Shell, System, and Plant Contributions to the Space Conditioning Energy Use of Commercial Buildings

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Knowledge of the contribution of the building shell, system, and plant towards the space conditioning energy consumption of commercial buildings is useful for estimating the benefits of retrofit programs and targeting areas of greatest conservation potential. This information is impossible to measure directly, but can be calculated through computer simulations. This paper describes a novel method to determine load contributions to heating and cooling energy consumption using DOE 2.1E simulations. The method is used to analyze a large set of commercial prototypes including 13 building types, 2 vintages, and 5 climates. The results are aggregated by building type to the national level and presented as pie charts.

The charts show the strong effect the system and plant have on energy consumption. In large buildings with reheat systems, the purchased heating energy is very high compared to the heating load, on average about twelve times the value. As a result, heating energy consumption approaches cooling consumption even for building types that are internal-load dominant. Heating consumption can be reduced in large buildings by improving reheat controls or removing the heating system from the cooling and ventilation system. The cooling load is most affected by internal gains. Reducing internal gains reduces the cooling energy consumption, on average, by twofold. But the net space-conditioning savings can be much reduced by the heating penalty.

INTRODUCTION

This study quantifies the approximate contribution of the major building components—roofs, walls, foundations, windows, infiltration, equipment, lighting, people, etc.—to the heating and cooling loads of the U.S. commercial building stock. These building loads, when multiplied by factors expressing the net efficiencies of the HVAC system and plant, give the estimated site energy consumed by commercial building for heating and cooling. According to the 1989 Commercial Building Energy Consumption Survey (CBECS) (EIA 1992), U.S. commercial buildings are responsible for 5.8 quadrillion Btu (Quads) per year of site energy use. Our extrapolated results come close to the CBECS estimates for total consumption. According to estimates determined using the COMMEND Forecasting program and 1989 CBECS data (Sezgen, Franconi, & Koomey 1995), space conditioning consumption accounts for about half of it, totaling nearly 3 Quads. Our extrapolated results for space conditioning come close to the COMMEND estimate. The knowledge of the contribution of the building shell, system, and plant towards space-conditioning consumption of commercial buildings is useful for estimating the benefits of retrofits or DSM programs, targeting areas of greatest conservation potential, and forecasting future energy use. This paper highlights the methods and results of the Commercial Component Load Analysis Project. A complete description of the commercial load study can be found in the final project report (Huang & Franconi 1995).

The analysis in this study utilizes DOE-2 simulations of a modified set of building prototypes developed by Lawrence Berkeley National Laboratory (LBNL) in 1991–1994 covering 12 commercial building types and two vintages. In the course of selecting and refining the prototypes for this work, a review of 17 engineering studies dating as far back as 1983 was performed. The decision to rely primarily on the existing LBNL prototypes is based on the consistent methodology used in defining those buildings, the suitability of the flexible data structure for the required parametric analysis, and the familiarity of the project team with the input files.

The results from the prototype simulation analysis are scaled by floor area to estimate space-conditioning energy use in commercial building sector. The data are presented in tables and pie charts. The first set of results is the building component loads which show how the building shell, operation, lighting, and equipment affect the need for heating and cooling. The second set of results are the distribution system load and plant energy consumption which, when compared to the building load, shows how efficiently the load is met. This information is useful in clarifying the major contributors to space conditioning load and the relationship of load to purchased energy. The results indicate the conservation potentials that exist for reducing space-conditioning energy consumption in the commercial building sector.

BACKGROUND

To select the prototypical buildings used in this study, a lengthy review was undertaken of existing prototypes from

17 engineering studies dating back to 1983 to assess their suitability for this study as well as to gain insight into typical commercial building characteristics. Details on the prototype study comparison are presented in the Component Load Final Report (Huang & Franconi 1995).

For both technical and pragmatic reasons, the research team decided to use the LBNL/GRI set of commercial prototypes with which they are most familiar as the basic framework for the simulations. The technical reasons for using them are that they were developed with a relatively consistent methodology based on national data, i.e., CBECS, and that, with Huang as its original author , the input assumptions are easier to trace and modify as needed. The pragmatic reasons are that the DOE-2 input files are readily available, understandable, and structured for parametric simulations.

