expected to use more cooling energy than Frostbelt homes. Homes with central air conditioning are expected to use more energy than those with room air conditioners.

Each category of homes was given a multiplier, expressed as a product of individual multipliers representing climate zone, house type, and air-conditioning system type. We saw no reason to change the values of these multipliers in the present report. Therefore, the multipliers used are the same as in the 1991 report, as follows:

Climate Zone: Sunbelt = 1.0 Frostbelt = 0.4

House Type: Single Family = 1.0 Multifamily = 0.6 Mobile Home = 0.6

System Type: Central = 1.0 Room = 0.5 None = 0.0

The next step is to break out the populations of various categories of housing. As in the 1991 report, this was done by using information from RECS (2001a and 2001c in the present case) and assuming statistical independence among the categories. The results of the calculation are shown in Table 13

Table 13. Populations of residential buildings with various types of air-conditioning systems (millions of households). Each matrix element contains three numbers, representing central air conditioning, room-unit air conditioning, and no air conditioning, in that order from top to bottom. Bold numbers are 2001 data. Light italics are corresponding values from Andrews and Modera 1991, Table 13.

House Type Climate Zone	Total U.S.		Single Family		Multifamily		Mobile Homes	
Total U.S.	**57.3**	*30.7*	**43.6**	*22.7*	**10.2**	*6.7*	**3.5**	*1.3*
	23.5	*26.9*	**14.0**	*16.3*	**7.8**	*8.7*	**1.7**	*1.9*
	26.2	*32.9*	**16.1**	*21.4*	**8.5**	*9.5*	**1.6**	*1.9*
Frostbelt (Northeast and Midwest)	**20.0**	10.2	**15.2**	*7.5*	**3.6**	*2.2*	**1.2**	*0.4*
	11.1	15.3	**6.6**	*9.3*	**3.7**	*4.9*	**0.8**	*1.1*
	14.4	15.9	**8.8**	*10.3*	**4.7**	*4.6*	**0.9**	*0.9*
Sunbelt (South and West)	**37.3**	20.5	**28.4**	*15.2*	**6.6**	*4.5*	**2.3**	*0.9*
	12.4	11.6	**7.4**	*7.0*	**4.1**	*3.8*	**0.9**	*0.8*
	11.8	17.1	**7.3**	*11.1*	**3.8**	*4.9*	**0.7**	*1.0*

The salient fact that emerges from this table is the sharp rise in the number of housing units with central air conditioning. This nearly doubled in the 14 years between 1987 and 2001, from 31 million to 57 million units. The trend cuts across all the categories. Units with room air conditioners or no air conditioning held steady or declined.

If the number of housing units in each category above is multiplied by the product of the appropriate multipliers, and the results are summed, one finds that there are the equivalent of 42 million single-family forced-air Sunbelt homes in the U.S., as far as air conditioning is concerned. Since DOE 2002 gives a value of 2.04 quads of primary energy for residential air conditioning, this implies a primary energy usage per single-family forced-air Sunbelt home of 42 million Btu. Using the multipliers, we can then obtain similar energy-use values for other housing categories of interest, as shown in the first two numerical rows of Table 14.

The next step was to obtain the ratio of units with central air conditioning to those with forced-air distribution systems. The former should be a subset of the latter, since essentially all residential central air conditioning systems in the U.S. use forced-air distribution, but not all forced-air systems are equipped with central air conditioners. The numbers of central air conditioning systems in each category were taken from Table 13, while the numbers of forced-air distribution systems in each category were taken from Tables 3b and 6. These are reproduced in the next two lines, with the resulting ratios in the following row.

Table 14. Space cooling primary energy use per household, by house type and climate zone for forced-air distribution systems. Bold numbers are 2001 data. Light italics are corresponding values from Andrews and Modera 1991, Table 14 (or text immediately above this table). The Multifamily numbers from the 1991 report did not include mobile homes.

Climate Zone	Frostbelt		Sunbelt	
Building Type	Single Family	Multifamily/ MobileHome	Single Family	Multifamily/ MobileHome
Multipliers (same as in Andrews and Modera 1991)	0.40	0.24	1.00	0.60
Primary Energy Use Per Household, Space Cooling (million Btu)	**17** *15*	**10** *9*	**42** *37*	**25** *22*
Units with Central Air (millions)	**15.2** *7.5*	**4.8** *2.2*	**28.4** *15.2*	**8.9** *4.5*
Units with Forced Air (millions)	**21.9** *13.9*	**6.8** *6.1*	**33.3** *15.7*	**12.7** *10.9*
Central-Air/Forced-Air Population Ratio	**0.69** *0.54*	**0.71** *0.36*	**0.85** *0.97*	**0.70** *0.41*
Average Primary Energy Use Per Household, Space Cooling via Forced-Air (million Btu)	**12** *8*	**7** *3*	**36** *36*	**18** *9*

Total Energy Use by Cell

Continuing as was done in the 1991 report, the annual primary energy usage values for heating and cooling in the ten well-populated cells of Table 7 were calculated as the number of units in the cell multiplied by the primary energy use per household for space heating (Table 12) and space cooling (Table 14). The results are displayed in Table 15.

These cells capture 95% of the 6.64 quads of primary energy used for space heating and and 83% of the 2.04 quads for space cooling (DOE 2002). The four cells composing the single-family forced-air category account for 4.48 quads in space heating (67% of the overall total) and 1.41 quads in space cooling (69% of the overall total). Thus, two-thirds of all the primary energy used for residential space heating and cooling is concentrated into single-family forced-air systems with ducts outside the conditioned space.

Table 15. Energy use by cell populations, existing housing. Bold numbers are 2001 data. Light italics are corresponding values from Andrews and Modera 1991, Table 15.

Cell Description	Number of Units (millions)	Space Heating		Space Cooling	
		Primary Energy Use Per Unit (million Btu)	Total Primary Energy (Quads)	Primary Energy Use Per Unit (million Btu)	Total Primary Energy (Quads)
Single-Family, Forced Air in Unconditioned Space, Sunbelt	**27.3** *12.9*	**70** *69*	**1.91** *0.89*	**36** *36*	**0.98** *0.46*
Single-Family, Forced Air in Partly Cond'd. Space,Frostbelt	**11.0** *7.0*	**108** *112*	**1.19** *0.78*	**12** *8*	**0.13** *0.06*
Single-Family, Forced Air in Unconditioned Space,Frostbelt	**9.6** *6.1*	**108** *112*	**1.04** *0.68*	**12** *8*	**0.12** *0.05*
Multifamily, Forced Air, Sunbelt	**8.4** *10.9*	**42** *41*	**0.35** *0.45*	**18** *9*	**0.15** *0.10*
Multifamily, Hydronic, Frostbelt	**5.6** *6.9*	**60** *67*	**0.34** *0.40*	**0** *0*	**0.00** *0.00*
Single-Family, Hydronic, Frostbelt	**5.2** *7.2*	**101** *107*	**0.53** *0.77*	**0** *0*	**0.00** 0.00
Multifamily, Forced Air, Frostbelt	**5.1** *6.1*	**64** *70*	**0.33** *0.43*	**7** *3*	**0.04** *0.02*
Single-Family, Forced Air in Partly Cond'd. Space, Sunbelt	**4.9** *2.3*	**70** *69*	**0.34** *0.16*	**36** *36*	**0.18** *0.08*
Mobile Homes, Forced Air, Sunbelt	**4.3** *N/A*	**42** *N/A*	**0.18** *N/A*	**18** *N/A*	**0.08** *N/A*
Mobile Homes, Forced Air, Frostbelt	**1.7** *N/A*	**64** *N/A*	**0.11** *N/A*	**7** *N/A*	**0.01** *N/A*
Totals	**83.1** *58.5*		**6.32** *4.56*		**1.69** *0.77*

MARKET SEGMENTATION--NEW RESIDENTIAL BUILDINGS

Assessing energy use in new buildings presents one difficulty not present in existing buildings. It requires one to foretell the future course of the housing construction industry. Nevertheless, an imperfect forecast is usually better than no forecast at all, because it provides a benchmark against which calculations can be made and which can be corrected as unfolding time provides additional information.

The first step was to compile from census data (U.S. Census 2001) a table of single-family housing completions for the years 1994 through 2001, both nationally and by climate zone. The data also broke out forced-air systems (warm-air furnaces and heat pumps). Averages over this period were then taken. For the U.S. as a whole, 1.18 million units were constructed annually, of which 0.37 million were in the Frostbelt and 0.81 million were in the Sunbelt. Of these, 1.09 million had forced-air distribution systems—0.32 million in the Frostbelt and 0.77 million in the Sunbelt. This means that 93% of houses built in this period had forced-air distribution.

Hydronic distribution systems are not widely used in new construction. Only 0.053 million hydronically heated units were constructed annually, of which 0.038 million were in the Frostbelt and 0.015 million were in the Sunbelt.

An alternative source of information is RECS 2001d, which gives housing units by year of construction. The most recent tabulated column, for housing units constructed between 1990 and mid-2001, can be used to gain insights into recent construction trends. This source reports an average construction rate of 1.36 million units annually, of which 1.01 million were single family, 0.175 million were multifamily, and 0.175 million were mobile homes. About half of the difference between the 1.18 million in the Census and the 1.01 million in RECS is due to the inclusion of recession years in the 1990-2001 time frame of the Census data. It was decided to use the higher number, to reflect a probable increase in housing construction rates over the next couple of decades.

Information from RECS 2001a allowed the regional distribution of all housing to be broken out, though this includes all units, not just single-family. The trends can be compared with those given in Andrews and Modera 1991, as shown in Table 16.

Table 16. Allocation of housing units by census region (percent of row totals).

X in column if multifamily included V		Census Region			
		Northeast	Midwest	South	West
Pre-1988 Stock*	X	21	25	34	20
Built 1980-1987*	X	14	15	48	23
Built in 1983*		11	15	52	22
Built 1994-2001 (Census)		10	21	45	24
Built 1990-2001 (RECS)	X	10	18	49	23

*From Table 16 of Andrews and Modera 1991

It can be seen that the strong concentration of new housing in the Sunbelt that was noted in the 1980's continued during the 1990's. Moreover, detailed examination of the Census data indicates that this trend remained fairly constant throughout the 1994-2001 period. We therefore see no reason to expect that it will not continue.

The next step was to gain information about the distribution of foundation types in new housing. This is important in assessing the distribution of ducts in conditioned, partly conditioned, or unconditioned spaces. RECS 2001d provided a breakdown of recent (1990-2001) single-family and small (2-4 units) multifamily housing, excluding large multifamily and mobile homes. The distribution of reported foundation types was:

- Basements – 38%
- Crawlspaces – 21%
- Slabs – 41%.

In all existing single-family and small multifamily housing (RECS 2001a) the distribution of foundations by climate zone is:

Frostbelt:

- Basements – 68%
- Crawlspaces – 16%
- Slabs – 16%

Sunbelt:

- Basements – 22%
- Crawlspaces – 34%
- Slabs – 44%

Do these data represent any kind of shift in the new construction relative to all existing units? Let us suppose that new construction is distributed the same as existing construction in each climate zone. Recognizing that ~30% of new construction is in the Frostbelt and ~70% in the Sunbelt (the exact proportions depending on the mix of single-family and multifamily in the sample), then under this hypothesis one would expect the reported breakdown of foundation types to be:

- Basements – 68% X 0.3 + 22% X 0.7 = 36%
- Crawlspaces – 16% X 0.3 + 34% X 0.7 = 29%
- Slabs – 16% X 0.3 + 44% X 0.7 = 35%

The proportion of basements is close to that in the 1990-2001 sample, but the predicted proportion of crawlspaces is higher and that of slabs lower. Let us hypothesize that this is due to a shift from crawlspace to slab construction in the Sunbelt. Specifically, let us assume that in the Sunbelt, crawlspaces in new construction have declined by 10 percentage points while slabs have increased by the same amount. This would give the following breakdown for new construction:

Frostbelt:

- Basements – 68%
- Crawlspaces – 16%
- Slabs – 16%

Sunbelt:

- Basements – 22%
- Crawlspaces – 24%
- Slabs – 54%

The resulting overall distribution would then be:

- Basements – 68% X 0.3 + 22% X 0.7 = 36%
- Crawlspaces – 16% X 0.3 + 24% X 0.7 = 22%
- Slabs – 16% X 0.3 + 54% X 0.7 = 42%

which is very close to the breakdown in RECS 2001d for the 1990-2001 cohort. We will therefore work with this assumption.

We now use the above information to develop a table distributing new housing into categories similar to those in Table 18 of Andrews and Modera 1991. As a preliminary, we display in Table 17 the calculations for the forced-air systems.

