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Environmental Energy Technologies Division

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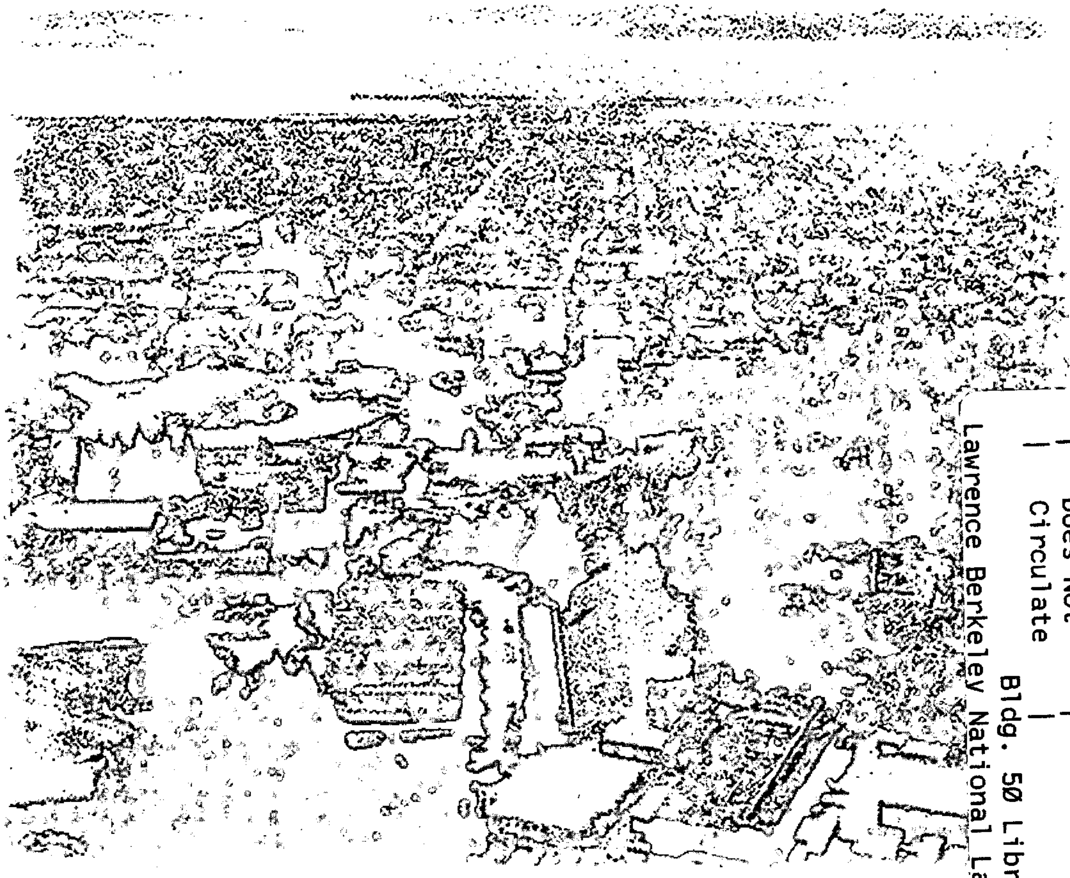

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INTERACTIONS BETWEEN LIGHTING AND SPACE CONDITIONING ENERGY USE IN U.S. COMMERCIAL BUILDINGS

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ABSTRACT

Reductions in lighting energy have secondary effects on cooling and heating energy consumption. In general, lighting energy reductions increase heating and decrease cooling requirements of a building. The net change in a building's annual energy requirements, however, is difficult to quantify and depends on the building characteristics, operating conditions, and climate.

This paper characterizes the effects of lighting/HVAC interactions on the annual heating/cooling requirements of prototypical U.S. commercial buildings through computer simulations using the DOE-2.1E building energy analysis program. Twelve building types of two vintages and five climates are chosen to represent the U.S. commercial building stock. For each combination of building type, vintage, and climate, a prototypical building is simulated with varying lighting power densities, and the resultant changes in heating and cooling loads are recorded. These loads are used together with market information on the saturation of the different HVAC equipment in the commercial buildings to determine the changes in energy use and expenditures for heating and cooling.

Results are presented by building type for the US as a whole. Therefore, the data presented in this paper can be utilized to assess the secondary effects of lighting-related federal policies with widespread impacts, like minimum efficiency standards. Generally, in warm climates the interactions will induce monetary savings and in cold climates the interactions will induce monetary penalties. For the commercial building stock in the U.S., a reduction in lighting energy that is well distributed geographically will induce neither significant savings nor significant penalties from associated changes in HVAC primary energy and energy expenditures.

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INTRODUCTION

There has been ongoing controversy over the size of changes in heating and cooling energy use associated with reductions of lighting energy use in commercial buildings. Many analysts have assumed that cooling savings totaling one third of the savings in lighting energy can be achieved because of interactions between lighting and HVAC (Heating, Ventilation, and Air Conditioning). However, these analysts have traditionally ignored the heating penalties. This report calculates the magnitude of the cooling benefits and heating penalties using a state-of-the-art data set for the commercial sector.

In a previous study, Sezgen and Huang (1994a) presented the effects of lighting/HVAC interactions on annual and peak HVAC requirements in commercial buildings. In that study, ten commercial building types of two vintages are simulated using the DOE-2.1E building energy analysis program, and the effect of reductions of lighting energy use on annual and peak HVAC loads are presented in look-up tables. These tables can be used to estimate the changes in annual heating and cooling *loads* in a given building type and region, but the study does not carry through the calculation to heating and cooling *energy*.

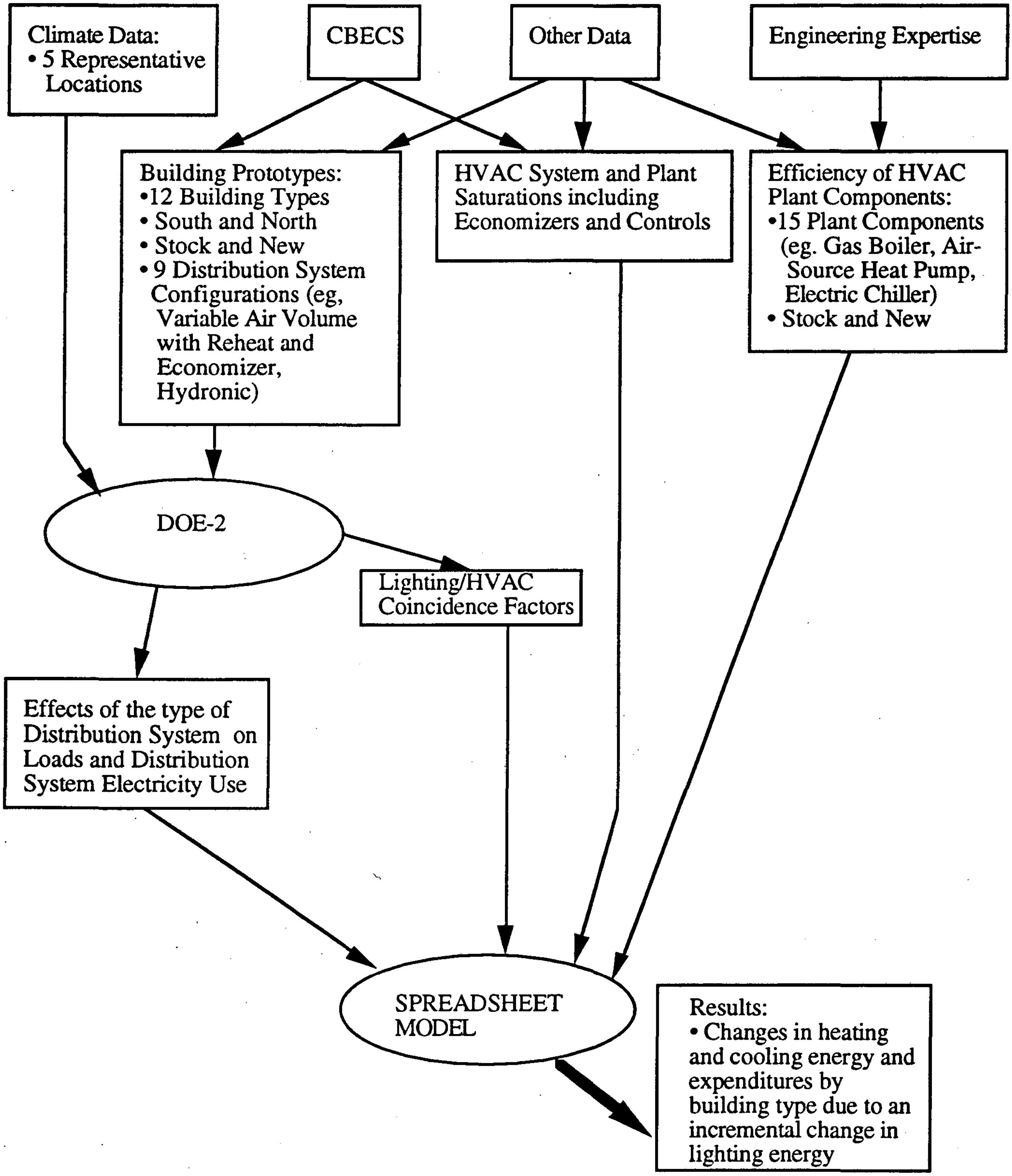
A somewhat similar approach is used by Rundquist *et al.* (1993) and Johnson (1996) to estimate the effects of lighting reduction on HVAC energy. This approach does not use prototypes for each building type. Instead, the perimeter area of the building is determined, and loads are calculated as a function of surface area to volume ratio. Again, lookup tables are presented to show how the HVAC loads will change in different climates. Finally, simple calculations using approximate efficiencies of HVAC system and plant are used to determine indirect energy effects.

Franconi and Rubinstein (1992) assess lighting/HVAC interactions in large office buildings for two HVAC system types in two climates. Treado and Bean (1992) evaluate the interactions of building lighting and HVAC systems, and the effects on cooling load and lighting performance using a full-scale test facility for selected equipment configurations. While not comprehensive in scope, these works are exemplary in their detailed treatment of these interactions for the specific cases considered.

Our analysis builds on the Sezgen and Huang (1994a) work, and characterizes the impacts of lighting/HVAC interactions on the annual heating/cooling *energy* of prototypical U.S. commercial buildings. We characterize HVAC system and plant types and associated efficiencies, and convert load results to energy results for the U.S. as a whole. The results are applicable to any policy that affects lighting or plug loads and has direct energy savings impacts that are geographically well-distributed around the country.

We first describe the methodology and present the results. We discuss the importance of those results, and assess limitations of and possible improvements to the analysis.