It should be emphasized that the LBNL/GRI prototypes were not built from scratch, but rather synthesized from many earlier studies, the most critical of which was a project supported by the Gas Research Institute (GRI). The outcome of that GRI project is a collection of 481 prototypical commercial buildings for 13 building types in 13 major U.S. cities (Huang et al 1990). These prototypes are refined and upgraded to DOE-2.1E through a follow-on GRI project (Huang 1994), and then further modified to two broad U.S. regions (North and South) based on 1989 CBECS data through work sponsored by DOE's Office of Policy, Planning and Analysis (Sezgen, Franconi, & Koomey 1995). In addition, new building prototypes are developed for three smaller building types not covered in the original LBNL/GRI work. These modeling efforts are continued in this project, resulting in a consistent set of prototypical buildings covering twelve commercial building types, with two variations by region and two by building vintage. This project, as in the COMMEND study (Sezgen, Franconi, & Koomey 1995), grouped the entire commercial building stock into the building type listed in Table 1.

Table 1. *welve Commercial Building Types*

Large Offices	Large Hotels
Small Offices	Small Hotels
Large Retail Stores	Fast-foods Restaurants
Small Retail Stores	Sit-down Restaurants
Schools	Food Stores
Hospitals	Warehouses

For all building types, the project defined prototypical buildings of two vintages (pre- and post-1980) based on statistical analysis of the 1989 CBECS to determine the average building conditions (size, levels of insulation, window type and area, etc.) within that building population. For the building types with sufficient number of observations—office, retail, school, and warehouse—the project also developed building prototypes for two broad U.S. geographical regions—North and South. The total number of building prototypes defined is 36 (6 buildings $\times$ 2 vintages $\times$ 2 regions $+$ 6 building types $\times$ 2 vintages).

To scale and compare the prototype simulation results, the 1989 CBECS data base files were analyzed to determine the total floor area, the percentages of floor area heated or cooled, and the total energy use for each of the prototypes. The data were determined by vintage for each of the five climate zones categorized in CBECS. For each climate, a representative location has been selected for use in the DOE-2 simulations. Table 2 presents the CBECS climate categories and the city representing each category in the simulation analysis.

Each prototype was modeled in 5 climates and 120 simulation runs were completed. The CBECS floor area data are used to extrapolate the prototype simulation run results to the commercial building sector. The aggregation of the component loads to the national level is done in a straightforward manner where the ''specific component loads'' per ft^2 of floor area of each prototypical building are multiplied by the floor area of the building sector represented by the prototype as determined from the 1989 Commercial Building Energy Consumption Survey (EIA 1992).

METHODOLOGY

This project follows an earlier residential component load study (Hanford & Huang 1993) in content but not in approach. In the residential study, component loads were estimated through regression analysis of the differences in total energy use from parametric simulations (Hanford & Huang 1993). Such a procedure was found to be unreliable for commercial buildings due to their intermittent hours of operation, large internal gains, and high thermal mass.

For this study, we determined component loads directly from the simulation calculations. To accomplish this in DOE-2 is not a simple task. In the DOE-2 program, component loads are approximated using a constant zone design temperature. At the component level, the final corrected load values are never calculated. The program adjusts the original calculation as a lumped sum and does not determine corrected loads for the individual components. To determine component loads using DOE-2, a set of four user-defined functions were developed to modify the DOE-2 program. The func-

Table 2. Analysis Climate Categories

Climate Zone	Region	Heating Degree-days (65F)	Cooling Degree-days (65F)	Representative city
1	North	above 7,000	below 2,000	Minneapolis
2	North	5,500–7,000	below 2,000	Chicago
3	North/South	4,000–5,499	below 2,000	Washington
4	South	below 4,000	below 2,000	Los Angeles
5	South	below 4,000	above 2,000	Houston

tions adjust the DOE-2 determined component loads using the actual zone temperatures and component UA values. The functions are not proprietary and are presented in detail in the project final report (Huang & Franconi 1995). Although this is a rigorous method that duplicates to a great extent how DOE-2 calculates the true system loads, it still ignores certain transient thermal effects when zone temperatures change from hour to hour. Overall, the sum of the component loads calculated by this procedure match the heating and cooling loads from the DOE-2 program to within 10%, and often within 2% when the loads are large.

To better understand how the net building load determined within the component load analysis relates to consumed energy, part of the modeling analysis evaluated the performance of typical HVAC systems and plants. The systems and plants modeled with each prototype that represent typical systems found in a particular building type. For this study, the systems/plants vary by building type and vintage. System and Plant Factors have been calculated for each prototypical building by modeling it with its prototypical HVAC system and plant, and then comparing the resulting system loads and energy consumptions at the system or plant level to the building loads. The system and plant equipment assumed for each prototypical building are based on the earlier LBNL/GRI study (Huang et al. 1990), and reflect engineering judgments of the equipment most likely to be installed by building type, vintage, and location.