Table 17. Annual units of single-family construction by climate zone and foundation type. All numbers in thousands per year.

	Frostbelt		Sunbelt	
Total Units	320		774	
	Percent	Units	Percent	Units
Basement	68	218	22	170
Crawlspace	16	51	24	186
Slab	16	51	54	418

The data that were used in Andrews and Modera 1991 included five categories of foundations. In addition to basements, crawlspaces, and slabs, there were "bilevel" and "split level." In the RECS data, it is noted that some houses may have more than one foundation type, and so split level houses are not a separate category. The term "bilevel" probably refers to the "raised ranch" type of house in which the basement is part of the living space. If this is the case, then these would be included under basements. Finally, the earlier data included built-in electric as a separate category. In the new data, these are not broken out but are included in "other or none."

The data are presented in Table 18. As in previous tables, the values from the 1991 report are shown for comparison. However, in this case, the values shown here are the 1991 values multiplied by 1.225, which is the ratio of anticipated single-family housing starts to the number of single-family detached houses actually completed in 1983. This provides a better basis for comparing the old and new numbers.

Table 18. Allocation of new single-family housing into categories. Bold numbers are 2001 data. Light italics are corresponding values, for single-family-detached housing, from Andrews and Modera 1991, Table 18, multiplied by the normalization factor 1.225 as explained in text. (In thousands of new houses per year.)

Distribution System Type	House Foundation Type	Frostbelt (Northeast and Midwest)	Sunbelt (South and West)
Forced Air	Basement	**218** *96*	**170** *61*
	Crawlspace	**51** *17*	**186** *94*
	Slab	**51** *55*	**418** *523*
	Bilevel	**category not used** *22*	**category not used** *36*
	Split Level	**category not used** *17*	**category not used** *47*
Hydronic	All	**38** *23*	**15** *7*
Built-In Electric	All	**category not used** *50*	**category not used** *25*
Other or None	All	**8** *5*	**20** *22*
Totals		**366** *285*	**809** *815*

The two sets of data are in broad agreement. Forced-air systems dominate. In houses with forced-air distribution systems, slab construction dominates in the Sunbelt, basements in the Frostbelt.

There are, however, some obvious differences. Basements and crawlspaces have picked up market share in both climate zones, while slab-on-grade construction, though still dominant in the Sunbelt, has declined slightly. To put it another way, the proportion of slab construction still exceeds that in the existing stock, but not by as great a ratio. Built-in electric, which is probably mostly electric baseboard, was a significant category in 1983 but now, as an unknown percentage of "other or none" has clearly become unimportant. Finally, construction in the Frostbelt appears to have revived somewhat compared with the Sunbelt.

It now remains to divide the forced-air systems into categories depending on whether the ducts are in unconditioned, partly conditioned, or conditioned spaces. In Andrews and Modera 1991, this was done by assuming that houses built on slabs had their ducts in the attic and houses built over crawlspaces had their ducts either in the crawlspace or the attic. All of these are unconditioned spaces. Basements were taken to be partly conditioned. The bilevel houses were assumed to have their ducts mostly between the levels, and although this does not guarantee that the ducts are totally within the conditioned space, these houses were taken as representative of what was probably a small proportion of homes with ducts in the living space.

For the current data, the treatment of slab and crawlspace houses will be the same as in Andrews and Modera 1991. Although significant research and demonstration work has been done on conditioned-space ducts, the fraction of houses that actually receive this treatment remains small. Houses with basements, however, present a problem in that some basements are deliberately heated and used as part of the living space and some are not. RECS 2001d gives information on whether basements are heated or not. Of 39.1 million existing single-family and small multifamily housing units with basements, 22.2 million or 57% were heated throughout. Of the 4.8 million such housing units built since 1990, 3.2 million or 67% were heated throughout. Although having a heated basement does not guarantee that the ducts are completely in the living space (there may be ducts in exterior walls and there may be leakage paths to outside). Nevertheless, the duct energy losses in such houses are probably relatively small, and it seems reasonable to assign them zero energy savings potential from improved thermal distribution.

The sorting out of categories with respect to distribution system location that results from these considerations is displayed in Table 19.

Table 19. Allocation of new single-family housing by distribution system location. Bold numbers are 2001 data. Light italics are corresponding values from Andrews and Modera 1991, Table 19. (In thousands of new houses per year.)

Distribution System Type	Distribution System Location	Frostbelt (Northeast and Midwest)	Sunbelt (South and West)
Forced Air	Unconditioned Space	**102** *89*	**604** *664*
	Partly Conditioned Space	**72** 96	**56** 61
	Conditioned Space	**146** 22	**114** 36
Hydronic	All	**38** *23*	**15** *7*
Built-In Electric	All	**category not used** *50*	**category not used** *25*
Other or None	All	**8** *5*	**20** *22*
Totals		**366** *285*	**809** *815*

These numbers indicate a slight decline in the placement of ducts in unconditioned and partly conditioned spaces and a large increase in ducts in conditioned spaces. To a large extent this may simply be an artifact of the way these categories were estimated, since in the earlier report no data were available on whether basements were heated or not. However, the apparent comeback of basements, most of which are heated, indicates that at least some of this change may be real.

Time Horizon for New Housing

In Andrews and Modera it was argued that 25 years was a reasonable time frame to use in assessing the aggregate of new housing, and that a time delay of ~5 years should be used from the time of the report to the time when "new" housing begins. The argument was that a time delay was necessary before the results of research on thermal distribution would be widely applied. It turned out that this estimate of 5 years was optimistic, given that we are only now beginning to see significant interest in thermal distribution improvements beginning to permeate the housing and HVAC industries. The publication by the Air Conditioning Contractors of America of a new manual on Duct Installation and Repair is one indicator of this interest; there are others. In the absence of any compelling argument to do things differently, we will use 2005 as the beginning of the period for "new" housing in this report, meaning that the assessment of energy savings potentials will use 2030 as the benchmark year. This is in contrast to Andrews and Modera 1991, which used 2020.

Primary Energy Per Household

In evaluating energy use in new housing, an additional factor that needs to be accounted for is the likelihood that, even without advances in thermal distribution, space conditioning in new housing is going to be more energy-efficient than in existing housing. This will be brought about by improvements in space-conditioning equipment, building materials, window technology, and construction practice. Counterbalancing this, however, is a slow but continuing increase in the size of new housing. In 1981, the average floor area of a new single-family house was 1720 ft^2 (DOE 2002). This had increased to 2080 ft^2 by 1990 and to 2266 ft^2 by 2000.

Despite this, it seems reasonable to assume some conservation in space heating and cooling over the next 25 years. Consistent with Andrews and Modera 1991, we will assume 10% conservation in existing housing (exclusive of thermal distribution). In line with the increasing size of new homes, however, the estimate for conservation in new housing (again exclusive of thermal distribution), has been reduced from the 40% used in the 1991 report to 10% in this update.

The base values of primary energy per housing unit are taken from Table 12 for heating and Table 14 for cooling. In the latter case, the second row rather than the last row is used because the new units are nearly all provided with central air conditioning.

New Multifamily

Information on multifamily completions between 1994 and 2001 is given in U.S. Census 2001. This is broken down, for each census region, by whether or not the housing unit has air conditioning, whether it has a heat pump, and what the main heating fuel is. The unnumbered table below gives the average values for relevant data.

Average multifamily housing units completed, 1994-2001, and subsets by equipment and fuel. Values in thousands per year.

Census Region	All	With Air Conditioning	Gas Heat	Heat Pump	Gas Heat or Heat Pump
Northeast	22	17	18	1	19
Midwest	58	56	44	5	49
South	134	133	28	64	92
West	73	51	42	15	57
All U.S.	287	257	132	86	218

RECS 2001d gives somewhat smaller average construction rates for multifamily housing constructed between 1990 and 2001. In part this is probably because the RECS data contains recession years from the early 1990's. The Census data are used here because they are more detailed, and because the very fact that they don't include recession years probably will make them more representative of the future, where expected population growth may counterbalance future recessions.

It is plausible to assume that most units with gas heat have forced-air distribution systems and that essentially all units with heat pumps are forced air systems. In the Northeast and Midwest, the total of these categories (mostly gas heated, few with heat pumps) nearly equals the number of units with air conditioning. It therefore seems reasonable to suppose that the "gas heat or heat pump" captures the units with air conditioning, and that these are nearly all forced-air systems. Therefore, in the Frostbelt, we will assume an annual construction rate of forced-air systems of 68,000 units, and that these are also centrally cooled.

In the South, almost all new units are air conditioned, but by no means all of these have gas heat or a heat pump. It is quite possible that some of the difference between 133 thousand with air conditioning and 92 thousand with gas heat or a heat pump have electric warm-air furnaces, but probably not too great an error will be made if we assume instead that these are mostly units with electric-powered through-the-wall or packaged terminal heating and cooling units. In the West, by contrast, the sum of gas and heat-pump units exceeds those with air conditioning, but the difference is slight. Here we will assume that all of the 149,000 gas and heat-pump units constructed annually have forced-air systems and that essentially all have air conditioning.

The residual in the Frostbelt between the 80,000 new units constructed annually and the 68,000 with forced-air distribution includes not only hydronic systems but also electric heat of various kinds. The number of new hydronically heated units is therefore smaller than ~12,000 units annually, and it may be much smaller. We will therefore assume it to be zero.

New Mobile Homes

RECS 2001d gives an average construction rate for mobile homes during the period 1990-2001 of approximately 190,000 units. For the same reasons as discussed in the previous section relative to multifamily housing, this number may be on the low side as an estimate for the next 25 years.

A report by J.P. Morgan Securities (Morgan 2002) shows "manufactured housing" sales varying between 10% and 15% of the total housing market during the years 1994-2002. The RECS data are consistent with this on a percentage basis, indicating "mobile home" sales averaging 13% of the housing market between 1990 and 2001. (We take "manufactured housing" and "mobile homes" to be essentially equivalent in this context.) If the 13% figure is used in conjunction with the single-family projections in Table 19, a projected construction rate of 212,000 units annually results.

Industry figures are higher than this. The Web site of the Manufactured Housing Institute (MHI 2003) gives starts and shipments of site-built and manufactured housing, respectively, for the years 1995 through 2001 of 1,207,000 units for site-built and 317,000 units for manufactured housing. The definition of "manufactured housing" used by this source is "HUD-Code housing," so it should be roughly equivalent to the above data. Their numbers for the last two years in the series were significantly lower than the rest, but whether this is the start of a decreasing trend cannot be said at this point.

We are going to assume an annual average of 300,000 units of manufactured housing for the next 25 years.

As for where these are located, one can look to existing mobile home data in RECS 2001c, which shows that 25% are in the Frostbelt and 75% are in the Sunbelt. New construction is likely to be at least this lopsided. Another source has stated that of the top ten states for sales of manufactured housing, only one is in the northern section of the country. It seems a reasonable assumption to take 250,000 of the new units in this category to be in the Sunbelt and the remaining 50,000 to be in the Frostbelt. Essentially all of these are expected to have forced-air distribution systems and be air-conditioned.

Notes to Table 20, next page:
Note 1. For single-family housing categories, table 19 values multiplied by 25. For others, see text.
Note 2. Table 12 values reduced by 10%.
Note 3. Table 14 (second row) values reduced by 10%.

Table 20. Annual energy use by cell populations, new housing constructed between 2005 and 2030. Bold numbers are 2001 data. Light italics are corresponding values from Andrews and Modera 1991, Table 20.

