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ABSTRACT

Proper skylight utilization can significantly lower energy requirements and peak electrical loads for space conditioning and lighting in commercial buildings. In this study we systematically explore the energy effects of skylight systems in a prototypical office building and examine the savings from daylighting. We used the DOE-2.1B energy analysis computer program with its newly incorporated daylighting algorithims to generate more than 2000 parametric simulations for seven U.S. climates. The parameters varied include skylight-to-roof ratio, shading coefficient, visible transmittance, skylight well light loss, electric lighting power density, roof heat transfer coefficient, and type of electric lighting control. For specific climates we identify roof/skylight characteristics that minimize total energy or peak electrical load requirements.

Keywords: skylights, daylighting, electric lighting, electrical demand, and total energy use.

INTRODUCTION AND PROJECT OVERVIEW

This study uses a powerful computer model to calculate annual energy requirements for a range of skylight and lighting parameters. A typical skylighted floor of a commercial office building is analyzed in seven locations in the United States with and without daylighting controls. The analytical tool used is DOE-2.1B, a large, state-of-the-art building energy simulation model [1] [2]. Results provide guidelines for designing skylights for a range of climates.

To generate general results applicable to a wide range of building types, a single prototypical building module was developed in which energy use patterns can be characterized according to per unit floor area and then applied to other configurations. In this 30.5 m by 30.5 m module, fenestration is limited to flat skylights uniformly distributed over a flat roof. In order to isolate the energy effects of interest, the exterior walls and the floor are modeled as adiabatic surfaces (no heat transfer). The envelope energy flows are thus limited to the roof and skylight system. Building operating and occupancy schedules are based on standard hourly profiles [1]. The space is considered to be one zone conditioned by a single, constant-volume, variable-temperature HVAC system that operates with an economizer. Heating is furnished by a gas-fired boiler and cooling by an electrically operated centrifugal chiller. Choice of HVAC system significantly affects energy use; the results discussed here apply only to the system modeled.

An extensive sensitivity study [1] was conducted with the module to determine details of the final design and to establish variables and limits for parametric consideration. The primary variables affecting skylight energy performance were found to be the overall heat transfer coefficient of the roof, skylight area, shading coefficient, visible transmittance, light well loss factor, and electric lighting power density. Other variables did not warrant parametric variation and were held constant at values typical of current design practice. References [1] and [3] describe in detail the building module and results of the sensitivity study.

We analyzed skylight performance over a broad range of climate types and latitudes: El Paso, TX; Lake Charles, LA; Los Angeles, CA; Madison, WI; New York, NY; Seattle, WA; and Washington, D.C. We evaluated three electric lighting power densities (L_w); three overall roof U values (U_o), skylight-to-roof ratios (SRR) between 0 and 0.05; and shading coefficients (SC), visible transmittances (VT), and light well loss factors (WF) [4] between 0.1 and 1.0.

ANALYSIS OF RESULTS

To simplify our analysis, we combine fenestration parameters that quantify the amount of visible light entering the space into one lumped parameter. This parameter, which we designate the <u>effective aperture</u> (A_e), is the product of the SRR, VT, and WF. For the daylighted cases, we define the ratio of the fraction of visible light transmitted by the skylight system to its shading coefficient as K_e (VT x WF/SC). This distinction is necessary because, with daylighting, a change in well factor reduces the light flux transmitted to the space but may not change solar gains. Without daylighting, energy quantities are not influenced by WF, which is therefore effectively 1.0 in both A_e and K_e.

Due to space limitations, this discussion fixes several parameters at values representative of current practice. These values are: (1) $K_e = 1.0$; (2) $L_w = 18.3\ W/m^2$; (3) illuminance level = 538 lux; (4) lighting control type = continuous dimming; and (5) overall roof conductances for each climate based on ASHRAE recommendations. A detailed analysis of the results, including an analysis of deviations from these fixed paramters, appears in Ref. [5].

Lighting Energy Reductions from Daylighting

In non-daylighted cases, electric lighting energy consumption is the same for all climates (51.7 KWH/m^2-yr). We normalize lighting energy consumption in the daylighted case to this value and plot normalized consumption against effective aperture. Daylighting results demonstrate the similarity of lighting energy savings curves for the seven climates considered here (Fig. 1). As effective aperture increases from 0, daylighting savings increase almost linearly, then level off quickly when effective aperture passes a certain point. At this point, daylight provides all mid-day lighting requirements. Additional glazing provides increased benefits during mornings and afternoons but adds unneeded daylight during mid-day hours, leading to daylighting saturation. At the same time, cooling loads induced by solar gains increase. The onset of this daylight "saturation effect" and the diminishing rate of increase in daylighting benefits (seen in Fig. 1) are climate-dependent and related to average total daily horizontal radiation levels.