A description of the systems and plant modeled for the prototypes can be found in the final report (Huang & Franconi 1995). Examples of some of the distribution systems modeled include: none for packaged systems, constant volume reheat, and variable air volume reheat. Examples of prototypical plants modeled are: packaged single-zone systems, a central chiller with cooling tower, and a boiler.

The system and plant factors are efficiency values relating (1) the HVAC distribution system load to the building load and (2) the plant energy consumption to the HVAC distribution system load, respectively. The system factor indicates how efficiently the supplied energy meets the load and is dependent on the type of distribution system and its control strategy. The plant factor indicates how efficiently the plant produces heating or cooling and distribution losses between the plant and the system. The terminology and definitions have been adopted from the COMMEND study (Sezgen, Franconi, & Koomey 1995).

RESULTS

The results from the component load analysis are presented by building type in Table 3. The data are for each building type at the national level. Thus, the values represent the area weighted component loads determined from ten simulation runs (2 vintages * 5 climates). The sum of the loads for all the buildings represents the component loads for the commercial building sector.

The table indicates the national floor areas determined for each building category from the 1989 CBECS (EIA 1992). The conditioned floor area for a building type generally differs between heating and cooling. The values were determined from the 1989 CBECS data from the total floor area, the percentage of the building floor area heated, and the percentage of the building floor area cooled. The loads are listed for the thirteen building components that contribute to the net load. A brief description of each component is given at the bottom of the table. The net heat or cooling load is determined by adding the gains and losses from all the components for each zone in the building for every hour in the simulation analysis. The net load in the zone for the hour is the energy that must be supplied by the HVAC system in order for comfort conditions to be met. A negative

Table 3. Aggregate Component Loads for Commercial Buildings

Building type	HVAC mode	Total area (M ft²)	Aggregate Component Loads (kBtu/ft² year)* Wndw	Wall	Roof	Floor	Grnd	Eqp	Src	Peop	Infl	Light	Solar	Outd. Air	Net
Large	heat	7800.0	−4.49	−2.00	−0.40	−0.09	0.00	0.69	0.00	0.09	−0.60	1.91	1.94	−0.44	−3.40
Office	cool	7056.9	−6.16	−0.78	−0.10	−0.60	0.00	7.75	0.00	1.30	−1.64	19.30	21.06	−1.22	38.87
Small	heat	3188.1	−5.27	−5.90	−2.16	−0.78	0.00	1.22	0.00	0.25	−3.04	5.14	3.23	−1.00	−8.31
Office	cool	2957.5	−2.70	0.61	0.64	−1.45	0.00	3.25	0.00	0.81	−1.69	12.98	16.03	−0.10	28.37
Large	heat	5174.6	−1.72	−1.86	−1.93	−0.48	0.00	1.00	0.00	0.35	−3.13	5.01	0.79	−0.99	−2.98
Retail	cool	3746.9	−1.36	−0.43	0.00	−1.65	0.00	4.83	0.00	2.16	−2.06	21.94	5.95	−0.72	28.72
Small	heat	5269.0	−6.93	−5.96	−5.03	−1.59	0.00	1.33	0.00	1.02	−4.78	7.27	3.07	−2.83	−14.44
Retail	cool	2966.1	−2.09	0.03	1.01	−2.46	0.00	3.10	0.00	3.10	−1.62	15.27	13.15	−0.20	29.37
Large	heat	1815.7	−4.74	−2.48	−0.61	−0.06	0.00	1.43	0.06	0.94	−1.60	2.04	2.15	−2.53	−5.45
Hotel	cool	1304.5	−3.07	0.00	0.15	−1.92	0.00	5.14	0.31	3.76	−1.15	17.48	16.79	−3.07	34.50
Small	heat	781.9	−4.60	−4.48	−1.41	0.00	−1.41	1.15	0.00	2.05	−4.09	2.30	3.20	0.00	−7.29
Hotel	cool	627.1	−3.99	−0.16	0.32	0.00	−4.62	3.67	0.16	5.58	−1.44	6.86	19.77	0.00	25.99
Fast Food	heat	506.7	−15.39	−6.51	−6.12	0.00	−5.92	2.57	0.39	4.74	−0.59	12.04	11.45	−27.83	−31.38
Restaurant	cool	426.8	−2.11	−2.11	0.70	0.00	−9.14	16.87	1.87	13.82	−0.23	33.74	25.54	−5.86	73.34
Sit-down	heat	506.7	−5.53	−7.50	−7.10	0.00	−4.54	3.36	0.79	5.53	−1.18	17.17	3.95	−31.38	−26.64
Restaurant	cool	426.8	−0.94	0.47	2.11	0.00	−5.15	11.72	3.05	11.72	−0.23	29.29	9.61	−6.79	54.83
Hospital	heat	1539.3	−3.31	−2.21	−0.39	0.00	0.00	1.04	0.00	1.10	0.00	2.73	1.43	−4.42	−4.03
	cool	1393.0	−4.16	−2.51	−0.57	0.00	0.00	52.26	0.00	8.47	0.00	46.16	13.93	−10.91	102.66
School	heat	7910.4	−6.67	−8.62	−3.65	0.00	−2.76	1.16	0.08	2.12	−11.12	6.31	5.16	−6.51	−24.54
	cool	3789.9	−1.11	0.32	0.77	0.00	−1.74	1.48	0.42	1.64	−1.27	5.67	5.96	−0.55	11.64
Super-	heat	655.7	−3.05	−4.88	−3.36	0.00	−1.22	1.53	0.00	2.29	−1.53	11.44	1.68	−11.44	−8.85
market	cool	553.1	−1.45	−1.81	0.00	0.00	−5.60	17.00	0.00	9.22	−0.90	41.22	9.04	−4.88	62.01
Ware-	heat	3532.8	−0.88	−1.30	−1.78	−0.40	−5.26	1.10	0.00	0.17	−0.57	2.32	0.93	−0.40	−6.11
house	cool	1663.8	0.06	0.30	0.84	−0.24	−1.92	0.66	0.00	0.18	0.00	2.04	1.02	0.00	2.95
Total	heat	38680.9	−4.73	−4.40	−2.42	−0.41	−1.23	1.12	0.03	0.98	−3.98	4.80	2.77	−3.32	−10.78
	cool	26912.4	−3.01	−0.32	0.35	−0.93	−0.81	7.49	0.16	2.66	−1.37	17.39	13.20	−1.54	33.26

