

# Net Energy Costs of Skylights

*Peter Kleinhenz, Rizwan Syed, and Kelly Kissock,  
University of Dayton Industrial Assessment Center*

## ABSTRACT

Skylights in industrial facilities have been documented to improve worker productivity and reduce absenteeism. Though productivity improvements alone may justify skylights, it is also useful to consider the net energy costs associated with skylights. This paper describes a methodology for calculating net energy savings from skylights as a function of skylight area, the required lighting level, and type of lighting. The methodology can be applied to plants located anywhere in the world, by using typical meteorological data from TMY2 or EPW files, which are available free-of-charge over the internet. The method uses the LightSim hour-by-hour daylighting simulation program to calculate the number of hours that daylighting can meet a target lighting level. Energy balances are employed to calculate net heating and cooling loads through a ceiling with and without skylights. The net energy cost savings are calculated as the difference between lighting and space conditioning costs with and without skylights.

Results show that the optimum skylight to floor area ratio and net energy cost savings increase as the target lighting level increases. For Dayton, Ohio, results indicate optimum skylight to floor area ratios range from about 1% to 6%, and net energy savings ranging from about 0.5 to 25 cents per square foot of floor area per year using average 2005 industrial energy costs. Net cooling energy savings are higher than net heating energy savings. This analysis demonstrates that an economically optimal area of skylights exists that results in net energy cost savings, but installing either too many or too few skylights can result in an increase in net energy costs. Thus, it is important to perform an analysis such as this to guarantee that skylights actually reduce net energy costs.

## Introduction

Because our eyes evolved to see in sunlight we distinguish colors best in natural lighting. Case studies conducted by Wal-Mart have proven that people are happier under natural lighting compared to artificial (Pierson, 1995). Furthermore, studies show that natural lighting from skylights improves worker productivity and reduces absenteeism (Romm and Browning, 1999; Heschong Mahone Group, 1999).

Previous studies on skylights include Arasteh et al. (1985), who applied multiple regression analysis to generate energy performances and energy saving potentials of skylights on a prototypical office building for different United States cities. In addition, a study conducted by Kaya (2003) evaluated energy gains/losses associated with installing high energy efficient lighting and skylights on several manufacturing facilities across Arizona.

This paper investigates net energy savings from skylights as a function of skylight area, required lighting level, and type of lighting. The analysis is performed for plants with heating only, cooling only and both heating and cooling. The methodology can be applied to plants located anywhere in the world; however, in this paper the methodology is demonstrated only on a plant located in Dayton, Ohio.

## Methodology

The methodology involves the following steps. These steps are explained in the following subsections.

- Calculate the number of electric lights required to provide a target lighting level on the work plane, and the lighting energy use without skylights.
- Calculate space heating energy use without skylights.
- Calculate space cooling energy use without skylights.
- Simulate lighting levels from daylighting due to skylights, calculate number of hours that daylighting meets target lighting level, and calculate lighting energy use with skylights.
- Calculate space heating energy use with skylights.
- Calculate space cooling energy use with skylights.
- Calculate net energy costs without and with skylights.

### Calculating Number of Electric Lights and Lighting Energy Use without Skylights

The number of lights required to provide a target lighting level on the work plane is calculated using the Lumen Method from the Illuminating Engineering Society of North America (IESNA, 2000). Using this method, the number of fixtures necessary to provide a specified lighting level,  $N$ , is:

$$N = \frac{(C_u F)}{A_w} \quad (1)$$

where

$N$  is number of fixtures,  
 $C_u$  is the coefficient of utilization,  
 $F$  is total lumens produced by the lamps and  
 $A_w$  is the area of work plane.

