The Impact of Variations in Building Parameters and Operating Conditions on Commercial Building Energy Use and Load Shapes

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Assessments of the applicability of equipment or the benefits of conservation measures within a building sector are frequent done using energy simulations of prototypical buildings with average physical and operational characteristics. Because of the large variations in size, hours of operations, energy-use intensity, and fuel-electric ratios even among buildings of the same type, vintage, and location, such an analysis risks the danger of missing "niche" markets for strategies such as cogeneration that may be attractive only under specialized conditions.

The objective of this study is to analyze the impact that variations in building conditions have on a building's energy use patterns, and to develop procedures to account for these variations in assessing market potentials. The study utilizes a set of 481 prototypical commercial buildings developed for the Gas Research Institute (GRI) to study the applicability of cogeneration for commercial buildings in 20 U.S. urban areas. The physical characteristics, system configurations, and operating conditions of the prototypical buildings are based on either statistical data or engineering studies and chosen to reflect the average among the buildings represented by that prototype. In the current study, we first compare the adequacy of these "average" prototypes to capture the range of conditions within a building sector, and then purposely modify the building parameters of the prototypes to study how atypical conditions affect building energy use patterns. From this sensitivity analysis, we develop a procedure to account for variations in building parameters in assessing the market potential for specialized applications.

Background

As part of a project to assess the potential of cogeneration in commercial buildings, the authors in 1991 defined a set of 481 prototypical commercial and multifamily buildings in 13 U.S. cities, which were then simulated using the DOE-2.1D program to create a data base of their energy usage and hourly load shapes. The 13 U.S. locations were selected either because of their amount of construction activity, or because their utility rate schedules were favorable to cogeneration (see Table 1). In each location, prototypical buildings were developed for 13 building types that tend to be energy-intensive and good candidates for cogeneration (see Table 2). For the two restaurant prototypes, two combinations of shell and equipment vintages are modeled - average/old and average/new. For the other 11 building types, three combinations are studied - old/old, old/new, and new/new. The total number of prototypes modeled is 481 (13 locations x 37 prototypes per location). A corollary effort estimated the number of buildings represented by each prototype.

The entire data set consists of DOE-2 input files, output files of hourly building loads (heating, total and latent cooling), electricity use (AC and non-AC), and outdoor temperature and humidity ratio, and a post-processor program to compute annual and monthly total and peak loads, and hourly loads shapes by end-use for each month.

In developing the prototypical buildings, we disaggregated the commercial building stock by building type, vintage, and location into hundreds of

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subsectors, and then represented each subsector with a building having the average physical, mechanical, and operational characteristics of that subsector.

The building descriptions and operational conditions for the 481 prototypes are described in Huang et al. (1991). General characteristics such as the building size and the number of floors are calculated from building permit data obtained from a commercial company, F.W. Dodge, Inc. Shell characteristics such as insulation levels and window areas, and general conditions such as the hours of use are derived mostly from the CBECS (Commercial Building Energy Consumption Survey, EIA 1989).* End-use intensities and schedules, system configurations, and thermostat settings are based on metered results when available, review of other studies, or engineering rules-of-thumb.

In this paper, we will present the result for two building types - large offices and hospitals. Large offices are defined as those larger than 50,000 ft^2 (5,000 m^2). Because of their prevalence and relatively easy-to-define operating conditions, more studies have been done of offices than other building types, and hence, more data was available on typical operating schedules, lighting intensities, etc. To account for the increasing number of computer centers, we developed separate operating schedules for 12- and 24-hour offices.

In comparison to offices, much less information was available on energy use patterns in hospitals, but their operations are much more varied and complex. We categorized hospital operations into generic space conditions, such as clinic, public areas, perimeter zones, kitchen, etc. - and estimated their amounts of floor area. We then defined their end-use intensities, operating conditions, and HVAC systems following review of actual hospital designs and discussions with engineers. Table 3 summarizes the building descriptions for the large office and hospital prototypes in two locations, Chicago and Houston.