*Key to Component Abbreviations

Wndw	Conduction through windows
Wall	Conduction through exterior walls
Roof	Conduction through roofs
Floor	Conduction through floors over unconditioned spaces, e g. basements crawl spaces
Grnd	Conduction through the ground or floor slab
Eqp	Internal heat gain from electrical equipment
Src	Internal heat gain from non-electrical equipment
Peop	Internal heat gain from occupants
Infl	Convection through infiltration (does not include outside air introduced by system)
Lights	Internal heat gain from lights
Solar	Solar heat gain through windows and skylights
Outdr.Air	Convection through outside air introduced by system to meet health requirements (does not include outside air from economizers or due to limitations in air-handling system).

load results in heating being supplied, a positive load results in cooling being supplied. The total building heat load is the sum of all zone heating loads over the year. Likewise, the total building cooling load is the sum of all zone cooling loads over the year.

At first glance, the computed loads from this study appear small compared to other estimates of the energy consumption of commercial buildings for space heating and cooling. However, such a comparison would be misleading since the computed building loads do not account for the interactions with the building system and plant, or their efficiency.

Several points are apparent on the table: (1) cooling loads are clearly dominant in all the large building types, and of that, more than half is due to lights and equipment and a third to solar heat gain through the windows; with conduction and infiltration generally providing ‘‘free cooling’’, (2) heating loads are appreciable in the smaller buildings and the schools due to their large amounts of wall and window area; windows, walls, and infiltration are roughly comparable in contributing to the total commercial heating loads, although nearly 60% of the window heat losses are offset by their solar heat gain; (3) restaurants are characterized by both high heating and cooling loads, the former because of the large amounts of outdoor air required for the kitchen, the latter because of the internal heat gain from the cooking equipment; and (4) supermarkets have relatively high cooling loads, almost all of it due to their high lighting levels.

The system and plant factors are shown on Table 4. The data are aggregated by building type at the national level. The data are based on the area weighted system load and consumption data for 10 simulation runs per building type. For system and plant factors determined for each building by vintage and climate, refer to the study final report (Huang and Franconi 1995). The table columns, beginning at the third from the left, give the following: (C) net building loads repeated from the component load tables, (D) system factor, (E) system load, (F) plant factors by fuel type, (G) plant energy consumption by equipment, and (H) the overall efficiency of the system and plant. The system factors are generally less than 1.00 because of the inefficiencies of the air-handling system, and can drop to below 0.30 for heating and 0.50 for cooling in large older buildings with constant volume reheat systems. However, there are numerous cases under low to moderate load conditions where the system factors can be greater than 1.00. In heating, this can be due to the ‘‘free heating’’ provided by the electricity fans and the effects of the throttling range. In cooling, this may be due to the ‘‘free cooling’’ provided by an economizer. For small hotels and schools, the low system factor results from the absence of cooling equipment in the older vintage building. The pre-1980 small hotels and schools have unit ventilators for the system type and no plant cooling equipment. The system factor is greater than one because the building load and therefore comfort conditions are not always met with ventilation only.

