HOW MUCH ENERGY DO DIFFERENT TOPLIGHTING STRATEGIES SAVE?

Summary

Skylights can introduce considerable heat gain and losses that may offset the benefits of electric light savings and cause an increase in yearly net energy use. The design of a toplight system needs to take into consideration different toplighting types, including aperture size and orientation, electric lighting control, and, most importantly, the local climate.

This study examines the impacts of a variety of toplighting strategies and glazing types on the total yearly energy loads for a prototypical open office space situated in different climates. Coordinated modeling, with an advanced daylight and electric lighting simulation program and a building thermal simulation program based on hourly weather data for an entire year, enabled the reliable estimation of annual lighting energy use in response to dynamically changing daylight conditions while addressing the interactions between lighting energy and total building energy. Annual lighting, cooling and heating loads for top-lit spaces were compared with those of a base case with an opaque roof.

The following were investigated in this study.

1. The required glazing area of eight different toplighting strategies to meet a 2% daylight factor.
2. The effects of eight different toplighting strategies on total yearly building energy consumption for five different climates.
3. Electric lighting energy reduction associated with three different lighting control methods and the changes in building cooling and heating loads.
4. The effects of a variety of glazings with different thermal and optical properties on the building loads.

The major conclusions drawn from this study are as follows.

1. The glazing size should be determined on the basis of total energy use rather than by a specific daylight factor.
2. Building toplighting strategies can save overall building energy consumption in a variety of climates compared to the base case with an opaque roof, with electric lighting control.
3. In regards to lighting control, switching performs as well as dimming does.
4. The energy performance of toplighting strategies is very sensitive to weather and the toplighting design must be based on local weather data.
5. As aperture size decreases, overall building energy consumption also decreases up to a certain point. Therefore, successful toplight design depends on small aperture size.

1. Introduction

The introduction of daylight to building interiors has the potential to enhance the quality of the environment while providing opportunities to save energy and reduce greenhouse gases. However, improper selection/design of the daylight delivery system can offset the benefits of electric lighting energy reduction and negatively affect building energy requirements and the quality of the environment. In order to compare the effectiveness of different toplighting strategies for reducing building energy demands, simulations based on hourly local weather data must be performed to estimate annual daylight availability and building energy use.

A design tool developed by Heschong and McHugh accounts for both lighting and thermal energy demands of skylights, but can only be applied to flat skylights (Heschong and McHugh 2000). This design tool uses a simplified lumen method toplighting models. Another existing toplighting design tool extends its capability to a variety of skylight types, but only calculates electric lighting energy savings (Lauoadi and Atif 1999). This presents an incomplete picture of the true impacts of toplighting strategies on overall building energy demands.

Existing whole-building energy modeling programs are not capable of handling advanced daylight systems (Winkelmann and Selkowitz 1985). An advanced lighting simulation engine is needed for reliable approximation of annual lighting load calculations based on hourly daylight data for different climates. The results can then be incorporated into building energy simulation software, such as DOE 2.1E, to receive the complete picture of the changes in total building energy consumption caused by the installation of toplighting strategies.

Studies have addressed the application of direct run-time coupling between building thermal simulation and lighting simulation using the ESP-r and Radiance simulation tools (Janak 1997). Because of the extensive calculation time required for lighting simulation, that study considered the month of March. This one-month simulation resulted in insufficient resolution for estimating impacts of lighting control on the building energy consumption for the rest of the year. To reduce the calculation time, the daylight coefficient method was implemented for ESP-r and Radiance system. However, the method showed unstable results, and special care was required for application to different daylight configurations (Janak and Macdonald 1999).

To address the complexity of this situation, this study investigates different toplighting strategies in a range of climates for a variety of different glazings by coupling the results from a lighting simulation (Radiance) program to building energy simulation software (DOE 2.1E). The thorough simulation of yearly energy data using both of these tools allows the most reliable estimation of electric lighting energy consumption and results in much more accurate calculation of cooling and heating energy demands. Radiance permits the simulation of advanced daylighting systems with complex geometries. As a result, correct determination of the yearly energy performance of a building with advanced daylight systems becomes possible.

A complete annual daylight simulation requires extensive computation power. Several simulation methods have been proposed to conduct annual daylight simulation by limiting the number of sky conditions to be simulated. These approaches include the daylight factor method (Tregenza and Waters 1983), the split flux method (Winkelmann 1983), a simplified weather data method (Herkel and Pasquay 1997), the daylight coefficient method (Reinhart and Herkel 2000), and the radiosity calculation method(Geebelen and Neuckermans 2003.). However, the split flux method provides unreliable results, and the radiosity calculation method considers only perfectly diffuse surfaces. Calculation accuracy in the other methods is sacrificed for calculation time, which is still expensive. Lengthy daylight simulation time restricts the analysis of integrated building performance to research institutions and limits the opportunity for energy saving in actual building design.

2. Method

In this study, we compared the energy efficiency of building toplighting strategies and glazing types in five different climates. A three-step approaches was taken. First, glazing area was determined to meet a 2% daylighting factor for each glazing and toplighting type in conformation to the Leadership in Energy and Environmental Design (LEED) Green Building Rating System, which requires a 2 % daylight factor for 75% of the critical work plane area to score one credit in “Indoor Environmental Quality” (U S Green building council 2002). Secondly, a new method permitting detailed approximate daylight simulation within a reasonable time based on hourly weather data was developed to calculate annual electric lighting power requirement. Thirdly, the impact of changes in toplighting strategies and glazing types on cooling and heating energy and the possible total yearly energy saving was determined.

To make these simulation data useful for building designers, tables showing hourly energy performance over the year, broken down into total heat losses, cooling loads and lighting loads were prepared. This information allows designers to select toplighting strategies based on specific hours of use of a building, e.g., schools. In this way, the building design team and owners can determine design details in the earliest phases of the building design process that will lead to a successful overall energy-conscious solution without requiring extensive and expensive simulation.

2.1. Five Locations Representative of Various Climate Conditions in the U.S.A.

The five climate locations considered are Phoenix, Houston, Philadelphia, Seattle, and Minneapolis as shown in table 1. The locations encompass hot and humid to temperate/cold and dry climates with different levels of cloudiness (ASHRAE 2001) (Weather history 2001).

Table 1 Five different locations and their climate characteristics

	Heating Degree Days	Cooling Degree Days	Heating Design Temp, ˚F	Cooling Design Temperature, ˚F		Annual Cloudiness (number of days)		
Region	HDD65	CDD50	99.6%	Dry-Bulb 1%	Wet-Bulb 1%	Clear	Partly cloudy	Cloudy
Phoenix	1,350	8,425	34	108	70	211	85	70
Houston	1,599	6,876	27	94	77	90	114	161
Philadelphia	4,954	3,623	11	89	74	93	112	160
Seattle	4,908	2,021	23	81	64	71	93	201
Minneapolis	7,981	2,680	-16	88	71	95	101	169

2.2. The Prototypical Office Space

A one-floor, one-zone space with a floor area of 232.3 m^2 measuring 15.2 m by 15.2 m (2500 ft^2, 50 ft by 50 ft,) was chosen for this analysis. The reflectances of the ceiling, wall, floor and roof were 80%, 50%, 20% and 40%, respectively. The floor to ceiling height was 3.6 m (12 ft). The plenum height was 0.3 m (1 ft) for horizontal skylights with vertical wells and 1.1 m (3.5 ft) for horizontal skylights with splayed wells and roof monitors. The walls have no windows.

2.3. The Eight Toplighting Strategies

Eight different toplight configurations were studied. To provide simplified naming of each combination of toplighting strategy and glazing type, abbreviated names are used throughout this report. H stands for horizontal skylights with vertical wells, while SH stands for horizontal skylights with splayed wells. V stands for vertical roof monitors, and T refers to tilted roof monitors (sawtooth). VB and TB mean vertical and tilted roof monitors with baffles, respectively. D and C refer to diffuse and clear glazing type. The eight toplighting strategies considered in this study and their abbreviated names are as follows (see Fig. 1-4).

1. Horizontal (Domed) skylight, 1 ft vertical well, diffuse glazing (HD)
2. Horizontal (Domed) skylight, 3.5 ft deep splayed well with 60˚, diffuse glazing (SHD)
3. Vertical roof monitors facing north and vertical clear glazing (VC)
4. Vertical roof monitors facing south and vertical diffuse glazing (VD)
5. Vertical roof monitors facing south with vertical clear glazing and vertical sunlight diffusing baffles at the ceiling plane within the skylight well to exclude direct sunlight (VBC)

6. Tilted roof monitors facing north and vertical clear glazing (TC)
7. Tilted roof monitors facing south and vertical diffuse glazing (TD)
8. Tilted roof monitors facing south with tilted clear glazing and variable-slope sunlight diffusing baffles at the ceiling plane within the skylight well to exclude direct sunlight (TBC)

The eight toplighting conditions are shown in Figs. 1–4 and Tables 2-5, which include the relevant dimensions, glazing size and orientation. The angle of vertical and tilted roof monitors with or without baffles was determined according to the latitude of the site location (Moore 1991) as shown in Appendix 1.In this study, the glazing area for each combination of toplighting strategy and glazing type was determined so that a minimum 2% daylight factor was achieved.

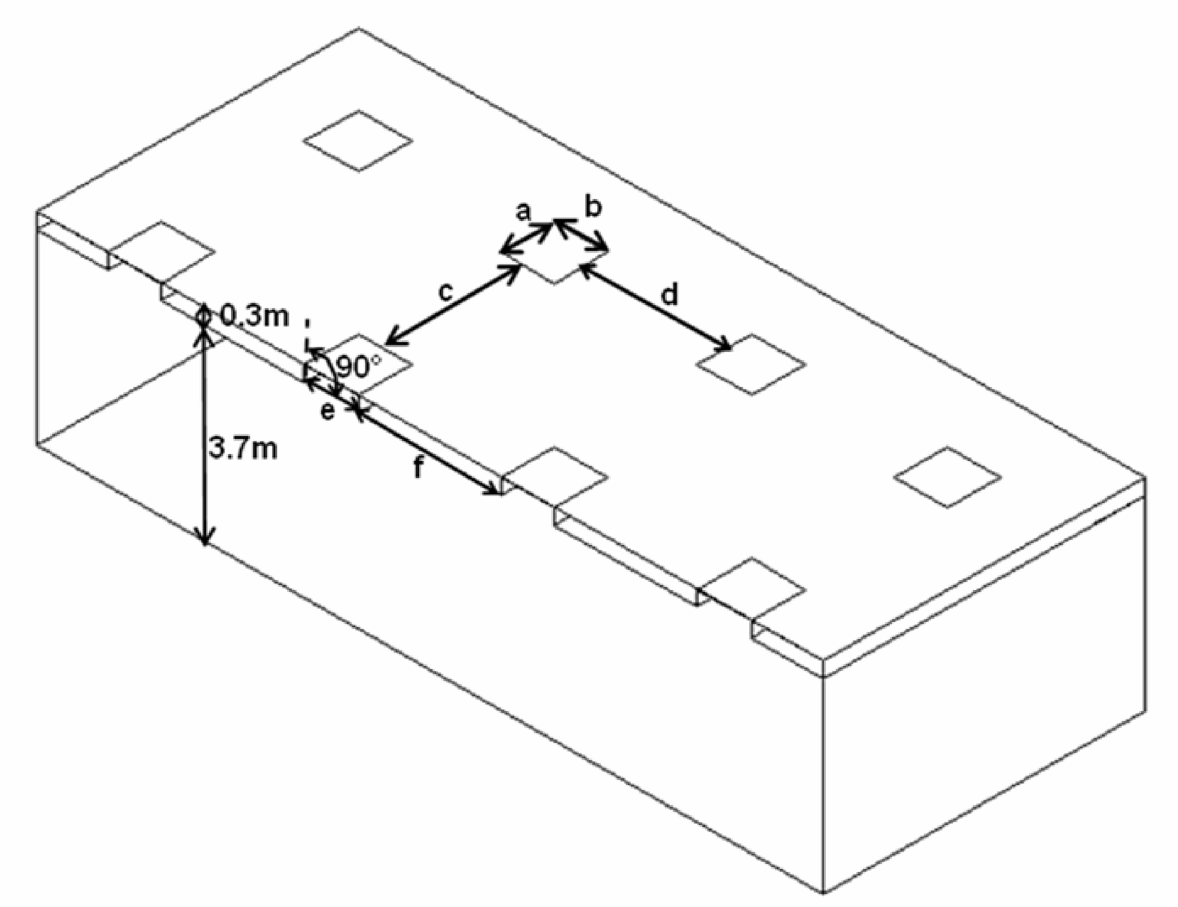

Figure 1: Toplighting case 1 –HD, 1.0ft vertical well, diffuse glazing

Table 2 Toplighting dimensions in meters for relevant symbols in figure 1.