After initial buildings descriptions have been defined, DOE-2 simulations are done and calibrated against the average fuel and electricity consumption and fuel/electricity ratio from the 1983 CBECS data by building type and region. Because of the statistical variations in the CBECS data and the large number of variables that can be changed, the approach taken in this calibration was not to match rigorously the measured data, but to guard against large offsets while maintaining consistency across the regions and prototypes.

The end result of this effort is a set of prototypical buildings that provide a great deal of information about the energy demand and loads shapes of typical buildings under typical operating conditions. What this methodology does not address, however, is how sensitive are those energy use patterns to changes in the building parameters, and what happens in the case of atypical building conditions.

Comparison of Prototypical Building Energy Use to Measured Data

The above-described development of prototypical buildings was predicated on the assumption that variations in commercial building energy use can be captured by careful disaggregation of the building stock by building type, vintage, and location. The first task in evaluating the validity of this approach is to compare the distribution of Energy-use Intensities (EUI) and Fuel-Electric Ratios (FER) using the prototypical buildings to that from actual survey data. EUI is defined as the annual energy use of fuel or electricity per floor area; FER is defined as the ratio of fuel to electricity use in a building, using a thermodynamic electricity-to-thermal conversion of 3413Btu/kW.

Figure 1 shows the aggregated distributions from the GRI data base of fuel and electricity EUI and FERs for large office buildings, superimposed over that reported by the 1989 CBECS. The GRI data base distribution is computed by aggregating the total floor area of buildings represented by each of the 78 prototypical buildings (13 locations x 2 hours of operations x 3 vintage/equipment combinations). The CBECS distribution is based on utility bill data of over 500 sample buildings. Although the GRI data base includes only 13 cities, the aggregate distribution should be close to the national total since each U.S. region was represented by at least three cities.

Both the fuel and electricity EUI distribution of the GRI prototypes are higher than that from the 1989 CBECS. One reason for this discrepancy is that the GRI prototypes were calibrated against the the 1983 CBECS which showed higher fuel and

* CBECS was called the Nonresidential Building Energy Consumption Survey (NBECS) prior to 1989. To avoid confusion, we will use CBECS to refer to all versions of this statistical data base.

electricity EUIs for office buildings. Although this suggests that the GRI offices prototypes may need to be recalibrated against the newer CBECS data, Figure 1 does indicate that the mix of vintages, hours of operations, and climates chosen seems to capture to a great extent the observed variations in office EUI and FER.

Figure 2 shows the aggregated distributions of total energy EUI (fuel plus electricity) for hospitals, based first on a survey of 3773 hospitals participating in U.S. Department of Energy's Institutional Conservation Program (ICP, Carroll et al. 1987), and then on the 33 prototypical buildings simulated in the GRI data base. * It is apparent that although the GRI prototypes corresponded to the the mean energy use, they failed to capture the wide variation in hospital EUIs shown in the ICP data. This suggests that, in addition to the physical and system-based variations represented among the 33 prototypical hospitals, it is necessary to consider other variations, such as lighting power density, process electricity and fuel use, etc., to account for the wide distribution of hospital energy use patterns.

Sensitivity of Building Energy Use Patterns to Changes in Building Parameters

Following the comparison to the measured distribution of energy use, we analyzed through parametric DOE-2 simulations the impact that variations in building parameters such as shell conditions, internal loads, operating schedules, etc., have on the energy use patterns of the prototypical buildings. This analysis was done by altering the input parameters from the averages used in the prototypical buildings, and noting the changes on electric and fuel EUIs, FER, and hourly load shapes.

For the large office prototype, we varied the following parameters : building floor area, glazing percentage, insulation level, number of people, lighting power density, and hours of operation. For those first two parameters which are based on statistical sampling, e.g., floor area or window percentage, we increased and decreased the average values by one standard deviation. For the other three parameters which are based on engineering judgement, we modified the average values up by 1.50 and down by 0.667. To simulate extreme bounding conditions, we also modeled an energy-intensive building of small size, with large glazing area, high occupancy, long hours of operation, and high lighting power density, and an energy-efficient building of large size, with small glazing area, low occupancy, short hours of operation, and low light power density.

For the hospital prototype, we varied the same building parameters, except eliminating hours of operations and substituting equipment power density. We did not consider hours of operation since hospitals by their function have to be operated 24-hour a day. Similar to the office prototype, we also simulated two bounding conditions of an energy-intensive and energy-efficient hospital. Table 4 summarizes the building parameters studied in the sensitivity analyses.