The system factors for the fast-food restaurants and hospitals are low not because their systems are inefficient, but because they require large amount of outside air. The fast-food restaurants are assumed to require 10 air-changes in the kitchens, and the hospitals operated with 100% outside air. These additional loads are simulated in the system routine of DOE-2, so they do not appear in the component loads calculation. However, since such outside air requirements are determined by the building use, it may be more appropriate to consider them part of the building loads instead.

In the table, the plant factors are given by fuel type because of the large differences in efficiency and cost between fuel and electricity. For example, the plant factors for gas in the large buildings are around 0.65, reflecting the seasonal efficiencies of boilers. The plant factors for electric heating are 1.00, indicating resistance heating, while for cooling they vary from 2.50 to over 5.00 depending on the seasonal efficiency of the chiller and cooling tower.

In addition to the energy consumed by the heating and cooling equipment, there is also the energy used by auxiliary equipment such as fans and pumps. These energy consumptions do not appear in the plant factors, but they are tabulated in Column G, and figured in calculating the overall source efficiency factors in Column H. A fuel multiplier of three is used in deriving this overall efficiency to reflect the unavoidable energy losses in electricity generation and transmission. Since the cost of electricity is roughly three times the cost of gas, determining source efficiency and thereby consumption is useful for comparing trade-offs between heating and cooling.

At the bottom of the table, the data for all commercial buildings are determined for three different cases: 1)all the twelve building types, 2) for 10 building types excluding small hotels and schools, and 3) for only small hotels and schools. Since comfort conditions are not always met in small hotels and schools, these were excluded for one of the cases. Included them with the other buildings which have cooling equipment can be misleading for identifying potential savings of cooling equipment efficiency. When small hotels and schools are excluded from the calculations, the overall cooling efficiency drops from 0.62 to 0.59. This is because the overall source efficiency for cooling in small hotels and buildings is artificially high at 2.22.

To facilitate understanding the relative contribution of component loads to heating and cooling energy consumption, the data are presented as pie charts. Figure 1 presents component loads for all commercial buildings, Figure 2 for large offices,

Table 4. *System and Plant Factors for Commercial Buildings*

A.	B.		C.	D.	E.	F.		G.			H.
								Plant Consumption (KBtu / ft^2)			
	Floor HVAC	Bldg Area	System Load	System Factor		Plant Factors		HVAC*	HVAC*	Aux*	Overall** Source
Location	mode	(M ft^2)	(kBtu/ft^2)		Load (kBtu /ft^2)	Gas	Elec	Gas	Elec	Elec	Efficiency
Large Office	heat	7800	3.4	0.18	18.8	0.68	1.0	27.8	1.1	4.0	0.08
	cool	7057	38.9	0.59	65.9	-	4.7	-	13.9	10.6	0.53
Small Office	heat	3188	8.3	1.28	6.5	0.45	1.0	14.5	0.0	1.1	0.47
	cool	2958	28.4	0.86	33.1	-	3.2	-	10.4	5.6	0.59
Large Retail	heat	5175	3.0	0.23	13.3	0.67	1.0	19.9	0.8	2.7	0.10
	cool	3747	28.7	0.59	48.9	-	4.7	-	10.4	7.6	0.53
Small Retail	heat	5269	14.4	1.15	12.5	0.63	1.0	19.8	0.0	1.8	0.57
	cool	2966	29.4	0.76	38.6	-	3.0	-	12.7	5.3	0.54
Large Hotel	heat	1816	5.4	0.71	7.6	0.67	1.0	11.4	0.5	1.8	0.30
	cool	1305	34.5	0.82	42.2	-	3.6	-	11.8	2.4	0.81
Small Hotel	heat	782	7.2	0.76	9.5	0.32	1.0	29.3	0.4	0.5	0.23
	cool	627	26.0	1.87	13.9	-	2.4	-	5.9	0.7	1.31
Fast Foods	heat	507	31.4	0.29	107.6	0.63	1.0	171.9	0.0	10.5	0.15
Restaurant	cool	427	73.3	0.65	112.4	-	3.1	-	35.9	12.8	0.50
Sit-down	heat	507	26.6	1.08	24.7	0.60	1.0	41.4	0.0	3.3	0.52
Restaurant	cool	427	54.9	0.61	90.5	-	3.2	-	28.4	11.4	0.46
Hospital	heat	1539	4.0	0.12	32.5	0.69	1.0	47.1	1.7	6.3	0.06
	cool	1393	102.7	1.10	93.4	-	4.2	-	22.1	12.0	1.00
School	heat	7910	24.5	1.04	23.6	0.67	1.0	35.4	1.3	0.5	0.60
	cool	3790	11.6	6.44	1.8	-	2.6	-	0.7	0.6	2.97
Supermarket	heat	656	8.9	1.65	5.4	0.52	1.0	10.4	0.0	1.8	0.56
	cool	553	62.0	0.79	78.2	-	3.1	-	25.2	20.7	0.45
Warehouse	heat	3533	6.1	1.27	4.8	0.64	1.0	7.5	0.0	0.9	0.60
	cool	1664	3.0	0.91	3.3	-	3.0	-	1.1	0.9	0.50
All Commercial	heat	38681	10.8	0.64	16.7	0.64	1.0	26.1	0.7	2.2	0.31
	cool	26912	33.3	0.75	44.5	-	4.0	-	11.2	6.7	0.62
Commercial w/	heat	29989	7.2	0.48	15.1	0.64	1.0	23.5	0.5	2.8	0.22
cooling equip***	cool	22495	37.1	0.71	52.5	-	4.0	-	13.1	7.9	0.59
Commercial w/o	heat	8692	22.9	1.03	22.3	0.64	1.0	34.9	1.2	0.5	0.57
cooling equip****	cool	4417	13.6	3.88	3.5	-	2.4	-	1.4	0.6	2.22