Cell Description	Number of Units [Note 1] (millions)	Space Heating		Space Cooling	
		Primary Energy Use Per Unit [Note 2] (million Btu)	Total Primary Energy (Quads)	Primary Energy Use Per Unit [Note 3] (million Btu)	Total Primary Energy (Quads)
Single-Family, Forced Air in Unconditioned Space, Sunbelt	**15.1** *16.6*	**63** *41*	**0.95** *0.68*	**38** *22*	**0.57** *0.37*
Single-Family, Forced Air in Partly Cond'd. Space,Frostbelt	**1.8** *2.4*	**97** *67*	**0.17** *0.16*	**15** *9*	**0.03** *0.02*
Single-Family, Forced Air in Unconditioned Space,Frostbelt	**2.6** *2.2*	**97** *67*	**0.25** *0.15*	**15** *9*	**0.04** *0.02*
Multifamily, Forced Air, Sunbelt	**3.7** *5.3*	**38** *25*	**0.14** *0.13*	**22** *13*	**0.08** *0.07*
Multifamily, Hydronic, Frostbelt	**0.0** *0.0*	**N/A**	**0.00** *0.00*	**N/A**	**0.00** *0.00*
Single-Family, Hydronic, Frostbelt	**1.0** *0.6*	**91** *64*	**0.09** *0.04*	**0** *0*	**0.00** *0.00*
Multifamily, Forced Air, Frostbelt	**1.7** *1.9*	**58** *42*	**0.10** *0.08*	**9** *5*	**0.02** *0.01*
Single-Family, Forced Air in Partly Cond'd. Space, Sunbelt	**1.4** *1.5*	**63** *41*	**0.09** *0.06*	**38** *22*	**0.05** *0.03*
Mobile Homes, Forced Air, Sunbelt	**6.2** *N/A*	**38**	**0.24** *N/A*	**22**	**0.14** *N/A*
Mobile Homes, Forced Air, Frostbelt	**1.2** *N/A*	**58**	**0.07** *N/A*	**9**	**0.01** *N/A*
Totals	**34.7** *29.0*		**2.10** *1.30*		**0.94** *0.52*

ATTRITION

In order to treat new and existing housing consistently and move from one time frame to another, it is necessary to account for attrition in housing. This means housing units that are taken out of service, either involuntarily (e.g., fire, flood, condemnation) or voluntarily (demolition). In Andrews and Modera 1991, a previous report by one of the authors was used to estimate an attrition rate of 0.64% annually. For this report, it was decided to use more current information contained in the American Housing Surveys published by the U.S. government (AHS 1985, 1995, 2001). These reports give populations of U.S. housing units by 5- or 10-year cohort. By observing the decrease in cohort population as time progresses, it is possible to obtain an estimate of the attrition rate, since no new housing can be added to any but the current cohort.

Three 5-year cohorts, beginning in 1980, 1975, and 1970, five 10-year cohorts, beginning in 1920, 1930, 1940, 1950, and 1960, and the pre-1920 cohort were used. If the 18 cases of the nine cohorts between 1985 and 1995 and between 1995 and 2001 are considered individually, the apparent annual attrition rate ranges from a high of 1.48% to a low of -0.26%. The existence of negative attrition rates indicates that a certain amount of error is present.

If the sixteen-year span from 1985 to 2001 is used, the negative attrition rates disappear, but there is still a broad range, with a high of 1.06% to a low of 0.09%. There is no significant linear correlation of attrition rate with age. The lowest values are in the middle of the time span, while the highest values are seen for the youngest and oldest cohorts. The slope of a regression line of attrition rate against cohort age is consistent with zero.

The overall average attrition rate is 0.47% per year with a standard deviation of 0.30%. In view of the uncertainty in this value, it was decided to use 0.50% per year as a benchmark, with the understanding that the actual attrition rate may be somewhat different. The main impact of attrition will be on the existing housing stock, when it is carried forward from 2005 to 2030. At a 0.5% annual attrition rate, 12% of this stock will be lost. Considering rates one standard deviation higher and lower, a 0.2% annual rate will cause 5% of the stock to be lost, while a 0.8% rate will result in a 19% loss. These uncertainties are probably no greater than the others encountered in an analysis of this type.

A CONSISTENT TREATMENT OF EXISTING AND NEW HOUSING

The purpose of this section is to complete the analysis of residential energy use by bringing together the discussions of existing and new housing into a single consistent treatment. In Andrews and Modera 1991 it was argued that ~25 years of new housing should be considered in the energy savings projections, and in the discussion above it was decided to continue with this plan. Consistent with the 1991 report, we have elected to do the following:

1. Bring the projections of existing housing in 2001, as shown in Table 7, forward to 2005 by the addition of 4 years of additional housing distributed as shown in Table 19, and accounting for attrition during the period. At this point the "existing" housing stock is frozen, subject to 25 more years of attrition, to bring it out to 2030.

2. Add 25 years of new housing, representing 2006-2030, distributed as shown in Table 19. No correction for attrition is made here, to balance the fact that no increase in housing starts over time is projected either. Although there is no pretense that these countervailing factors will precisely cancel, the uncertainties are sufficient for us to make the judgment that any effort at greater accuracy is probably unwarranted.

The author believes that this procedure will provide a reasonable projection of the various cell populations in "snapshot" form for 2030, and therefore a sound basis for setting research and policy priorities. What these priorities should be is, of course, beyond the scope of this study.

Existing Housing—Built in 2005 or Before

In line with this assumption, the attrition factor for moving from 2001 to 2005 is $(1-0.005)^4 = 0.98$, while that for moving from 2005 to 2030 is $(1-0.005)^{25} = 0.88$.

The results of these calculations on the existing housing stock are shown in Table 21.

In the same way that the 2001 cell populations for existing housing were used to develop the energy-use estimates of Table 15, we now use the 2030 cell populations for the 2005-and-earlier "existing" housing, just derived in Table 21, to develop energy-use estimates. The computations, exactly like those of Table 15, are illustrated in Table 22. These are our projections for space heating and cooling energy use for the ten major cells, as of 2030, for housing units constructed in 2005 or earlier.

New Housing—Built 2006 through 2030

For the 25 years of post-2005 housing included in the projected 2030 housing stock, the estimates for 25 years of new housing given in Table 20 will be used. Attrition will be ignored, in part to compensate for expected increases in construction rates in later years, which have also been ignored.

Table 21. Cell populations, existing housing brought forward to 2030. Bold numbers are values used in the current study. Light italics show comparable values from Andrews and Modera 1991 (for 2020 .) All numbers are in millions of housing units.

Cell Description	Number of Units in 2001 (Note 1)		Annual New Units (Note 2)		Number of Units in 2005		Number of Units in 2030
Single-Family, Forced Air in Unconditioned Space, Sunbelt	**27.3** *12.9*	X 0.98 + 4 X →	**0.604**	= →	**29.2**	X 0.88 = →	**25.7** *14.9*
Single-Family, Forced Air in Partly Cond'd. Space,Frostbelt	**11.0** *7.0*		**0.072**		**11.1**		**9.8** *6.3*
Single-Family, Forced Air in Unconditioned Space,Frostbelt	**9.6** *6.1*		**0.102**		**9.8**		**8.6** *5.5*
Multifamily, Forced Air, Sunbelt	**8.4** *10.9*		**0.148**		**8.8**		**7.7** *10.2*
Multifamily, Hydronic, Frostbelt	**5.6** *6.9*		**0.000**		**5.5**		**4.8** *5.0*
Single-Family, Hydronic, Frostbelt	**5.2** *7.2*		**0.038**		**5.2**		**4.6** *6.0*
Multifamily, Forced Air, Frostbelt	**5.1** *6.1*		**0.068**		**5.3**		**4.7** *5.5*
Single-Family, Forced Air in Partly Cond'd. Space, Sunbelt	**4.9** *2.3*		**0.056**		**5.0**		**4.4** *2.3*
Mobile Homes, Forced Air, Sunbelt	**4.3** *N/A*		**0.250**		**5.2**		**4.6** *N/A*
Mobile Homes, Forced Air, Frostbelt	**1.7** *N/A*		**0.050**		**1.9**		**1.7** *N/A*
Totals	**83.1** *58.5*						**76.6** *55.7*

Note 1: From Table 15 Note 2: From Table 19 (single-family) or text.

Table 22. Energy use by cell populations for 2005-and-earlier ("existing") housing, projected to 2030. Light italics show values from Andrews and Modera 1991 (for 2020.)

Cell Description	Number of Units (millions)	Space Heating		Space Cooling	
		Primary Energy Use Per Unit [1] (million Btu)	Total Primary Energy (Quads)	Primary Energy Use Per Unit [2] (million Btu)	Total Primary Energy (Quads)
Single-Family, Forced Air in Unconditioned Space, Sunbelt	**25.7** *14.9*	**63** *62*	**1.62** *0.92*	**33** *33*	**0.85** *0.49*
Single-Family, Forced Air in Partly Cond'd. Space,Frostbelt	**9.8** *6.3*	**97** *101*	**0.95** *0.64*	**11** *6*	**0.11** *0.04*
Single-Family, Forced Air in Unconditioned Space,Frostbelt	**8.6** *5.5*	**97** *101*	**0.83** *0.56*	**11** *6*	**0.09** *0.03*
Multifamily, Forced Air, Sunbelt	**7.7** *10.2*	**38** *37*	**0.29** *0.38*	**16** *8*	**0.12** *0.08*
Multifamily, Hydronic, Frostbelt	**4.8** *5.0*	**54** *60*	**0.26** *0.30*	**0** *0*	**0.00** *0.00*
Single-Family, Hydronic, Frostbelt	**4.6** *6.0*	**91** *96*	**0.42** *0.58*	**0** *0*	**0.00** 0.00
Multifamily, Forced Air, Frostbelt	**4.7** *5.5*	**58** *63*	**0.27** *0.35*	**6** *3*	**0.03** *0.02*
Single-Family, Forced Air in Partly Cond'd. Space, Sunbelt	**4.4** *2.3*	**63** *62*	**0.28** *0.14*	**32** *33*	**0.14** *0.08*
Mobile Homes, Forced Air, Sunbelt	**4.6** *N/A*	**38** *N/A*	**0.17** *N/A*	**16** *N/A*	**0.07** *N/A*
Mobile Homes, Forced Air, Frostbelt	**1.7** *N/A*	**58** *N/A*	**0.10** *N/A*	**6** *N/A*	**0.01** *N/A*
Totals	**76.6** *53.4*		**5.19** *3.87*		**1.42** *0.74*

Notes: [1] Table 12 values reduced by 10%. [2] Table 14 (2nd row) reduced by 10%.

Energy-Use Summary, Residential Housing in 2030

The cells in this analysis, including both the “existing” and “new” categories, total 111.3 million housing units. DOE 2002 projects 127.1 million housing units in 2020, and if the 2000 through 2020 numbers are extrapolated to 2030, a projection of ~138 million housing units is obtained. The cells in this analysis therefore contain 80% of all the housing in 2030. The discussion surrounding Table 7 showed that the same cells in 2001 included 78% of all housing units. Given that new single-family housing is mostly in the forced-air category, the projected inclusion rate would appear to be reasonable and perhaps conservative. One factor that might go in the other direction would be a market surge toward putting ducts in the conditioned space in new construction. Aside from houses with conditioned basements, no such surge has taken place yet, but if it does the benefit would greatly overshadow any error it might cause in this analysis.

Another projection in DOE 2002 relates to energy intensity. According to this source, the primary energy consumption per household was 189 million Btu in 2000 and will be 192 million Btu in 2010 and 191 million Btu in 2020. Another “straw in the wind” is the delivered (not primary) energy consumption per square foot by vintage. DOE 2002 reports the following values:

- 46,400 Btu/ft^2 in houses built between 1980 and 1986,
- 48,400 Btu/ft^2 “ “ “ “ 1987 and 1989,
- 45,300 Btu/ft^2 “ “ “ “ 1990 and 1995,
- 46,600 Btu/ft^2 “ “ “ “ 1996 and 1967.

This essentially flat profile does not mean that individual components have not been getting better, even though house size has been factored out. Increasing use of energy-intensive appliances and air conditioning may compensate for improved equipment and envelope efficiency measures.

Focusing on changes in space heating and cooling energy per household, Andrews and Modera 1991 reported DOE values for residential primary energy use, in 1989, of 6.07 quads for space heating and 1.08 quads for space cooling. The number of households in November 1987 was 90.5 million. Ignoring the slight time offset of the data, the indicated heating and cooling primary energy use per household was 79,000 Btu. In the 2001 data used in this report, there were 107.0 million households (Table 1), while the heating and cooling primary energy numbers (DOE 2002) were 6.64 quads and 2.04 quads, respectively, indicating a primary energy use per household of 81,000 Btu. Again the relationship between the earlier and the later data is one of essentially no change.

We therefore conclude that our assumption of 10% conservation in existing and new housing over the next few decades is a reasonable benchmark, although we certainly hope that events will prove this to be overly pessimistic.

Table 23 summarizes the energy-use projections for housing in a form similar to that used in Andrews and Modera 1991. In that report, the cells were given the letter designations A through I. Some readers reported that this was confusing. We therefore are moving to a more mnemonic classification scheme in which each cell has three designators, each of which takes on values as follows:

- type of residence: sf=single family; mf=multifamily; mh=mobile home
- thermal distribution: Dunc=ducts in unconditioned space; Dptc=ducts in partly-conditioned space; Dall=ducts in all spaces; Hyd=hydronic
- climate zone: Sun=Sunbelt; Fro=Frostbelt

Table 23. Total primary energy use for space heating and cooling by cell populations. Existing and new housing aggregated in projected 2030 housing stock. Light italics show comparable values from Andrews and Modera 1991 (for 2020.)