Tables 5 and 6 show the results for the large office and hospital prototypes in two cities, Chicago and Houston. The sensitivity analysis for large offices indicate that their EUIs are highly sensitive to the modeled lighting power density and hours of operation, moderately sensitive to the building size and glazing characteristics for gas use, and insensitive to the insulation level, occupancy density, and building size and glazing characteristics for electricity usage. The relative uniformity in office operating conditions and the differentiation between 12- and 24-hour offices has allowed the GRI prototypes to account for much of the observation distribution of office EUIs. For this building type, the engineering-based disaggregation used in the GRI study seems adequate.

The sensitivity analysis for hospitals indicate that their EUIs are basically unaffected by the modeled building configuration, but dominated mostly by the modeled lighting and equipment power density. When these conditions are combined for the energy-intensive and energy-efficient cases, the differences in gas and electric EUIs are much larger than those using the traditional vintage and location disaggregations. While the six original hospital prototypes for Chicago and Houston had similar total EUIs from 473 to 525 kBtu/ft^2, the sensitivity analysis showed a greater variation from 393 to 635 kBtu/ft^2. This suggests that further work in identifying "niche" markets for technologies that are sensitive to EUIs and load factors such as gas cogeneration would benefit from the development of scenario-based rather than engineering-derived pro-

* In accordance with the methodology of the ICP project, electricity has been converted to fuel consumption with a multiplier of 3.5, i.e., 1 kW = 11.8 kBtu, in calculating the total building EUIs on Figure 2 and Tables 5 and 6.

totypes. For example, the hospital stock can be disaggregated into average, high, and low energy-intensity prototypes. These prototypes could have the same shell conditions, but vary in their lighting and equipment power density, and amount of process loads.

Conclusion

Many engineering studies of commercial building energy use patterns are done using prototypes designed to reflect average or typical conditions within a certain building population. This procedure is adequate for building types such as large offices with fairly uniform internal conditions, so that the variation in their energy use patterns can be expressed as a function of the building vintage and location. However, for building types whose loads are process-dominated and characterized by large variations, it may be more useful to define a set of internal conditions ranging from low to high energy-intensity and forego the typical building definitions based on vintage, location, system type, etc.

Our sensitivity analysis also implies that more care and study needs to be devoted to defining the range and variability of end-use conditions in commercial buildings, rather than their shell conditions. In most simulation efforts, the building is most rigorously defined in terms of its physical structure, less so for the equipment and operating schedules, and almost haphazard for the end-use intensities. Our preliminary sensitivity study suggests that the specificity in defining of the building shell conditions may be swamped by the inaccuracies in modeling the lighting and equipment power density and schedules.

References

Carroll,W.L., Kammerud,R.C., Birdsall,B.E. et al. 1987. "An estimate of aggregate energy savings due to the ICP Program", Report LBL-24053, Lawrence Berkeley Laboratory, Berkeley CA.

Energy Information Administration (EIA) , 1989. *Commercial Buildings Consumption and Expenditures* (Commercial Buildings Energy Consumption Survey), U.S. Department of Energy, Washington DC.

Huang,Y.J., Akbari, H., Rainer, L., and Ritschard, R.L. 1991. "481 Prototypical Commercial Buildings for Twenty Urban Market Areas (Technical documentation of building loads data base developed for the GRI Cogeneration Market Assessment Model)", LBL Report 29798.