Figure 1: Structure of The Analysis



METHODOLOGY

Our analysis has three main parts: designing and simulating prototype commercial buildings in different regions, characterizing the efficiency of space conditioning equipment, and integrating the efficiency data and the results of those simulations to estimate overall average effects for the U.S. **Figure 1** summarizes the overall methodology. Changes in heating and cooling energy consumption are a function of the interaction between the lighting and HVAC loads, equipment saturations, plant efficiencies, and distribution system efficiencies.

Designing and simulating prototype commercial buildings

Because the building and operating characteristics of commercial buildings are very different for the different building types (e.g. office buildings, warehouses, hospitals), it is inaccurate to represent such buildings with a single commercial sector prototype. In Sezgen et al. (1995), using the results of the CBECS (US DOE/EIA, 1992), we developed prototypes for the different building types. This set of prototypes gives an accurate national picture of building characteristics in the U.S., properly accounting for equipment saturations, distribution-system characteristics, equipment efficiencies, and shell characteristics.

The climate also plays an important role in the way lighting and HVAC end uses interact. For this reason we differentiated our prototypes by region. We simulated the energy behavior of our prototypes under five different climate assumptions. Results of such simulations yielded: (1) building loads and lighting/HVAC coincidence factors, and (2) effects of HVAC distribution system on the building loads.

Building Loads and Coincidence Factors

In our analysis, the building load is defined as the amount of heating or cooling the system must supply to a building to meet the temperature set-points. Because we wanted to include the load from ventilation with the building load, we developed a user-defined DOE-2 function to modify the load calculation so that it included the outdoor air load during the hours that the system fan was scheduled to be on. The ventilation requirement for the modeled buildings is 15 ft^3 of fresh air per person per minute. The model determines the total flow rate based on the building's occupant density, floor area, and ventilation requirement.

One of the outputs of the DOE-2 simulations is the HVAC load. By varying the lighting levels in the prototypes in parametric simulation runs, we characterized the interaction between the lighting loads and the HVAC loads. Coincidence factors are used to characterize the interaction between end uses, as described in Sezgen and Huang (1994a). Cooling coincidence factors for lighting represent the fraction of annual energy input for lighting that ends up as an internal heat gain during the cooling period. Similarly, heating coincidence factors give the amount of annual lighting energy that ends up as internal gain during heating periods. The coincidence factors are presented in **Tables 1a** and **1b**.

Table 1a: Changes in building loads, energy use, and energy expenditures caused by one kWh decline in lighting load, a one kWh decline in lighting energy use, or a one dollar decline in lighting energy expenditures in existing commercial buildings

Building Type	End-Use	Loads * (kWh)	% of Floor Area	Site Energy (kWh of fuel or elect.)			Dollars (1995)			
				Electricity	Natural Gas	Oil	Electricity	Natural Gas	Oil	Total HVAC
All Buildings §	Heating	0.29	75%	0.09	0.32	0.03	0.09	0.07	0.01	-0.03
	Cooling	-0.48		-0.19			-0.19			
Small Office	Heating	0.28	5%	0.14	0.27	0.02	0.14	0.06	0.00	-0.03
	Cooling	-0.48		-0.23			-0.23			
Large Office	Heating	0.16	13%	0.08	0.21	0.03	0.08	0.05	0.01	-0.16
	Cooling	-0.7		-0.30			-0.30			
Small Retail	Heating	0.39	9%	0.06	0.42	0.04	0.06	0.09	0.01	0.02
	Cooling	-0.45		-0.14			-0.14			
Large Retail	Heating	0.29	9%	0.13	0.51	0.03	0.13	0.11	0.01	-0.02
	Cooling	-0.62		-0.27			-0.27			
Small Hotel	Heating	0.2	2%	0.14	0.25	0.02	0.14	0.05	0.00	-0.01
	Cooling	-0.43		-0.21			-0.21			
Large Hotel	Heating	0.16	2%	0.06	0.33	0.02	0.06	0.07	0.00	-0.14
	Cooling	-0.66		-0.27			-0.27			
Hospital	Heating	0.1	3%	0.05	0.23	0.01	0.05	0.05	0.00	-0.23
	Cooling	-0.87		-0.33			-0.33			
Grocery	Heating	0.3	1%	0.22	0.39	0.06	0.22	0.08	0.01	-0.02
	Cooling	-0.57		-0.34			-0.34			
School	Heating	0.48	12%	0.13	0.53	0.06	0.13	0.11	0.01	0.07
	Cooling	-0.4		-0.18			-0.18			
Restaurant	Heating	0.36	2%	0.14	0.39	0.05	0.14	0.08	0.01	-0.01
	Cooling	-0.56		-0.24			-0.24			
Warehouse	Heating	0.24	17%	0.02	0.14	0.00	0.02	0.03	0.00	-0.01
	Cooling	-0.22		-0.05			-0.05			

* change in heating/cooling load caused by a 1kWh decline in lighting energy also corresponds to heating/cooling coincidence factor

§ values for the sector calculated using floor area to weight the results for the different building types

Table 1b: Changes in building loads, energy use, and energy expenditures caused by one kWh decline in lighting load, a one kWh decline in lighting energy use, or a one dollar decline in lighting energy expenditures in new commercial buildings

Building Type	End-Use	Loads* kWh	% of Floor Area	Site Energy (kWh of fuel or elect.)			Dollars (1995)			
				Electricity	Natural Gas	Oil	Electricity	Natural Gas	Oil	Total HVAC
All Buildings §	Heating	0.27	76%	0.10	0.25	0.01	0.10	0.05	0.00	-0.03
	Cooling	-0.50		-0.19			-0.19			
Small Office	Heating	0.29	5%	0.16	0.16	0.01	0.16	0.03	0.00	0.00
	Cooling	-0.46		-0.20			-0.20			
Large Office	Heating	0.15	16%	0.11	0.15	0.01	0.11	0.03	0.00	-0.13
	Cooling	-0.7		-0.28			-0.28			
Small Retail	Heating	0.36	12%	0.04	0.37	0.00	0.04	0.08	0.00	-0.01
	Cooling	-0.46		-0.13			-0.13			
Large Retail	Heating	0.23	11%	0.18	0.41	0.00	0.18	0.09	0.00	-0.04
	Cooling	-0.72		-0.31			-0.31			
Small Hotel	Heating	0.19	0%	0.15	0.27	0.00	0.15	0.06	0.00	0.00
	Cooling	-0.45		-0.20			-0.20			
Large Hotel	Heating	0.12	0%	0.05	0.24	0.00	0.05	0.05	0.00	-0.16
	Cooling	-0.69		-0.27			-0.27			
Hospital	Heating	0.06	0%	0.03	0.10	0.00	0.03	0.02	0.00	-0.24
	Cooling	-0.91		-0.29			-0.29			
Grocery	Heating	0.16	1%	0.26	0.23	0.00	0.26	0.05	0.00	0.00
	Cooling	-0.73		-0.31			-0.31			
School	Heating	0.44	11%	0.16	0.42	0.04	0.16	0.09	0.01	0.02
	Cooling	-0.42		-0.24			-0.24			
Restaurant	Heating	0.24	2%	0.10	0.18	0.01	0.10	0.04	0.00	-0.13
	Cooling	-0.69		-0.28			-0.28			
Warehouse	Heating	0.25	18%	0.04	0.10	0.00	0.04	0.02	0.00	0.01
	Cooling	-0.23		-0.05			-0.05			

* change in heating/cooling load caused by a 1kWh decline in lighting energy also corresponds to heating/cooling coincidence factor

§ values for the sector calculated using floor area to weight the results for the different building types

HVAC Distribution System Load Factors and Electrical Energy Use

The *system load* is the amount of heating and cooling the HVAC plant has to provide to the distribution system for the building load to be met. The *system load factor* is a multiplier used with the base-case building load to translate the building load to the system load; the system factor varies depending on the type of distribution system and its control strategy. In addition to affecting the heating and cooling loads, the HVAC system uses electrical energy to drive fans and pumps.

System load factors were calculated as the ratio of the system load to the building load (both of which are DOE-2 outputs). System electricity use is calculated as the sum of the pump and fan electricity use. For air conditioners, packaged unitary systems, and heat-pump loops, the system efficiency and the system electricity use are included as part of the plant efficiency. System load factors and electrical energy use for different building types are presented in Appendix A (section A3). We did not utilize the data on system electricity use in this report because the difference of electricity used by the pumps and the fans between the scenarios with different lighting levels is not significant.

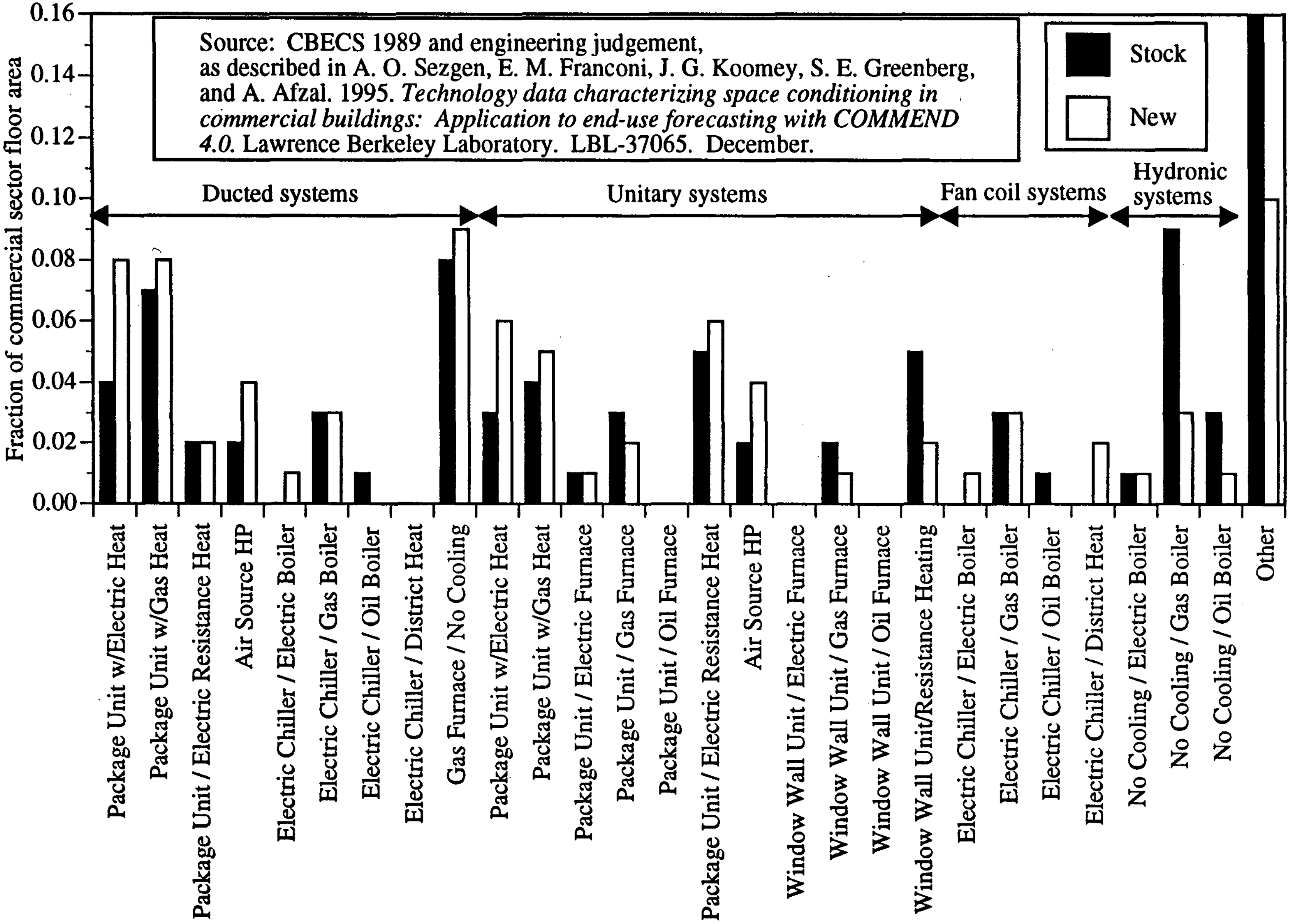
Economizers tend to decrease the system loads under suitable conditions. The data on which we relied characterize this effect comparing the outputs of parametric runs with and without economizers. However, the market penetration of economizers is not significant with the exception of large office buildings where this penetration was around 8% in 1989. Therefore in this study we ignored the effect of economizers.