	Cell Description	Projected Energy Use (Quads)		
		Heating	Cooling	Total
sf Dunc Sun	Single-Family, Forced Air in Unconditioned Space, Sunbelt	**2.57** *1.60*	**1.42** *0.86*	**3.99** *2.46*
sf Dptc Fro	Single-Family, Forced Air in Partly Cond'd. Space, Frostbelt	**1.12** *0.80*	**0.14** *0.06*	**1.26** *0.86*
sf Dunc Fro	Single-Family, Forced Air in Unconditioned Space,Frostbelt	**1.08** *0.71*	**0.13** *0.05*	**1.21** *0.76*
mf Dall Sun	Multifamily, Forced Air, Sunbelt	**0.43** *0.51*	**0.20** *0.15*	**0.63** *0.66*
mf Hyd Fro	Multifamily, Hydronic, Frostbelt	**0.26** *0.30*	**0.00** *0.00*	**0.26** *0.30*
sf Hyd Fro	Single-Family, Hydronic, Frostbelt	**0.51** *0.62*	**0.00** *0.00*	**0.51** *0.62*
mf Dall Fro	Multifamily, Forced Air, Frostbelt	**0.37** *0.43*	**0.05** *0.03*	**0.42** *0.46*
sf Dptc Sun	Single-Family, Forced Air in Partly Cond'd. Space, Sunbelt	**0.37** *0.20*	**0.19** *0.11*	**0.56** *0.31*
mh Dall Sun	Mobile Homes, Forced Air, Sunbelt	**0.41** *N/A*	**0.21** *N/A*	**0.62** *N/A*
mh Dall Fro	Mobile Homes, Forced Air, Frostbelt	**0.17** *N/A*	**0.02** *N/A*	**0.19** *N/A*
	Totals	**7.29** *5.17*	**2.36** *1.26*	**9.65** *6.43*

The 9.65 quads of primary energy used for residential space heating and cooling in the ten cells identified above (which was estimated to be ~80% of the total residential heating and cooling primary energy in 2030) breaks down by categories as follows:

- The single largest cell, single-family forced-air systems with ducts in unconditioned spaces, in the Sunbelt, used 41% of the energy.
- Single-family homes use 78% of the energy; the remainder is split between multifamily (14%) and mobile homes (8%).
- Forced-air systems use 92% of the energy, hydronic systems 8%.
- Sunbelt housing uses 60% of the energy, Frostbelt 40%.

SMALL COMMERCIAL BUILDINGS

At the time Andrews and Modera 1991 was being prepared, not much research had been done on thermal distribution systems in small buildings. Although it is still true today that much more research has been done in the residential sector, the information on small commercial buildings is beginning to form a coherent picture. We will therefore be in a position to estimate energy savings potentials for this sector, instead of simply leaving it "undetermined" as in the 1991 report. In this section, however, we simply wish to update the 1991 estimates of energy use. The procedures of that report will be followed except where modifications seem advisable.

It may be useful to review the factors that make small commercial buildings similar to residential ones, and in what ways they are likely to be different. These comparisons are summarized in the following unnumbered table:

Building Type Characteristic	Residential	Small Commercial	Large Commercial
Type of heating and cooling load	Envelope dominated	Envelope dominated	Core dominated
HVAC system type	Central unit + ducts	Central unit + ducts	Complex system
Location of air barrier and thermal barrier	Together	May be separate, particularly in the ceiling space	May be a less critical issue if core dominates.
Active outside air induction/exhaust	Absent or rudimentary	May include outside air, exhaust air, and makeup air system.	Usually includes extensive ventilation & exhaust systems.
Airflow rates	1000-1500 cfm	1000-10000 cfm	10000 cfm and up
Occupancy and use effects	Variability not a serious concern	Highly variable	Highly variable
Duct-equipment interactions	Simple formulas sufficient	Situation can be more complex	Situation is usually more complex

The key similarities are those shown in the first two rows of the table—envelope-dominated loads and a relatively simple system topology. The key differences are shown in the next two rows—the impact of ceiling-space configuration and the presence of significant ventilation/exhaust/makeup air systems in the small commercial case.

Stock Characteristics

The first step is to quantify the numbers of buildings and floorspace by building size category. Table 24 shows this breakdown (CBECS 1999, Table B1). As was the case a decade earlier, about half the buildings are in the smallest size category, but about half the floorspace is in buildings larger than 50,000 ft^2. The average area is up from 14,000 ft^2 in 1986 to 14,500 ft^2 today.

One departure from the 1991 report is that we set the cutoff in size for small commercial buildings to be 25,000 ft^2 instead of 10,000 ft^2. That is, the 10,000 to 25,000 ft^2 category is included in the small commercial definition. In discussions on the subject of where to draw the cutoff line between "small" and "large" commercial buildings, it was generally agreed that there is no definite line. However, where it is deemed necessary to make some sort of arbitrary cutoff, the consensus seems to be that the right number is closer to 20,000 ft^2 than 10,000 ft^2. A recent report on two projects of the Air-Conditioning and Refrigeration Technology Institute (Jacobs and Henderson 2002) on design tools intended for use in small commercial buildings, the dividing line was set at 20,000 ft^2.

Table 24. Number of commercial buildings and total floorspace by individual-building floor area. Light italics show comparable values from Andrews and Modera 1991.

Floorspace Category (ft^2)	Number of Buildings (thousands)	Total Floorspace (million ft^2)
1,001 to 5,000	**2348** *2220*	**6774** *6209*
5,001 to 10,000	**1110** *931*	**8238** *6861*
10,001 to 25,000	**708** *557*	**11153** *9119*
25,001 to 50,000	**257** *242*	**9311** *8661*
50,001 to 100,000	**145** *123*	**10112** *8559*
100,001 to 200,000	**59** *52*	**8271** *7191*
200,001 to 500,000	**23** *23*	**6851** *6737*
over 500,000	7 *6*	**6628** *4893*
Totals	***4657*** *4154*	**67338** 58229

One objective justification for choosing the dividing line to be ~ 25,000 ft^2 is that central chillers and district chilled water, which are hallmarks of large commercial buildings, start to come into use above 25,000 ft^2. The unnumbered table below shows data (CBECS 1999, Table B35) on the use of these cooling technologies by building floorspace category. The 10,000 to 25,000 ft^2 category looks like the smaller categories in the minimal use of these large-building cooling technologies. Admittedly, the use of these techniques comes in gradually as size increases, so one might argue for an even larger cutoff point. However, for the purposes of this report, 25,000 ft^2 will be used.

In general, though, this move is in line with informal discussions held over a period of years. The consensus seems to be that 10,000 ft^2 is on the low side as a cutoff for what is considered small commercial. Of course, there is no hard-and-fast line. Building size is only a rough guide to whether the thermal distribution system found inside will be more typical of residential practice (central air conditioner with a direct-expansion coil feeding a single duct system).

Table 25. Floorspace (million square feet) by floorspace category with central chillers or district chilled water. (Does not correspond to Table 25 in Andrews and Modera 1991.)

Floorspace Category (square feet per building)	Cooled Floorspace	Floorspace Cooled by Central Chillers	Floorspace Cooled by District Chilled Water	Percent Cooled by Central Chillers or District Chilled Water
1,001 to 5,000	4879	177*	201*	3
5,001 to 10,000	6212			3
10,001 to 25,000	9530	307		4
25,001 to 50,000	8116	919	294	15
50,001 to 100,000	9401	1989	525	27
100,001 to 200,000	7609	2331	630	39
200,001 to 500,000	6345	2963	470	54
over 500,000	6382	4223	630	76

*Residuals labeled "Q" in CBECS, obtained by subtracting other categories from totals. Apportioned among relevant categories in relation to cooled floorspace.

Energy Use in Commercial Buildings

DOE 2002 states that in 2000, commercial buildings used a total of 16.51 quads of primary energy, of which 2.63 quads were for space heating and 1.91 quads were for space cooling. (Interestingly, the energy use for space heating is down from 1987, whereas that for cooling is up.) Small buildings (<25,000 ft^2) had 39% of the total commercial floorspace. Assuming that energy use pro-rates roughly by floorspace, this means that small commercial buildings will use 1.03 quads for space heating and 0.74 quads for space cooling.

Projecting growth rates for energy use is a trickier proposition. Andrews and Modera 1991 reported that both space-heating and space-cooling energy use in commercial buildings were projected by the DOE to rise significantly by 2010, to 5.0 quads for heating and 1.9 quads for cooling. It appears that cooling energy has already outstripped this projection, while heating energy has actually declined. Projecting future growth rates therefore will be difficult and subject to a high uncertainty.

Determining reasonable values for primary energy use per square foot for heating and cooling required some analysis. We would have preferred to work with data on small buildings only. However, since all the necessary information on this subset was not available, we chose instead to develop average energy-use values for all commercial buildings and to assume that these are approximately valid for those under 25,000 ft^2. We would expect that this will underestimate heating energy-use estimates somewhat, since the larger buildings tend to have greater internal gains relative to envelope losses than smaller buildings do.

Our approach was as follows:

1. Determine the number of heated (or cooled) square feet for all commercial buildings in each climate zone.

2. Determine the ratio of heating (or cooling) primary energy use in the Frostbelt to that in the Sunbelt.

3. Combine these results with the overall energy use figures given above to obtain an energy-use figure per unit heated (or cooled) area.

CBECS 1999 (Table B3) gives breakdowns, by census region, of fraction of floorspace that is heated or cooled, with categories of 100%, 51-99%, 1-50%, and 0%. Assuming that the heating or cooling fractions for the second and third categories are at the midpoints of the ranges, the Frostbelt had 29.1 billion total square feet of which 24.6 billion square feet (85%) were heated and 16.0 billion square feet (55%) were cooled. The Sunbelt had 38.2 billion square feet of which 28.6 billion square feet (75%) were heated and 25.6 billion square feet (67%) were cooled.

No direct information on the ratio of energy use for heating or cooling between the Frostbelt and Sunbelt was found for commercial buildings, although some information on total energy use does exist. In the residential case, the average heating energy use in the Sunbelt, per unit area, was 46% as great as in the Frostbelt. This was determined using the primary-energy data in Tables 8-11 together with the residential square-footages given in RECS 2001a. (This ratio is down from 65% in Andrews and Modera 1991.) We judged it a better procedure to base our Frostbelt/Sunbelt breakdown on residential space conditioning than on commercial-building total energy. In line with the probable uncertainty in this ratio, we judged it reasonable to use a one-significant-figure estimate of 0.5 for the Sunbelt/Frostbelt ratio of primary energy use for heating, per unit heated area. In a similar manner, the information in Table 14 was used to find the ratio of Sunbelt-to-Frostbelt primary energy for cooling. This ranged between 2.47 and 2.55 over the three categories of single-family, multifamily, and mobile homes. In line with this, we chose 2.5 as a benchmark ratio for our small commercial study.

For heating, we set the total primary energy use equal to the sum, for Frostbelt plus Sunbelt, of the products of square footage and heating energy use per square foot. If we let H equal the heating energy use per square foot in the Frostbelt, then

$$2.63 \times 10^{15} = 24.6 \times 10^{9}\ H + 0.5 \times 28.6 \times 10^{9}\ H$$

and the solution for H is 68,000 Btu/ft^2. The Sunbelt heating energy use per square foot is then 0.5 H or 34,000 Btu/ft^2.

For cooling, a similar argument, using C for the cooling energy use per square foot in the Frostbelt, gives the equation

$$1.91 \times 10^{15} = 16 \times 10^9 C + 2.5 \times 25.6 \times 10^9 C$$

which yields $C = 24{,}000$ Btu/ft^2. The Sunbelt cooling energy use per square foot is then 2.5 C or 60,000 Btu/ft^2.

Existing Buildings—Forced-Air Distribution

The next step is to determine the amount of floorspace in small commercial buildings that is cooled using forced-air distribution systems. To do this, we need to look at the categories of cooling systems in commercial buildings. Essentially, these can be broken down into three broad types. Westphalen and Koszalinski (1999) [referred to below as W&K1999] give a good description of these:

1. Central Systems, defined as any HVAC systems that use chilled water as a cooling medium.

2. Packaged Systems, which include split systems and unitary systems such as rooftop units.

3. Individual Room Air Conditioning, which includes window AC units, packaged terminal air conditioners (PTACs), packaged terminal heat pumps (PTHPs), and water-loop heat pumps.

This taxonomy seems fairly clear, with possible confusion in that the word "packaged" occurs in categories 2 and 3.