$C_u$  is a function of ceiling reflectivity, wall reflectivity and the room cavity ratio,  $RCR$ , is:

$$RCR = \frac{5h(w+l)}{wl} \quad (2)$$

Based on  $RCR$ , values of  $C_u$  can be obtained from tables in the IESNA Lighting Handbook (IESNA, 2000, Figure 8-20, pg. 8-12)

Lighting power,  $Q_{lights}$ , is the product of number of fixtures,  $N$ , and the Watts per fixture,  $WPF$ .

$$Q_{lights} = N \times WPF \quad (3)$$

## Calculating Space Heating Energy Use Without Skylights

Based on an energy balance, the net heating load,  $Q_{heatreq}$ , due to heat losses through the ceiling,  $Q_{heatlossceil}$  and heat gains from the lights  $Q_{lights}$  is:

$$Q_{heatreq} = Q_{heatlossceil} - Q_{lights} \quad (4)$$

Heat lost through the ceiling is calculated using Equation 5 and the heat gain from lights is calculated using Equation 3.

$$Q_{heatlossceil} = U_{ceil} A_{ceil} (T_{ia} - T_{sa}) \quad (5)$$

where

$$U_{ceil} = 1/R_{ceil}$$

$A_{ceil}$  is the area of ceiling,

$T_{ia}$  is the indoor air temperature, and

$T_{sa}$  is the solair temperature, which includes the effect of solar radiation on the ceiling.

$$T_{sa} = T_{oa} + \frac{\bar{I}\alpha}{h} \quad (6)$$

where

$T_{oa}$  is the outdoor air temperature,

$\bar{I}$  is solar radiation in units of power per area

$\alpha$  is the absorbtivity of the roof

$h$  is the convection coefficient

The amount of natural gas,  $Q_{fuel}$ , required to generate the required heating load,  $Q_{heatreq}$ , depends on the efficiency of the burner,  $eff$ .

$$Q_{fuel} = \frac{Q_{heatreq}}{eff} \quad (7)$$

## Calculating Space Cooling Energy Use Without Skylights

Based on an energy balance, the net cooling load,  $Q_{AC}$ , due to heat gains through the ceiling and heat gains from the lights is:

$$Q_{AC} = Q_{heatgainceil} + Q_{lights} \quad (8)$$

Heat gain through the ceiling is calculated using the Equation 9 and heat gain through the lights is calculated using the Equation 3.

$$Q_{\text{heatlossceil}} = U_{\text{ceil}} A_{\text{ceil}} (T_{\text{sa}} - T_{\text{ia}}) \quad (9)$$

The amount of electricity,  $E_{AC}$ , necessary to provide the required cooling is dependent upon the coefficient of performance of the air conditioner,  $COP_{AC}$ .

$$E_{AC} = \frac{Q_{AC}}{COP_{AC}} \quad (10)$$

## Simulate Lighting Levels Produced by Skylights

Lighting levels produced by skylights were calculated using the LightSim daylighting analysis software. LightSim simulates hour-by-hour illuminance on a work plane from daylighting using TMY2 meteorological data. Based on these simulated lighting levels, LightSim calculates the fraction of time that the specified daylighting design can meet or exceed a target illumination on a work plane. LightSim is available at no cost from the University of Dayton IAC (Kissock, 2000). The methodology used by LightSim is described by Kissock (2004). Sample LightSim input and output screens are shown in Figure and Figure 2. In this simulation, a skylight to floor area ratio of 10% could achieve a target lighting level of 30 fc for 3,999 hours per year in Dayton, Ohio.

Figure 1: LightSim Input Screen

The screenshot shows the 'Skylight Simulation Parameters' dialog box. It is divided into three sections: Skylights, Room, and Simulation Parameters. In the Skylights section, Length (ft) is 10, Width (ft) is 10, Number is 10, and Solar Transmittance (0 to 1) is 0.9. In the Room section, Length (ft) is 100, Width (ft) is 100, Height above workplane (ft) is 30, Ceiling Reflectivity (0 to 1) is 0.8, and Wall Reflectivity (0 to 1) is 0.7. In the Simulation Parameters section, Start Hour (1-24) is 1, End Hour (1-24) is 24, and Target Illumination (fc) is 30. There are OK and Cancel buttons on the right side.