Development of HVAC saturations and efficiencies

One of the key issues in estimating the potential energy effects of changes in lighting loads is the prevalence (saturation) of different combinations of heating and cooling equipment. Direct estimations of the saturation of HVAC equipment combinations are not possible using only the 1989 CBECS. However, we combined the CBECS data with engineering judgment regarding the compatibility of combinations of heating/cooling equipment and distribution systems to estimate saturations by building type. Saturations of heating/cooling equipment combinations are shown in **Figure 2** for both stock and new buildings (more detailed data, and data by building type, are contained in *Tables B.1 and B.2* in Appendix B). We ignored the less important equipment combinations within each building type to create a rough characterization of these saturations.

Plant and distribution system efficiencies are another key input to the analysis. We rely on annual integrated part load efficiencies that reflect operational differences over a typical year (*Table C.1* in Appendix C). These efficiencies are then multiplied by the annual loads to estimate annual energy use. Integrated part load efficiencies are generally less than efficiency measured under full load conditions.

Figure 2: Saturation of heating/cooling combinations in the commercial sector--All building types (fraction of total commercial sector floor area)



Source: CBECS 1989 and engineering judgement, as described in A. O. Sezgen, E. M. Franconi, J. G. Koomey, S. E. Greenberg, and A. Afzal. 1995. *Technology data characterizing space conditioning in commercial buildings: Application to end-use forecasting with COMMEND 4.0.* Lawrence Berkeley Laboratory. LBL-37065. December.

Integration of data and determination of energy and monetary effects of interactions

The market shares for the different equipment types by building type are combined with (1) heating and cooling coincidence factors by building type; (2) plant efficiencies; and (3) distribution system losses to calculate the change in HVAC energy use due to a unit reduction in lighting energy. A unit reduction in lighting changes the heating and cooling loads by amounts determined by the coincidence factors. These incremental changes in heating and cooling loads need to be satisfied by the HVAC system. These changes in building loads are first modified using the system load factors to account for distribution system losses and then multiplied by plant efficiencies to determine the changes in fuel use. Finally, the change in fuel use is multiplied by fuel prices[1] to determine the monetary impact of interactions.

RESULTS

A reduction in lighting energy causes a reduction in cooling load and an increase in heating load. **Figures 3a** and **3b** presents the changes in heating/cooling loads due to a one unit (kWh) change in lighting energy (these can also be read from Tables 1a and 1b above). These changes correspond to the coincidence factors mentioned above. The annual energy coincidence factors for heating and cooling in general correlate to the duration of the heating and cooling seasons of the buildings. However, there is noticeably less coincidence for heating as compared to cooling, even when the lengths of the seasons are considered, because the lights are almost always on when cooling is required during the day, but frequently off when heating is required during the night.

For larger building types, the sums of the heating and cooling coincidence factors are larger, indicating that any changes in their lighting power density ultimately manifest themselves in modifying the buildings' heating or cooling loads. For the smaller or less energy-intensive buildings such as lodging or warehouse buildings, the sum of coincidence factors is lower. The coincidence factor for cooling is very high in hospitals because internal gains are high and these buildings are being cooled most of the time. In schools and colleges, the heating coincidence factors are larger than the other building types because the percentage of activity during the heating season is larger in these building types. Generally, cooling coincidence factors are larger than heating coincidence factors. The building types in which heating coincidence factors are larger are schools and warehouses: again, in educational buildings the activity is more during the heating season, and in warehouses cooling is utilized usually only in the offices which constitute a small area of this building type.

How these changes in cooling and heating loads affect the energy use and energy expenditures depends on the saturations of the different kinds of HVAC equipment. In terms of site energy, as seen in **Figures 4a** and **4b** (also summarized in Tables 1a and 1b), the penalty due to heating is higher than the gains due to cooling. Although the increase in heating load is generally less than the decrease in cooling loads in absolute terms, more site energy is needed to satisfy one unit of heating load compared to one unit of cooling loads. Reductions in lighting energy increase HVAC site energy use in all building types (the increase in heating site energy is larger than the reduction in cooling energy) except in hospitals.

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[1] Fuel prices are taken from US DOE/EIA (1996). The prices are for 1995 in 1995 dollars.

The picture changes somewhat when we examine expenditures (which also parallel the situation at the primary energy level). As seen from **Figures 5a** and **5b** (also summarized in Tables 1a and 1b), the changes in heating and cooling expenditures are comparable, with benefits outweighing penalties by a small margin (3-4%). Benefits significantly dominate penalties in large offices, large hotels, hospitals, and new restaurants. Penalties significantly dominate benefits in schools. Electricity is generally three times more expensive than other fuels, and cooling equipment is predominantly driven by electricity. When considering expenditures, the higher price of electricity offsets the lower site energy use for cooling, and brings cooling benefits close to heating penalties.

Figure 3a. Change in heating and cooling loads caused by a 1 kWh decline in lighting loads in existing commercial buildings

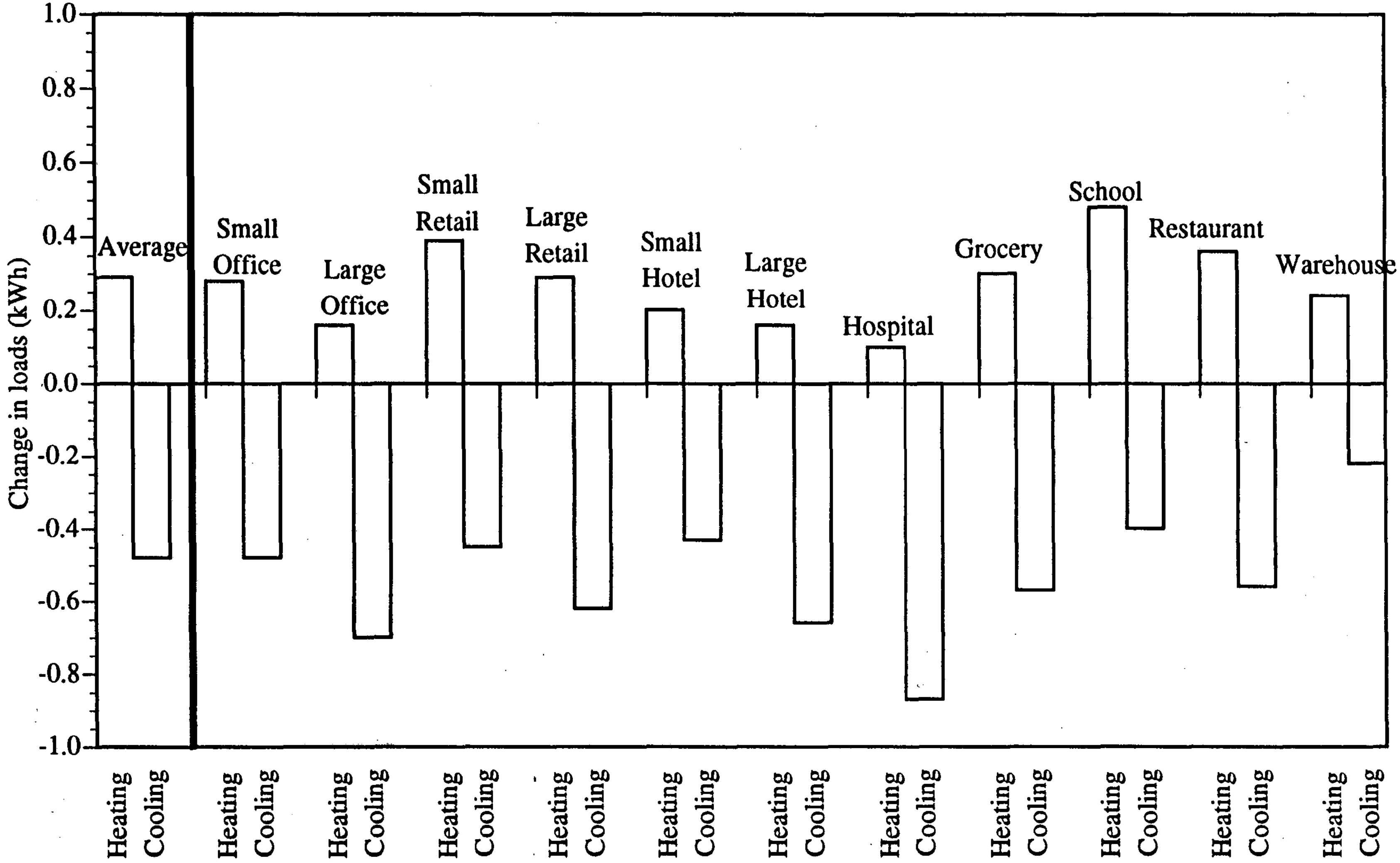


Figure 3b. Change in heating and cooling loads caused by a 1 kWh decline in lighting loads in new commercial buildings