This is important because it is the Category 2 systems that will concern us. These have forced-air distribution systems of one type or another. In contrast, the Category 1 systems use chilled water for most of the distribution, in combination with fan/coil units and perhaps segments of ductwork that cover individual zones within the building. These are mostly found in the larger buildings anyway, so they need not concern us. The distinction between Category 2 and Category 3 is important here, however, because the Category 3 systems do not have thermal distribution but deliver conditioned to the room directly from the heating/cooling unit.

Let us now look at the definitions used in CBECS 1999. These include:

Individual Air Conditioner: A type of cooling equipment installed in either walls or windows (with heat-radiating condensers exposed to the outdoor air). These self-contained units are characterized by a lack of pipes or duct work for distributing the cool air; the units condition only air in the room or areas where they are located.

Packaged Unit: A type of heating and/or cooling equipment that is assembled at a factory and installed as a self-contained unit. Packaged units are in contrast to engineer-specified units built up from individual components for use in a given building. Some types of electric packaged units are also called "Direct Expansion," or DX, units.

Residential-Type Central Air Conditioner: A type of cooling equipment in which there are four basic parts: (1) a condensing unit, (2) a cooling coil, (3) ductwork, and (4) a control mechanism, such as a thermostat. There are two basic configurations of residential central systems: (1) a "split system," where the condensing unit is located outside and the other components are inside, and (2) a packaged-terminal air-conditioning (PTAC) unit that both heats and cools, or only cools. This system contains all four components encased in one unit and is usually found in a "utility closet." If the residential type is a "PTAC," it is considered a "Packaged air-conditioning unit."

Central units (Category 1 of W&K1999) are listed in CBECS in the categories of Central Chillers and District Chilled Water. As discussed above, these are found mostly in large commercial buildings. CBECS 1999 has a small category of "swamp coolers" that could be either in-room units or units associated with forced-air distribution. Because the floorspace covered by these units is small, they will be ignored.

The term "Individual Air Conditioner" of CBECS appears to be essentially the same as Category 3 of W&K1999. The "Packaged Unit" of CBECS is clearly included in Category 2 of W&K1999.

The remaining question is then, which category does the "Residential-Type Central Air Conditioner" of CBECS 1999 fall into? From the definition, it would seem that Category 2 of W&K is the proper assignment, except that the term PTAC is also included. Individual room units such as are found in hotels and motels are often called PTACs. Still, the reference to a "utility closet" appears to indicate that the motel-type ptac is not what is meant here. For this reason, we will assign the "residential-type central air conditioners" of CBECS 1999 to Category 2 of W&K1999.

The upshot of this perhaps convoluted discussion is that the following CBECS categories will be considered to have associated forced-air distribution systems:

- Residential-Type Central Air Conditioners
- Heat Pumps
- Packaged Air-Conditioning Units

The following will be considered not to have forced-air distribution:

- Individual Air Conditioners
- District Chilled Water
- Central Chillers
- Swamp Coolers
- Other

Referring now to CBECS 1999 (Table B35), we can obtain a breakdown of small commercial buildings by cooling equipment type. This breakdown, unfortunately, has two drawbacks. First, it doesn't crosscut by census region. Second, it considers floorspace that is only partially cooled to be completely cooled, and it double-counts floorspace in buildings that have more than one type of cooling system.

We attempt to cut through this fog in the following straightforward manner:

1. Apportion cooled floorspace in all commercial buildings between small commercial and large commercial in the same proportion as total floorspace.

2. Apportion cooled floorspace in small commercial buildings between the two climate zones in the same proportion as cooled floorspace in all commercial buildings.

3. Apportion cooled floorspace in small commercial buildings between forced-air and non-forced air in the proportion indicated by CBECS 1999 (Table B35) even though the numbers add to more than the total cooled floorspace.

4. Assume that any floorspace cooled by a forced-air system is also heated with the forced-air system. Ignore any floorspace that is heated but not cooled. We justify the latter with the argument that most small commercial buildings that have uses that justify the installation of a distribution system probably will have cooling as well as heating.

Applying criterion 1, the total floorspace in all commercial buildings was 67.3 billion square feet, while the cooled floorspace was 41.6 billion square feet. The ratio is 0.62.

Applying criterion 2, with 16.0 billion cooled square feet (for all commercial buildings) in the Frostbelt and 25.6 billion cooled square feet in the Sunbelt, we conclude that for small commercial buildings, the cooled square feet break out in the same proportion, namely 38% in the Frostbelt and 62% in the Sunbelt.

Applying criterion 3, the cooled square footages for small commercial buildings in all categories add to 24.3 billion square feet, while those for the forced-air categories totaled 18.4 billion square feet. Accordingly, the fraction of cooled square footage that is cooled via a forced-air system is taken to be 76%.

The total floorspace for small commercial buildings, according to CBECS 1999 (Table B35) is 26.2 billion square feet. Applying criterion 1, 62% of this, or 16.2 billion square feet, is cooled. Applying criterion 3, 76% of that, or 12.4 billion square feet, is cooled via a forced-air distribution system. Criterion 2 splits this 4.5 billion square feet in the Frostbelt and 7.9 billion square feet in the Sunbelt.

Using Criterion 4, we say that the same floor areas are heated via forced-air systems.

The above information now enables the primary energy for heating and cooling small commercial buildings in the two climate zones to be estimated. To recapitulate, in the Frostbelt, the heating and cooling energy per square foot were 68,000 and 24,000 Btu, respectively, while the comparable numbers for the Sunbelt were 34,000 and 60,000 Btu. Applying these rates to the square footages with forced-air distribution found immediately above, i.e., 4.5 billion square feet in the Frostbelt and 7.9 billion square feet in the Sunbelt, we obtain the values shown in Table 26.

Table 26. Space Conditioning Primary Energy Use in Existing (1999) Small Commercial Buildings with Forced-Air Distribution. In Quads.

Function Climate Zone	Heating	Cooling	Total
Frostbelt	0.31	0.11	0.42
Sunbelt	0.26	0.47	0.73

Attrition and Construction Rates

Key parameters affecting the addition of new commercial building floorspace are the annual rate of addition and the annual rate of attrition. The Annual Energy Outlook of the Energy Information Agency (U.S. Department of Energy) provides information on the assumptions used in their projections of commercial-building energy use.(EIA 2002, 2001, 2000) These publications give year-by-year projections, through 2020, of commercial-building floorspace and also of what is left after attrition is accounted for. This makes it possible to extract the DOE's projections of attrition and construction in the commercial sector. Table 27 shows the data, averaged over the 21 to 23 years given in the Annual Energy Outlook for the years 2000, 2001, and 2002. The table gives averages through 2020 and also averages just through 2005.

Table 27. Projected attrition, construction, and annual increase rates (in percent) for commercial building floorspace as reported y the Annual Energy Outlook (AEO).

	Projection through 2005				Projection for 2006 – 2020			
Issue of AEO	2000	2001	2002	**Weighted Average**	2000	2001	2002	**Weighted Average**
Attrition	1.16	1.17	1.20	**1.2**	1.21	1.15	1.13	**1.1**
Construction	2.54	3.26	3.39	**3.2**	2.12	2.49	2.84	**2.3**
Annual Increase	1.34	2.05	2.15	**2.0**	0.88	1.31	1.68	**1.2**

One thing that is quite obvious is the large changes in some of these parameters from one year to the next. This would indicate, at the very least, a high degree of uncertainty in the true value, at least for the construction and annual increase rates. It also makes it difficult to know which values to select for use in this study. One could simply take the latest available values, but who is to say that they won't be out of data tomorrow?

It seemed reasonable to us to take a compromise position: use all the above available information but weight the more recent items more heavily. In the end we took weighted averages, giving 2002 data a 50% weight, the 2001 numbers a 33% weight, and the 2000 values a 17% weight. The weighted averages, to one significant figure, are given in the bold-type columns of Table 27.

Four other issues need to be dealt with. The first is that these projections are for all commercial buildings, not just small ones. Are these rates of change applicable to small commercial buildings as a distinct subset of the total population, or are there significant differences between small and large buildings with respect to the above parameters?

Useful information on this point can be found in CBECS 1999 (Table B7). There, populations of buildings are broken down by floorspace and vintage. From these data, it can be seen that the proportion of floorspace built in recent decades in small (<25,000 ft^2) buildings has generally been growing, from a low of 30% in the 1960s through 38% in the 1970s, 36% in the 1980s, and 43% in the 1990s. (This assumes that the attrition rate is not a strong function of building size.) According to the same source, the percentage of floorspace in small buildings of all vintages is 46%. We make the judgment that there is not enough difference between the overall percentage and that for the most recent decade to warrant any correction, given the uncertainties in future trends and given also that the past trend, to the extent that there is any, seems to be in the direction of increasing small commercial representation in the new building stock.

The second point is whether the relative prevalence of forced-air systems in small commercial buildings is increasing. One could argue by analogy with residential buildings that the proportion of forced-air systems in new buildings is increasing. In the existing stock, we found that about half of the existing stock is heated and cooled using forced air, so there is certainly room for increase.

Some information can be gleaned from CBECS 1999 Table B35. According to the data presented, the prevalence of forced-air cooling system categories (residential central, heat pumps, and packaged units) was 7% greater in buildings constructed since 1970 than in all buildings. This is for all commercial buildings, not just small ones. Since forced-air systems are somewhat more concentrated in the smaller buildings (because they are underrepresented in the central-chiller category) we are probably justified in assigning a somewhat greater effect for these buildings. We therefore will assume that in new small commercial buildings, the increasing prevalence of forced air should be accounted for by multiplying the calculated new population by 1.1.

The third issue is whether the rates of change in Table 27 will vary between the Frostbelt and the Sunbelt. It is well known that rates of new construction are higher in the Sunbelt than in the Frostbelt. The existing floorspace is also skewed towards the Sunbelt, both of all commercial buildings and of small commercial buildings with forced-air thermal distribution systems. The question is, if one applies the above rates of change to the existing stock, will this accurately reflect new additions? In particular, won't the older vintages of buildings, which exist mostly in the Frostbelt, skew the analysis if such a straightforward method is applied?

To investigate this question, CBECS 1999 (Table B3) was consulted. From the data in this table, it was possible to determine that the percentage of floorspace built in recent decades in the Sunbelt was 57% in the 1960s, 65% in the 1970s, 65% in the 1980s, and 62% in the 1990s. The percentage of all existing floorspace in the Sunbelt was 57%. From our analysis above, the allocation of floorspace heated and cooled with forced-air distribution systems was 64% in the Sunbelt and 36% in the Frostbelt. Thus, the division of the floorspace of interest to this analysis was close to the overall trends in recent construction. Within the uncertainties of the data and of future projections, it seems reasonable to use the same rates of change, equal to the ones in Table 27 for the Sunbelt and Frostbelt.

A fourth point is whether the above values, projected by the DOE for the period through 2020, can be used through 2030. Given the uncertainties involved, it seems unreasonable to expect any greater accuracy through greater effort. The above numbers are the best we are able to develop. We think they give a reasonable expectation sufficiently accurate for the kind of planning that this analysis is likely to be used for, without expecting more than one-figure accuracy (if that) to be realized in the actual unfolding of events.

On all of the above counts, therefore, we consider it reasonable to use the bold-faced projections from Table 27 in the analysis, except for the correction factor of 1.1 to account for increasing use of forced air.

Existing Buildings Projected to 2030

We've already estimated that as of 1999 the floorspace heated and cooled using forced-air distribution systems in small commercial buildings was 4.5 billion square feet in the Frostbelt and 7.9 billion square feet in the Sunbelt. Using the information in Table 27, we first project these forward to 2005 using the overall rate of increase for this period, namely 2.0%. The floorspace values for the Frostbelt and Sunbelt therefore increase to 5.1 billion and 8.9 billion, respectively. We then apply the 2006-2020 annual attrition rate of 1.1% over the period 2006-2030, which causes these populations to subside to 3.9 billion and 6.7 billion, respectively.

In line with the residential case, we will assume that conservation efforts will make these buildings 10% more efficient (in all respects other than thermal distribution) by 2030. We therefore reduce the calculated energy consumption rates for heating and cooling by this amount. This produces energy consumption in Btu per square foot for heating and cooling, respectively, as follows:

Mode Climate Zone	Heating	Cooling
Frostbelt	61,000	22,000
Sunbelt	31,000	54,000

These values, combined with the floor area of existing (2005 and before) buildings in the Sunbelt and Frostbelt projected to remain in 2030, produce the energy use values for these "cells" as shown in Table 28.

Table 28. Space Conditioning Primary Energy Use in Existing (2005 and before) Small Commercial Buildings with Forced-Air Distribution, Projected to 2030. In Quads.