Region	Toplighting +glazing	No.	a	b, e	c	d, f
Seattle, WA	HD1	16	1.1	1.1	2.8	2.8
	HD2	16	1.3	1.3	2.5	2.5
	HD3	16	1.4	1.4	2.4	2.4
	HD4	16	1.5	1.5	2.3	2.3
	HD5	16	2.0	2.0	1.8	1.8
	HD6	16	2.0	2.0	1.8	1.8
Houston, TX	HD1	16	1.1	1.1	2.8	2.8
	HD2	16	1.3	1.3	2.5	2.5
	HD3	16	1.4	1.4	2.4	2.4
	HD4	16	1.5	1.5	2.3	2.3
	HD5	16	2.0	2.0	1.8	1.8
	HD6	16	2.0	2.0	1.8	1.8
Philadelphia, PA	HD1	16	1.1	1.1	2.8	2.8
	HD2	16	1.3	1.3	2.5	2.5
	HD3	16	1.4	1.4	2.4	2.4
	HD4	16	1.5	1.5	2.3	2.3
	HD5	16	2.0	2.0	1.8	1.8
	HD6	16	2.0	2.0	1.8	1.8
Minneapolis, MN	HD1	16	1.1	1.1	2.8	2.8
	HD2	16	1.3	1.3	2.5	2.5
	HD3	16	1.4	1.4	2.4	2.4
	HD4	16	1.5	1.5	2.3	2.3
	HD5	16	2.0	2.0	1.8	1.8
	HD6	16	2.0	2.0	1.8	1.8
Phoenix, AZ	HD1	16	1.1	1.1	2.8	2.8
	HD2	16	1.3	1.3	2.5	2.5
	HD3	16	1.4	1.4	2.4	2.4
	HD4	16	1.5	1.5	2.3	2.3
	HD5	16	2.0	2.0	1.8	1.8
	HD6	16	2.0	2.0	1.8	1.8

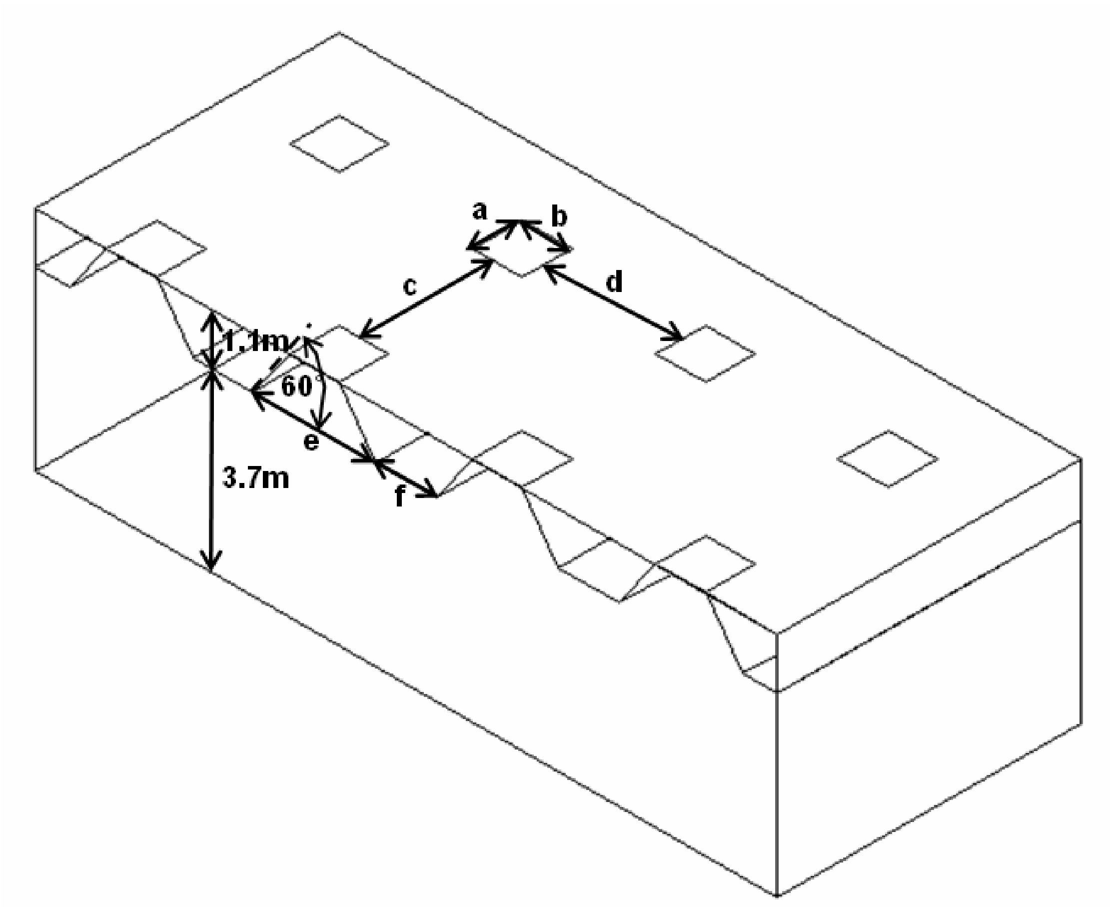

Figure 2: Toplighting 2 –SHD, 3.5ft splayed well, diffuse glazing

Table 3 Toplighting dimensions in meters for relevant symbols in figure 2

Region	Toplighting +glazing	No.	a	b	c	d	e	f
Seattle, WA	SHD1	16	1.0	1.0	2.7	2.7	2.5	1.2
	SHD2	16	1.3	1.3	2.5	2.5	2.8	0.9
	SHD3	16	1.4	1.4	2.4	2.4	2.9	0.9
	SHD4	16	1.5	1.5	2.3	2.3	3.0	0.8
	SHD5	16	2.0	2.0	1.8	1.8	3.5	0.2
	SHD6	16	2.0	2.0	1.8	1.8	3.5	0.2
Houston, TX	SHD1	16	1.0	1.0	2.7	2.7	2.5	1.2
	SHD2	16	1.3	1.3	2.5	2.5	2.8	0.9
	SHD3	16	1.4	1.4	2.4	2.4	2.9	0.9
	SHD4	16	1.5	1.5	2.3	2.3	3.0	0.8
	SHD5	16	2.0	2.0	1.8	1.8	3.5	0.2
	SHD6	16	2.0	2.0	1.8	1.8	3.5	0.2
Philadelphia, PA	SHD1	16	1.0	1.0	2.7	2.7	2.5	1.2
	SHD2	16	1.3	1.3	2.5	2.5	2.8	0.9
	SHD3	16	1.4	1.4	2.4	2.4	2.9	0.9
	SHD4	16	1.5	1.5	2.3	2.3	3.0	0.8
	SHD5	16	2.0	2.0	1.8	1.8	3.5	0.2
	SHD6	16	2.0	2.0	1.8	1.8	3.5	0.2
Minneapolis, MN	SHD1	16	1.0	1.0	2.7	2.7	2.5	1.2
	SHD2	16	1.3	1.3	2.5	2.5	2.8	0.9
	SHD3	16	1.4	1.4	2.4	2.4	2.9	0.9
	SHD4	16	1.5	1.5	2.3	2.3	3.0	0.8
	SHD5	16	2.0	2.0	1.8	1.8	3.5	0.2
	SHD6	16	2.0	2.0	1.8	1.8	3.5	0.2
Phoenix, AZ	SHD1	16	1.0	1.0	2.7	2.7	2.5	1.2
	SHD2	16	1.3	1.3	2.5	2.5	2.8	0.9
	SHD3	16	1.4	1.4	2.4	2.4	2.9	0.9
	SHD4	16	1.5	1.5	2.3	2.3	3.0	0.8
	SHD5	16	2.0	2.0	1.8	1.8	3.5	0.2
	SHD6	16	2.0	2.0	1.8	1.8	3.5	0.2

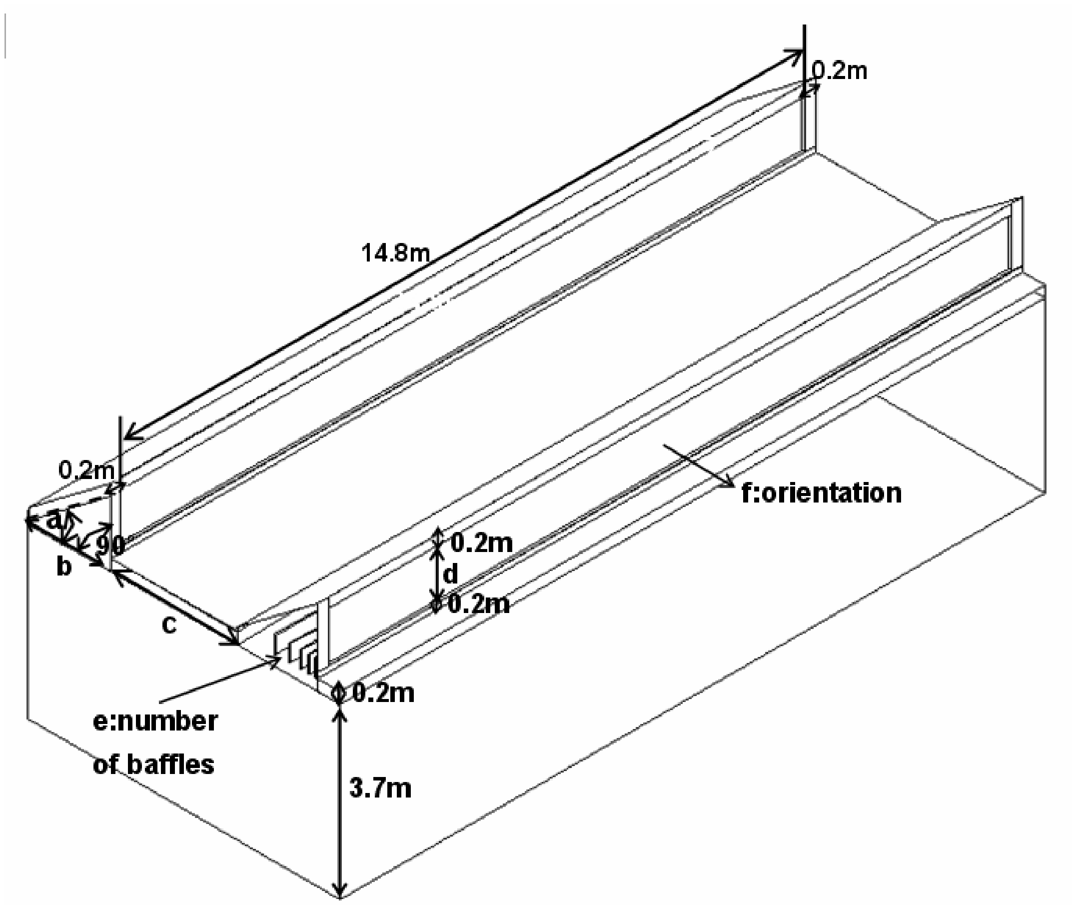

Figure 3:

Toplighting case 3–VC, Vertical roof monitors facing north, and vertical clear glazing

Toplighting case 4–VD, Vertical roof monitors facing south, and vertical diffuse glazing

Toplighting case 5–VBC, Vertical roof monitors facing south, vertical clear glazing and with vertical sunlight diffusing baffles

Table 4 Toplighting dimensions in meters for relevant symbols in figure 3 (f*: No. of baffles)

Region	Toplighting + glazing	No.	a ,°	b	c	d	e	f
Seattle, WA	VC1	4	20	1.9	2.1	0.6		N
	VC2	4	20	1.9	2.0	0.6		N
	VC3	4	20	2.2	1.7	0.7		N
	VC4	4	20	3.3	0.7	1.1		N
	VD1	4	20	2.6	1.3	0.9		S
Houston, TX	VC1	4	37	1.6	2.9	0.9		N

	VC2	4	37	1.6	2.9	0.9		N
	VC3	4	37	1.7	2.8	1.0		N
	VC4	5	37	1.8	1.5	1.1		N
	VD1	4	37	1.8	2.6	1.1		S
	VD2	7	37	1.7	0.6	0.9		S
	VBC1	6	37	1.7	0.5	1.0	6	S
Philadelphia, PA	VC1	3	27	2.1	4.3	0.9		N
	VC2	3	27	2.2	4.3	1.0		N
	VC3	3	27	2.4	3.7	1.1		N
	VC4	4	27	2.4	1.8	1.1		N
	VC5	4	27	2.9	1.1	1.4		N
	VD1	4	27	1.9	2.2	0.9		S
	VD2	5	27	2.4	0.7	1.1		S
	VD3	6	27	2.4	0.2	1.1		S
Minneapolis, MN	VC1	3	22	2.7	3.5	0.9		N
	VC2	3	22	2.8	3.4	0.9		N
	VC3	3	22	3.0	3.0	1.1		N
	VC4	4	22	3.0	1.0	1.1		N
	VD1	4	22	2.7	1.4	0.9		S
Phoenix, AZ	VC1	3	34	2.1	4.3	1.0		N
	VC2	3	34	2.1	4.3	1.0		N
	VC3	3	34	2.3	4.1	1.1		N
	VC4	4	34	2.2	2.1	1.1		N
	VC5	5	34	2.2	1.0	1.1		N
	VD1	4	34	2.1	2.3	1.0		S
	VD2	7	34	1.9	0.3	0.9		S

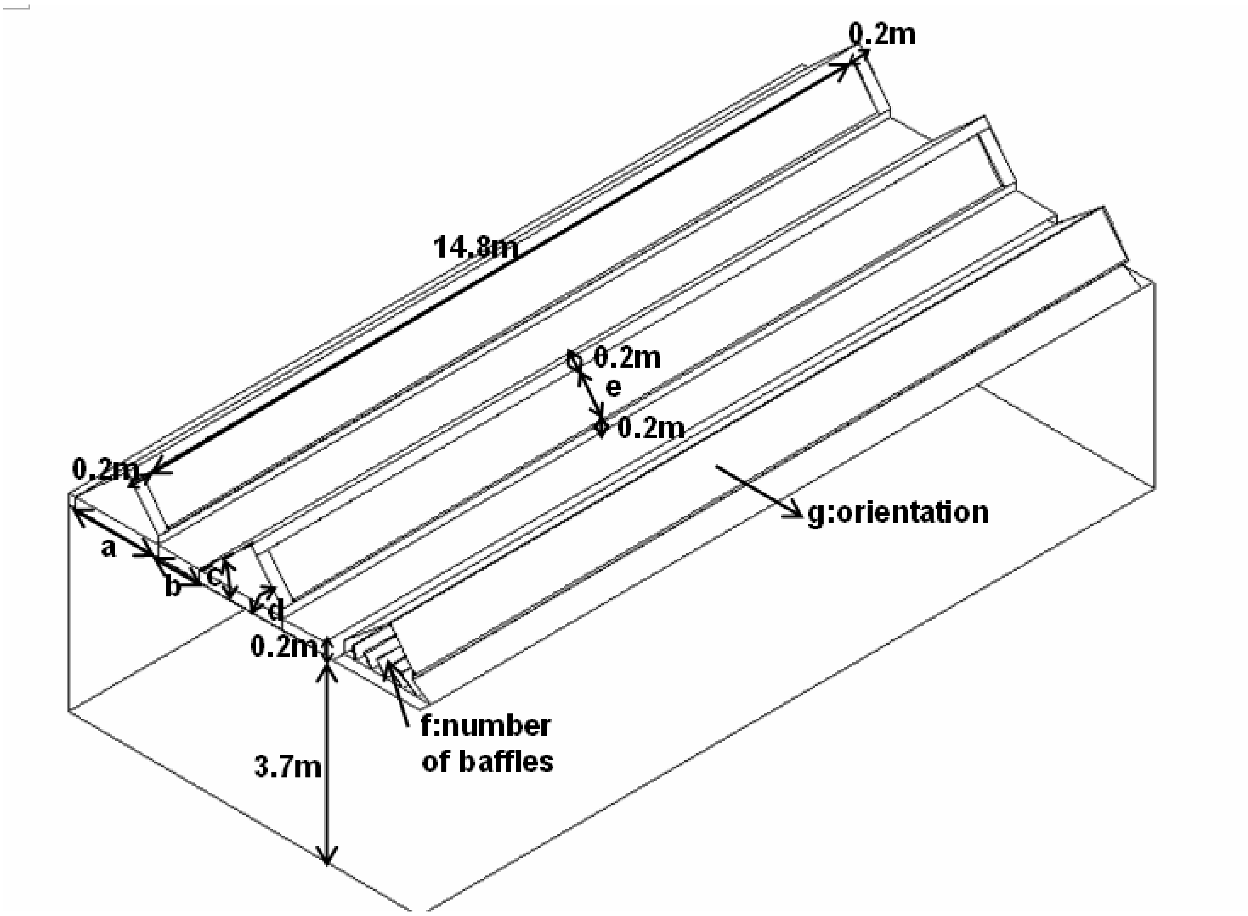

Figure 4:

Toplighting case 6–TC, Sloped roof monitors facing north and sloped clear glazing

Toplighting case 7–TD, Sloped roof monitors facing south and sloped diffuse glazing

Toplighting case 8–TBC, Sloped roof monitors facing south, with sloped clear glazing and variable-slope sunlight diffusing baffles

Table 5 Toplighting dimensions in meters for relevant symbols in figure 4

Region	Toplighting +glazing	No.	a	b	c, °	d, °	e	f	g
Seattle, WA	TC1	4	2.0	1.8	23	70	0.5		N
	TC2	4	1.9	1.9	23	70	0.6		N
	TC3	4	1.8	2.0	23	70	0.5		N
	TC4	4	1.4	2.4	23	70	0.7		N
	TC5	4	0.7	3.1	23	70	0.9		N
	TD1	4	1.8	2.0	23	70	0.5		S
	TD2	4	1.2	2.6	23	70	0.8		S
Houston, TX	TC1	3	4.7	1.7	40	53	0.8		N

	TC2	3	4.7	1.7	40	53	0.8		N
	TC3	3	4.6	1.8	40	53	0.9		N
	TC4	3	4.0	2.1	40	53	1.1		N
	TC5	4	2.7	1.6	40	53	0.7		N
	TD1	3	4.8	1.6	40	53	0.8		S
	TD2	4	2.8	1.5	40	53	0.7		S
	TD3	4	2.6	1.6	40	53	0.8		S
	TD4	4	2.5	1.8	40	53	0.9		S
	TD5	6	0.6	1.9	40	53	1.0		S
	TBC1	6	0.9	1.7	40	53	0.8	5	S
Philadelphia, PA	TC1	3	4.3	2.0	30	63	0.8		N
	TC2	3	4.3	2.0	30	63	0.8		N
	TC3	3	4.1	2.2	30	63	0.9		N
	TC4	4	2.2	2.0	30	63	0.8		N
	TC5	4	2.0	2.1	30	63	0.9		N
	TD1	3	4.4	2.0	30	63	0.8		S
	TD2	4	2.1	2.1	30	63	0.8		S
	TD3	5	1.3	1.9	30	63	0.7		S
	TD4	5	1.1	2.0	30	63	0.8		S
Minneapolis, MN	TC1	3	3.6	2.5	24	68	0.8		N
	TC2	3	3.6	2.5	24	68	0.8		N
	TC3	3	3.3	2.7	24	68	0.9		N
	TC4	4	1.6	2.5	24	68	0.8		N
	TC5	5	0.6	2.4	24	68	0.8		N
	TD1	3	3.5	2.6	24	68	0.8		S
Phoenix, AZ	TC1	3	4.6	1.7	34	56	0.8		N
	TC2	3	4.6	1.9	34	56	0.8		N
	TC3	3	4.4	2.0	34	56	0.8		N
	TC4	4	2.5	1.8	34	56	0.8		N
	TC5	4	2.3	2.0	34	56	0.8		N
	TD1	3	4.6	1.9	34	56	0.8		S
	TD2	4	2.5	1.8	34	56	0.8		S
	TD3	4	2.2	2.0	34	56	0.9		S
	TD4	4	2.0	2.2	34	56	0.9		S
	TBC1	7	0.5	2.1	34	56	0.9	5	S

2.4. The Five Clear and Six Diffuse Glazings

Five clear and six diffuse glazings were applied in this study. The clear glazings were used for north-facing roof monitors, as well as for south-facing roof monitors with light diffusing baffles. The diffuse glazings were used for south-facing roof monitors and horizontal skylights. All glazing types are commercially available products, and their properties are presented in table 6. Note that the sixth diffuse glazing type, a translucent glazing with aerogel insulation, has approximately the same heat transfer coefficient as opaque facades and a low light transmission (16%) (Dengler and Witterwear 1994). This glazing material was investigated specifically for heating dominated climates.