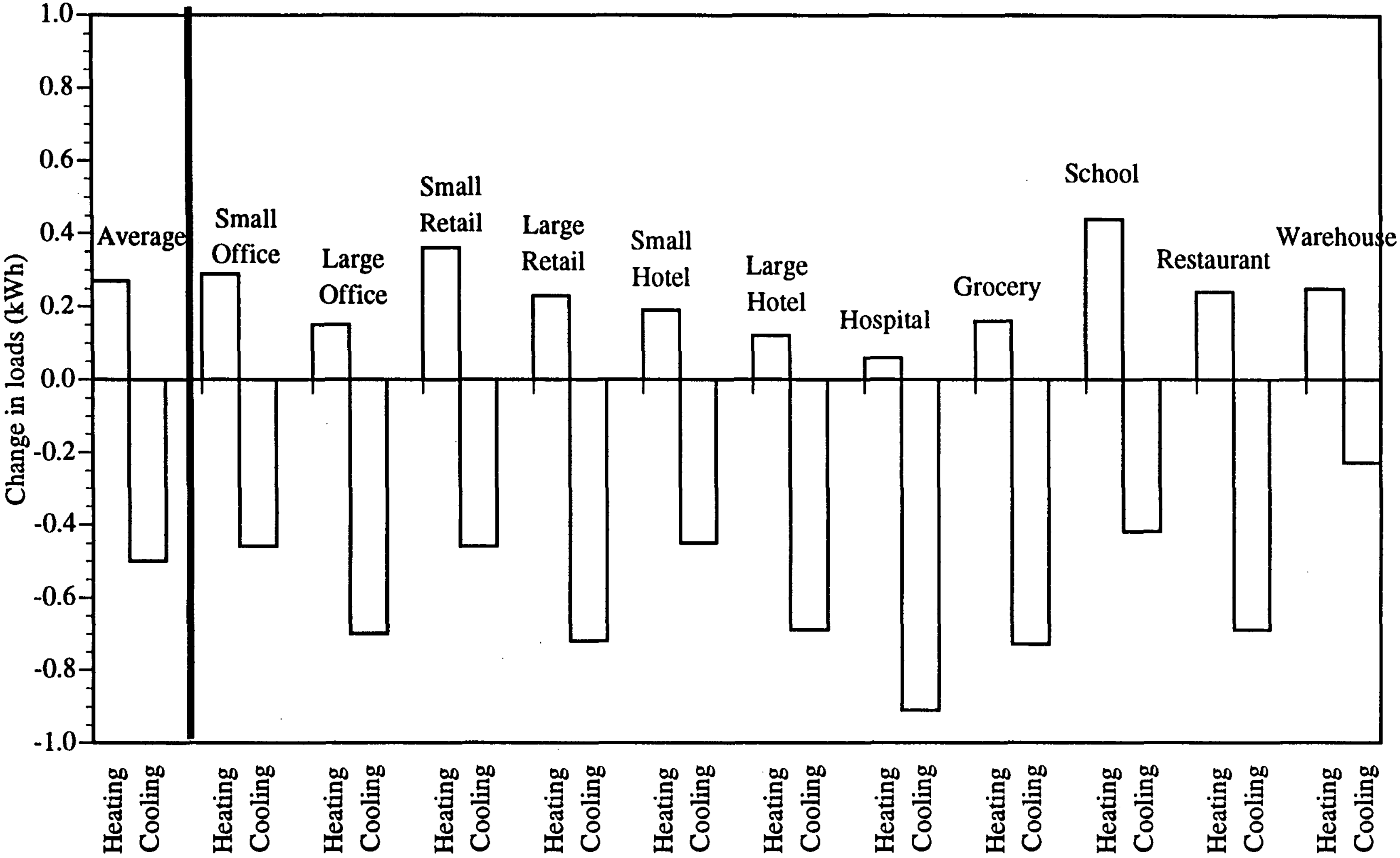


Figure 4a: Change in heating and cooling site energy use caused by a 1 kWh decline in lighting energy use in existing commercial buildings

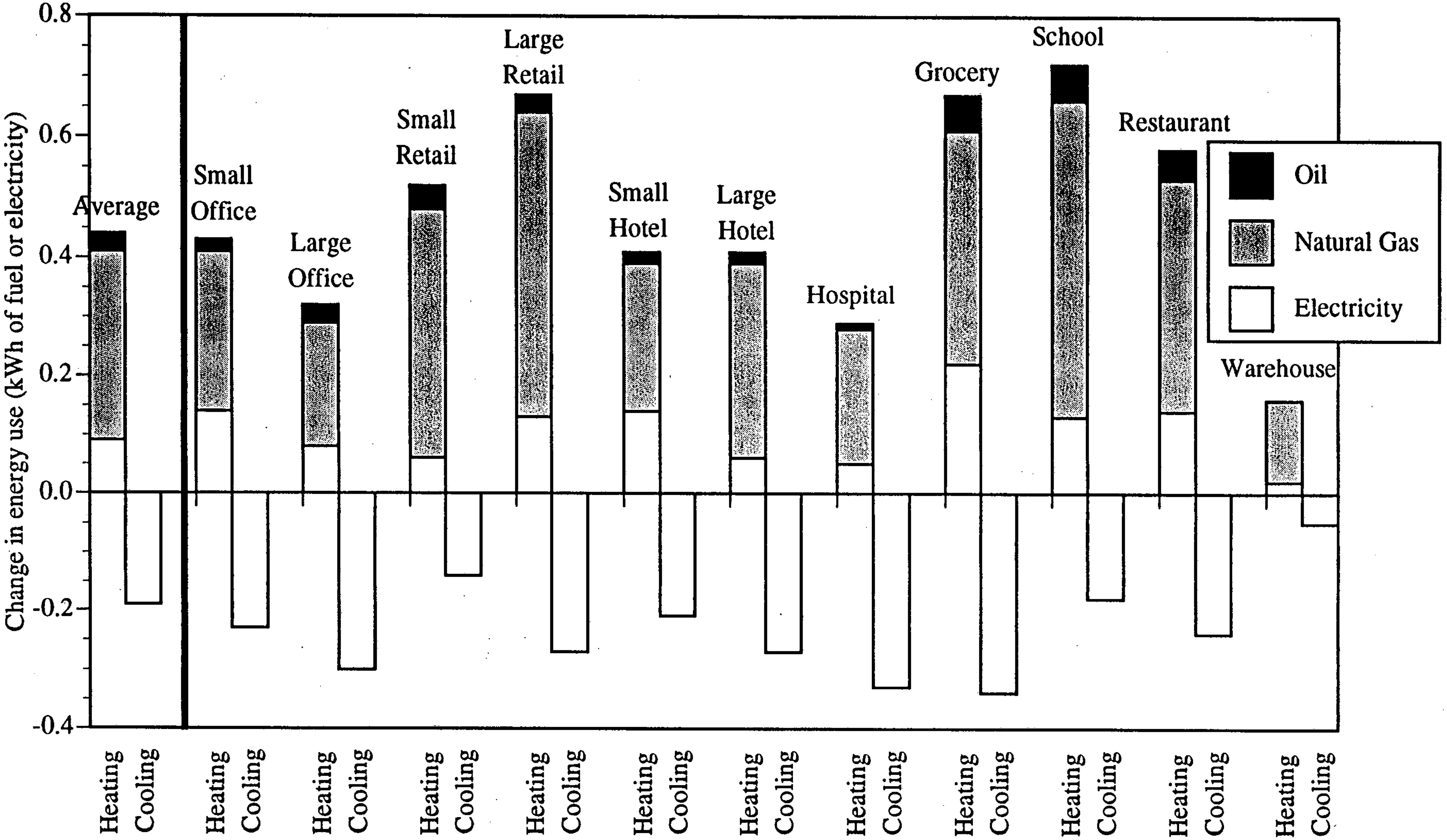


Figure 4b: Change in heating and cooling site energy use caused by a 1 kWh decline in lighting energy use in new commercial buildings

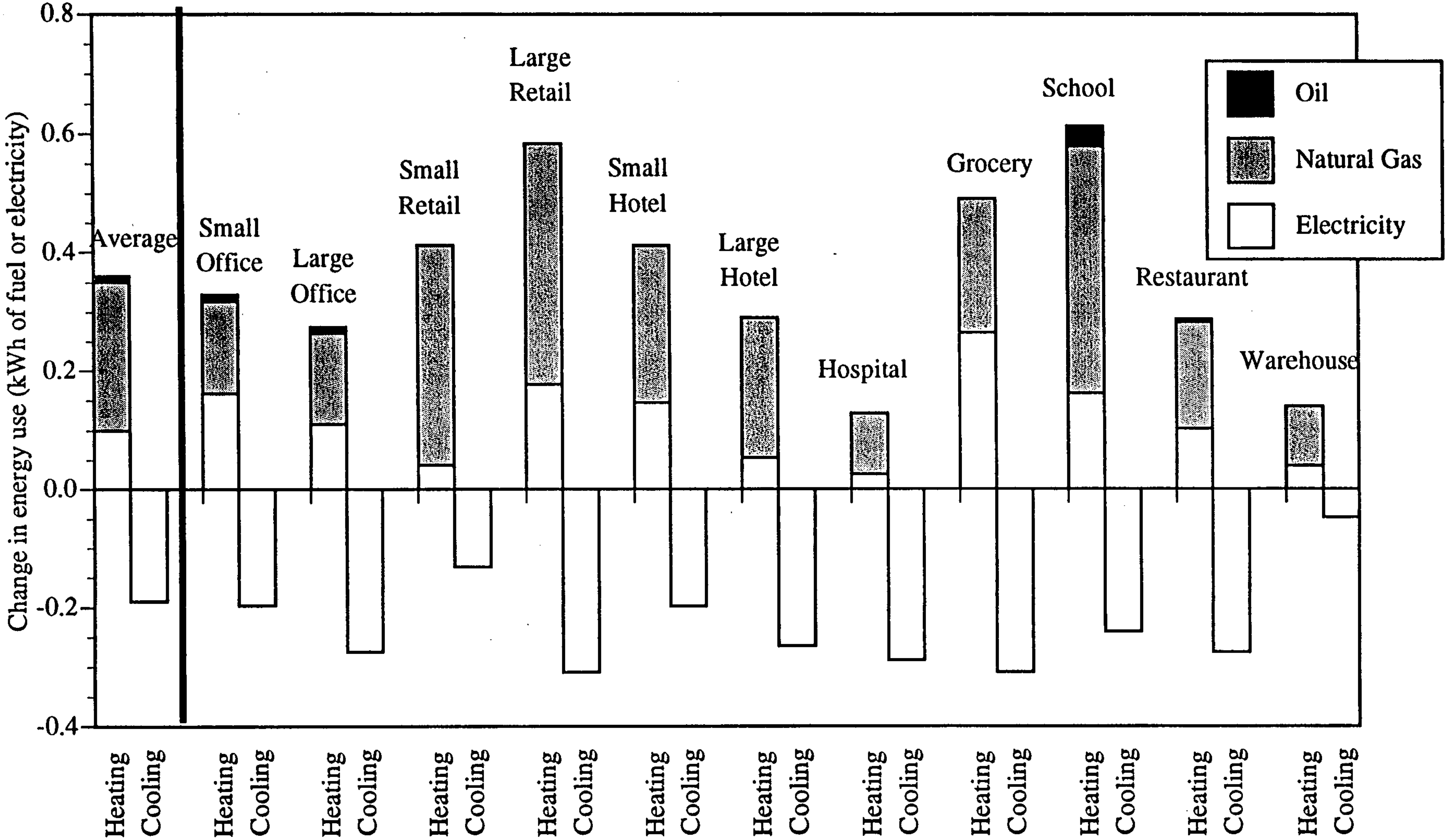


Figure 5a: Change in heating and cooling energy expenditures caused by a $1 decline in lighting energy expenditures in existing commercial buildings