Function Climate Zone	Heating	Cooling	Total
Frostbelt	0.24	0.09	0.33
Sunbelt	0.21	0.36	0.57

New Small Commercial Buildings

In line with the program outlined for residential buildings, we take the set of small commercial buildings to be constructed during the years 2006-2030 as the "new" buildings that could benefit from improved thermal distribution system design practices "from the ground up."

In the preceding section, we made the judgment that no useful purpose would be served in complicating the analysis over these three questions:

- Are the projected rates of construction for commercial buildings applicable to small commercial buildings?
- Are the rates of change applicable to the Frostbelt and Sunbelt equally?
- Can the projections through 2020 be extrapolated to 2030?

We therefore will use the 2.3 percent annual new construction rate as displayed in Table 27.

A real question exists, however, concerning an appropriate attrition rate for new buildings. Despite indications from the residential side that attrition is not a strong function of building age, it seems intuitively reasonable to assign a lower attrition rate to newer commercial buildings. In the residential case, the overall attrition rate seems to be lower, which may simply mean that attrition occurs mostly through involuntary effects such as fire, natural disaster, and condemnation, and not because of building obsolescence. In the commercial-building case, the overall attrition rate is higher, and this is presumably caused by additional, profit-related reasons for taking buildings out of service.

We make the argument that for relatively new commercial buildings, the attrition will more closely resemble the residential case, since profit-related reasons for taking buildings out of service take time to appear. This is, admittedly, a very rough argument, and we wish we had better information. However, we don't, and therefore we are going to use the residential attrition rate of 0.5% annually here. The upshot of this is that a net addition rate of new small commercial buildings between 2006 and 2030 will approximate the difference between 2.3% construction and 0.5% attrition, or 1.7%.

We also need to remember the factor of 1.1, explained above, to account for the increased use of forced air in new small commercial buildings, compared with the existing stock.

It then becomes a simple matter to project the number of such newer buildings that will be in the stock in 2030.

$$\text{New Buildings (2030)} = 1.1 \times \text{Existing Stock (2005)} \times [1.017^{25} - 1]$$

The factor in brackets is equal to 0.52. Therefore, the projection is that in 2030, there will be 1.1 X 0.52 X 4.5 = 2.6 billion square feet of new small commercial floorspace, heated and cooled with forced air, in the Frostbelt and 1.1 X 0.52 X 7.9 = 4.5 billion square feet in the Sunbelt.

In the residential case, we argued that the increasing size of new houses will to a great extent counteract improvements in energy efficiency on a per-square-foot basis. Here, however, we are doing the analysis on the basis of square feet, not buildings, so this argument doesn't apply. It seems reasonable to assume an improvement in energy efficiency other than from thermal distribution in these buildings. In line with Andrews and Modera 1991, therefore, we will continue to use a 20% conservation factor, relative to current energy use.

This produces energy consumption in Btu per square foot for heating and cooling, respectively, as follows:

Mode Climate Zone	Heating	Cooling
Frostbelt	54,000	19,000
Sunbelt	27,000	48,000

These values, combined with the floor area of existing (2005 and before) buildings in the Sunbelt and Frostbelt projected to remain in 2030, produce the energy use values for these "cells" as shown in Table 29.

Table 29. Space Conditioning Primary Energy Use in New (2006-2030) Small Commercial Buildings with Forced-Air Distribution. In Quads.

Function Climate Zone	Heating	Cooling	Total
Frostbelt	0.14	0.05	0.19
Sunbelt	0.12	0.21	0.33

Energy-Use Summary, Small Commercial Buildings in 2030

Combining the existing and new buildings analyzed in the preceding sections, we exhibit in Table 30 the primary energy use for space heating and cooling of the two "cells" of small commercial buildings with forced-air distribution in the Frostbelt and Sunbelt.

Table 30. Total primary energy use for space heating and cooling by cell populations. Existing and new small commercial buildings aggregated in projected 2030 stock. Light italics show comparable values from Andrews and Modera 1991 (for 2020.)

	Cell Description	Projected Energy Use (Quads)		
		Heating	Cooling	Total
sc Dall Sun	small commercial, forced-air, Sunbelt	**0.33**	**0.57**	**0.90** *0.64*
sc Dall Fro	small commercial, forced-air, Frostbelt	**0.38**	**0.14**	**0.52** *0.55*

PART II. ENERGY SAVINGS POTENTIALS

METHODOLOGY

Andrews and Modera 1991 had two roughly equal sections. In the first section, the primary energy used by significant clusters of buildings similar in type, distribution system, and climate zone were estimated. This was similar to everything above this point in the present report. The second section estimated the energy savings potential from thermal distribution improvements in each of these "cells" of buildings.

When the scope of work for this report was defined, it was anticipated that an update of the second section would be performed largely by another laboratory, with the results to be incorporated into this analysis. For various reasons, that additional work was not included in the other laboratory's work plan.

The discussion below will therefore not be a thoroughgoing recalculation of the energy savings potentials by "cell." Rather, it will look at new information that has become available since 1991, with a view toward revising, upward or downward as appropriate, the potential estimates made at that time. If no strong reason is found to make an adjustment, the 1991 estimates will be left alone. Also, some of the "cells" of buildings did not have enough information to make any estimate at all in 1991. These were called "undetermined." Perhaps some of these can be filled in now.

The two objectives of this necessarily limited effort are to answer these questions:

- Have any of the estimates made in 1991 changed significantly, either because of new analysis or because the housing market has changed?
- Can any of the "undetermined" potentials from 1991 be quantified now?

In defining energy savings potentials, the 1991 report made a distinction between "current" potentials and "full" potentials. Current potentials included technologies that "are developed, and that are reasonably well understood, at least in the buildings research community." Full potentials included "what we considered to be the ultimate potential for savings possible by modifications to the thermal distribution systems within each cell for which we had sufficient information."

The reason for making this distinction was essentially that the known and proven means of upgrading duct systems were essentially limited to hand sealing with mastic and possibly the placement of additional layers of duct wrap around existing ducts. Available techniques in new construction, although theoretically more extensive, were in practice limited to the same restricted repertoire.

Today, the available options are broader. For retrofit of existing buildings, we have aerosol duct sealing as a commercially available option. Research is ongoing into optimal methods of adding insulation to existing ductwork. In new construction, it is widely recognized that placing the ducts within the conditioned space is the optimal solution, not only for energy savings, but also for health, safety, and comfort considerations. If that cannot be done, then guidelines for optimal design of a duct system that is partly outside the conditioned space have also been given. Finally, government-sponsored development of inherently leak-free ducts is ongoing. Some of this is ready to enter the commercialization stage.

We therefore will base our energy savings potential estimates on the widespread application of these techniques. The one restriction that we place on this is the recognition that, even in the best of all possible worlds, not all ducts in new construction will be placed within the living space. What fraction of homes can ultimately be expected to receive this treatment is unknown. In estimating the energy savings potential, however, we have judged it reasonable to say that 50% of the new houses built between 2006 and 2030 could get this treatment if there were a strong national effort to convince stakeholders of the energy, comfort, and health benefits of doing this.

Some might say, "Why not 100%?" while others will respond "a few percent at most is all we can expect." While understanding both points of view, we offer no further justification for our middle-of-the-road approach.

On small commercial buildings, we start with the recent literature on energy losses and then try to determine how much of these might be amelioriated through retrofits and through changes in new-construction practice. Where small commercial buildings are similar to residences, we use the residential experience as a guide. In areas where they are different, we are forced to strike out on a new path.

RESIDENTIAL BUILDINGS

In Andrews and Modera 1991, energy savings potentials for both existing and new housing were calculated using then-current practice as a benchmark. The business-as-usual assumption was that in the absence of change, ducts in unconditioned spaces would typically lose ~35% of the heating or cooling energy given to them by the equipment. Ducts in partly conditioned spaces would continue to lose ~20% of the heating or cooling energy.

In 1991, there was as yet no concerted effort within the homebuilding or HVAC industry to change the current practice. It therefore seemed reasonable to benchmark any improvements against these values.

Today, however, the situation is not so clear. Pessimists would argue that nothing really has changed, and that most ductwork going into houses today is not much better than it has been in the past. Optimists would counter that we are at the beginning of a revolution, that the industry is in the process of change that will continue and build on itself.

To the best of the author's knowledge, the research that would be needed to settle this question with any certainty has not yet been done. To a large extent, it will depend on decisions yet to be made.

Let us suppose, however, that the truth is somewhere between the optimistic and pessimistic outlooks described above. What would this mean with regard to the calculation of energy savings potentials. In particular, what benchmark should be used as the "business as usual" case against which the savings are to be calculated. Should improvements already "in the pipeline" be folded into the business-as-usual scenario? This would, of course, reduce the savings potentials yet to be obtained, and in the view of some would "penalize" past efforts for their very success. On the other hand, if a savings potential estimate is to give a true picture of what further value might be achieved by additional effort on the part of the DOE or other government agencies, then successes already achieved (or reasonably to be expected) should be included in the baseline.

We take the latter view. For new housing constructed after 2005, we will assume some improvement in distribution efficiency even in the absence of further DOE effort. Specifically, instead of the ~35% losses typical of existing duct systems in unconditioned spaces, we will assume ~25% losses as the baseline, a ten percentage-point improvement. Similarly, instead of ~20% losses in existing systems in partly conditioned spaces, we will assume 15% losses as the baseline, a five percentage-point improvement. The percentage breakdown between conduction and leakage losses will remain unchanged.

Single-Family Forced-Air Systems with Ducts in Unconditioned Spaces

In Andrews and Modera 1991, the energy loss from a typical existing duct system in unconditioned spaces was 35% in heating and 34% in cooling. Forty percent of this was found to come from heat conduction through the duct walls and the remaining 60% was attributed to air leakage.

The "current" energy savings potentials for forced-air systems with ducts in unconditioned spaces was benchmarked at 17 percentage points. This was based on the assumption that in a typical retrofit, duct leakage would be reduced by 50% and duct insulation would be increased to R-8, typically by the addition of R-4 to an existing R-4 insulated system.

Have there been any developments that should cause us to change these estimates?

Perhaps the most significant technology development in the ensuing 12 years has been the commercialization of aerosol duct sealing. Aerosol sealing was developed and tested during the 1990's and is now commercially available. Field evaluations of its effectiveness have been carried out.(Ternes and Hwang 2002, Modera et al. 1996) Both reports found that aerosol sealing is superior to hand sealing. Ternes and Hwang (2002) found that it achieved 16% to 60% better air leakage reductions than hand sealing and potentially could reduce labor and repair costs by 30%. They also recommended extending the use of the technique to mobile homes. Modera et al. (1996) found that aerosol sealing was capable of sealing ~80% of the leakage it encountered, assuming that catastrophic leaks such as disconnected ducts had first been repaired. The entire sealing protocol, including setup, supplementary conventional sealing, and cleanup, was found to take an average of 5.5 person-hours of labor, a significant saving over conventional sealing, which would have required an estimated 10.5 person-hours on average. The injection process itself consumed about 20% of this time.

In view of these findings, we consider it reasonable to increase the estimate of duct sealing effectiveness from 50% to 75%.

No comparable technology to improve the effectiveness or reduce the labor cost of retrofit duct insulation has been developed. Research is underway, however, on a method of adding internal insulation to runout ducts accessed from the registers.(Andrews 2002) If successful, this would greatly reduce the labor effort required to add insulation to runout ducts, which are usually harder to reach than trunk ducts and, even if reachable, tend to have greater length relative to surface area. This means that the amount of "technician crawl" would be greatly reduced if the runouts could be insulated internally through the registers, and external insulation only needed to be added to the trunk ducts. Another retrofit option, perhaps most useful for flexible-duct runouts, would be to replace them with higher R-value runs that are properly sized and hung to minimize pressure drops. Although ideas such as these remain to be proved, they may add some credibility to the notion that duct insulation levels can be increased in retrofit. They do not, in our judgment, provide any reason for increasing the estimate of how much additional insulation can be added to existing ductwork. We will continue to use R-8 as a benchmark goal.

We recalculate the energy savings potential as follows, based on 34% losses in the as-found system. The conductive losses are 40% of this, or 13.6 percentage points. These are reduced by half, for a savings of 6.8 percentage points. The leakage losses are 60% of the total, or 20.4 percentage points. Andrews and Modera estimated that half of this could be saved, or 10.2 percentage points. The total "current" savings potential, therefore, was 17 percentage points. In this report, we increase the leakage savings estimate to three-fourths of the as-found leakage losses, or 15.3 percentage points. The total savings potential is therefore 22.1 percentage points, which we round to 22% of the as-found heating and cooling energy use.