Table 6 Glazing properties (C: Clear, D: Diffuse)
(U-value IP conversion: 1.0 w/m^{2}k = 0.176 Btu/ (hr•ft^2•°F))

Glazing	Manufacturer	Product Name	U-factor, W/m^2-K	Shading Coefficient	Visible light Transmittance
C1	VersaLite	Clear/Clear w/Low E on #3	2.05(Summer) /1.88(Winter)	0.76	0.72
C2	Cardinal	Double LoE -170	1.65(Summer) /1.42(Winter)	0.41	0.7
C3	SouthWall	California Series Laminated Insulating Glass, 1" thickness (1/4" glass thickness)	2.73	0.45	0.63
C4	AFG Industries	Dual Glazed Comfort Ti-R(Surface #3) with Tint Substrates, Air 1/2", Bronze 5mm glass	1.68	0.40	0.45
C5	SouthWall	HM SC75/Clear (1" thick)	1.76	0.28	0.37
D1	SunOptics	Flat style CoolOptics (Fixed skylights with insulated thermal break)	1.98	0.37	0.67
D2	Versalite	2 3/4” Fiberglass Translucent Panel (Ext: Crystal, Int: White)	2.27	0.59	0.4
D3	Major Skylights	Guardian 275 (Crystal (Exterior) /White(Interior)), No insulation	3.69(Sloped)/ 3.47(Vertical)	0.43	0.34
D4	Kalwall	Crystal (Exterior)/ Crystal(Interior)	1.65	0.31(Roof)/ 0.26(Vertical)	0.3

D5	Major Skylghts	Guardian 275 (Crystal (Exterior)/ Crystal(Interior)), high density insulation 45g	2.05(Roof)/ 1.82(Vertical)	0.21	0.16
D6	Kalwall	20/20 Nanogel	0.28	0.12	0.16

2.5. The Glazing Area Requirement for a 2% Daylight Factor

Glazing area requirements for achieving a 2% daylight factor in the space for the five climate locations are shown in table 7. The daylight factor defined as the ratio of the actual illuminance at a point in a room and the illuminance available from an identical unobstructed sky (Tregenza and Waters 1983). For the roof monitor strategies, the total roof area includes sloped, vertical and horizontal area excluding the glazing area. When a toplighting strategy with a specific glazing could not provide the 2% daylight factor with a specified glazing transmittance, the corresponding cell in the table was left blank. The base case considers a solid flat opaque roof with a U-value of 0.16 W/m^2·K. The geometries of horizontal skylights (HD) and sloped horizontal skylights (SHD) are identical for all five locations across a single glazing type due to the 2% daylight factor requirement. The glazing size for the other toplighting strategies vary depending on the climate locations since the sloped angles of roof monitors are determined by latitudes according to Moore's formula (see figure A-1) which affects the glazing area needed to achieve the 2% daylight factor. With the same number of toplight units, the product of the visible transmittance of a glazing and the glazing area to meet the 2% daylight factor criterion remains the same as the transmittance increases. In general, HD and SHD need much less glazing area (30% to 50%) than other toplighting types to obtain the 2% daylight factor.

Table 7 Required glazing areas for a 2% daylight factor

(A*: The ratio of glazing area to ceiling area (232m^2(2500 ft^2)), B*: The ratio of glazing area to roof area)

	Houston			Minneapolis			Philadelphia			Seattle			Phoenix		
	Roof,m^2	A*	B*	Roof,m^2	A*	B*	Roof,m^2	A*	B*	Roof,m^2	A*	B*	Roof,m^2	A*	B*
Base	232	0	0	232	0.00	0.00	232	0	0	232	0	0	232	0	0
HD1	215	0.08	0.08	215	0.08	0.08	215	0.08	0.08	215	0.08	0.08	215	0.08	0.08
HD2	205	0.12	0.13	205	0.12	0.13	205	0.12	0.13	205	0.12	0.13	205	0.12	0.13
HD3	201	0.14	0.16	201	0.14	0.16	201	0.14	0.16	201	0.14	0.16	201	0.14	0.16
HD4	197	0.15	0.18	197	0.15	0.18	197	0.15	0.18	197	0.15	0.18	197	0.15	0.18
HD5	168	0.28	0.39	168	0.28	0.39	168	0.28	0.39	168	0.28	0.39	168	0.28	0.39
HD6	168	0.28	0.39	168	0.28	0.39	168	0.28	0.39	168	0.28	0.39	168	0.28	0.39

SHD1	216	0.07	0.08	216	0.07	0.08	216	0.07	0.08	216	0.07	0.08	216	0.07	0.08
SHD2	205	0.12	0.13	205	0.12	0.13	205	0.12	0.13	205	0.12	0.13	205	0.12	0.13
SHD3	202	0.13	0.15	202	0.13	0.15	202	0.13	0.15	202	0.13	0.15	202	0.13	0.15
SHD4	198	0.15	0.17	198	0.15	0.17	198	0.15	0.17	198	0.15	0.17	198	0.15	0.17
SHD5	170	0.27	0.37	170	0.27	0.37	170	0.27	0.37	170	0.27	0.37	170	0.27	0.37
SHD6	170	0.27	0.37	170	0.27	0.37	170	0.27	0.37	170	0.27	0.37	170	0.27	0.37
VC1	288	0.23	0.18	260	0.17	0.16	262	0.18	0.16	258	0.15	0.13	265	0.19	0.16
VC2	289	0.23	0.19	261	0.18	0.16	264	0.19	0.16	259	0.15	0.14	265	0.19	0.16
VC3	291	0.25	0.20	264	0.20	0.18	264	0.20	0.18	262	0.18	0.16	268	0.21	0.18
VC4	309	0.34	0.25	275	0.27	0.23	276	0.27	0.23	277	0.29	0.24	279	0.28	0.23
VC5							288	0.35	0.28				291	0.34	0.27
VD1	294	0.27	0.21	273	0.22	0.18	269	0.22	0.19	267	0.22	0.19	276	0.25	0.21
VD2	333	0.42	0.29				287	0.34	0.27				302	0.39	0.30
VD3							296	0.41	0.32						
VBC1	337	0.45	0.31												
TC1	236	0.15	0.15	243	0.15	0.14	241	0.15	0.14	247	0.12	0.11	237	0.14	0.14
TC2	236	0.16	0.15	243	0.15	0.15	241	0.15	0.14	247	0.12	0.12	237	0.15	0.14
TC3	236	0.17	0.17	243	0.17	0.16	242	0.16	0.16	248	0.14	0.13	237	0.16	0.16
TC4	235	0.21	0.20	246	0.20	0.19	245	0.20	0.19	249	0.19	0.17	239	0.19	0.19
TC5	238	0.19	0.19	249	0.24	0.23	245	0.22	0.21	253	0.23	0.21	238	0.21	0.21
TD1	240	0.15	0.15	244	0.16	0.15	241	0.15	0.14	247	0.13	0.12	238	0.15	0.14
TD2	240	0.17	0.17				244	0.21	0.20	251	0.21	0.20	241	0.19	0.18
TD3	239	0.20	0.19				247	0.23	0.22				239	0.22	0.21
TD4	238	0.23	0.22				247	0.26	0.24				239	0.24	0.23
TD5	239	0.37	0.36												
TBC1	241	0.32	0.31										243	0.34	0.32

2.6. Weather Details

Hourly weather data obtained from the "METEONORM" software were used for both the daylight and thermal simulations (Meteotest 2004).

2.6.1. Daylight simulation: Radiance

A series of hour-by-hour daylight simulations based on the Perez sky model (Perez, Ineichen and Seals 1990) was undertaken using RADIANCE. Illuminance levels were calculated over the work plane for six days (1st, 6th, 11th, 16th, 21st, and 26th) for each month during occupied hours from 8 A.M. to 6 P.M. for

40 points randomly distributed over the work plane area, yielding 792 Perez skies per year.

Maintenance factors to account for dirt accumulation were applied and were 0.9, 0.8 and 0.7 for vertical roof monitors, tilted roof monitors and horizontal skylights, respectively.

2.6.1.1. Determining Similar Sky Models and the Errors Involved

A full annual simulation requires an extremely long calculation time and extensive computation power, which inhibits its feasibility for practical application by building designers. This has prevented annual daylight availability modeling in the past.

To predict dynamically changing interior daylight levels and perform annual energy modeling, a new method using similar hourly weather was developed. The generation of representative models from limited computational results provides a high level of accuracy with manageable lighting analysis computation time and effectively considers every hour of the year in the electric lighting load calculation.

In order to match every sky for every hour of the year to one from the pre-calculated set of daylight cases described above (6 days per month), three approaches were investigated:

1. Matching skies by the closest illuminance level on the exterior glazing surface.
2. Matching skies by the closest vertical-to-horizontal illuminance ratio on the exterior glazing surface.
3. Matching skies by the nearest normalized illuminance vectors Δx, Δy, and Δz (where Δx = difference in east and west illuminance, Δy = difference in north and south illuminance, Δz = difference in upward and downward illuminance). See figure 5.

For each of the three methods, the sky that best matches the desired sky according to the above criteria was determined. For the approaches 2 and 3, the illuminance values were scaled using Eq. (1), while 1 required no scaling.

$$Scaling\ factor = \frac{E_{incident,\,under\,the\,sky\,in\,question}}{E_{incident,\,under\,the\,representative\,sky}}$$

$$E_{is} = E_{i\,,\,under\,the\,representative\,sky} \times scaling\ factor \tag{1}$$

Where, $E_{incident}$ = illuminance on the exterior glazing

E_i=interior illuminance for a point on the workplane

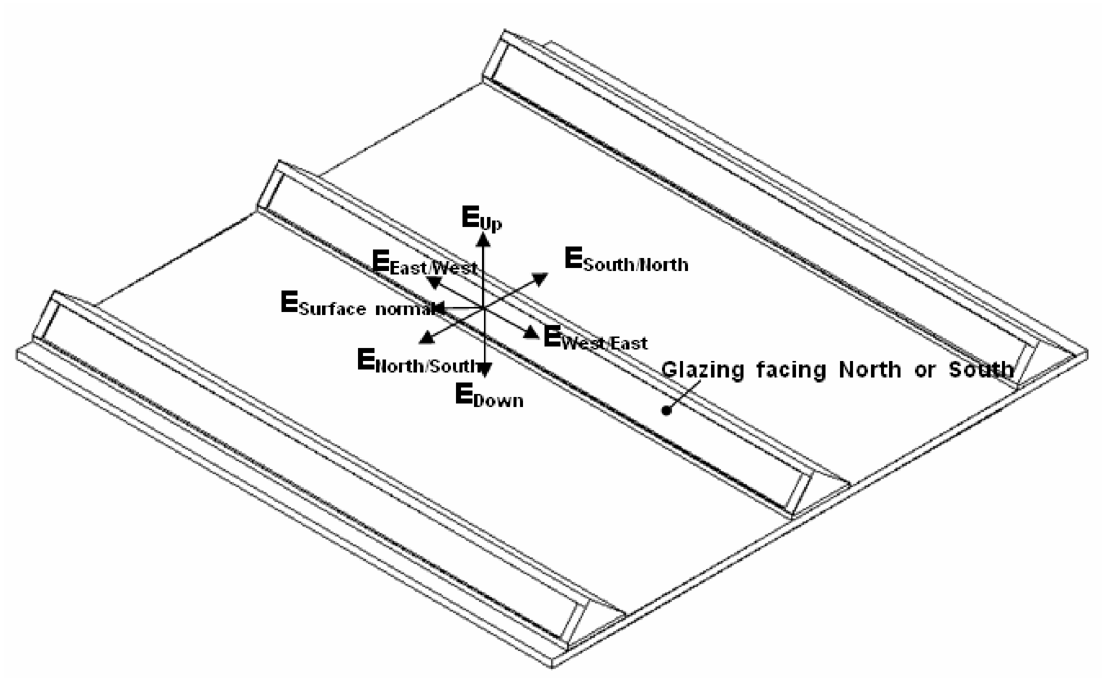

Figure 5: Description of vectors used in exterior illuminance ratios methods

Table 8 shows the percent error calculation between the calculated illuminances and the derived illuminances for each of the three methods. Phoenix and a toplighting strategy, TC, were chosen for this analysis because sunlight causes extreme illuminance differences at the glazing. The ratio of beam and diffuse radiation on a horizontal surface is provided in the table.