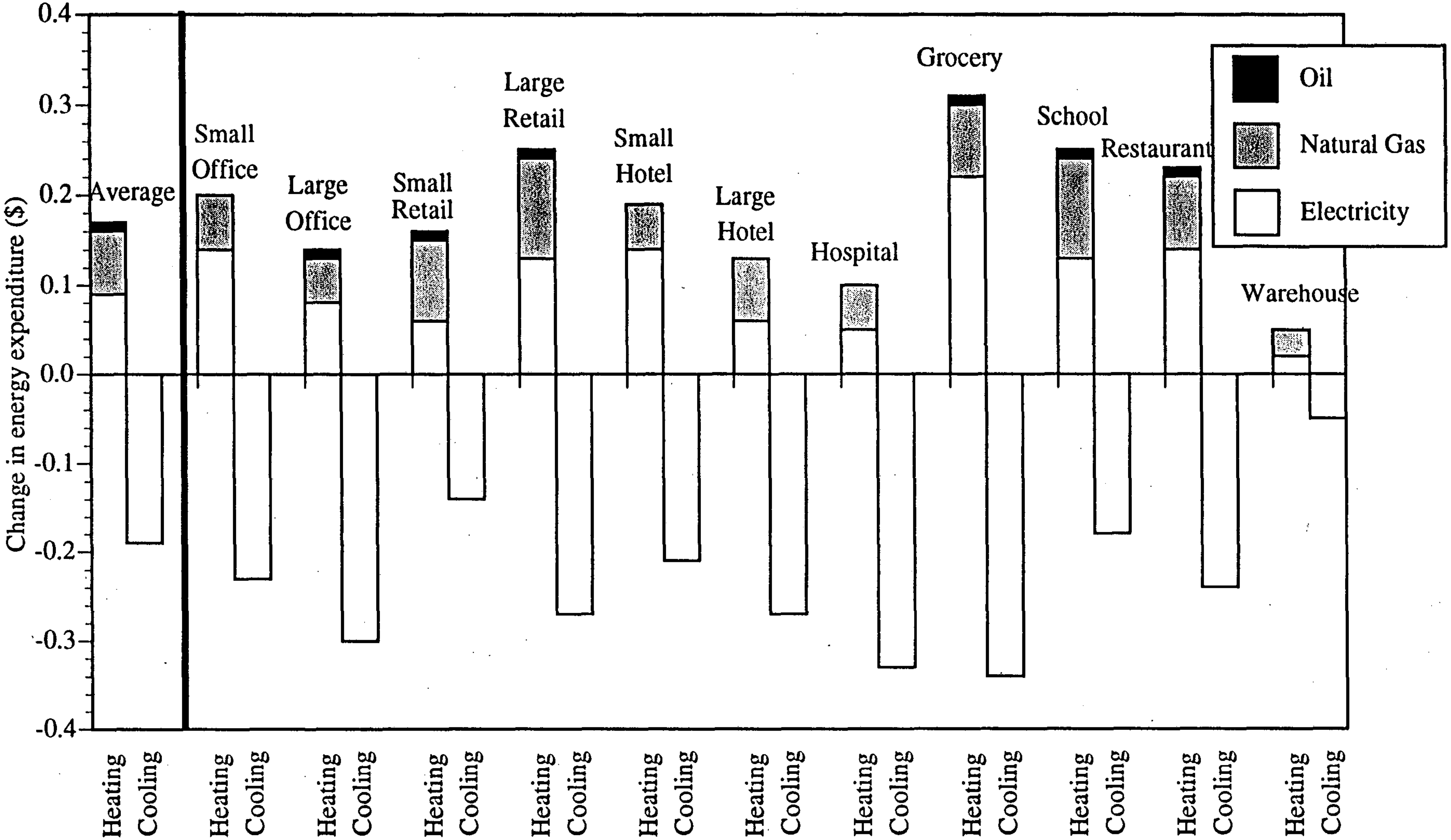
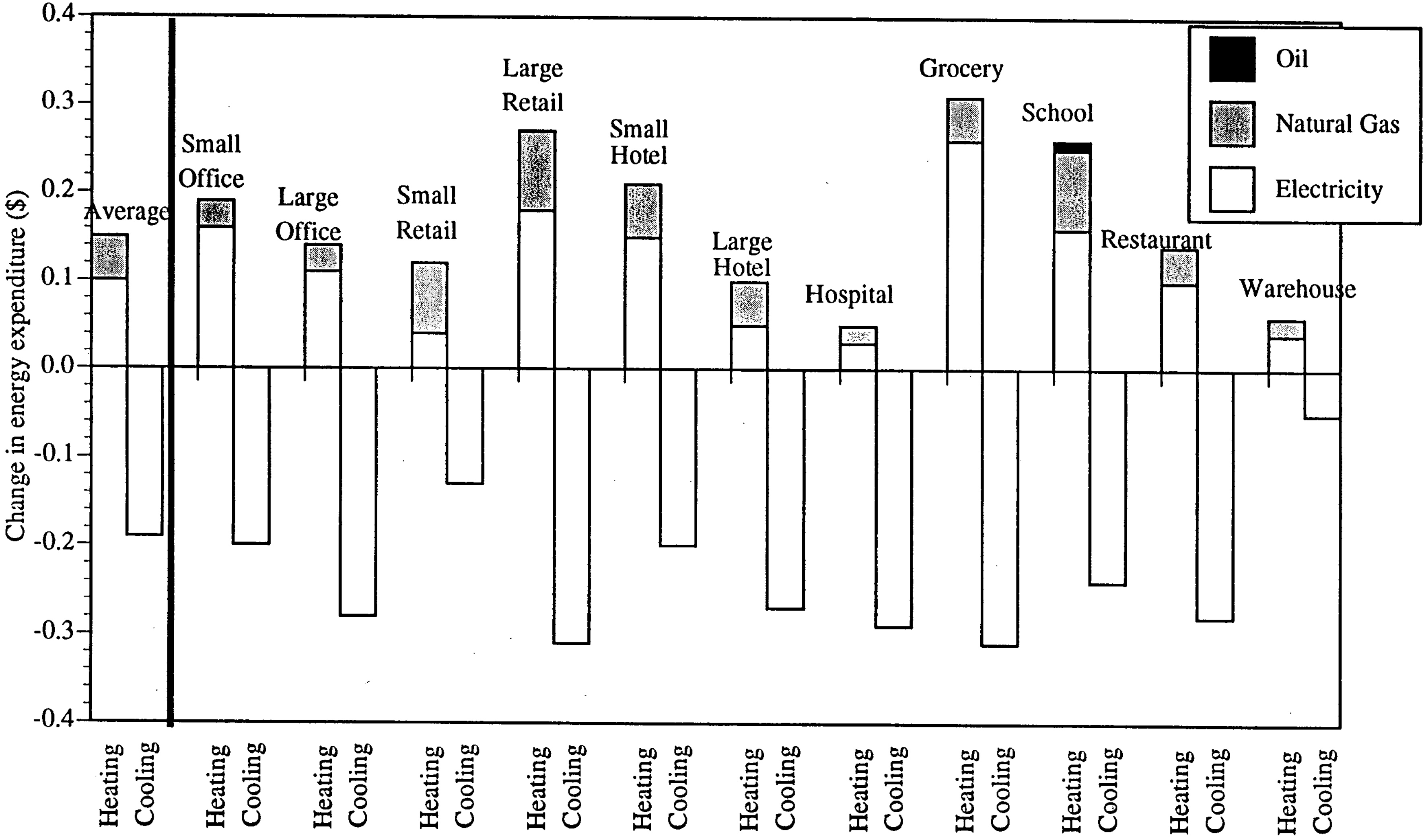


Figure 5b: Change in heating and cooling energy expenditures caused by a $1 decline in lighting energy expenditures in new commercial buildings



DISCUSSION

The building types covered in this report constitute about 75 percent of the commercial building area in the US. For this section of the commercial floor stock, the net reduction in HVAC bills due to a reduction in lighting is about 3.4 percent of the change in lighting bill. This report presents the results in terms of site energy and energy expenditures, and not in terms of source energy. However, for the above mentioned section of the commercial building area, the change in HVAC source energy.due to lighting/HVAC interactions is approximately zero.

One may wonder how the lighting/HVAC interactions in the other 25 percent of the commercial floorstock will change this picture. Vacant buildings, garages, buildings for religious worship, buildings related to public order and safety, and public assembly buildings (including theaters, conference halls) make up this 25 percent of the commercial floorstock for which we did not develop prototypes. About 4 percent of the commercial floor area is vacant and therefore uses minimal HVAC energy. Garages are about 2.5 percent of the floor area and again use practically no HVAC energy and therefore there is no need to analyze the secondary effects of lighting energy reduction on HVAC energy use. Buildings for religious worship constitute about 5 percent of the area and such buildings can be loosely compared to warehouses (some offices but mostly open space with some heating). Therefore we can assume that there will not be significant savings due to lighting/HVAC interactions in these buildings. Buildings related to public order and safety constitute about 2.5 percent of the commercial floor area and again these building types are very similar to warehouses. About 7 percent of the commercial floorstock is assembly buildings. In such buildings there might be net savings in HVAC energy bills due to lighting/HVAC interactions. Buildings which are not included in any of the above mentioned building types constitute about 4 percent of the commercial area and it is not possible to characterize them. It is clear that the only building type that will affect our results and conclusions is related public assembly buildings. If we assume that the situation in public assembly buildings is as favorable as that in large office buildings (net gain in HVAC expenditure equal to an amount which is 16 percent of the gain in lighting bill), the overall secondary dollar savings of 3.4 percent for all building types will increase to 4.6 percent.