*HVAC Gas includes boilers and furnaces; HVAC Elec includes resistance heat, chiller, and cooling towers; Aux. Elec includes fans and pumps.
**Overall Source Efficiency relates space-conditioning energy consumption to the building load. Electricity consumption has a multiplier of 3 to convert site electricity to source energy use.
***The older vintage of schools and small hotels are modeled with unit ventilators and do not have cooling equipment. Without cooling equipment comfort conditions are not always met. In this row, the calculations exclude schools and small hotels to better indicate the savings potential for cooling HVAC equipment.
****Schools and small hotels only.

***Figure 1.** Aggregate Component Loads for All U.S. Commercial Buildings (Trillion Btu per Year)*

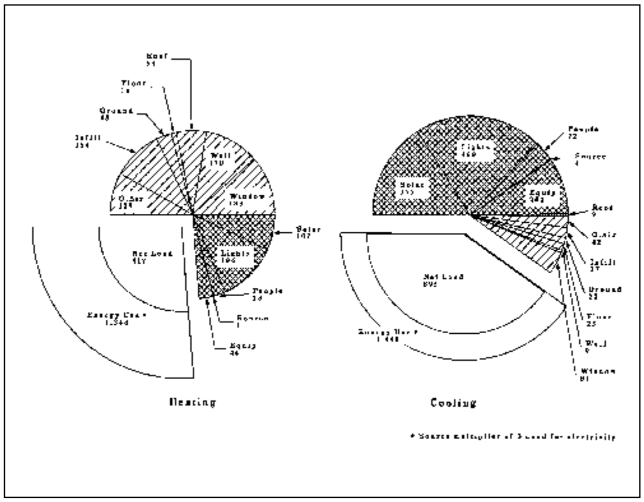


***Figure 2.** Aggregate Component Loads for U.S. Large Office Buildings (Trillion Btu per Year)*

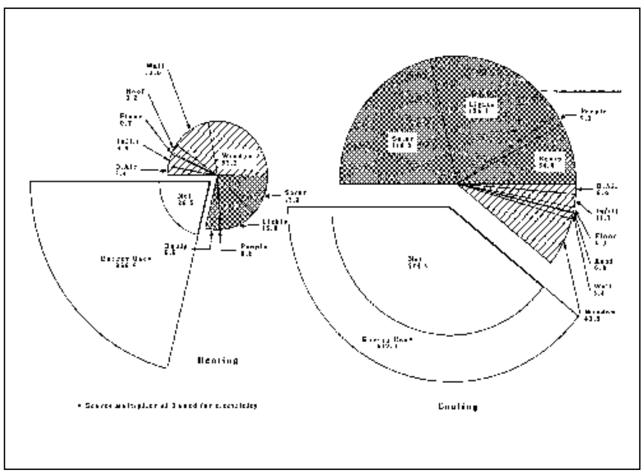
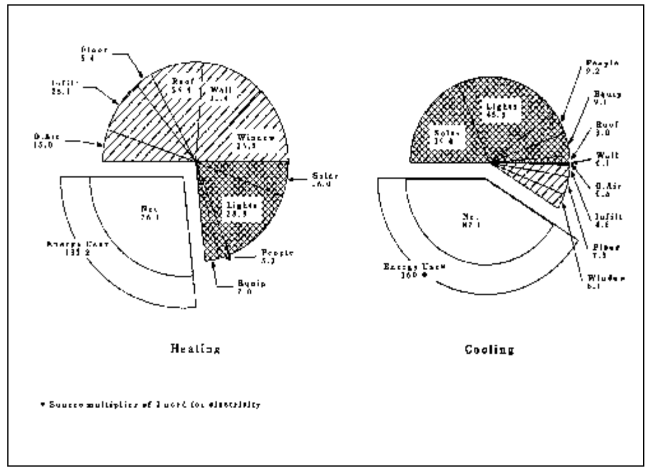


***Figure 3.** Aggregate Component Loads for U.S. Small Retail Buildings (Trillion Btu per Year)*



and Figure 3 for small retail. Pie charts for each prototype by climate, vintage, and aggregated to the national level are available in the Component Load Final Report (Huang & Franconi 1995). Each pie chart consists of two pies -heating and cooling-scaled by the size of the load. On the heating and cooling pies, the heat gains (+ loads) are shown as cross-hatched pie slices and the heat losses (—loads) as hatched pie slices. The remaining exploded pie slice shows the imbalance between the heat gains and losses and represents the net heating or cooling load that must be supplied by the building's HVAC system. The component loads and net loads correspond to the data presented in Table 3. On the heating pies, the heat losses (or loads) are plotted on the top half and the heat gains (or ‘‘free heat’’) on the bottom half. On the cooling pies, the heat gains (or loads) are plotted on the top half and the heat losses (or ‘‘free cooling’’) on the bottom half. The component load pie charts depict qualitatively which building components are the greatest sources of space conditioning loads. To indicate the relative magnitudes of the component loads, all the pies on each chart are plotted on the same scale.