Annual Energy Savings with Daylighting

In order to satisfy envelope performance criteria of the type of ASHRAE Standard 90, the overall roof heat transfer coefficient in each climate is held constant over the range of effective apertures studied. Thus, the relationship between increasing effective aperture and annual energy requirements is primarly a function of the light- and heat-admitting properties of the skylight system. For the non-daylighted cases--that is, for buildings without controls that vary electric lighting outputs in response to changing daylight levels--this relationship is nearly linear over a wide range of climate types (Fig. 2). In cool and cold climates (Seattle and Madison), increasing solar gains lower annual heating requirements, rather than offsetting any increase in cooling energy. Thus, overall energy consumption drops slightly with increasing effective aperture. This trend is reversed in hot climates such as Lake Charles and El Paso, where, because of minimal heating requirements, increasing solar gains serve only to increase cooling loads.

With daylight-responsive controls, annual energy requirements for all cities drop significantly. These savings are a function not only of differing reductions in lighting requirements, but also of climatic conditions, as seen in Fig. 2. In climates where cooling is not a major portion of the total load (i.e., Madison and Seattle), daylighting causes total energy use to drop with effective aperture. However, in Lake Charles, total energy use quickly reaches a minimum and then begins to increase slightly with increasing effective aperture. This minimum is more pronounced in El Paso, a hot climate sensitive to variations in effective aperture because of its minimal cloud cover. In these two cases total energy use is roughly constant for effective apertures between 0.01 and 0.03. The range of maximum potential energy savings, values governed by both daylighting and thermal issues, varies from 34% in El Paso (where daylighting performs best and there is a high cooling load) and 31%

in Lake Charles (where cooling dominates) to 22% in Seattle (where the daylighting potential is lowest) and 21% in Madison (where heating dominates). In heating-dominated climates, daylighting's only real savings are to reduce lighting energy, as seen by the component breakdown in Fig. 3. Here, slight cooling savings cancel out a heating energy increase of equal magnitude. However, in cooling-dominated climates, lighting savings are augmented by up to a 25% drop in cooling loads and up to a 10% decrease in HVAC energy. In all cases, daylighting dramatically reduces energy consumption compared to an opaque roof. Properly designed skylight systems can thus save energy, the potential economic benefits depending on utility rates and hardware costs. Additional savings can also be achieved with more complex rooflighting systems.

Electrical Peak Demand Reductions with Daylighting

Peak electrical demand without daylighting increases with increasing effective aperture in all climates (Fig. 4). Electrical peaks for the system modeled here typically occur during summer afternoons when electric lighting is coincident with maximum cooling loads. With daylighting, the lighting loads and subsequent cooling loads are substantially reduced, significantly lowering electrical peaks in all climates. However, daylighting's influence on annual electrical peaks varies with climate. While Lake Charles and El Paso have similar electrical peaks for cases without daylighting, peak savings with daylighting are greater in El Paso because much of Lake Charles's peak cooling load comes from high latent loads that are related to ambient air enthalpy and thus not diminished by daylighting. El Paso, a dry climate, does not have this condition. In daylighted buildings in El Paso, Lake Charles, and Madison, peak electrical loads are lowest with effective apertures of about 0.01, after which cooling loads induced by solar gains begin to increase electrical peak. Seattle's low ambient temperatures and persistent cloud cover result in a continual drop in peak electric demand with increasing effective aperture (over the range studied).

CONCLUSIONS

The effect of climate on lighting energy savings from skylighting is moderate and is associated primarily with differences in daylight availability due to cloud cover. In cooling-dominated climates, daylighting can also significantly lower cooling requirements, while in heating-dominated climates, heating needs will increase moderately. Where cooling loads dominate, total energy use will increase if the effective aperture is significantly greater than optimal. Daylight can provide large peak electrical savings; however, the electrical peaks increase if the effective aperture increases beyond an optimal value.

Within the parameters specified for the basic building module, this analysis indicates the magnitude of energy savings achievable with skylights. The initial sensitivity studies discussed in Ref. [1] indicate which building parameters can change without significantly affecting end-use patterns. For example, all other conditions being equal, small changes in ceiling height should not greatly affect end-use energy patterns. However, using clear instead of diffusing skylights or different HVAC systems, or greatly changing the spacing between skylights, will affect the accuracy of results.

Skylight performance data from this project have been converted (using multiple regression techniques) into a series of simple analytical expressions and graphic displays for fuel consumption, electric energy consumption, and peak electrical demand. From this data reduction, presented in Refs. [3] and [5], a building designer can easily determine the energy effects of various combinations of skylight parameters and assess the impact of daylighting strategies on overall building performance. In addition, we determine the effective apertures for which annual energy consumption and peak electrical demand are at minimums. This effective aperture, $(A_e)_{min}$, is predominantly a function of L_w and K_e. Graphs of $(A_e)_{min}$ for annual energy consumption and peak electrical demand for several cities are presented in Ref. [5].

Our building module is useful for characterizing energy performance for office spaces. Retail spaces show significantly different energy-savings trends from daylighting, due primarily to internal loads and operating schedules [4]. Energy performance trends for warehouses, which are more suitable for stepped switching and lower lighting levels, must also be analyzed separately.

The results presented here should give a better understanding of the parameters affecting energy savings and electrical peak demand reductions in skylighted buildings. However, measured data from operating skylighted buildings are not available to compare to calculated results. Until they become available, results of this and other simulation studies must be interpreted with caution.