Figure 2: LightSim Output Screen

The screenshot shows the 'LightSim' output window. It displays simulation results for a room with 10 skylights. The results are summarized as follows:

Category	Value
Weather file	dayton.m2
Analysis between hours	1 and 24
Number skylights	10
Trans glazing	0.9
Skylight width	10
Skylight length	10
Room width	100
Room length	100
Room height	30
Perfect ceiling	0.9
Perfect Walls	0.7
Target Illuminance	30 [fc]
Coefficient of Utilization	0.093
Total hours analyzed	5256
Number hours when illuminance > target illuminance	3999
Fraction hours illuminance > target illuminance	47.5%
Average illuminance during hours analyzed	137 [fc]
Minimum illuminance	0 [fc] on 1 / 1 at 2 hours
Maximum illuminance	807 [fc] on 5 / 31 at 13 hours

Monthly breakdown of results:

- For month 1: Fraction hours illuminance > target illuminance = 36.9%
- For month 2: Fraction hours illuminance > target illuminance = 41.6%
- For month 3: Fraction hours illuminance > target illuminance = 46.4%
- For month 4: Fraction hours illuminance > target illuminance = 52.5%
- For month 5: Fraction hours illuminance > target illuminance = 55.0%
- For month 6: Fraction hours illuminance > target illuminance = 57.0%
- For month 7: Fraction hours illuminance > target illuminance = 57.5%
- For month 8: Fraction hours illuminance > target illuminance = 55.1%
- For month 9: Fraction hours illuminance > target illuminance = 46.6%
- For month 10: Fraction hours illuminance > target illuminance = 44.2%
- For month 11: Fraction hours illuminance > target illuminance = 38.7%
- For month 12: Fraction hours illuminance > target illuminance = 35.6%

Annual summary:

- For 4 winter months: Fraction hours illuminance > target illuminance = 38.1%
- For 8 summer months: Fraction hours illuminance > target illuminance = 52.3%

## Calculating Space Heating Energy Use With Skylights

Based on an energy balance, the net heat load,  $Q_{\text{heatreq}}$ , due to heat losses through the ceiling,  $Q_{\text{heatlossceil}}$ , the skylights,  $Q_{\text{heatlosssky}}$ , heat gain from lights,  $Q_{\text{lights}}$ , and solar radiation through the skylights,  $Q_{\text{sol}}$ , is:

$$Q_{\text{heatreq}} = Q_{\text{heatlossceil}} + Q_{\text{heatlosssky}} - Q_{\text{lights}} - Q_{\text{sol}} \quad (11)$$

The heat loss through the ceiling, the heat loss through the skylights and the heat gain from solar radiation through skylights are:

$$Q_{heatlossceil} = U_{ceil}(A_{ceil} - A_s)(T_{ia} - T_{sa}) \quad (12)$$

$$Q_{heatlosssky} = U_s A_s (T_{ia} - T_{oa}) \quad (13)$$

$$Q_{sol} = I_w (SGHC) A_s \quad (14)$$

where

$I_w$  is the solar radiation during winter,  
 $SGHC$  is the solar heat gain coefficient during winter,  
 $U_s = 1/R_s$  is the conductive coefficient of skylights,  
 $A_s$  is area of skylights.

The amount of natural gas,  $Q_{fuel}$ , required to generate the required heating load,  $Q_{heatreq}$ , depends on the efficiency of the burner,  $eff$ , and is calculated using Equation 7.

### Calculating Space Cooling Energy Use With Skylights

Based on an energy balance, the net cooling load,  $Q_{AC}$ , due to conduction through the ceiling,  $Q_{heatgainceil}$ , conduction through the skylights,  $Q_{heatgainssky}$ , heat gain from lights,  $Q_{lights}$ , and from solar radiation through the skylights,  $Q_{sol}$ , is:

$$Q_{AC} = Q_{heatgainceil} + Q_{heatgainssky} + Q_{lights} + Q_{sol} \quad (15)$$

Heat gains through the ceiling and the skylights are:

$$Q_{heatgainceil} = U A_{ceil} (T_{sa} - T_{ia}) \quad (16)$$

$$Q_{heatgainssky} = U_s A_s (T_{oa} - T_{ia}) \quad (17)$$

The amount of electricity necessary,  $E_{AC}$ , to cool  $Q_{AC}$ , depends on the coefficient of performance of the air conditioner,  $COP_{AC}$ , and is calculated using Equation 10.