The overall system and plant efficiencies presented in Table 4, column H, are used to scale the net load pie slices to produce the expanded pie slices labeled ‘‘Energy Use’’ in the figures. The expanded slice shows the amount of energy that is purchased to meet the heating or cooling load. Thus, the pie charts show the relative contributions of the building components to the building load and the relationship between the building load and the purchased energy. All energy are Trillion Btu. The purchased energy is determined for source not site energy. Therefore, the values are roughly proportional to the cost of purchased energy.

With the aggregated energy consumptions presented in Table 4, it is possible to compare the simulation results to measured energy data to determine the accuracy of the building prototypes and the modeling technique. Table 5 compares the total energy consumption of the commercial building types covered in this study to the entire commercial building sector reported by the 1989 CBECS. Total energy consumption of the prototypes include spaced-conditioning, domestic hot water, lighting, and equipment energy consumption. These space-conditioning and end-use consumptions are all based on the prototype DOE-2 simulation results. The 12 building types included in the component load study represents 75% of the building floor area reported by CBECS. Not covered are assembly buildings, parking garages, public order, and buildings listed as ‘‘other’’. When compared at the aggregate level for all 12 building types, the electricity consumption derived by this study agrees almost exactly with the CBECS estimate (2.2 Quads), while the fuel consumption is smaller by 35% (1.4 to 2.1 Quads). When compared for each building sector, this study agrees well with CBECS in total energy consumptions in the largest or best understood commercial sectors such as office and mercantile (1.0 versus 1.2 Quads, and 0.9 versus 1.0 Quads, respectively), within 20% in the other sectors, but over 60% off for warehouses. If the warehouses are omitted from the comparison, the discrepancy in total energy use from CBECS decreases from 16% to 12%. The difference in the electricity-to-fuel breakdown can be attributed in part to the difficulty with the prototype building approach to capture fuel mixes within the building stock.