Maximum, minimum, mean and standard deviation values for 40 workplane illuminance values were compared for both scaled and fully analyzed conditions. The intent was to determine the minimum daylight level that occurred across the work-plane and set the electric light accordingly. The first method, matching skies by incident illuminance, failed to provide stable and reliable error estimates because the percent errors in comparing the minimum illuminance range from -68% to 55 %. The second method showed reliable estimation of the minimum work plane daylight level, where the percent errors vary from -19 % to 12 %. Percent errors within 20% successfully met the intent of this study. The third method showed inferior performance relative to the second method (with errors of -41.8 to 42). As a result, the second method, applying the vertical to horizontal illuminance ratio at the glazing, was used for this study.

At a few solar positions, for example September, 27 at 12 P.M. in table 8, sloped roof monitors facing north with clear glazing (TC) still permit some direct sunlight to enter the space. Narrow sunlight strips cause a sharp increase in the maximum illuminance among 40 calculation points at the workplane. The sharp increase in the maximum illuminance leads to high mean illuminance and mean errors, but it has little effect on the minimum illuminance. Therefore, the maximum and mean illuminances are not robust performance measures, while the minimum illuminance is reliable because of its indifference to the presence of direct sunlight.

Table 8 Calculation errors between the calculated illuminance and the derived illuminance using the three methods for VD1 and TC1, Phoenix

Toplight & Glazing	Month	Day	Hour	Beam/ Diffuse	Method 1				Method 2				Method 3			
					Max	Mean	Min	Std.dev	Max	Mean	Min	Std.dev	Max	Mean	Min	Std.dev
TC1	3	18	8	9.7	-42.1	-40.5	-36.8	-51.5	-4.1	-9.1	-9.7	-2.2	-8.4	5.8	11.7	-39.6
TC1	3	18	9	6.2	-33.7	-33.7	-33.8	-37.5	-6.5	-9.5	-7.9	-3.6	-10.4	-1.7	3.1	-27.1
TC1	3	18	10	5.7	-130.2	-90.3	-60.4	-236.9	-4.0	-10.6	-11.7	4.3	6.8	1.3	0.7	10.3
TC1	3	18	11	5.4	-18.8	-19.2	-19.7	-16.0	-3.5	-6.7	-7.9	0.5	-6.0	-10.9	-13.3	-1.9
TC1	3	18	12	6.5	-1510.3	-136.3	-3.1	-1149.5	-5.7	-14.0	-18.7	8.3	0.2	0.3	0.5	-1.1
TC1	3	18	13	5.1	10.1	7.3	4.6	13.7	3.1	-4.9	-10.6	16.9	-2.6	-1.7	-2.1	-2.4
TC1	3	18	14	3.5	17.5	16.6	17.9	17.6	4.4	-9.6	-18.6	24.8	-11.9	-9.0	-9.3	-14.9
TC1	3	18	15	7.2	0.2	2.1	4.7	-0.1	-4.3	-6.3	-8.3	-1.3	6.0	14.2	18.5	-4.9
TC1	3	18	16	6.4	-83.4	-68.8	-68.2	-108.0	-0.9	-8.3	-14.0	10.0	0.5	7.3	9.3	-8.1
TC1	3	18	17	5.4	-29.1	-31.9	-38.9	-18.6	-13.0	-1.9	-0.7	-23.6	-12.1	-3.9	-1.9	-22.2
TC1	9	27	8	1.5	-2.3	-5.9	-5.5	5.2	-1.7	-8.3	-10.9	1.2	-8.4	5.0	10.3	-28.5
TC1	9	27	9	3.3	16.2	13.2	16.3	20.6	0.1	-5.2	-7.0	2.0	5.4	11.0	14.4	-5.5
TC1	9	27	10	5.2	24.9	22.2	22.2	20.4	0.0	-6.9	-10.0	7.7	-1342.9	-41.5	14.2	-552.7
TC1	9	27	11	5.8	-1210.5	-71.9	-12.2	-476.1	-3.2	-6.2	-7.4	3.3	-26.5	-33.1	-36.8	-15.5
TC1	9	27	12	10.2	-2029.0	-83.1	8.0	-742.5	-4.9	-7.8	-9.9	-0.6	-34.7	-38.9	-41.8	-28.3
TC1	9	27	13	11.1	-1569.1	-117.0	-44.9	-591.9	-5.5	-5.3	-7.7	-4.0	7.7	10.6	11.0	5.5
TC1	9	27	14	8.0	-11.6	-15.4	-17.6	1.4	-5.5	-5.3	-7.7	-4.0	7.0	8.7	9.3	4.9
TC1	9	27	15	4.8	-3.1	-0.2	2.0	-8.0	-2.4	-7.6	-12.5	4.9	36.1	39.9	42.0	28.0
TC1	9	27	16	5.5	31.3	34.2	43.5	23.2	-5.6	-9.5	-15.0	1.1	4.2	12.6	15.1	-5.9
TC1	9	27	17	2.4	-14.9	-8.2	-11.3	-31.1	-10.2	-4.7	-9.2	-13.6	-33.6	-0.2	14.8	-97.4

2.6.1.2. Electric Lighting Control Methods

The minimum illuminance calculated at an interior calculation grid on the work plane according to method 2 was selected for determining the amount of electric light output required to meet a target illuminance level of 500 lux.

For the electric lighting energy studies, suspended direct luminaires using two 32W T8 lamps with parabolic low glare metal baffles were used as electric lighting sources. The luminaires were laid out in three rows with 12 luminaires per row. The suspension plane was 1.2 m (4 ft) below the ceiling. A two-lamp electronic dimming ballast was assumed, considering a 88% ballast factor at full lighting output and 66 input watts.

Three electric lighting control methods were considered.

1. 1% minimum light output at a minimum 15% of a full ballast input power
2. 10% minimum light output at a minimum 21 % of a full ballast input power
3. 4-step switching (100%, 50%, 25% and 0% of light output and input power)

First, for 1% dimming method, the light level can be dimmed to 1% of total light output, where a minimum of 15% of full ballast input power was consumed. The change in lighting power consumption associated with the change in illuminance was assumed to be linear according to Eq. (2). Second, for 10% dimming method, the minimum 10% light output was attained at a minimum of 21% of the full ballast input power, and the light output above 10% followed a linear fashion according to Eq. (3). If a daylight light level exceeded the target level, the luminaires were completely turned off both for 10% and 1% dimming strategies. Thirdly, 4-step switching works such that if the required electric light is zero, below 125 lux, between 125 lux and 250 lux, and between 250 lux and 500 lux, the electric lighting power consumed is 0%, 25%, 50% and 100% of the total input power, respectively.

For 1% dimming control,

If (5 lux<Electric light requirement):

Powr = 0.15×14 W/m^2

Else if (Electric light requirement >= 5 Lux):

Power = $(0.14 + 0.0017 \times \text{Electric light requirement}) \times 14$ W/m^2 (2)

For 10% dimming control,

If (Electric light requirement <50 lux):

Power =0.21×14 W/m^2

Else if (Electric light requirement > 50 lux);

Power = $(1.0 - (500- \text{Electric light requirement}) \times 0.00176) \times 14$ W/m^2 (3)

The required lighting power density to achieve illuminance levels of 500 lux, without any daylight contribution on the work plane, was 14 W/m^2 (1.3 W/ft^2). Lighting power density for non-occupied hours (from 7 P.M. to 8 A.M. of the next day) was set at zero. The space was assumed to be occupied seven days per week. In this way, results of daylight simulation with RADIANCE have been translated into a yearly (8760 hours) schedule describing the hourly profile of power used for the electric lighting system and used for the input to DOE 2.1E.

2.6.2. Thermal simulation: DOE 2.1E

DOE 2.1E (DOE 2) (James J. Hirsch and Associates 1998) was used to compute hour-by-hour building cooling and heating loads. Input to the program consists of geometric, material, and equipment information for the building/space being analyzed, hourly schedules of occupants, equipments, lighting, and set point temperatures.

DOE 2 cannot model solar gain passing through one space into another, for example through a toplight in a roof above a plenum to an interior space (James J. Hirsch and Associates 2004). To overcome this problem, toplights in the roof above the plenum were positioned in a dummy roof with a negligible heat transfer rate located at the actual roof height, and loads transmitted through the glazing were thus assigned to the interior zone. The dummy roof U-value was 0.003 W/m^2 (0.001 Btu/hr-ft^2) in order to eliminate the heat conduction effect.

To isolate the energy effect of the toplight, walls and the floor enclosing the space were assumed to be adiabatic surfaces in DOE 2. Therefore, the major external sources of heat gain for the space were from solar radiation through the toplight glazing and conduction through the roof. Electric lighting power consumption is a major component of internal heat gain in the space because 100% of heat generated by the electric lighting was assigned to the space.

U-values for roof construction, efficiency of heating system, and number of occupants comply with requirements or default in ANSI/AHSRAE/IES Standard 90.1-2001(ASHRAE. 2001). Cooling and heating design temperatures are maintained at 24˚C (76˚F) and 21˚C (70˚F), respectively, with fans operating continuously. The window shading coefficient method was used to specify the solar and thermal properties of the glazings since this method is ideal for conceptual design (James J. Hirsch and Associates. 2004). The infiltration air change ratio for the conditioned zone was zero because the conditioned zone is pressurized and, therefore the flow of air across the conditioned zone and unconditioned zone (the plenum space) is negligible. Air flow rate and coil size were determined automatically by DOE 2. A sizing factor of 1.15 or higher for satisfying total cooling loads was applied. Table 9 shows DOE 2 simulation assumptions for this study and reference sources.