### Calculating Net Energy Costs Without and With Skylights

The annual energy cost of lighting,  $C_{lights}$ , heating,  $C_{heat}$ , and cooling,  $C_{cool}$ , are calculated by multiplying the rate of energy use by the annual operating hours and the cost of the fuel.

$$C_{lights} = Q_{lights} \times \text{Annual Operating Hours} \times \text{Electricity Cost} \quad (18)$$

$$C_{heat} = Q_{fuel} \times \text{Annual Operating Hours} \times \text{Natural Gas Cost} \quad (19)$$

$$C_{cool} = E_{AC} \times \text{Annual Operating Hours} \times \text{Electricity Cost} \quad (20)$$

The net energy cost savings from installing skylights, *Net Cost Savings*, is the difference between the total energy cost without and with skylights.

$$\text{Net Cost Savings} = (C_{light} + C_{heat} + C_{cool})_{\text{without skylight}} - (C_{light} + C_{heat} + C_{cool})_{\text{with skylights}} \quad (21)$$

## Case Study

The methodology was applied to a typical industrial facility. The facility has a 30 ft ceiling with an R-value of 10 hr-ft<sup>2</sup>-F/Btu. The roof has an absorptivity of 0.2. The reflectivity of the interior walls is 0.7 and the reflectivity of the ceiling is 0.8. Net energy savings were calculated for the case when the electric lighting is supplied by 400-W metal halides (MH) lights and by high-bay fluorescents (HBF) lights. 400-W MH fixtures draw about 460 W each and HBF fixtures draw about 235 W each (Grainger, 2005-2006). It is assumed that the plant requires lighting all 8,760 hours of the year and that whenever sufficient light is provided by the skylights the lighting fixtures are shut off.

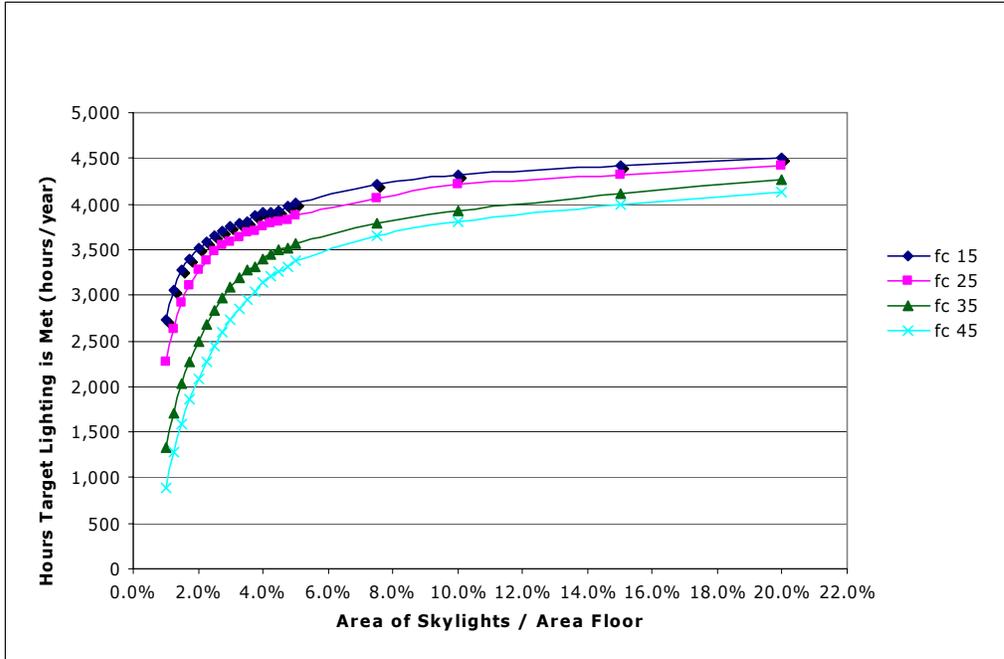
The building is equipped with an 80%-efficient gas-fired heating unit and electric air conditioning with coefficient of performance, COP, of 3 (which corresponds to a Seasonal Energy Efficiency Rating, SEER, of 10.2 Btu/Wh). Convection coefficients for outdoor surfaces are 6 Btu/hr-ft<sup>2</sup>-F in winter and 4 Btu/hr-ft<sup>2</sup>-F in summer (Mitchell, 1983). The building is heated from November through February and cooled from May through August. The indoor air temperature is maintained at 72 F. The electricity and natural gas costs are 5.57 cents per kWh and \$8.48 per mmBtu, based on the 2005 national average for industries (EIA, 2005).