CONCLUSIONS

The inefficiencies of the system and plant have a magnifying effect on the building load. At the national level, heating inefficiencies increase the energy that needs to be supplied

Table 5. *Comparison of Component Loads Analysis Project Commercial Building Energy Use to 1989 CBECS*

	1989 CBECS					Component loads analysis study				
	floor area	Energy use (10^{12} MBtu)		Specific energy use (kBtu/ft²)		floor area	Energy use (10^{12} MBtu)		Specific energy use (kBtu/ft²)	
Building type	(10^6 ft²)	Elec	Fuel	Elec	Fuel	(10^6 ft²)	Elec	Fuel	Elec	Fuel
Assembly	6909	186	254	26.9	36.8					
Education	8076	217	394	26.9	48.8	8137	163	332	20.1	40.8
Food Sales	792	105	27	132.6	34.1	793	92	7	116.9	9.7
Food Service	1167	113	128	96.8	109.7	1172	172	217	147.1	185.4
Health Care	2054	154	295	75.0	143.6					
(hospitals only *)	1636	123	235	75.0	143.6	1636	232	158	141.9	97.0
Lodging	3476	138	197	39.7	56.7					
(hotels only *)	2882	114	163	39.7	56.7	2882	105	103	36.8	35.9
Mercantile	12365	550	492	44.5	39.8	12404	628	229	50.6	18.5
Office	11802	781	448	66.2	38.0	11888	675	284	56.8	23.9
Parking Garage	983	18	0	18.3	0.0					
Public Order	616	29	25	47.1	40.6					
Warehouse	9253	243	259	26.3	28.0	9308	152	54	16.3	5.9
Other	1529	201	102	131.5	66.7					
Vacant	4161	39	49	9.4	11.8					
All buildings	63183	2774	3015	43.9	47.7					
Component loads bldg sectors only	47975	2246	2146	46.8	44.7	48224	2231	1387	46.1	28.8

* scaled by floor area represented by LBNL prototypes.

to the building by more than three. For cooling, source energy consumed for cooling is about 1.7 times the load. Although the aggregate heating load is less than half the cooling load, total source energy consumed for heating is nearly equal to the total source energy consumed for cooling.

Based on the national results, retrofits affecting the building heating load have a small cooling penalty. While retrofitting the building shell has the largest effect on decreasing the heating load, improving the HVAC controls or modifying the heating equipment may be easier to implement and may be more effective. This is especially true for large buildings with reheat systems in mild climates. For cooling, decreasing internal gains has the largest effect on decreasing the national cooling load But the heating penalty can be significant. For example, decreasing the internal gains from lighting by 50% will save about 1.1 Quads in source cooling energy but heating consumption will increase by 0.3 Quads.

In the study, old and new large office buildings are modeled with constant volume and variable air volume reheat systems, respectively. The plant equipment for both vintages are a boiler, chiller, and cooling tower. The purchased heating energy for large offices is very high compared to the heating load, on average about twelve times the value. As a result, heating energy consumption approaches cooling consumption even for this building type that is internal-load dominant. Heating consumption can be reduced in large buildings by improving reheat controls or removing the heating system from the cooling and ventilation system. Reducing internal gains reduces the cooling energy consumption, on average, by twofold. But the net space-conditioning savings can be much reduced by the heating penalty for reheat systems. For example, decreasing the internal gains from lighting by 50% will save about 0.13 Quads of source cooling energy but the heating consumption will increase by 0.10 Quads. Of course, the major savings from a lighting retrofit result from decreased lighting energy consumption and not the secondary savings from space conditioning. But it should be kept in mind that a major lighting retrofit may cause the heating plant to be undersized for the increased load with reheat systems.

The small retail results presented in the paper indicate trends for shell-dominant commercial buildings. Both the old and new small retail buildings are modeled with packaged HVAC systems. The new system is equipped with an economizer. Total source heating energy consumption is almost equal to total source cooling energy. The overall system and plant efficiency for heating is much higher than that for larger buildings which frequently have simultaneous heating and cooling loads. Heating retrofits that effect the building shell have a small cooling penalty. Cooling retrofits that decrease internal gains have a significant heating penalty. For example, decreasing the internal gains from lighting by 50% will save about 0.04 Quads of source cooling energy but the heating penalty is 0.03 Quads of heating energy.

The differences in system and plant efficiencies between the old and new vintage HVAC equipment often overwhelm the original difference in building loads due to construction differences. This is especially true in large buildings. In the smaller buildings with packaged HVAC systems, the differences in system and plant factors are smaller. Consumption follows loads more closely in small buildings than in large buildings.

Breaking down building energy consumption between building load, system load, and plant consumption helps to pinpoint the most effective conservation strategy. Also, the trade-offs for components that affect both heating and cooling can be seen more readily. While the data presented in this paper is on the national level and offers an overall evaluation of the commercial building stock, individual measures can be evaluated most effectively by performing a similar analysis at the building level.

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