The main application of this analysis is to policies that promote efficient lighting equipment (or any other efficient equipment that reduces internal gains in commercial buildings) in all commercial buildings across the U.S. One example of such a policy would be the minimum efficiency standard on ballasts passed in 1988 as an amendment to the National Appliance Energy Conservation Act of 1987. This standard eliminated the manufacture and sale of inefficient magnetic ballasts throughout the U.S. starting in 1990 (Koomey et al., 1996). The results of our analysis could be used to assess the overall secondary effects on HVAC energy use from this efficiency standard.

These results should ***not*** be used to draw conclusions about the importance of HVAC interactions in particular buildings or building types in particular regions. For example, it would be inappropriate and incorrect to use our results to assess HVAC interactions in a particular large office building in San Francisco or New York. Our results for large office buildings represent an average across five climate zones and all HVAC system types found in large offices throughout the U.S., and would be misleading for any assessment of interactions in a particular building.

LIMITATIONS OF THIS ANALYSIS AND FUTURE WORK

The data set generated for this report has much more detail than used in this report. For the purposes of this report, we averaged prototype simulation results for the different climate regions. In other words we suppressed information on regional characteristics. The methodology of this report can be applied to the more detailed data set to generate useful information to building designers and for local analysis purposes. Such an effort would calculate and report the HVAC interaction results by building type and by region of the U.S.

Another area of future work is to update the analysis to reflect more recent survey data on commercial building characteristics (e.g., CBECS 1995).

CONCLUSIONS

This study examines the effects of lighting/HVAC interactions on the HVAC energy consumption of the U.S. building stock as a whole, as a result of uniform reductions in lighting energy. The findings apply to the analysis of lighting policies like standards at the federal level. In summary, for the commercial building stock in the U.S., a reduction in lighting energy that is well-distributed geographically and across building types will induce neither significant savings nor significant penalties in HVAC primary energy and small benefits in HVAC energy expenditures.

When lighting/HVAC interactions are examined regionally, the picture is different. Generally, in warm climates the interactions will induce monetary savings and in cold climates the interactions will induce monetary penalties. Region-specific and building-specific analyses would be required to deduce precise conclusions for particular regions and buildings.

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Treado, S.J. and J.W. Bean. 1992. *The Interactions of Lighting, Heating and Cooling Systems in Buildings*. NISTIR-4701. U.S. Department of Commerce, Technology Administration, National Institute of Standards and Technology, Gaithersburg, MD. March.

APPENDIX A: PROTOTYPE SIMULATIONS

In this section, we describe our development of prototypes that represent the U.S. commercial building stock.

A.1 Developing Commercial Building Prototypes

To generate input data for characterizing the U.S. commercial building stock, we used the DOE-2 computer program to simulate the performance of 12 categories of commercial building prototypes:

- Large Offices,
- Small Offices,
- Large Retail,
- Small Retail,
- Warehouses,
- Schools,
- Hospitals,
- Fast-food Restaurants,
- Sit-down Restaurants,
- Large Hotels,
- Small Hotels, and
- Supermarkets.

The details of these prototypes are given in detail in Sezgen et al.[1]. The prototypes are based on average building characteristics determined from the Commercial Building Energy and Consumption Survey (CBECS)[2], engineering judgment, and some of the original assumptions used in a previous LBNL studies by Huang et al.[3] and Akbari et al.[4].

Building survey statistics from the 1989 CBECS were used to characterize the 12 categories of commercial building prototypes. The 1989 survey contains data for more than 6000 buildings. Since the inception of CBECS in 1979, five commercial building surveys have been completed by the Energy Information Administration (EIA). The 1992 CBECS was not available in an electronic format at the time these prototypes were developed.

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[1] Sezgen, Osman, Ellen M. Franconi, Jonathan G. Koomey, Steve E. Greenberg, Asim Afzal, and Leslie Shown. 1995. *Technology Data Characterizing Space Conditioning in Commercial Buildings: Application to End-Use Forecasting with COMMEND 4.0*. LBL-37065. Lawrence Berkeley National Laboratory, Berkeley, CA.

[2] U.S. Department of Energy/Energy Information Administration, 1992. *Commercial Building Energy Consumption Survey 1989: Characteristics of Commercial Buildings 1989*. DOE/EIA-0246(89), U.S. Department of Energy, Washington, D.C.

[3] Huang, J., H. Akbari, L. Rainer, R. Ritschard. 1991. *481 Commercial Building Prototypes for 20 Urban Market Areas*. GRI-90/0326, LBL-29798, Prepared for the Gas Research Institute by Lawrence Berkeley National Laboratory, Berkeley, CA.

[4] Akbari, H., J. Eto, S. Konopacki, et al. 1993. *Integrated Estimation of Commercial Sector End-Use Load Shapes and Energy-Use Intensities in the PG&E Service Area*. LBL-34263, Lawrence Berkeley National Laboratory, Berkeley, CA.

EIA develops a weighting factor for each building surveyed by CBECS based on region and floor area. The factor represents the number of buildings in one of the four census regions that are similar to the surveyed building in terms of floor area. The weighting factor and the floor area of each surveyed building are used to extrapolate total floor area by building type. We also used this CBECS weighting factor to determine building characteristics related to floor area such as shell and occupancy. We assume that buildings of the same type and floor area, if they are located in the same region, have the same construction, equipment, and operating characteristics. Although this is not necessarily precisely correct, using the weighting factor to characterize many buildings based on a sample of buildings is a reasonable first-order approximation.

Based on the 12 prototype building categories listed above, as well as differences in climate and building vintage, we developed 36 specific building prototypes for the simulations that were used. These 36 prototypes are indicated in **Table A.1**.

Table A.1: The 36 Commercial Building Prototypes

Building Prototype Categories	Stock Prototype	New Prototype
Large Offices	North & South	North & South
Small Offices	North & South	North & South
Large Retail	North & South	North & South
Small Retail	North & South	North & South
Warehouses	North & South	North & South
Schools	North & South	North & South
Hospitals	Entire U.S	Entire U.S
Fast-food Restaurants	Entire U.S	Entire U.S
Sit-down Restaurants	Entire U.S	Entire U.S
Large Hotels	Entire U.S	Entire U.S
Small Hotels	Entire U.S	Entire U.S
Supermarkets	Entire U.S	Entire U.S

Separate prototypes for northern and southern climates were developed only for building types in which energy use was significantly affected by climate (large and small offices, large and small retail, warehouses, and schools). The other six building prototype categories are characterized for the U.S. as a whole. This climatic disaggregation is discussed in greater detail below.

In addition, each of the 12 building types is characterized and modeled as both "stock" and "new". Stock building prototypes are based on 1989 CBECS data for all vintages in the survey. New building prototypes are based on CBECS data for buildings constructed between 1980 and 1989.

A.2 Prototype Characteristics

For each prototype building category, we developed climate, shell, operating, and lighting characteristics. We based our development of building characteristics on engineering judgment and CBECS data. In general, except for lighting and equipment energy use, the shell and operating characteristics are based on CBECS data. Because our goal in developing data was to represent energy use for each building type rather than specifically matching the energy use of individual buildings, we specified prototype floor areas based on mean rather than median values for building floor area.

Climate Categorization

We characterized six of the 12 prototype building categories by regional data for the North and South. Our regional categorization of "North" includes the CBECS northeast and midwest census regions; and "South" includes the CBECS south and west census regions. The other six building categories are characterized for the entire U.S. Generally, the buildings subdivided by region were better represented in the CBECS data base because they make up a larger percentage of the commercial building floor area.

Table A.2 presents five CBECS degree-day categories and the five cities that we chose to represent these climate categories: Minneapolis, Chicago, Washington D.C., Pasadena, and Charleston. Table 3.2 also presents the cooling degree days (CDD) and heating degree days (HDD) for each of the five cities. Minneapolis and Pasadena were selected because they are large population centers within their climate classification. Chicago and Charleston were selected because they represent the population-weighted average climate for the northern and southern U.S., respectively. Washington, D.C. was selected because it is the population-weighted, national average climate[5]. The CDD and HDD for these five cities represent those for the entire zone.

Table A.2. Cities Representing the CBECS Climate Categories

CBECS Climate Classification	Location	CDD*	HDD*
Zone 1: CDD<2000; HDD>7000	Minneapolis	750	8070
Zone 2: CDD<2000; 5500<HDD<7000	Chicago	998	6194
Zone 3: CDD<2000; 4000<HDD<5500	Washington, D.C.	1425	4236
Zone 4: CDD<2000; HDD<4000	Pasadena	1053	1670
Zone 5: CDD>2000; HDD<4000	Charleston	2047	2193

* At 65° F

For the six building types that were modeled using regional data, the floorstock in Zones 1 and 2 was modeled using the North prototypes and the appropriate climates (Minneapolis and Chicago, respectively). The floorstock in Zones 4 and 5 was modeled using the South prototypes and the corresponding climate data (Pasadena and Charleston, respectively). The floorstock in Zone 3, represented by Washington, D.C. climate data, is divided into two parts. One part of Zone 3's floorstock is modeled using the North prototypes and the other part is modeled using the South prototypes. For the remaining six building types that were not modeled using regional prototypes, the same prototype was simulated in all five climates.

Shell Characteristics

To specify shell characteristics for the prototypes, we used floor area weighted averages determined from CBECS "present" or "not present" percentages and nominal R-values which we specified. For wall insulation, we used a nominal value of R-7. For roof insulation, the nominal value was R-14. For windows, the nominal value for single glazing was R-1.1; for double glazing (storm windows present) the value was R-2.0. To determine the prototype shading coefficient (SC), we averaged nominal SC values for tinted and non-tinted single- and double-paned windows. We assumed that if 40% of the windows were reported to be tinted, 40% of both the single-paned and double-paned windows were tinted. To calculate the SC for each prototype, we

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[5] Andersson, B., W. Carroll, and R.M. Marlo. 1986. *Aggregation of U.S. Population Centers Using Climate Parameters Related to Building Energy Use*. Journal of Climate and Applied Meteorology, Vol. 25, Issue 5, pp. 596-614.

set the SC of single-paned non-tinted office windows to 0.9, single-paned tinted windows to 0.75, double-paned non-tinted windows to 0.77, double-paned tinted windows to 0.65, and found the weighted average.

Operating and Lighting Characteristics

CBECS provides limited information regarding energy end uses. For lighting, CBECS specifies the percentage of floor area lit by different categories of lighting equipment, but the extent to which the systems overlap and the amount of energy they use is not provided. In addition, details on office equipment are not requested by the survey. The energy use of lighting and equipment that is specified in the prototypes is based on values established in previous prototype studies and measured end-use studies[3 4 6 7]. When reconciling inconsistent lighting power density values from different studies, we used the CBECS equipment combination data to choose the more appropriate value.