Net energy costs were simulated using TMY2 meteorological data from Dayton, Ohio (NREL, 1995). Based on TMY2 data for Dayton, Ohio, the average outdoor air temperatures and solar radiation during winter months November through February are 32 F and 625 Btu/ft<sup>2</sup>-dy, respectively. During the summer months May through August, the average outdoor air temperatures and solar radiation are 68 F and 1,844 Btu/ft<sup>2</sup>-dy, respectively.

### Light Levels and Skylight Area

Figure 3 shows LightSim results of the number of hours daylighting meets the target lighting levels with respect to the ratio of skylight to floor area, which is also the number of hours that lighting could be turned off. The trend lines indicate that the number of hours that lighting can be turned off increases quickly at small values of skylight to floor area ratio, and more slowly with increasing skylight to floor area ratios. This pattern of diminishing returns suggests the existence of an optimum skylight to floor area ratio that balances heat gain/loss through the skylights and lighting savings.

**Figure 3: Annual Hours Per Year Target Lighting Is Met**

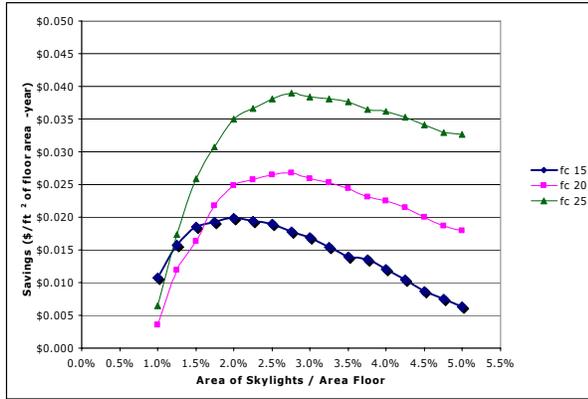


### Cost Savings Results

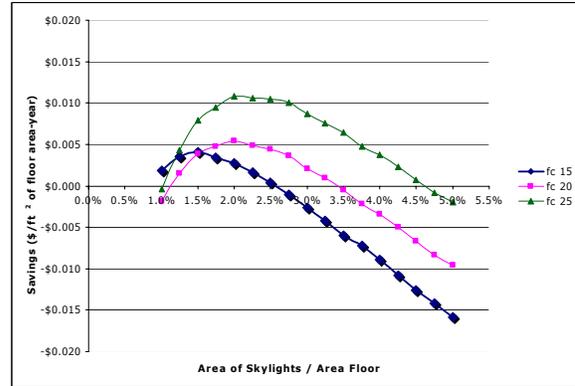
The values obtained from LightSim in Figure 3 were used with Equations 1 -20 to calculate net energy cost savings for various skylight/floor area ratios and target lighting levels. Net energy cost savings are presented in terms of annual energy cost savings per square foot of floor area. Figures 4-7 show results for heating only. Figures 8-11 show results for cooling only. Figures 12-15 show results for heating and cooling. The results are divided into target lighting levels appropriate for warehouses (5 fc – 30 fc) and production activities (30 fc – 50 fc). In addition, results are provided for metal halide and high-bay fluorescent lights.