ACKNOWLEDGEMENT

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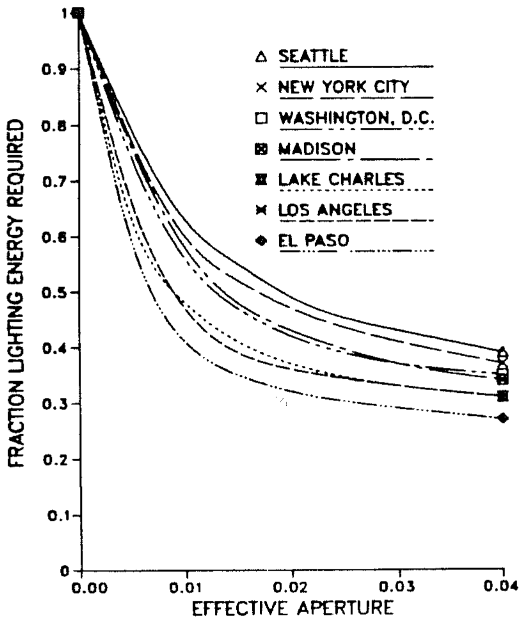

Figure 1. Skylight lighting requirements with daylighting: required lighting level = 538 lux; continuous dimming controls.

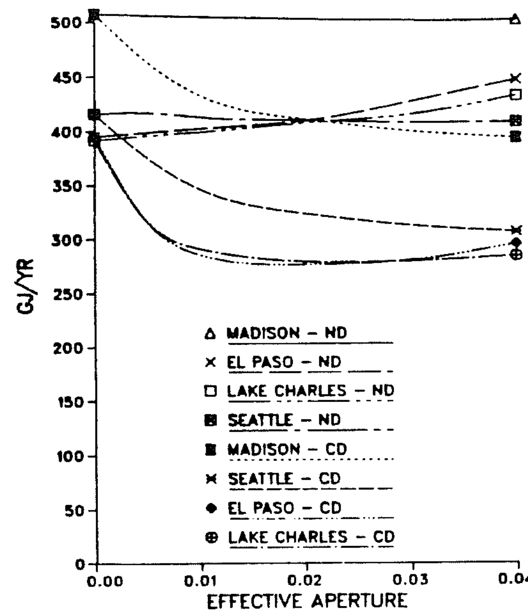

Figure 2. Total skylight module plant energy. Ke = 1.0. ASHRAE U_o values: lighting = 18.3 W/m^2; lighting level = 538 lux; continuous dimming controls.

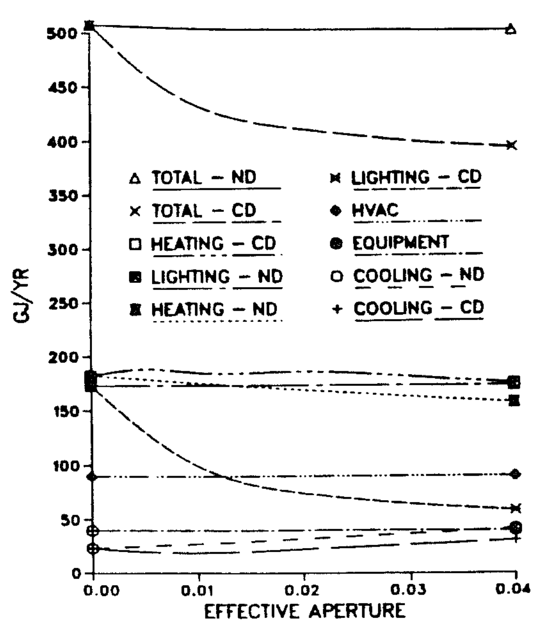

Figure 3. Total skylight module plant energy for Madison. Component breakdown: Ke = 1.0; lighting = 18.3 W/m^2; U_o = 0.01 W/m^2-°C.

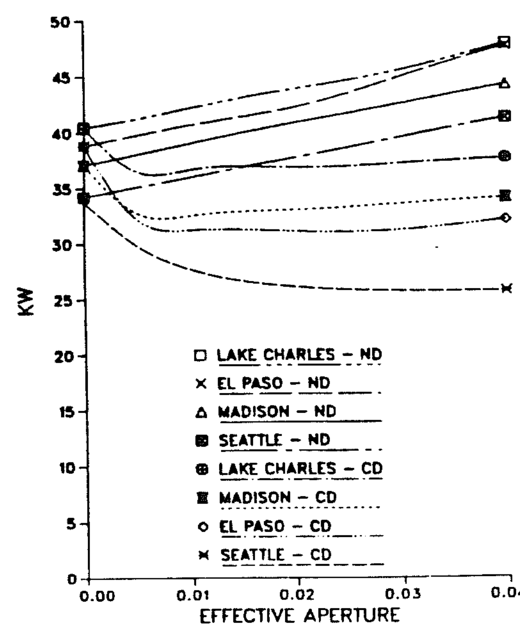

Figure 4. Total skylight module electrical peak. Ke = 1.0. ASHRAE U_o values: lighting = 18.3 W/m^2; lighting level = 538 lux; continuous dimming controls.