Table 1. Building Locations in GRI Cogeneration Project

Northeast	**South**
Boston	Miami
New York	New Orleans
Philadelphia	Houston
North Central	**West**
Chicago	Los Angeles
Detroit	San Diego
St. Louis	San Francisco
	Phoenix

Table 2. Building Prototypes in GRI Cogeneration Project

Hospital	Prison
Apartment	Secondary School
Large Hotel	Sit-down Restaurant
Small Hotel/Motel	Fast-food Restaurant
Large Office 12-hour	Supermarket 18-hour
Large Office 24-hour	Supermarket 24-hour
Large Retail	

Table 3. Large Office and Hospital Prototypes for Chicago and Houston

Building Parameter	Large Office	Hospital
Floor Area (1000 ft²)		
Stock Vintage	Chi : 349 Hou : 204	Chi : 364 Hou : 254
Current Vintage	Chi : 352 Hou : 253	Chi : 364 Hou : 254
No. of floors	9	Chi : 6 Hou : 4
Shell characteristics		
Stock vintage:		
Ceiling R-value	Chi : 9.1 Hou : 7.9	Chi : 7.4 Hou : 5.9
Wall R-value	Chi : 1.5 Hou : 1.1	Chi : 1.2 Hou : 1.0
Window glass	1-pane	1-pane
Current vintage	ASHRAE-90.1	ASHRAE-90.1
Window shad. coeff	0.60	0.60
Window/wall ratio	Chi : 0.41 Hou : 0.50	0.178 †
Internal loads		
Ft²/person	Chi : 380 Hou : 360	310 †
Lights W/ft²		
Stock	Chi : 1.9 Hou : 2.0	2.1 †
Current	1.57	2.1 †
Equip W/ft²		
12-hour	0.75	0.9 †
24-hour	1.2	
Hot Water Btu	175/person	6.76/ft²
Process Btu/ft²	N/A	1.80
Process W/ft²	N/A	0.07
System Configuration	2 (perimeter, core).	5 (clinic, perim., kit., hallway, lobby/core).
System Type		
Old equip.	Const.Volume	Const.Volume
New equip.	VAV	VAV for lobby, Const.Volume other 4 zones.
Heating Sched (F)	74 day, 65 night	72 all day
Cooling Sched (F)	78 day, 85 night	76 all day
Heating plant	gas boiler	gas boiler
Chiller type	hermetic centrifugal	hermetic centrifugal
Hot water plant	gas boiler	gas boiler

† varies by zone.

Table 4. Building Parameters Modified in Sensitivity Analysis

Building Parameter	Increase	Decrease
Building Size	+1 std. dev.	-1 std. dev.
Glazing Pct.	+1 std. dev.	-1 std. dev.
Insulation	ASHRAE-90.1	None
No. of People	+1 std. dev.	-1 std. dev.
Hrs Operation	24 hrs/day	8 hrs/day
Lighting kWh	1.5 average	0.667 average
Equipment kWh	1.5 average	0.667 average
High/Low EUI	small, high glass pct, no insul., high light. & equip. power, long hours	large, low glass pct, low light. & equip. power, short hours

Table 5. Impact of Building Parameters on Large Office Building Energy Use

	Parametric Variation			
	Increase		Decrease	
	Gas	Elec	Gas	Elec
Current Vintage with New Equipment in Chicago (Gas=45.1, Elec=17.30, Tot. EUI=249.2)				
Building Size	39.3	16.90	51.6	17.63
Glazing Pct	37.6	16.36	52.7	18.27
Insulation	-	-	45.8	17.45
No. of People	46.3	17.52	45.9	17.39
Lighting kW	39.4	20.50	50.8	15.44
Hrs Operation	36.5	26.74	42.5	15.24
High/Low EUI	46.1	33.97	35.1	12.33
(Tot. EUI)	446.9		180.6	
Current Vintage with New Equipment in Houston (Gas=26.7, Elec=21.78, Tot. EUI=283.7)				
Building Size	23.2	21.17	29.6	22.04
Glazing Pct	31.3	23.20	19.9	20.42
Insulation	-	-	17.3	19.87
No. of People	18.7	20.42	17.0	19.53
Lighting kW	17.1	24.29	17.9	16.86
Hrs Operation	17.0	31.57	23.7	19.52
High/Low EUI	21.5	39.88	21.1	15.81
(Tot. EUI)	492.1		207.7	

Gas in kBtu/ft², electricity in kWh/ft².
Total EUI in kBtu/ft², 1 kWh = 11.8 kBtu.