## Heating Only

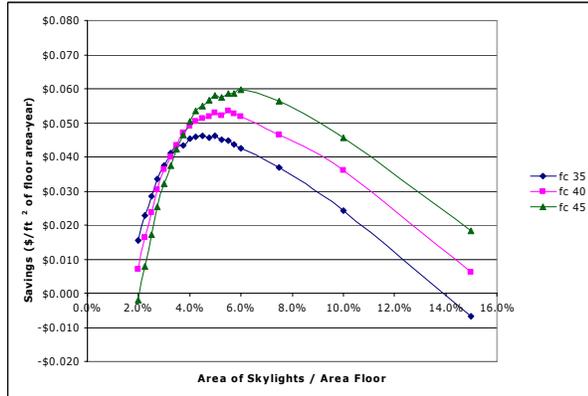
**Figure 4: Metal Halides – Heating Only Savings Warehouse Lighting Levels**



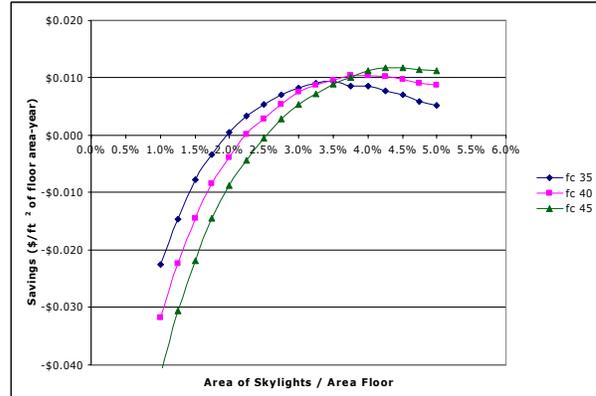
**Figure 5: High-Bay Fluorescents – Heating Only Savings Warehouse Lighting Levels**



**Figure 6: Metal Halides – Heating Only Savings Production Lighting Levels**

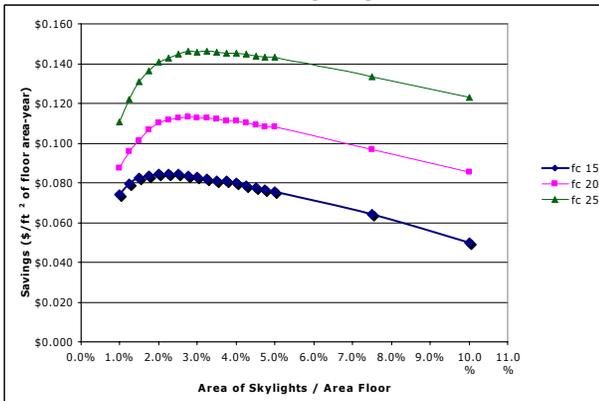


**Figure 7: High-Bay Fluorescents – Heating Only Savings Production Lighting Levels**

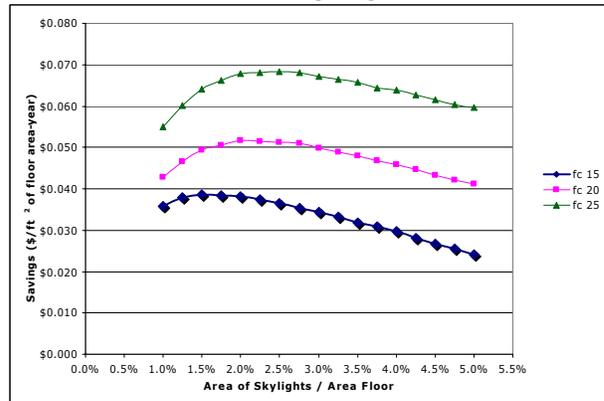


## Cooling Only

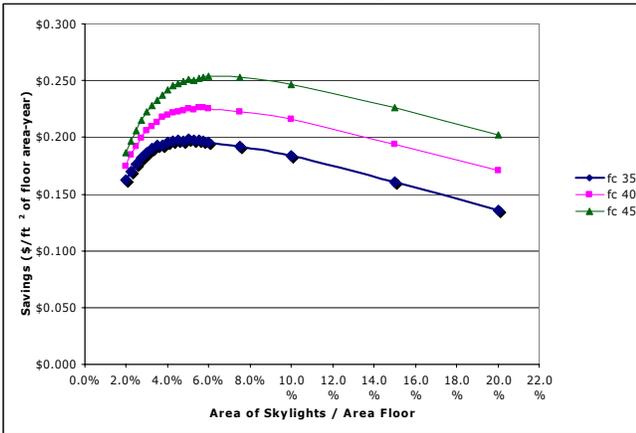
**Figure 8: Metal Halides – Cooling Only Savings Warehouse Lighting Levels**