Table 9 DOE 2.1-E Operating Assumptions

Model Parameter		Value	Reference Document
Shape		Rectangular, 15mx15m (50ftx50ft)	
Conditioned floor area		232 m^2 (2500 ft^2)	
Interior ceiling area		Varies from 73m^2(789 ft^2) to 215m^2 (2315 ft^2)	
Exterior roof construction		U-value (W/m^2•K)=0.16; Built-Up Roof 3/8in Polystyrene 6in R-5/in, Plywd 5/8in, Roof Cons Mat 4 (R=2.8)	ANSI/ASHRAE/IESNA Standard 90.1-2001, Table 5.3 - Building Envelope Requirements
Roof absorptivity and roughness		0.6 / 1(built-up roof with stones)	
Interior ceiling construction		U-value (W/m^2•K)= 2.16; Acoustic tiles	
Infiltration rate	Plenum Zone	AIR-CHANGES/HR = 0.3	http://www.energyusernews.com/CDA/Article_Information/Fundamentals_Item/0,2637,15033,00.html
No. of people		7 People /93 m^2(1000ft^2)	
Equipment power density		6.9 W/m^2(0.64 W/ ft^2)	ASHRAE Fundamentals 2001 Ch.29 Table 11
Lighting power density		14 W/m^2(1.3 W/ ft^2)	ANSI/ASHRAE/IESNA Standard 90.1-2001: Table 9.3.1.2
Outdoor air		OA-FLOW/PER = 20	ANSI/ASHRAE Standard 62-2001 Table 2.
HVAC system		Packaged Single Zone	
Heat source		Gas boiler (HIR = 1.25)	ANSI/ASHRAE/IESNA Standard 90.1-2001, Table 6.2.1F
Return system type		Plenum	
Sizing options		Automatic sizing	
Sizing ratio		1.15 or higher number	
Minimum supply air temperature		55 F	

Maximum supply air temperature	105 F	
Economizer low limit temperature	75 F (for Phoenix, Seattle) 70 F (for Minneapolis) 65 F (for Philadelphia, Houston)	ANSI/ASHRAE/IESNA Standard 90.1-2001, Table 6.3.1.1.3A and 6.3.1.1.3B
Economizer Lockout	No	
OA- control	Temperature	

3. Results

3.1. Lighting Energy Reductions with Daylighting Controls

Electric lighting energy consumption of 56.8 Kwh/m^2·yr (18 Mbtu/ft^2·yr) is the same for all five locations in the base case for an installed lighting power of 14 W/m^2 (1.3 W/ft^2). The general electric lighting energy savings compared to the base case are very substantial for all locations and vary between 57% and 88%. Seattle has lower lighting energy savings because of extensive overcast periods while Phoenix has the highest lighting energy savings.

Table 10 shows daylight saturation rates, the percentage of working hours that exceed the target illuminance. From the perspective of reducing electric lighting requirements, daylight saturation represents the point when maximum electric lighting savings occur and additional daylight will result in no additional electric lighting savings (Design Guidelines 1998). As shown in table 10, daylight saturation can be achieved with horizontal skylights between 56 % and 75 % of total working hours. For south-facing vertical and tilted roof monitors, between 68.5 % and 92 % of total working hours have no need for electric lighting to supplement daylight level. It is likely that the south-facing roof monitors will have a high risk of excessive solar heat gain introduction and visual discomfort because the minimum daylight level would be 2000 lux or higher more than 20% of the working year. It is expected that an illuminance level of 2000 lux will cause occupants to take actions to reduce the light level (Azza 2002). Therefore, under some conditions, toplighting design based on the 2% daylight factor provides too much daylight. Smaller glazing areas are necessary to optimize energy savings and visual comfort. However, how small these windows need to be to optimize performance requires further investigation..

Table 10 Percentage of daylight availability for five different toplighting strategies

Toplighting +glazing	Minimum Illuminance Range	Houston	Minneapolis	Philadelphia	Seattle	Phoenix
HD1	Emin<500 lux	24.8 %	29.5 %	31.3 %	43.7 %	14.9 %
	500 lux<Emin<2000 lux	75.0 %	69.7 %	68.3 %	56.3 %	77.3 %
	Emin>2000 lux	0.3 %	0.8 %	0.4 %	0.0 %	7.8 %

TD1	Emin<500 lux	17.5 %	18.4 %	21.5 %	31.5 %	8.0 %
	500 lux<Emin<2000 lux	65.4 %	53.4 %	56.6 %	48.1 %	51.3 %
	Emin>2000 lux	17.1 %	28.3 %	21.9 %	20.4 %	40.7 %
VD1	Emin<500 lux	17.1 %	16.0 %	20.0 %	27.9 %	13.2 %
	500 lux<Emin<2000 lux	62.2 %	48.0 %	56.3 %	47.8 %	49.6 %
	Emin>2000 lux	20.6 %	36.0 %	23.7 %	24.4 %	37.2 %
TC1	Emin<500 lux	46.9 %	62.4 %	60.6 %	58.7 %	70.7 %
	500 lux<Emin<2000 lux	53.1 %	37.6 %	39.4 %	41.3 %	29.3 %
	Emin>2000 lux	0.0 %	0.0 %	0.0 %	0.0 %	0.0 %
VC1	Emin<500 lux	24.1 %	62.7 %	63.0 %	58.6 %	66.7 %
	500 lux<Emin<2000 lux	75.9 %	37.1 %	37.0 %	41.4 %	33.3 %
	Emin>2000 lux	0.0 %	0.1 %	0.0 %	0.0 %	0.0 %

3.2. The Effect of Lighting Control Scenarios on Electric Lighting Energy Consumption

Among the three different daylight control scenarios, 1% minimum light level dimming control with off–control below 1% dimming saves the most. 10% dimming control performs worst because of the highest standby load of 21% of electric power at the lowest dimming level. 4-light level switching provides comparable electric lighting saving as 1% dimming control. Additionally, it has an advantage that lighting energy consumption is higher in winter when lighting heat generation is beneficial for reducing heating energy, and lighting energy demands are lower in summer when lighting heat is unfavorable to cooling energy (increase cooling load). The maximum and minimum annual lighting energy savings due to variation of toplighting strategy and lighting control method for five climate locations vary between 8% and 20% for Houston, 12% to 27% for Minneapolis, 9% to 18% for Seattle, 11% to 26% for Philadelphia, and 13% to 31% for Phoenix.

3.3. The Effect of Toplighting Strategy on Electric Lighting Energy Consumption

Lighting energy savings show little variation for the same type of toplighting strategy when the glazing type is varied. They also show little variation in relation to the orientation of roof monitors since glazings were sized to provide a 2% daylight factor.

South-facing roof monitors consume the least electric lighting energy because they receive maximum daylight enough for electric light to be dimmed for most of a year. As shown in table11, horizontal skylights, both with vertical and splayed wells, consume more electric lighting energy than south-facing roof monitors by 1–8 percentage points, but less energy than north-facing roof monitors by 5–22 percentage points. North-facing roof monitors only receive daylight from the darker north sky, as well as reflected roof light and require the highest electric lighting loads.

Horizontal skylights produce high illuminance levels in summer and lower illuminance levels in winter. For vertical and tilted roof monitors, lighting energy consumption increases in summer months compared to horizontal skylights because relatively less daylight enters vertical/tilted toplight glazings at grazing angles of solar incidence. In winter months, abundant daylight enters the south-facing tilted and vertical glazing system enabling electric lighting energy to be decreased in comparison to horizontal skylights, because they take advantages of low winter sun angles. The monthly lighting energy use for vertical and tilted roof monitors with sunlight diffuse baffles is very constant throughout the year.

3.4. The Effect of Toplighting Strategy and Climate on Cooling and Heating Energy Consumption

Table 11 shows the annual space lighting, cooling and heating loads and site energy consumption for lighting, cooling, and heating equipments. In this study, internal equipment power density is relatively low. As a result, cooling load is low and heating load is high. If a higher equipment power density was used, a higher cooling load would be expected. Space loads are converted to site energy using Eq (4). For heating equipment, the gas boiler has an annual average efficiency ranging from 56% to 67% for the five locations based on a nominal efficiency of 80%. The annual average COP of the cooling equipment, excluding electric energy use for the air distribution fan, ranges from 2.8 to 3.4 based on a nominal COP of 3.65.

$$E_{annual,total} = E_{lighting} + \frac{E_{heating}}{\eta_{boiler,annual}} + \frac{E_{cooling}}{COP_{chiller,annual}} \quad (4)$$

Where, $E_{\text{annual, total}}$ = Annual total space loads

E_{lighting} = Annual total space lighting loads

E_{heating} = Annual total space heating loads

E_{cooling} = Annual total space cooling loads

$\eta_{boiler,annual}$ =Annual efficiency of the gas boiler

$COP_{\text{chiller, annual}}$ = Annual COP of the chiller

Annual cooling and heating loads increase relative to the base case for most combinations of toplighting strategies and glazings for the five different locations studied. For heating dominated climates, north-facing tilted roof monitors provide a reduction in cooling energy use compared to the base case, but saving effects are minimal considering the low cooling energy contributions to the total energy consumption. Similarly, the reduction in heating energy use for cooling dominated climates plays little role in changing total energy use.

Vertical roof monitors facing south with diffuse glazing type 2 (VD2) performs best in lowering lighting energy use, but significantly increases cooling and heating energy use. The lighting energy savings can lower cooling energy consumption only when the glazing exhibits low solar heat gain

South-facing vertical and titled roof monitors with sunlight diffusing baffles and clear glazing involve large glazing areas (a glazing area equal to 32% of the total floor area) to meet the 2% daylight factor requirement. Solar radiation entering through the glazing area lowers annual heating energy consumption. However, interior baffles provide for low daylight delivery efficiency while allowing high solar loads to enter the space during the cooling periods. This results in three times the cooling load than south-facing roof monitors using diffuse glazings without baffles, which apply much smaller glazing areas.

For Minneapolis and Seattle, the maximum increase in heating loads occurs in horizontal skylights using diffuse glazing type 5. This glazing type has the lowest shading coefficient among the six diffuse glazings and a modest U-value, but low visible daylight transmittance. The large glazing area conducts heat to the exterior. The minimum heating load increase occurs in horizontal skylights using diffuse glazing type 6, which has a very high thermal resistance and avoids heat loss caused by temperature difference between exterior and interior space, but it has a low visible transmittance and requires a large glazing area.

For Phoenix and Houston, the minimum increase or largest reduction in cooling energy use occurs in horizontal skylights with splayed welsl and diffuse glazing type 1(SHD1). It has the smallest glazing area and a low shading coefficient. Therefore, SHD1 admits comparatively less solar heat than other toplighting types.

For Seattle, the maximum cooling load reduction is 27% for vertical roof monitors facing north with clear glazing type 2 compared to the base case. This cooling load reduction can be explained by substantial economizer operation because of a low average outside temperature and a low U-value.