System Prototypes

Efficiencies of the different HVAC systems are also developed through prototype simulations. Each prototype building described above is modeled with the following nine HVAC systems:

- Hydronic
- Constant-Volume Reheat
- Constant-Volume Reheat with Economizer
- Multizone
- Multizone with Economizer
- Variable-Air-Volume with Reheat
- Variable-Air-Volume with Reheat and Economizer
- Fan-Coil
- Heat-Pump Loop

A.3 System Multipliers

The system load multipliers used in this study are presented in Table A.3. These multipliers are results of the prototype simulations. Building loads or changes in building loads are multiplied by these factors before they are multiplied by plant efficiency factors to determine the fuel use. These multipliers account for duct losses and also heat added to the system by the distribution system fans and pumps that need to be removed by the HVAC plant equipment.

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[6] NEOS Corporation. 1993. *Technology Energy Savings: Summary of Building Prototype Descriptions and Detailed Measures Tables*. Prepared for the California Conservation Inventory Group by NEOS Corporation, Sacramento, CA.

[7] Sezgen, A.O., Y.J. Huang, B.A. Atkinson, J.H. Eto, and J.G. Koomey. 1994. *Technology Data Characterizing Lighting in Commercial Buildings : Application to End-Use Forecasting With COMMEND 4.0.* LBL- 34243, Lawrence Berkeley National Laboratory, Berkeley, CA.

Table A.3: System Load Multipliers (U.S. Average)

STOCK VINTAGE

	Small Office	Large Office	Small Retail	Large Retail	Small Hotel	Large Hotel	Hospital	Grocery	School	Restaurant	Warehouse
Plant Heating Multiplier-Hydronic System	1.24	1.18	1.03	1.34	1.51	1.34	0.88	0.81	1.01	1.61	0.91
Plant Heating Multiplier-Ducted CV System	0.86	3.59	0.83	3.08	3.74	3.95	9.50	4.27	1.86	0.88	2.00
Plant Heating Multiplier-Multizone System	2.13	2.41	1.54	2.18	2.94	2.87	6.63	3.14	1.34	2.07	1.41
Plant Heating Multiplier-Ducted VAV System	1.78	1.92	1.60	1.84	2.27	2.08	1.00	1.56	1.71	1.16	1.67
Plant Heating Multiplier-Fan Coil System	1.08	1.07	1.02	1.02	1.77	1.49	1.26	0.99	1.04	1.09	0.91
Plant Cooling Multiplier-Ducted CV System	1.43	2.20	1.44	2.13	4.20	2.60	2.05	3.50	5.85	1.79	4.96
Plant Cooling Multiplier-Multizone System	2.45	1.86	2.47	1.84	3.65	2.20	1.82	3.00	4.03	2.96	3.74
Plant Cooling Multiplier-Ducted VAV System	1.97	1.62	2.30	1.64	2.59	1.71	1.33	2.16	4.96	1.98	3.49
Plant Cooling Multiplier-Fan Coil System	1.08	1.09	1.11	1.08	1.21	1.10	1.09	1.16	1.13	1.23	0.89

NEW VINTAGE

	Small Office	Large Office	Small Retail	Large Retail	Small Hotel	Large Hotel	Hospital	Grocery	School	Restaurant	Warehouse
Plant Heating Multiplier-Hydronic System	1.27	1.20	1.04	1.64	1.48	1.37	0.77	0.63	1.01	2.06	0.91
Plant Heating Multiplier-Ducted CV System	0.93	3.53	0.84	4.43	3.67	4.49	11.01	9.16	1.90	0.86	1.92
Plant Heating Multiplier-Multizone System	1.94	2.42	1.59	3.17	2.94	3.25	7.68	6.65	1.37	2.89	1.37
Plant Heating Multiplier-Ducted VAV System	1.75	1.91	1.54	2.17	2.23	2.14	0.83	0.79	1.71	1.10	1.63
Plant Heating Multiplier-Fan Coil System	1.10	1.10	1.02	1.03	1.81	1.56	1.28	1.01	1.05	1.07	0.91
Plant Cooling Multiplier-Ducted CV System	1.45	2.34	1.44	2.16	4.06	2.51	1.78	2.70	5.73	1.86	4.48
Plant Cooling Multiplier-Multizone System	2.59	1.96	2.39	1.91	3.57	2.16	1.62	2.41	4.01	2.75	3.50
Plant Cooling Multiplier-Ducted VAV System	2.17	1.69	2.21	1.64	2.56	1.67	1.30	1.64	4.85	1.98	3.05
Plant Cooling Multiplier-Fan Coil System	1.09	1.11	1.12	1.11	1.23	1.12	1.09	1.15	1.17	1.32	0.90

(1) The building loads are multiplied by these factors to account for the heating/cooling loads added to the building loads by the particular distribution system.
The load obtained by the above multiplication is what the heating/cooling plant has to satisfy.

(2) A value less than 1 indicates that building loads are reduced due to heat added or removed by the system. For example, operation of pumps adds heat to the system reducing the heating load.

APPENDIX B: HVAC SYSTEM AND PLANT SATURATIONS

In this section, we summarize the technology options considered in this study and estimate current saturation levels for these options. Saturation indicates how much floorspace is already equipped with the type of equipment or measure under consideration. The primary source of our saturation data is the 1989 CBECS[1] as summarized in Sezgen et al.[2].

An HVAC application is a combination of a heating plant, a cooling plant, and an HVAC system that distributes the heat and/or coolth in the building. More than one of these three components may be embedded in a single piece of equipment. For example, heat pumps and package units function as both heating and cooling plant. Also, unitary systems do not always utilize an external distribution system - in this case, the system and the plant overlap.

Direct estimations of the saturation of HVAC equipment combinations are not possible using only the 1989 CBECS. However, we combined the CBECS data with engineering judgment regarding the compatibility of combinations of heating/cooling equipment and distribution systems to estimate saturations by building type. Saturations of heating/cooling equipment combinations are shown in **Tables B.1 and B.2** for both stock and new buildings. Tables B.1 and B.2 also show the weighted average of the saturations for the different building types, using the 1989 floor areas attributable to each building type from CBECS 1989. Based on CBECS 1989, it is impossible to estimate the saturations of different types of ducted distributed systems (multizone, VAV, and constant-volume); therefore, in Tables B.1 and B.2, all ducted systems are grouped into a single category. In our analyses, we assume that multizone and dual-duct systems, constant volume systems, and variable air-volume systems represent 35%, 50% and 15% of the floor area served by the ducted systems in the building stock, respectively. For new construction we assumed that constant volume systems and variable air-volume systems each represent 50%. We ignored the less important equipment combinations within each building type to create a rough characterization of these saturations.

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[1] U.S. Department of Energy/Energy Information Administration (US DOE/EIA), 1992. *Commercial Building Energy Consumption Survey 1989: Characteristics of Commercial Buildings 1989.* DOE/EIA-0246(89), U.S. Department of Energy, Washington, D.C.

[2] Sezgen, Osman, Ellen M. Franconi, Jonathan G. Koomey, Steve E. Greenberg, Asim Afzal, and Leslie Shown. 1995. *Technology Data Characterizing Space Conditioning in Commercial Buildings: Application to End-Use Forecasting with COMMEND 4.0.* LBL-37065. Lawrence Berkeley National Laboratory, Berkeley, CA. December.

Table B.1: Saturations of combinations of heating/cooling equipment and system options (Stock buildings)

System	Cooling/Heating Equipment	Small Retail	Large Retail	Small Office	Large Office	School	Restaurant	Hospital	Small Hotel	Large Hotel	Grocery	Warehouse	Total
Ducted	Package Unit w/Electric Heat	3%	10%	7%	4%	1%	3%	1%	3%	3%	5%	2%	4%
	Package Unit w/Gas Heat	9%	15%	7%	4%	4%	8%	4%	1%	4%	7%	5%	7%
	Package Unit / Electric Resistance Heat	3%		12%	2%		5%	2%	6%	1%	9%		2%
	Air Source HP	3%	2%	7%	3%	1%	3%		1%	2%	5%	1%	2%
	Electric Chiller / Electric Boiler		1%		1%			1%		1%			
	Electric Chiller / Gas Boiler		4%	2%	7%	2%	1%	8%	1%	10%	2%		3%
	Electric Chiller / Oil Boiler		1%	1%	2%	1%		1%		1%	2%		1%
	Electric Chiller / District Heat				0%			0%					
	Gas Furnace / No Cooling	23%	11%	13%	3%	4%	14%	2%	8%	6%	9%	5%	8%
Unitary System	Package Unit w/Electric Heat	1%	5%	4%	4%	1%	2%		4%	3%	6%	1%	3%
	Package Unit w/Gas Heat	4%	8%	4%	5%	2%	3%	2%	2%	4%	7%	3%	4%
	Package Unit / Electric Furnace	1%	1%	1%	1%				1%		1%		1%
	Package Unit / Gas Furnace	6%	3%	6%	2%	1%	5%		2%	2%	5%	1%	3%
	Package Unit / Oil Furnace	1%					1%		1%		2%		
	Package Unit / Electric Resistance Heat	1%	1%	6%	11%	10%	15%	15%	6%	3%	3%		5%
	Air Source HP	2%	1%	4%	4%	1%	2%		2%	3%	6%	1%	2%
	Window Wall Unit / Electric Furnace	1%	1%	1%					2%		1%		
	Window Wall Unit / Gas Furnace	5%	3%	3%	1%	2%	3%		7%	4%	4%	2%	2%
	Window Wall Unit / Oil Furnace	1%							2%		1%		
	Window Wall Unit/Resistance Heating	1%	1%	3%	6%	13%	8%	12%	17%	7%	3%	1%	5%
Fan Coil System	Electric Chiller / Electric Boiler		1%		1%			1%	1%	1%			
	Electric Chiller / Gas Boiler		3%	1%	8%	2%		12%	3%	13%	1%		3%
	Electric Chiller / Oil Boiler		1%		2%	1%		2%	1%	1%			1%
	Electric Chiller / District Heat				2%				0%				
Hydronic System	Electric Boiler /No Cooling	1%	2%	1%	2%		1%	1%	3%	1%			1%
	Gas Boiler / No Cooling	4%	8%	4%	11%	16%	8%	15%	11%	14%	2%	4%	9%
	Oil Boiler / No Cooling	4%	2%	2%	3%	5%	5%	2%	2%	1%	2%	1%	3%
Other		13%	9%	11%	13%	34%	16%	24%	15%	17%	4%	11%	16%
Fraction of area with heating and/or cooling equipment		87%	94%	100%	100%	100%	100%	100%	100%	100%	87%	38%	84%