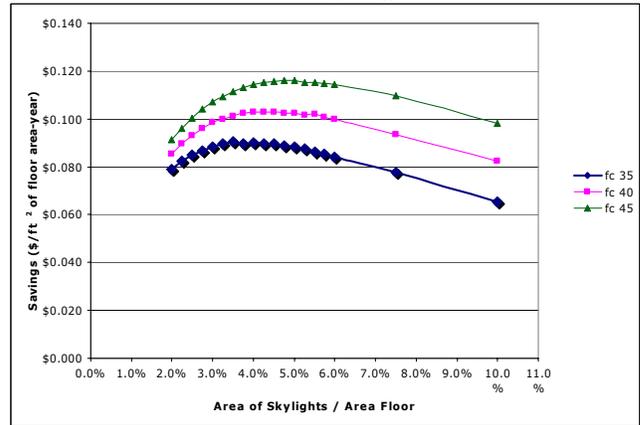
**Figure 9: High-Bay Fluorescents – Cooling Only Savings Warehouse Lighting Levels**



**Figure 10: Metal Halides – Heating Only Savings  
Production Lighting Levels**

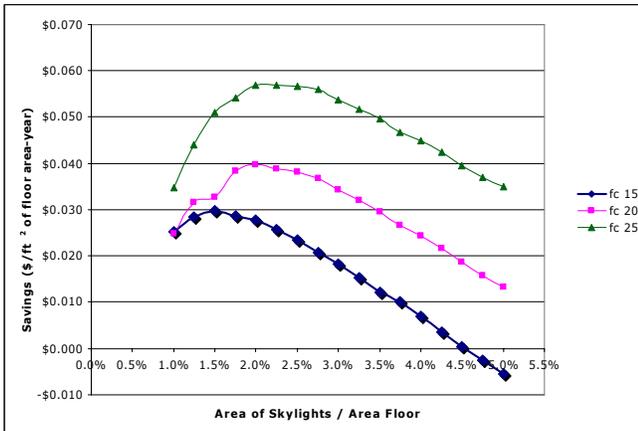


**Figure 11: High-Bay Fluorescents – Heating Only Savings  
Production Lighting Levels**

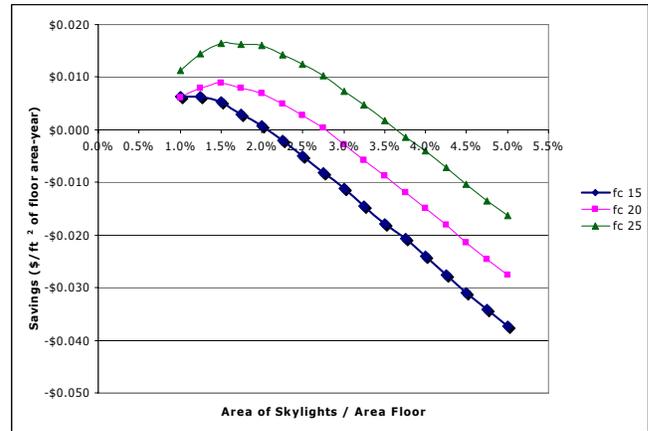


**Heating and Cooling**

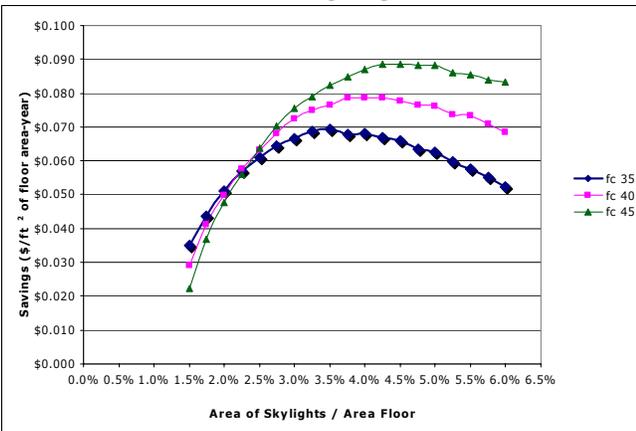
**Figure 12: Metal Halides – Heating and Cooling Savings  
Warehouse Lighting Levels**