Table 11 Annual space load and HVAC system energy consumption in MWH
(C*: Cooling, H*: Heating, L*: Lighting)

Climates	Houston						Minneapolis						Seattle						Philadelphia						Phoenix					
	Space loads			Equip loads			Space loads			Equip loads			Space loads			Equip loads			Space loads			Equip loads			Space loads			Equip loads		
	C*	H*	L*	C	H	L	C	H	L	C	H	L	C	H	L	C	H	L	C	H	L	C	H	L	C	H	L	C	H	L
BASE	29.6	2.3	13.2	9.1	4.3	13.2	6.5	15.7	13.2	1.9	25.3	13.2	2.4	6.7	13.2	0.6	11.7	13.2	13.3	8.6	13.2	3.9	14.3	13.2	23.6	1.7	13.2	8.1	3.2	13.2
HD1	28.0	3.6	2.9	9.1	6.1	2.9	6.8	23.0	3.5	2.1	34.6	3.5	2.6	10.0	4.5	0.6	16.1	4.5	12.9	12.7	3.2	3.9	19.8	3.2	24.8	3.0	2.0	8.7	5.1	2.0
HD2	43.4	3.1	2.8	14.0	5.7	2.8	12.0	21.8	3.5	3.6	34.1	3.5	5.1	9.3	4.4	1.5	16.1	4.4	22.0	11.5	3.2	6.8	19.0	3.2	40.0	2.5	2.0	14.3	4.8	2.0
HD3	38.2	4.8	2.8	12.4	8.3	2.8	9.9	29.5	3.6	3.1	44.4	3.6	4.1	13.8	4.4	1.2	23.6	4.4	18.6	16.3	3.2	5.7	25.6	3.2	35.9	4.3	2.0	13.0	7.4	2.0
HD4	35.0	3.7	2.8	11.3	6.4	2.8	9.0	24.1	3.5	2.7	36.6	3.5	3.7	10.7	4.4	1.0	17.5	4.4	16.9	13.1	3.2	5.2	20.8	3.2	31.6	3.2	2.0	11.2	5.6	2.0

HD5	37.0	5.5	2.7	12.1	9.3	2.7	9.4	32.9	3.4	2.9	48.9	3.4	3.9	15.8	4.3	1.1	25.1	4.3	17.8	18.3	3.1	5.4	28.4	3.1	35.0	5.2	1.9	12.7	8.7	1.9
HD6	29.9	3.0	2.7	9.6	5.3	2.7	7.5	20.4	3.4	2.2	30.9	3.4	4.1	7.5	4.3	1.2	12.7	4.3	14.1	11.1	3.1	4.3	17.4	3.1	26.2	2.4	1.9	9.3	4.3	1.9
SHD1	27.7	3.8	2.9	8.8	6.3	2.9	6.7	23.3	3.7	2.0	35.0	3.7	2.4	10.1	4.5	0.6	16.5	4.5	12.6	13.1	3.4	3.8	20.3	3.4	24.2	3.1	2.1	8.6	5.2	2.1
SHD2	43.4	3.3	2.8	14.0	6.1	2.8	11.9	22.4	3.6	3.6	35.0	3.6	5.1	9.8	4.4	1.5	16.7	4.4	22.0	12.0	3.3	6.8	19.8	3.3	39.7	2.8	2.0	14.2	5.2	2.0
SHD3	37.6	5.0	3.0	12.1	8.6	3.0	9.7	29.6	3.8	2.9	44.4	3.8	4.0	14.0	4.5	1.1	22.5	4.5	18.2	16.5	3.4	5.6	25.9	3.4	35.1	4.4	2.1	12.5	7.5	2.1
SHD4	34.5	3.9	3.0	11.2	6.7	3.0	8.8	24.4	3.8	2.7	37.0	3.8	3.6	11.0	4.5	1.0	17.9	4.5	16.6	13.4	3.4	5.1	21.2	3.4	31.0	3.4	2.1	10.9	5.8	2.1
SHD5	35.9	5.9	2.9	11.8	9.8	2.9	9.3	32.7	3.7	2.9	48.5	3.7	3.9	16.1	4.4	1.1	25.3	4.4	17.6	18.3	3.4	5.3	28.3	3.4	34.4	5.3	2.1	12.4	8.9	2.1
SHD6	29.6	3.2	2.9	9.5	5.5	2.9	7.4	20.5	3.7	2.2	30.9	3.7	4.6	7.6	4.4	1.3	13.0	4.4	14.0	11.2	3.4	4.2	17.6	3.4	25.7	2.6	2.1	9.1	4.5	2.1
VC1	38.3	4.4	2.7	12.3	7.3	2.7	9.2	24.6	5.3	2.8	36.4	5.3	3.3	10.6	5.2	1.0	16.6	5.2	17.5	13.6	4.8	5.2	20.8	4.8	32.7	3.3	4.6	11.7	5.4	4.6
VC2	28.9	4.6	2.7	9.1	7.4	2.7	6.7	25.0	5.2	2.0	36.5	5.2	1.7	10.6	5.2	0.5	16.8	5.2	12.9	14.0	4.6	4.0	21.2	4.6	25.6	3.3	4.8	8.9	5.4	4.8
VC3	31.1	6.3	2.8	10.0	10.0	2.8	7.2	30.5	5.2	2.1	45.1	5.2	2.5	14.3	5.2	0.7	21.6	5.2	13.6	18.1	4.5	4.2	27.0	4.5	28.4	4.6	4.8	10.1	7.3	4.8
VC4	31.5	5.7	2.9	10.1	9.0	2.9	6.9	29.6	5.0	2.1	42.7	5.0	2.7	14.0	5.5	0.7	21.2	5.5	13.9	16.6	4.5	4.2	24.8	4.5	27.6	4.1	3.7	9.7	6.6	3.7
VC5																			12.3	19.9	4.6	3.8	29.2	4.6	27.6	4.8	5.6	9.8	7.8	5.6
VBC1	71.9	2.4	2.7	23.1	5.5	2.7																								
VD1	37.1	4.2	2.4	11.8	7.4	2.4	8.5	24.2	2.8	2.6	36.9	2.8	3.2	11.5	3.5	0.8	19.4	3.5	15.7	13.8	2.5	4.8	21.7	2.5	34.7	3.1	1.8	12.2	5.6	1.8
VD2	56.2	4.0	2.3	18.1	8.1	2.3													27.1	13.7	2.9	8.3	23.3	2.9	56.1	2.4	1.9	19.6	5.6	1.9
VD3																			20.6	24.8	2.9	6.3	38.5	2.9						
TC1	41.8	3.3	3.8	13.5	6.0	3.8	8.5	24.1	5.2	2.5	35.7	5.2	2.7	10.2	5.2	0.6	16.1	5.2	57.9	13.0	4.7	5.2	20.1	4.7	32.3	3.0	4.9	11.7	5.2	4.9
TC2	31.4	3.6	3.8	10.2	6.2	3.8	6.5	23.7	5.5	1.9	35.5	5.5	1.8	10.4	5.2	0.4	16.3	5.2	42.7	13.3	4.7	3.7	20.4	4.7	25.8	3.1	5.1	9.3	5.3	5.1
TC3	33.4	4.8	3.9	11.0	8.2	3.9	6.4	30.0	5.2	2.0	43.3	5.2	1.8	13.3	5.3	0.5	20.2	5.3	43.8	17.0	4.7	3.8	25.2	4.7	28.0	4.2	5.2	10.1	6.9	5.2
TC4	35.2	4.0	4.2	11.5	7.0	4.2	6.7	26.4	5.5	2.0	38.8	5.5	2.3	11.9	5.4	0.6	18.3	5.4	45.9	14.9	5.2	4.1	22.4	5.2	27.1	3.7	4.9	9.6	6.1	4.9
TC5	29.1	4.5	4.5	9.4	7.4	4.5	5.6	30.1	5.7	1.5	43.3	5.7	1.9	13.8	5.5	0.6	20.9	5.5	41.1	16.2	5.3	3.7	24.2	5.3	25.3	4.2	5.2	9.1	6.8	5.2
TD1	34.7	3.5	2.5	10.8	6.1	2.5	9.6	22.1	3.0	3.0	33.9	3.0	2.9	10.3	3.7	0.8	17.1	3.7	54.8	12.3	2.6	4.8	19.6	2.6	32.9	2.9	1.6	11.6	5.1	1.6
TD2	47.4	3.0	2.5	15.1	5.7	2.5							6.3	9.4	3.7	1.9	17.4	3.7	94.0	11.2	2.6	8.2	19.2	2.6	50.6	2.2	1.7	17.6	4.5	1.7
TD3	42.0	5.1	2.5	13.5	8.9	2.5													76.5	18.0	3.3	7.0	28.2	3.3	45.1	4.3	1.7	16.1	7.8	1.7
TD4	38.1	3.6	2.5	11.9	6.5	2.5													67.3	13.0	3.3	6.0	21.0	3.3	38.0	2.8	1.7	13.1	5.3	1.7
TD5	38.0	6.0	2.5	12.0	10.0	2.5																								
TD6	30.1	2.8	2.5	9.5	5.0	2.5																								
TBC1	86.4	1.9	4.4	27.6	4.6	4.4																			93.5	0.8	4.0	32.3	2.7	4.0

3.5. The 2% daylight factor and Cooling and Heating Energy Consumption

For roof monitors, the 2% daylight factor requirement results in more than twice as much glazing area than for horizontal skylights. Excessive glazing provides more available daylight than needed to meet the target illuminance, especially for south-facing roof monitors. The luminous efficacy of daylight is higher than that of electric light, and therefore, the resulting cooling load from the same light output is less for daylight (IESNA 2000). However, if there is more daylight than needed, an unnecessary increase in cooling load is an unavoidable consequence.

For climates with sunny skies, south-facing roof monitors can positively utilize solar heat gain to cut heating requirements during the heating season. However, the large glazing area prevents south-facing monitors from turning winter solar heat gain to reduction in heating load because of the significant increase in thermal losses occurring at the glazing, especially at night.

It is very likely to have cooling and heating load increases for most combinations of toplighting strategies and glazings because less thermally resistive skylights or roof monitors are installed in place for the roof, except for special materials like diffuse glazing type 6. However, what makes toplighting strategies energy efficient, while satisfying the 2% daylight factor, is the substantial reduction in lighting loads, which offset heating and cooling losses.