Table B.2: Saturations of combinations of heating/cooling equipment and system options (New buildings)

		Small Retail	Large Retail	Small Office	Large Office	School	Restaurant	Hospital	Small Hotel	Large Hotel	Grocery	Warehouse	Total
Ducted	Package Unit w/Electric Heat	3%	18%	11%	9%	5%	8%	2%	11%	6%	13%	3%	8%
	Package Unit w/Gas Heat	14%	22%	5%	4%	6%	18%	5%	2%	9%	5%	5%	8%
	Package Unit / Electric Resistance Heat			9%	2%	1%	16%		1%		14%		2%
	Air Source HP	6%	4%	12%	4%	2%	2%		1%		3%	2%	4%
	Electric Chiller / Electric Boiler			1%	3%			1%	2%	1%			1%
	Electric Chiller / Gas Boiler		1%	1%	8%	3%		6%		5%			3%
	Electric Chiller / Oil Boiler			1%	1%	1%							
	Electric Chiller / District Heat								5%	5%			
	Gas Furnace / No Cooling	28%	12%	8%	2%	2%	25%		20%	5%	14%	7%	9%
Unitary System	Package Unit w/Electric Heat	1%	7%	11%	10%	3%	1%	1%	7%	5%	8%	2%	6%
	Package Unit w/Gas Heat	6%	8%	5%	4%	5%	2%	3%	2%	7%	3%	3%	5%
	Package Unit / Electric Furnace	1%	1%	2%	2%	1%			1%		6%	1%	1%
	Package Unit / Gas Furnace	5%	1%	5%	2%	1%	2%		3%	1%	7%	2%	2%
	Package Unit / Oil Furnace												
	Package Unit / Electric Resistance Hea	1%		4%	11%	13%	14%	11%	4%	4%	5%	3%	6%
	Air Source HP	4%	1%	12%	7%	2%			1%		2%	2%	4%
	Window Wall Unit / Electric Furnace		1%			1%			2%		2%		
	Window Wall Unit / Gas Furnace	3%	2%			1%			9%	3%	2%	1%	1%
	Window Wall Unit / Oil Furnace												
	Window Wall Unit/Resistance Heating	1%	1%		2%	5%	1%	12%	12%	8%	1%	2%	2%
Fan Coil System	Electric Chiller / Electric Boiler				2%	1%		1%		1%			1%
	Electric Chiller / Gas Boiler		1%	1%	7%	4%		11%		10%		1%	3%
	Electric Chiller / Oil Boiler				1%	2%							
	Electric Chiller / District Heat				8%					3%			2%
Hydronic System	Electric Boiler /No Cooling			1%	2%	1%	2%	1%	4%	1%			1%
	Gas Boiler / No Cooling	1%	1%	1%	6%	7%	3%	13%		8%			3%
	Oil Boiler / No Cooling			1%	1%	2%	1%						1%
Other		15%	9%	11%	6%	33%	6%	32%	14%	19%	3%	3%	10%
Fraction of area with heating and/or cooling equipment		89%	90%	100%	100%	100%	100%	100%	100%	100%	88%	37%	82%

APPENDIX C: EFFICIENCY DATA FOR HVAC PLANT OPTIONS

Given the building loads, effect of distribution system type on loads and electricity use, and equipment saturations, energy use can be calculated if the typical plant efficiencies are known. The loads within the methodology of this report are annual. Therefore, we are interested in efficiency parameters which would convert annual loads to annual energy use. Seasonal plant heating and cooling efficiencies taken from Sezgen et al. (1995)[1] are presented in **Table C.1.** These are integrated part load efficiencies and therefore can be directly used to convert annual loads to annual energy. Integrated part load efficiencies are generally less than efficiency measured under full load conditions. Efficiencies were developed both for stock and new equipment.

For combined heating/cooling equipment, there generally exists a secondary heating option which is utilized if and when the heating requirements are extreme. Efficiencies for these secondary features are also presented in Table C.1.

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[1] Sezgen, Osman, Ellen M. Franconi, Jonathan G. Koomey, Steve E. Greenberg, Asim Afzal, and Leslie Shown. 1995. *Technology Data Characterizing Space Conditioning in Commercial Buildings: Application to End-Use Forecasting with COMMEND 4.0.* LBL-37065. Lawrence Berkeley National Laboratory, Berkeley, CA. December.

Table C.1: Seasonal Heating and Cooling-Plant Efficiency Data (*)

	Seasonal Heating Plant Efficiency (BTU out/BTU in)		
Plant Type	Average (stock)	Marginal (new const.)	Notes
HEATING			
Electric Resistance	1.0	1.0	1
Electric Furnace	0.93	0.96	2
Electric Boiler	0.94	0.94	3
Gas Furnace, Typical	0.63	0.76	4
Gas Furnace Efficient	0.85	0.89	5
Gas Boiler, Typical	0.6	0.65	6
Gas Boiler Efficient	0.85	0.9	7
Oil Furnace	0.68	0.77	8
Oil Boiler	0.6	0.68	9

	Seasonal Plant Efficiency or COP (BTU out/BTU in)						
	Primary Heating		Secondary Heating		Cooling		
Plant Type	Average (stock)	Marginal (new const.)	Average (stock)	Marginal (new const.)	Average (stock)	Marginal (new const.)	Notes
COMBINED							
Electric Packaged	0.93	0.96	n.a.	n.a.	2.2	2.7	10
Air-Source HP, Std.	2.4	3	0.93	0.96	2.2	2.7	11
Air-Source HP, Effic.	2.8	3.2	0.93	0.96	2.5	3	12
Dual-Fuel HP	2.8	3.2	0.63	0.76	2.5	3	13
Water-Loop HP	3.5	4	n.a.	n.a.	2.6	3.5	14
Gas Packaged	0.7	0.8	n.a.	n.a.	2.2	2.7	15

	Seasonal Cooling Plant COP (BTU out/BTU in)		
Plant Type	Average (stock)	Marginal (new const.)	Notes
COOLING			
Centrifugal Chillers:			
w/tower	3.5	4.5	16
w/evap. condenser	3.8	4.8	17
Reciprocating Chillers:			
w/air-cooled cond.	2.3	3	18
w/tower	3.4	4	19
w/evap. condenser	3.7	4.4	20
Screw Chillers:			
w/tower	3.7	3.9	21
w/evap. condenser	4	4.2	22
Gas Chiller	0.5	0.9	23
Window/Wall Unit	2.2	2.7	24

Sources:

[1] Usibelli, A., S. Greenberg, M. Meal, A. Mitchell, R. Johnson, G. Sweitzer, F. Rubinstein, D. Arasteh. 1985. Commercial-Sector Conservation Technologies. LBL-18543, Lawrence Berkeley National Laboratory, Berkeley, CA.

[2] Electric Power Research Institute. 1992. TAG Technical Assessment Guide, Volume 2: Electricity End Use, Part 2: Commercial Electricity Use. Electric Power Research Institute, Palo Alto, CA.

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Notes:

(*) Table reflects the effects of EPACT Standards which affect gas furnaces and boilers, packaged units and heat pumps.

1. Assumes that resistance heater and electrical wiring are in space to be heated, so all heat beyond electric meter is useful.
2. Average assumes 2% loss from furnace housing and 5% duct leakage to/from unheated space. Marginal assumes 1% and 3%.
3. Assumes 2% of rated input is lost through boiler shell; average boiler load is 33%.
4. Average assumes 70% seasonal burner efficiency, less 1% each for pilot lights and shell losses and 5% for duct losses; marginal assumes 80%, no pilot, 1% shell, and 3% duct loss.
5. Average assumes 90% Calif. Seasonal Efficiency (rather than AFUE, since CSE accounts for fan energy) less 5% duct losses; marginal same except 92% CA Seasonal Effic., 3% duct loss.
6. Average assumes boiler at 80% new steady-state efficiency degraded by 5% due to water and fire-side rust, scale, and soot; 2% of input rating lost through boiler casing, 3% through stack; two boilers kept hot all year, average boiler load is 33% of one boiler. Marginal same except no rust, soot, or scale.
7. Average assumes condensing boiler used, but heat exchangers not large enough to lower return water to condensing temperature. Marginal assumes condensing boiler used, heat exchangers allow condensing.
8. Average assumes 5% better than gas furnace (due to powered burner with controlled excess air and off-cycle air); marginal 1% more efficient than marginal gas (both have power burner or induced draft).
9. Average assumed same as gas. Marginal assumes 83% efficiency with the reductions which apply to marginal gas. Oil boilers have more efficiency degradation due to soot, but all have forced or induced draft; effects are assumed to cancel.
10. Electric packaged means direct expansion air conditioner with air-cooled condenser and resistance heat. Heating efficiency assumed same as electric furnace. Cooling: Average from [1], [2], and [3]; marginal assumed 0.5 COP point (absolute) higher.
11. Primary heating from [2] and [3]; secondary same as electric furnace. Cooling same as electric packaged.
12. Primary heating from [2] and [3]; secondary same as electric furnace. Cooling from [3].
13. Dual fuel HP means direct expansion cooling and heating with refrigerant-to-air outdoor coil; gas backup. Heat pump COPs assumed same as effic. air-source; gas effic. assumed same as std. gas furnace.
14. Numbers are from [2] and [3]; averaged assumed to be at lower end of range of most-common COPs; marginal at upper end.
15. From [3]: cooling same as electric packaged; heating at lower end of range of conventional and effic. units to account for seasonal effects.
16. From EPRI and [5]. Approx. 0.1 points of COP reduction for tower fan and condensing water pump; degradation from fouling approx. balances improved efficiency at part load. Marginal assumes mid-range of high-effic. equip.
17. Same as with tower except about 0.3 point of COP increase for the evaporative condenser. Based on [5].
18. From [2] and [3]. Average assumes COP of 3.3 less 0.8 for fans and 0.2 for wear and fouling degradation. Marginal assumes 0.5 above average (approx. diff. between conventional and high efficiency).
19. From EPRI and [1]. Assumed 0.1 points of COP reduction (for tower and pump) in mid-range conventional COP for average; same for high-efficiency for marginal.
20. Assumes 10% COP improvement for evaporative condenser.
21. From [3], using upper end of ranges of conv. and high-effic. less 0.1% for tower and pump.
22. Same as screw with tower except 10% COP improvement with evap. condenser.
23. Average assumes 0.6 COP (single-effect); marginal assumes 1.0 COP (double-effect); discounted for tower and pump usage.
24. Assumed same as electric packaged unit. While window/wall units are smaller, they borrow from the more efficient residential technology.

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