What about new construction? Considerable effort has been put into the development of guidelines for better duct systems, and this has been largely endorsed by the building and HVAC industries. Both industries have published manuals advocating better design and installation practices.

The National Association of Home Builders Research Center has published several fact sheets, guides, and research reports dealing with the issue of ducts in the conditioned space. The placement of ducts in the living space is enthusiastically endorsed: "Heating, Ventilating and Air Conditioning (HVAC) equipment and, especially, associated ductwork, is often placed in locations such as crawlspaces, attics, and garages. There is an opportunity to have a positive impact on energy efficiency, comfort, and health by instead placing HVAC equipment and ductwork fully inside the insulated and air-sealed shell of the house, known as conditioned space." (NAHBRC 2003) A builders' manual

(NAHBRC 2001) on practical ways to implement conditioned-space ductwork has also been published by this building industry research center.

The Air Conditioning Contractors of America has published a manual on residential duct diagnostics and repair (ACCA 2003) that advocates placement of ducts in the conditioned space in new construction. It also outlines a strategy for minimizing energy losses from ducts in the event that the conditioned-space option is not chosen.

In Andrews and Modera 1991, the "current" energy savings potential for new housing with forced-air systems in unconditioned spaces was based on a projection that 30% of the new houses would have zoned, 90% efficient duct systems and the other 70% would have 80% tighter ducts than the current average with R-12 insulation and balanced returns. This produced a savings potential of 32 percentage points for heating and 30 percentage points for cooling.

In this report, we will assume that the available energy savings potential will be captured if half the new housing is constructed with ducts in the conditioned space (~100% efficient) and the other half has ducts outside the conditioned space, insulated and sealed equivalently to the values projected for retrofits of existing buildings, namely 75% lower leakage losses and 50% lower conduction losses than in the current existing building stock. For the latter systems, we estimated that the remaining losses would be ~12%. Thus, the average losses would be 50% of zero plus 50% of 12%, or 6%. The benchmark losses are 25%, which leaves a savings potential of 19%.

For single-family houses with ducts in unconditioned spaces in the Sunbelt (cell sfDunc Sun), the energy-use values displayed in Table 22, for existing buildings, are 1.62 quads for space heating and 0.85 quads for space cooling. Using the 22% savings possibility found above, the quad savings potential for both heating and cooling is 0.54. For new houses in this cell, the corresponding energy-use values (Table 20) are 0.95 quads for heating and 0.57 quads for cooling. Using the savings potential of 19% for these buildings yields a quad savings of 0.29. The total energy savings potential for cell sfDunc Sun is then 0.83.

For single-family houses with ducts in unconditioned spaces in the Frostbelt (cell sfDunc Fro), the energy-use values displayed in Table 22, for existing buildings, are 0.83 quads for space heating and 0.09 quads for space cooling. Using the 22% savings possibility found above, the quad savings potential for both heating and cooling is 0.20. For new houses in this cell, the corresponding energy-use values (Table 20) are 0.25 quads for heating and 0.04 quads for cooling. Using the savings potential of 19% for these buildings yields a quad savings of 0.05. The total energy savings potential for cell sfDunc Sun is then 0.25.

Single-Family Forced-Air Systems with Ducts in Partly-Conditioned Spaces

Andrews and Modera 1991 projected an average distribution loss of ~20% for ducts in partly conditioned spaces (i.e., basements that are not intentionally conditioned). The "current" energy savings potential was estimated to be 8%. The major reason why both the energy losses and the savings potential are lower than for ducts in unconditioned spaces is thermal regain. This is defined as any effect that mitigates the losses. One cause of thermal regain is reduced heat loss from the house because the basement is warmer with ducts than without. Another effect is that the ducts, generally located near the basement ceiling, are in a warmer environment because of the heat losses; this retards conductive losses relative to what they would be if this heat just went away immediately to the outside, as for the most part it does when the ducts are in, say, a vented attic.

Because of our more optimistic estimate of the potential for sealing ducts, compared with the "current" estimate of the 1991 report, the savings potential in existing buildings increased from 17% (1991 "current" estimate) to 22%. If the 8% savings estimate is increased in a similar manner, a new estimate of 10% results. Because of the small difference, closer analysis would not seem to be warranted.

New housing with ducts in basements are prime candidates for pulling all the ductwork within the conditioned space. The basement ductwork is already there; it is only required to insulate the basement walls to make this space fully conditioned. Any risers (to the second floor, for example) can just as easily be run through interior walls as exterior ones. We therefore will project energy savings potentials for this type of system on the basis that the ducts will now be in the conditioned space, by means of basement wall insulation and all risers in the building interior. Builders will need to be cautioned to avoid strategies that apparently bring the ducts within the conditioned space, but that in reality do not. Use of the space between the first and second floors as a plenum is an example of such a misapplication.

Since the baseline losses in new housing with ducts in partly conditioned spaces have been projected at 15%, it would not be unreasonable to estimate the savings potential at 15%. Interactive effects might reduce this somewhat. For example, if the basement walls are insulated instead of the basement ceiling, the overall heating load might increase somewhat. It is beyond the scope of this report to estimate this possibility via simulation, and we find no data on the question. We will, somewhat arbitrarily, reduce the savings potential estimate to 12% to account for any such effects and for any lingering losses in duct risers even though they are located in interior walls.

For single-family houses with ducts in partly conditioned spaces in the Sunbelt (cell sf Dptc Sun), the energy-use values displayed in Table 22, for existing buildings, are 0.28 quads for space heating and 0.14 quads for space cooling. Using the 10% savings possibility found above, the quad savings potential for both heating and cooling is 0.04. For new houses in this cell, the corresponding energy-use values (Table 20) are 0.09 quads for heating and 0.05 quads for cooling. Using the savings potential of 12% for these buildings yields a quad savings of 0.02. The total energy savings potential for cell sf Dunc Sun is then 0.06.

For single-family houses with ducts in partly conditioned spaces in the Frostbelt (cell sf Dptc Fro), the energy-use values displayed in Table 22, for existing buildings, are 0.95

quads for space heating and 0.11 quads for space cooling. Using the 10% savings possibility found above, the quad savings potential for both heating and cooling is 0.11. For new houses in this cell, the corresponding energy-use values (Table 20) are 0.17 quads for heating and 0.03 quads for cooling. Using the savings potential of 12% for these buildings yields a quad savings of 0.02. The total energy savings potential for cell sf Dunc Sun is then 0.13.

Single-Family Hydronic

This cell is significant only in the Frostbelt, and is labeled sf Hyd Fro. Energy-use values for this cell were projected at 0.42 quads for pre-2006 housing ("existing") and 0.09 for housing built between 2006 and 2030 ("new"). This is all heating, since hydronic cooling is rare in residential applications. Andrews and Modera 1991 projected energy savings possibilities through the provision or addition of insulation to piping in unconditioned spaces and through a strategy that involved the use of a condensing boiler in conjunction with a reduced water flow rate (which reduces the return-water temperature enough to make condensing possible, at least in gas-fired boilers).

How efficient are existing hydronic systems? Much higher than the typical existing forced-air system, very probably. First, hydronic systems do not have leakage losses. Second, the proportion of systems in partly conditioned spaces is probably higher for hydronic systems than forced-air, because hydronic systems are concentrated in the Northeast, which also has a disproportionately large fraction of its houses with basements. The hydronic section of ASHRAE Standard 152 (ASHRAE 2002) projects efficiencies in the 80% to 90% range for system configurations that appear typical. Andrews and Modera projected a 10% savings potential, on average, for these systems. Given the small contribution of hydronic systems to the total energy savings potential, it does not appear warranted to attempt any more accurate estimate than this. The energy savings potential for these houses is therefore 0.05 quads.

Mobile Homes

Mobile homes (otherwise known as HUD-code housing) were not represented in Andrews and Modera 1991. The increasing levels of interest in the energy efficiency of this category of housing among researchers, the DOE, the EPA, and HUD motivated their inclusion this time around.

One significant source of information on the distribution efficiency in HUD-Code housing is Conlin 1996. This study gathered field data on 24 "typical" new manufactured homes in four U.S. regions. Losses were quantified via a combination of measurements and modeling. Losses attributable to air distribution systems in the heating mode averaged 32% with R-7 insulation and 51% for uninsulated ducts. There appeared to be no provision for thermal regain in these calculations. In the cooling mode, the losses averaged ~27% without regain. For underfloor ducts, estimated thermal regain raised the final estimate of distribution efficiency to 88%, while for attic ducts the final estimate for distribution efficiency was 73%. The work, although in many respects preliminary, was seen as strong motivation for the manufactured home industry to address thermal inefficiency in duct systems.

For the homes with attic ducts, efficiency was in the range generally quoted for attic-duct systems, albeit at the higher end of the range. For underfloor ducts, the efficiency was higher than our estimate for ducts in partly-conditioned spaces. Of course, these tests were done on new homes. The existing stock is almost certainly not as good as this.

The following assumptions will be made. Mobile homes in the Frostbelt will be assumed to have most of their ducts under the floor, while most of those in the Sunbelt will be assumed to have most of their ducts in the attic. This is based on the generally accepted optimal register locations near the ceiling for cooling and near the floor for heating. Existing homes with underfloor ducts will be assumed to resemble existing single-family homes with ducts in partly conditioned spaces (i.e., 10% energy-savings potential), while existing homes with attic ducts will be assumed to resemble existing single-family homes with ducts in unconditioned spaces (i.e., 22% energy-savings potential). The baseline projection for new mobile homes will assume the above efficiencies of 88% for underfloor ducts and 73% for attic ducts, with energy-savings potentials pro-rated from the estimates for new housing with ducts in partly conditioned and unconditioned spaces, respectively. That is, for new mobile homes with underfloor ducts, the savings potential will be 12/15 of the 12% losses found by Conlin, or 10%. For new mobile homes with attic ducts, the savings potential will be 22/34 of the 27% losses found by Conlin, or 17%.

For mobile homes with forced-air systems in the Sunbelt (cell mh Dall Sun), the energy-use values displayed in Table 22, for existing buildings, are 0.17 quads for space heating and 0.07 quads for space cooling. Under the assumption that most of these have attic ducts, we use the 22% savings possibility found above. The quad savings potential for both heating and cooling is 0.05. For new houses in this cell, the corresponding energy-use values (Table 20) are 0.24 quads for heating and 0.14 quads for cooling. Using the savings potential of 17% for these buildings yields a quad savings of 0.07. The total energy savings potential for cell mh Dall Sun is then 0.12.

For mobile homes with forced-air systems in the Frostbelt (cell mh Dall Fro), the energy-use values displayed in Table 22, for existing buildings, are 0.10 quads for space heating and 0.01 quads for space cooling. Under the assumption that most of these have underfloor ducts, we use the 10% savings possibility found above. The quad savings potential for both heating and cooling is 0.01. For new houses in this cell, the corresponding energy-use values (Table 20) are 0.07 quads for heating and 0.01 quads for cooling. Using the savings potential of 10% for these buildings yields a quad savings of 0.01. The total energy savings potential for cell mh Dall Fro is then 0.02.

Multifamily

Three cells of multifamily buildings are included in this analysis: forced-air Sunbelt, forced-air Frostbelt, and hydronic Frostbelt. Andrews and Modera 1991 estimated 10%

energy savings potential for multifamily forced-air systems and 14% "current" savings potential for multifamily hydronic. The forced-air estimate was little more than a guess. The hydronic estimate was based on field data for currently applicable retrofits.

Since 1991, some work has been done on multifamily thermal distribution, but not enough to improve much upon the above estimates. Walker and Modera (1996) made field measurements on four forced-air heating systems in two apartment buildings in upper New York State. The buildings had gas furnaces located in their basements. Uninsulated sheet metal ducts served the apartments. One system served two apartments while the other three served one apartment each. The as-found systems had numerous "catastrophic" leaks, some large enough for personnel to put their heads into. These were repaired pre-retrofit with the idea that the study should investigate the effects of sealing and insulating a system that was at least apparently sound, and should not achieve inflated results by starting with a clearly decrepit system. The retrofit consisted of sealing leaks with mastic and tape and wrapping the ducts in two-inch-thick foil-backed insulation. Only the ducts in the basement were repaired, since risers to the apartments were not accessible. Despite this, pre-retrofit leakage was high, averaging 34% of system fan flow on the supply side and 85% on the return side. These values were reduced to 22% and 57%, respectively, by the retrofit. However, much of this leakage was to the inside of the apartments rather than to the basement or the outside.