3.6. Operating Cost for Cooling and Heating Energy Consumption

Table 12 shows the annual operating costs for energy and the cost is calculated using Eq (4) using a fixed commercial cost for natural gas and electricity rates. In reality, actual energy rates are different at different locations, but a single set of energy were used here for comparison. The maximum annual operating cost savings for Houston, Phoenix, Philadelphia, Minneapolis, and Seattle are 41%, 45%, 40%, 33%, and 45%, respectively.

$$Cost_{annaul,total} = (E_{lighting} + \frac{E_{cooling}}{COP_{chiller,annual}}) \times \frac{\$}{kwh} + \frac{E_{heating}}{\eta_{boiler,annual}} \times \frac{\$}{therm} \qquad (4)$$

Where, $Cost_{annual,\ total}$ = Annual energy cost for total energy use

Table 12 Annual costs ($/m^2) for site energy consumption

(Cost assumption: $0.1/kwh of electricity, $0.96/therm of natural gas[1])

	Houston				Minneapolis				Seattle				Philadelphia				Phoenix			
	C	H	L	Total	C	H	L	Total	C	H	L	Total	C	H	L	Total	C	H	L	Total
Base	3.9	0.6	5.7	10.2	0.8	3.6	5.7	10.1	0.3	1.6	5.7	7.6	1.7	2.0	5.7	9.4	3.5	0.5	5.7	9.6
HD1	3.9	0.9	1.2	6.0	0.9	4.9	1.5	7.3	0.3	2.3	1.9	4.5	1.7	2.8	1.4	5.8	3.7	0.7	0.9	5.3
HD2	6.0	0.8	1.2	8.1	1.5	4.8	1.5	7.9	0.6	2.3	1.9	4.8	2.9	2.7	1.4	7.0	6.2	0.7	0.9	7.7
HD3	5.3	1.2	1.2	7.7	1.3	6.3	1.5	9.1	0.5	3.3	1.9	5.7	2.5	3.6	1.4	7.5	5.6	1.0	0.9	7.5

[1] Energy information administration http://tonto.eia.doe.gov/dnav/ng/ng_pri_sum_dcu_nus_m.htm

HD4	4.9	0.9	1.2	7.0	1.2	5.2	1.5	7.8	0.4	2.5	1.9	4.8	2.2	2.9	1.4	6.5	4.8	0.8	0.9	6.5
HD5	5.2	1.3	1.2	7.7	1.2	6.9	1.5	9.6	0.5	3.5	1.9	5.9	2.3	4.0	1.3	7.7	5.5	1.2	0.8	7.5
HD6	4.1	0.7	1.2	6.0	0.9	4.4	1.5	6.8	0.5	1.8	1.9	4.2	1.9	2.4	1.3	5.6	4.0	0.6	0.8	5.4
SHD1	3.8	0.9	1.3	5.9	0.9	4.9	1.6	7.4	0.3	2.3	1.9	4.5	1.6	2.9	1.5	5.9	3.7	0.7	0.9	5.3
SHD2	6.0	0.9	1.2	8.1	1.5	4.9	1.6	8.0	0.6	2.4	1.9	4.9	2.9	2.8	1.4	7.1	6.1	0.7	0.9	7.7
SHD3	5.2	1.2	1.3	7.7	1.2	6.3	1.6	9.1	0.5	3.2	1.9	5.6	2.4	3.7	1.5	7.5	5.4	1.1	0.9	7.3
SHD4	4.8	0.9	1.3	7.0	1.2	5.2	1.6	8.0	0.4	2.5	1.9	4.9	2.2	3.0	1.5	6.6	4.7	0.8	0.9	6.4
SHD5	5.1	1.4	1.3	7.7	1.2	6.8	1.6	9.7	0.5	3.6	1.9	5.9	2.3	4.0	1.5	7.7	5.3	1.3	0.9	7.5
SHD6	4.1	0.8	1.3	6.1	0.9	4.4	1.6	6.9	0.6	1.8	1.9	4.3	1.8	2.5	1.5	5.7	3.9	0.6	0.9	5.4
VC1	5.3	1.0	1.1	7.5	1.2	5.1	2.3	8.6	0.4	2.3	2.2	5.0	2.2	2.9	2.1	7.2	5.0	0.8	2.0	7.8
VC2	3.9	1.0	1.2	6.1	0.9	5.2	2.3	8.3	0.2	2.4	2.2	4.8	1.7	3.0	2.0	6.7	3.8	0.8	2.1	6.7
VC3	4.3	1.4	1.2	6.9	0.9	6.4	2.2	9.5	0.3	3.0	2.2	5.6	1.8	3.8	1.9	7.5	4.3	1.0	2.1	7.4
VC4	4.3	1.3	1.3	6.9	0.9	6.0	2.1	9.1	0.3	3.0	2.3	5.6	1.8	3.5	1.9	7.2	4.2	0.9	1.6	6.7
VC5													1.6	4.1	2.0	7.71	4.2	1.1	2.4	7.7
VBC1	9.9	0.8	1.1	11.9																
VD1	5.1	1.0	1.0	7.1	1.1	5.2	1.2	7.5	0.3	2.7	1.5	4.6	2.1	3.1	2.0	7.1	5.3	0.8	0.8	6.8
VD2	7.8	1.1	1.0	9.9									3.6	3.3	1.1	7.9	8.4	0.8	0.8	10.0
VD3													2.7	5.4	1.3	9.4				
TC1	5.8	0.8	1.6	8.3	1.1	5.0	2.2	8.3	0.3	2.3	2.2	4.8	2.2	2.8	1.2	6.3	5.0	0.7	2.1	7.9
TC2	4.4	0.9	1.7	6.9	0.8	5.0	2.3	8.2	0.2	2.3	2.3	4.7	1.6	2.9	2.0	6.5	4.0	0.7	2.2	6.9
TC3	4.7	1.2	1.7	7.6	0.9	5.0	2.2	8.1	0.2	2.8	2.3	5.3	1.6	3.6	2.0	7.2	4.3	1.0	2.2	7.6
TC4	4.9	1.0	1.8	7.7	0.9	6.1	2.4	9.3	0.3	2.6	2.3	5.2	1.8	3.2	2.0	7.0	4.1	0.9	2.1	7.1
TC5	4.0	1.0	2.0	7.0	0.6	5.5	2.4	8.5	0.3	2.9	2.4	5.6	1.6	3.4	2.2	7.2	3.9	1.0	2.3	7.1
TD1	4.6	0.9	1.1	6.6	1.3	6.1	1.3	8.7	0.3	2.4	1.6	4.3	2.1	2.8	2.3	7.1	5.0	0.7	0.7	6.4
TD2	6.5	0.8	1.1	8.4					0.8	2.4	1.6	4.9	3.5	2.7	1.1	7.4	7.6	0.6	0.7	8.9
TD3	5.8	1.3	1.1	8.2									3.0	4.0	1.1	8.1	6.9	1.1	0.7	8.8
TD4	5.1	0.9	1.1	7.1									2.6	3.0	1.4	7.0	5.6	0.7	0.7	7.1
TD5	5.2	1.4	1.1	7.7																
TD6	4.1	0.7	1.1	5.9																
TBC1	11.9	0.6	1.9	14.4													13.9	0.4	1.7	16.0

4. Conclusion

This study has involved an analysis of the following issues regarding the performance of toplighting strategies.

1. The required glazing area for each type of toplighting strategy to meet the 2% daylight factor

provision of LEED.

2. The effects of these toplighting strategies on electric lighting energy reduction associated with lighting control method and electric building energy consumption.
3. The impacts of climatic conditions on the performance of different toplighting strategies.
4. The effects of a variety of glazings with different thermal and illumination characteristics on building energy consumption.

This detailed study on the energy performance of a variety of toplighting strategies included using both an accurate lighting simulation tool and a building energy simulation tool to determine the impacts on lighting and building energy consumption across a number of lighting control methods. Among the selected toplighting strategies and glazings, horizontal skylights and diffuse glazing type 1 perform best for all five locations.

The following general conclusions are made from the data gathered in this study.

1. Determining toplight glazing area based on the 2% daylight factor requirement is not reasonable because it can oversize the glazing area and introduce additional solar heat gain and thermal losses. The determination of glazing size must be approached from a total energy point of view. For that reason, detailed simulations of hourly and yearly electric lighting energy use and cooling and heating energy demands must be conducted.
2. Estimating the extra costs of adopting toplighting strategies is very difficult. In general it costs more to have larger aperture (glazing) areas and smaller opaque roof areas. The large glazing size requirement to meet the 2% daylight factor causes high initial cost for glazings. This high cost is difficult to justify by the reduction in total energy consumption. The cost may be optimized at smaller glazing area/daylight factor.
3. Exterior illuminance ratios can be used to select a pre-calculated daylight condition that has similar calculated illuminance values. This method permits whole year hour-by-hour daylight simulation without taking excessive calculation time and computation power.
4. A toplighted building can have reduced total building energy use, but only if electric lighting controls exist. Without lighting controls, however, building cooling and heating energy consumption would be higher than with a completely opaque roof.
5. Horizontal skylights are better in reducing total building energy than roof monitors when glazing area is designed to satisfy a 2% daylight factor. Energy performance of vertical/tilted glazing may be optimized at lower daylight factor design conditions.
6. Lighting control has more impact in cooling dominant climates because lighting energy saving leads to a further reduction in cooling energy
7. The total energy performance of toplighting strategies is very sensitive to weather. For heating

dominant locations, such as Seattle and Minneapolis, toplighting strategies that allow the least amount of heating load increase are the best performers. For cooling dominant locations, such as Phoenix and Houston, toplighting strategies that reduce cooling loads or allow the least amount of cooling load increase perform best.

8. With regards to glazing selection, for heating dominant locations, the majority of heat loss occurs by conduction, and therefore it is very important to use glazings with low U-value. For cooling dominant locations, solar radiation should be prevented from entering an indoor space by using glazings with low shading coefficients. For moderate climates, low shading coefficients and low U-values are required in order to reduce the thermal energy losses of glazings. In addition to the energy conscious selection of glazing, sizing the aperture properly is also important so that daylight can be best used to displace electric lighting energy consumption without significant heat loss or gain to offset the lighting load savings.

To summarize the above results, horizontal skylights provide a reduction in total building energy if glazings with desirable thermal performances suitable for climate locations and high visible daylight transmittances, such as diffuse glazing type 1, are selected. It is not that horizontal skylights perform the best regardless of climatic conditions, but it is more likely that they require the least glazing area to achieve a 2% daylight factor and therefore, provide the lowest heat losses and gains among eight different toplighting strategies selected for this study. It should be noted that the next version of LEED is likely to have a clear sky illuminance value in addition to the daylight factor requirement, which will provide the daylight credit at smaller glazing areas.

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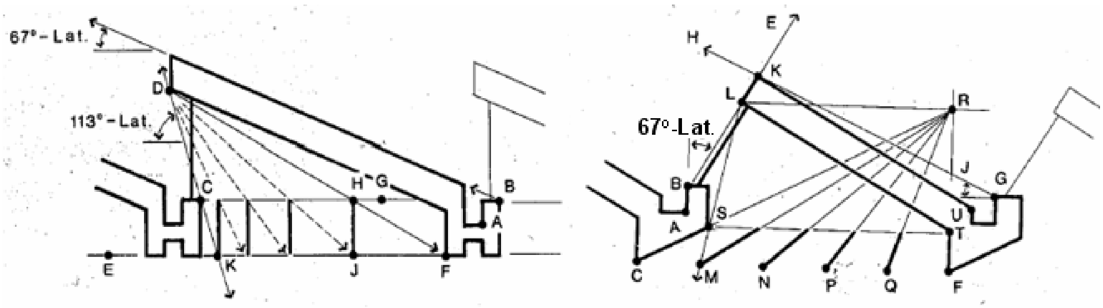
Appendix 1



(a) Roof monitor with vertical glazing (b) Roof monitor with sloped glazing

Figure A-1. Design geometry for roof monitors

Appendix 2

An opening at the middle of the ceiling that transfers daylight entering from a toplight unit to the interior space was modeled as imaginary light source surfaces using mkillum in the Radiance. Then, the resulting illum data were copied to the remaining toplight units because the surroundings, including sky and adjacent roof areas seen by the toplight opening are almost identical for each toplighting unit.

The general simulation parameters applied in the Radiance analyses are as follows:

mkillum -ab 4 -ad 1024 -as 512 -ar 2000

rtrace -h -w -I -ds 0.1