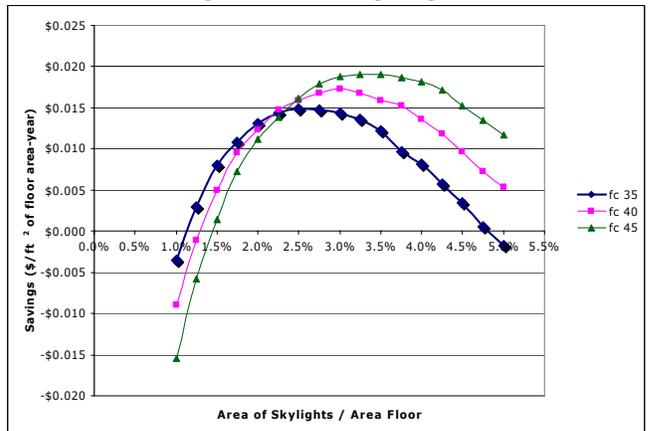
**Figure 13: High-Bay Fluorescents – Heating and Cooling Savings  
Warehouse Lighting Levels**



**Figure 14: Metal Halides – Heating and Cooling Savings  
Production Lighting Levels**



**Figure 15: High-Bay Fluorescents – Heating and Cooling Savings  
Production Lighting Levels**



In each case, the results indicate the existence of an economically optimum skylight to floor area ratio. The optimum skylight to floor area ratio increases as the target lighting level increases. Net energy cost savings also increase as the target lighting level increases. The optimum skylight to floor area ratio is greater with metal halide lights than with high-bay fluorescent lights. Net energy cost savings are also greater with metal halide lights than with high-bay fluorescent lights. The results also show that that net energy cost savings can be negative, which indicates that adding skylights actually increases energy costs, when the skylight to floor area ratio deviates significantly from the optimum value.

Results also indicate optimum skylight to floor area ratios ranging from about 1% to 6%, Peak cooling savings range from about 4 to 25 cents/ft<sup>2</sup>-yr, while heating savings range from about 0.5 to 4 cents/ft<sup>2</sup>-yr. For plants with both heating and cooling, peak savings range from about 1 to 9 cents/ft<sup>2</sup>-yr.

For Dayton, Ohio, results indicate optimum skylight to floor area ratios range from about 1% to 6%, and net energy savings ranging from about 0.5 to 25 cents per square foot of floor area per year using average industrial energy costs. Net cooling energy savings are higher than net heating energy savings.

This analysis demonstrates that an economically optimal area of skylights exists that results in net energy cost savings, but installing either too many or too few skylights can result in an increase in net energy costs. Thus, it is important to perform an analysis such as this to guarantee that skylights actually reduce net energy costs.

## **Future Work**

This paper describes a methodology for calculating net energy savings from skylights as a function of skylight area, the required lighting level, and type of lighting. However, there are several other variables used in the calculations, and it would be informative to consider the sensitivity of the results to variations in these variables.

One of the most important variables is location, which determines average outdoor air temperature and solar radiation. Future work should extend the analysis to include other climates. It would also be informative to consider the sensitivity of the results to the costs of electricity and natural gas, since these costs can vary widely among manufacturers and over time.

It would also be useful to account for the quantity of heat from lighting fixtures that actually contributes to the facility heating or cooling load. In this paper, it was assumed that air from the ceiling is circulated down to the work floor, and all heat from lights contributes to the heating or cooling loads. However, many industrial facilities employ ceiling-mounted exhaust fans and little of the heat from lights actually becomes part of the heating or cooling energy requirements.

Lastly, it would be informative to analyze more complex lighting control systems, in which lighting output and energy use would vary more continuously than the on/off control considered here. For example, the light output and electricity requirements of metal halide lights can be varied using two-stage dimmable ballasts controlled by a photo sensor. Similarly, lighting output and electricity requirements of high-bay fluorescent lights can be varied by controlling the number of active ballasts with a photo sensor.

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