Table 6. Impact of Building Parameters on Hospital Building Energy Use

	Parametric Variation			
	Increase		Decrease	
	Gas	Elec	Gas	Elec
Current Vintage with New Equipment in Chicago (Gas=142.8, Elec=27.99, Tot. EUI=473.1)				
Building Size	138.9	27.97	148.8	27.82
Glazing Pct	155.7	28.48	134.2	27.66
Insulation	-	-	142.4	28.00
No. of People	142.8	28.09	142.6	27.94
Lighting kW	143.4	35.49	146.4	23.26
Equipment kW	146.3	31.35	140.5	25.75
High/Low EUI	167.0	39.63	153.6	21.40
(Tot. EUI)	634.6		406.1	
Current Vintage with New Equipment in Houston (Gas=79.9, Elec=33.35, Tot. EUI=473.4)				
Building Size	78.4	33.30	82.1	32.94
Glazing Pct	83.3	33.88	77.8	33.01
Insulation	-	-	79.6	33.37
No. of People	79.5	33.51	80.1	33.29
Lighting kW	76.4	41.90	85.4	28.14
Equipment kW	79.9	37.27	80.1	30.76
High/Low EUI	82.0	46.52	84.9	26.14
(Tot. EUI)	630.9		393.3	

Gas in $kBtu/ft^2$, electricity in kWh/ft^2,
Total EUI in $kBtu/ft^2$, 1 kWh = 11.8 kBtu.

Figure 1. EUIs and Fuel/Electric Ratios for Large Offices: Total U.S.