This work suggests that the percentage energy savings from improving thermal distribution in multifamily buildings may be much larger than the 1991 estimates, but it is only a suggestion. No definitive study on a national basis has been made. Nevertheless, it seems reasonable now to raise the 10% energy savings estimate for forced-air systems in multifamily buildings to 20%, more in line with the single-family values.

For multifamily buildings with forced-air systems in the Sunbelt (cell mf Dall Sun), the energy-use values displayed in Table 22, for existing buildings, are 0.29 quads for space heating and 0.12 quads for space cooling. Using the 20% savings possibility found above, the quad savings potential for both heating and cooling is 0.08. For new houses in this cell, the corresponding energy-use values (Table 20) are 0.14 quads for heating and 0.08 quads for cooling. Using the savings potential of 20% for these buildings yields a quad savings of 0.04. The total energy savings potential for cell mf Dall Sun is then 0.12.

For multifamily buildings with forced-air systems in the Frostbelt (cell mf Dall Fro), the energy-use values displayed in Table 22, for existing buildings, are 0.27 quads for space heating and 0.03 quads for space cooling. Using the 20% savings possibility found above, the quad savings potential for both heating and cooling is 0.06. For new houses in this cell, the corresponding energy-use values (Table 20) are 0.10 quads for heating and 0.02 quads for cooling. Using the savings potential of 20% for these buildings yields a quad savings of 0.02. The total energy savings potential for cell mh Dall Fro is then 0.08.

For multifamily buildings with hydronic systems in the Frostbelt (cell mf Hyd Fro), the energy-use values displayed in Table 22, for existing buildings, are 0.26 quads for space heating and nothing for space cooling. The number of new units in this category was not found large enough to include in the analysis. Using the 14% savings possibility found above, the quad savings potential for heating and cooling is 0.04. There being no new housing to consider, this equals the total energy savings potential for cell mf Hyd Fro.

SMALL COMMERCIAL BUILDINGS

At the time Andrews and Modera 1991 was written, not much was known about the impact of thermal distribution losses in small commercial buildings. During the ensuing decade, a significant body of research has been done. True, it remains much less extensive than what has been done on residential buildings, but it is enough to get at least an approximate indication of what the potential for energy savings in these buildings is likely to be. A search of the literature uncovered seven published sources, concentrated in Florida and California. A summary of the topics and results is given in Table 31.

The main problems identified with small commercial buildings were:

- leaky ducts
- poorly controlled links to outside air
- suboptimal ceiling space configurations.

Conduction and leakage losses were similar in magnitude to those found in residential buildings. These reports found conduction losses in the 10% - 20% range, leakage losses of a similar magnitude, or overall losses of ~25%. See Table 32 for a summary. These are consistent with the commonly cited residential benchmark that duct losses are typically in the 25% to 40% range.

Small commercial buildings, however, have two additional problems that either are not seen in residences or are of relatively minor importance. The first of these is poorly controlled linkage to outside air. In contrast to residences, which traditionally have not had active ventilation systems and whose exhaust fans have typically moved a few hundred cfm of air on an intermittent basis, small commercial buildings often move thousands of cfm between the inside and the outside, sometimes more or less continuously. These buildings may have three different categories of active air movement between the inside and the outside. Outside air refers to the use of a controllable damper in the return duct to admit a quantity of ventilation air from the outside, when the system is operating. Makeup air is a separate dedicated system intended to balance airflows across the envelope. Exhaust air refers to the use of dedicated exhaust fans, e.g. in restaurants, to eliminate air contaminants and odors.

The second problem that small commercial buildings tend to have, which residences do not, is caused by different placement of the thermal and air barriers, particularly in the ceiling spaces. The optimal situation is to have both the thermal and air barriers above the ductwork (which is generally in the ceiling space). However, many buildings have suboptimal placement of these barriers, with one or both below the ductwork. Some buildings may even have a vented attic combined with a leaky drop ceiling, in which case there is essentially no air barrier at all (or at best, a very porous one).

Table 31. Summary of papers on thermal distribution in small commercial buildings.

Citation	Qualitative Findings	Quantitative Results
1. Cummings and Withers 1998	Study of 70 Buildings in FL 33 used building cavities as ducts. These included air-handler support platforms, mechanical rooms and closets, ceiling spaces, and wall cavities. Tended to leak. Air and thermal boundaries both above the ductwork (in the ceiling space) in 26 buildings.	Various measurements on individual buildings, but no overall averages that would bear on energy savings potential estimates..
2. Cummings et al. 1996	Field Study of 7 Restaurants in FL Problems: large exhaust fans cause depressurization; too little makeup air; intermittent outdoor air caused by cycling; dirty filters, tight envelopes. Air and thermal barriers should be in the same plane.	Depressurization ranged from –1 Pa to –43 Pa.
3. Withers & Cummings 1998	Office Building Retrofit Study in FL Ducts were very leaky. An attic exhaust fan also led to UAF*	Duct repair reduced energy use 31%. Turning off the attic fan saved 36% more.
4. Withers et al. 1996	Retrofit Study of 18 Buildings in FL Duct repair the most common retrofit (16). Modified outdoor air or exhaust air (4). Sealing building shell (1).	Duct sealing reduced avg. leakage 68%, to 288 cfm25 Energy-use reduction was 15% for all retrofits, 13% for duct repair only.
5. Delp et al. 1998a	Study of a Building with Ducts on the Roof, CA Putting ducts on a roof in the hot sun can seriously degrade delivery effectiveness even if the theoretical value of conduction efficiency is high. This is because of the high sol-air temp.	Conduction efficiency 97%, delivery effectiveness only 73%. Adding insulation and a reflective coating reduced system energy use by 22%.
6. Delp et al. 1998b	Performance Test of 15 Buildings in CA All ducts between drop ceiling and roof deck. Each building had at least one of: torn/missing external duct wrap; poor workmanship at fittings; disconnected ducts; improperly installed mastic.	Duct ELA25 averaged 3.4 cm^2/m^2 vs.1.3 cm^2/m^2 for residential. Temp. rise plenum – register averaged ~5 F while ΔT plenum-ambient averaged 30 F → 83% conduction eff.
6a. Delp et al. 1997.	Additional information from the report that was the basis for the above paper: • Light commercial ductwork leaks 2X residential systems. • Duct systems are outside the conditioned space. Primary air barrier often located at the drop ceiling: i.e., **NO** barrier.	
7. Xu et al. 2000	Study of 5 Thermal Distribution Systems in CA In addition to conductive and leakage losses from the ducts, problems of frequent cycling and improper system control were observed.	Supply-duct leakage avg. 10% of fan flow. Conduction losses 9% to 24% of capacity. Overall loss 25% of capacity on average.

*UAF=Uncontrolled airflow

Table 32. Summary of conduction and leakage loss quantification in the sources cited.

Paper	State	Conduction Loss, %	Leakage Loss, %	Overall Loss, %	
1-3	FL	Case studies of deficiencies of small commercial buildings			
4	FL		19% (N=13)		
5	CA	Efficiency impact of exposing ductwork to the sun on a roof			
6	CA	17% (N=15)			
7	CA	16% (N=5)	10% (N=5)	25% (N=5)	

In view of this, admittedly somewhat limited, data, we make the following assumptions. First, the losses from duct leakage are 25% on average, spread over all buildings. The impact of poor control of outside air is not quantified, either in percentage terms or in the fraction of buildings affected. We will use a default estimate of 10% on average. Similarly, the impact of suboptimal ceiling spaces is not quantified, either in percentage terms or in the fraction of buildings affected. Again, we will use a default estimate of 10% on average.

For existing buildings, it will be assumed that the impact of duct leakage can be addressed approximately to the same extent as that in residential buildings with ducts in unconditioned spaces. That is, the 22% savings will be pro-rated downward by the ratio of the 25% losses estimated here to the 34% losses for the residential case. The result is that the savings potential from reduced duct leakage will be 22/34 X 25%, or 16%. A similar savings estimate will be used for new buildings.

Second, it will be assumed that poor control of outside air can be effectively addressed in both existing and new buildings. Hence, a 10% savings potential will be used.

Third, no energy savings potential from better ceiling-space design will be credited to existing buildings, but for new buildings a 10% improvement will be assumed.

These savings are probably not additive, but rather each will act on the energy use left after the preceding one is affected. In other words, the net savings potential will be
$1 - (1-0.16)(1-0.10) = 0.24$, or 24% for existing buildings and
$1 - (1-0.16)(1-0.10)(1-0.10) = 32\%$ for new buildings.

For small commercial buildings with forced-air distribution systems in the Sunbelt (cell sc Dall Sun), the energy-use values displayed in Table 28, for existing buildings, are 0.21 quads for space heating and 0.36 quads for space cooling. Using the 24% savings possibility found above, the quad savings potential for both heating and cooling is 0.14. For new buildings in this cell, the corresponding energy-use values (Table 30) are 0.12 quads for heating and 0.21 quads for cooling. Using the savings potential of 32% for these buildings yields a quad savings of 0.10. The total energy savings potential for cell sc Dall Sun is then 0.24.

For small commercial buidings with forced-air distribution systems in the Frostbelt (cell sc Dall Fro), the energy-use values displayed in Table 28, for existing buildings, are 0.24 quads for space heating and 0.09 quads for space cooling. Using the 24% savings possibility found above, the quad savings potential for both heating and cooling is 0.08. For new buildings in this cell, the corresponding energy-use values (Table 30) are 0.14 quads for heating and 0.05 quads for cooling. Using the savings potential of 32% for these buildings yields a quad savings of 0.06. The total energy savings potential for cell sf Dunc Sun is then 0.14.

SUMMARY OF ENERGY SAVINGS POTENTIALS

The potentials found in the preceding sections are summarized in Table 33. Salient points to be observed are:

- The total estimated potential has nearly doubled since 1991 (albeit we now are considering the year 2030 rather than 2020).
- About half of the savings potential is in single-family houses with forced-air systems in unconditioned spaces.
- About one-fifth of the savings potential is in small commercial buildings.
- Quad savings potential per building is highest for the small commercial cases: about 0.14 quads per million buildings. For the residential forced-air systems with ducts in unconditioned spaces, it is about 0.02 quads per million houses. For all other cases, it is about 0.01 quads per million housing units.

Table 33. Total energy savings potentials for space heating and cooling by cell populations in residential and small commercial buildings. Existing and new buildings aggregated in projected 2030 stock. Light italics show either “current” or “undetermined” values from Andrews and Modera 1991 (for 2020.)

	Cell Description	No. of Buildings (millions)	Projected Energy Savings Potentials (Quads)		
			Heating	Cooling	Total
sf Dunc Sun	Single-Family, Forced Air in Unconditioned Space, Sunbelt	**40.8**	**0.54**	**0.29**	**0.83** *0.57*
sf Dptc Fro	Single-Family, Forced Air in Partly Cond’d. Space, Frostbelt	**11.6**	**0.12**	**0.01**	**0.13** *0.05*
sf Dunc Fro	Single-Family, Forced Air in Unconditioned Space,Frostbelt	**11.2**	**0.22**	**0.03**	**0.25** *0.13*
mf Dall Sun	Multifamily, Forced Air, Sunbelt	**11.4**	**0.08**	**0.04**	**0.12** *0.07*
mf Hyd Fro	Multifamily, Hydronic, Frostbelt	**4.8**	**0.04**	**0.00**	**0.04** *0.04*
sf Hyd Fro	Single-Family, Hydronic, Frostbelt	**5.6**	**0.05**	**0.00**	**0.05** *0.06*
mf Dall Fro	Multifamily, Forced Air, Frostbelt	**6.4**	**0.07**	**0.01**	**0.08** *0.05*
sf Dptc Sun	Single-Family, Forced Air in Partly Cond’d. Space, Sunbelt	**5.8**	**0.04**	**0.02**	**0.06** *0.02*
mh Dall Sun	Mobile Homes, Forced Air, Sunbelt	**10.8**	**0.08**	**0.04**	**0.12** *N/A*
mh Dall Fro	Mobile Homes, Forced Air, Frostbelt	**2.9**	**0.02**	**0.00**	**0.02** *N/A*
sc Dall Sun	Small Commercial, Forced Air Sunbelt	**1.8**	**0.09**	**0.15**	**0.24** *0.08*
sc Dall Fro	Small Commercial, Forced Air Frostbelt	**1.0**	**0.10**	**0.04**	**0.14** *0.07*
	Totals		**1.45**	**0.63**	**2.08** *1.14*

Note: for small commercial buildings, the number of buildings was determined by dividing total floorspace by the mean floorspace of small commercial buildings in 1999, which was 6270 ft^2. This may not equal the mean floorspace of these buildings in 2030.

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