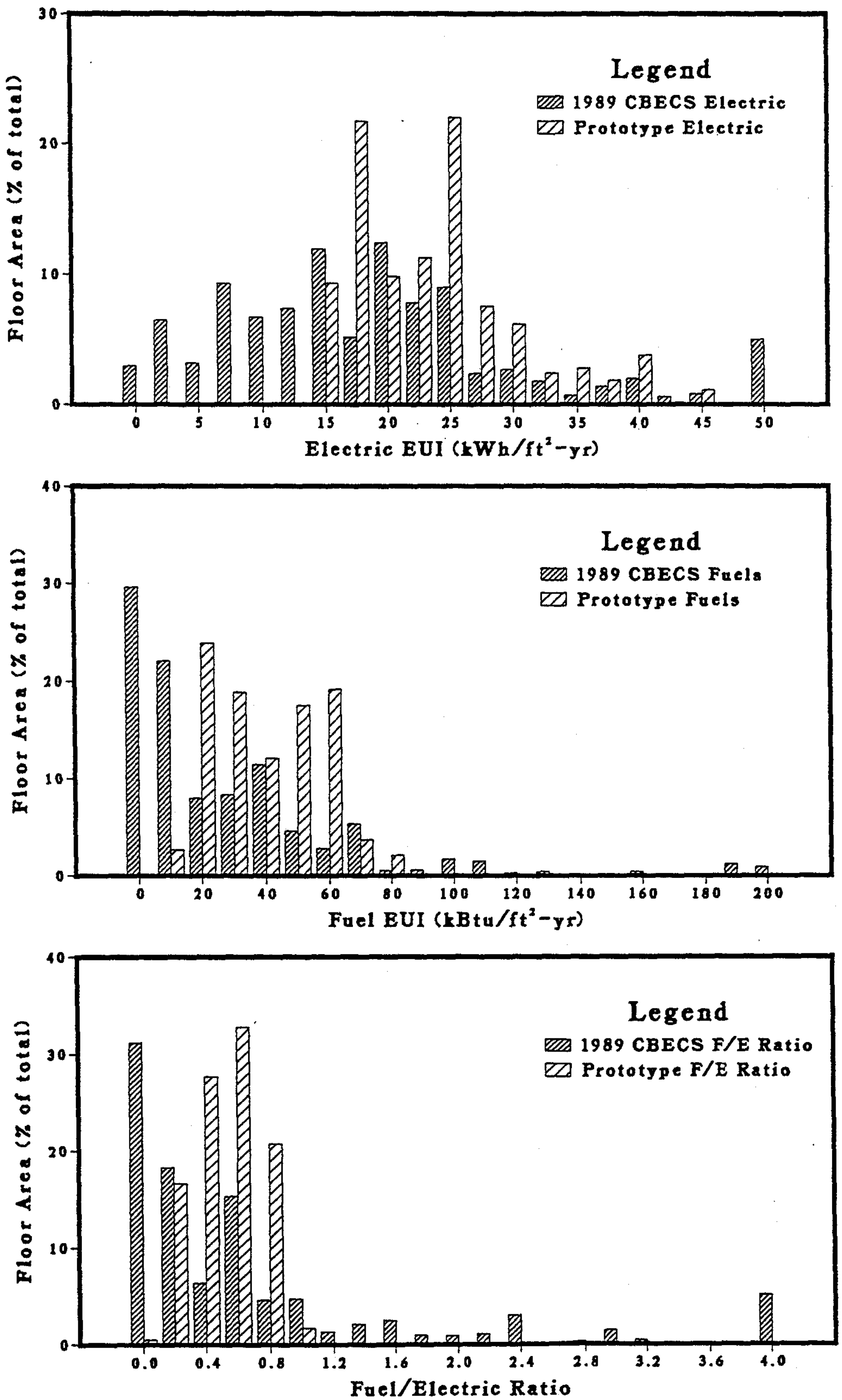
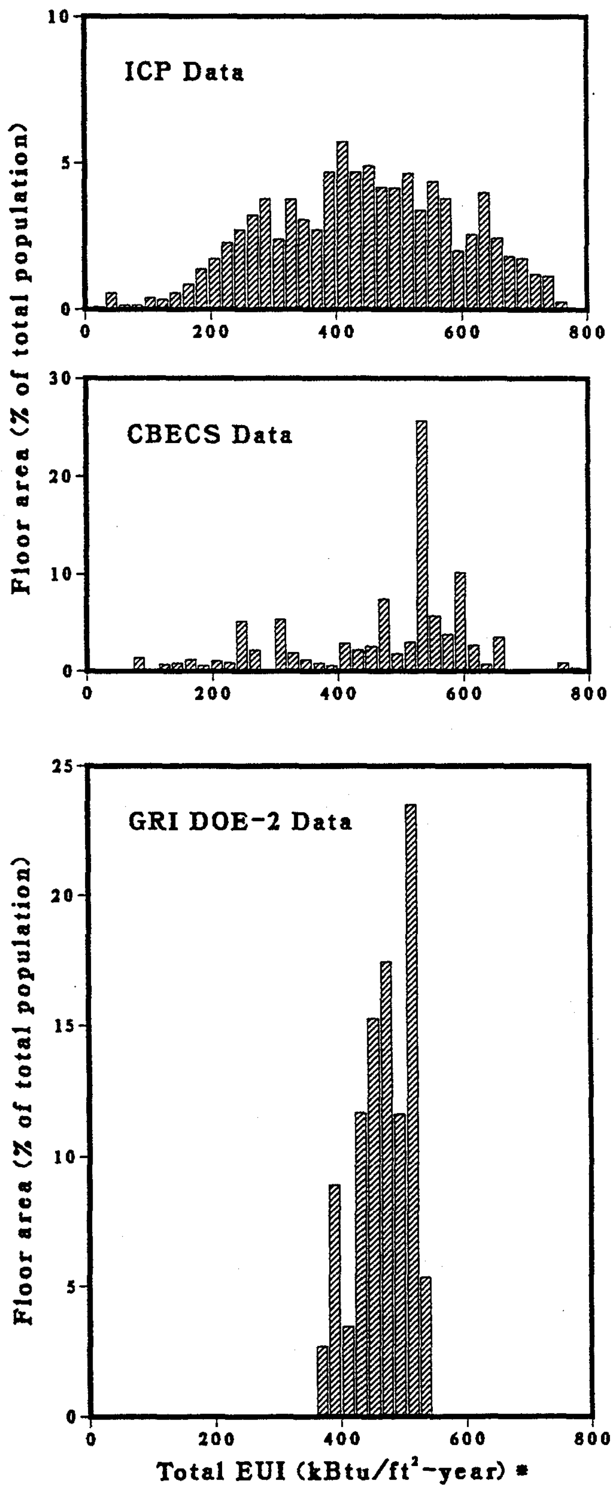


Figure 2. Distribution of Hospital End-Use Intensities



* electricity conversion 1 kWh = 11.8 kBtu