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Energy Analysis of Toplighting Strategies for Office Buildings in Austin

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Energy Analysis of Toplighting Strategies for Office Buildings in Austin

by

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Thesis

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Dedication

I dedicate this thesis to my husband, Ehsan, for his faithful love, support, sacrifice and patience throughout these past years. I am thankful to him for believing in me and encouraging me to achieve my dreams. I also want to thank my family here for all their supports, and prayers.

Acknowledgements

It is a pleasure to thank the many people who made this research possible. I am so grateful to Prof. Moore who manages the M.S.S.D. program, and gives me the chance to study what I am interested in.

My sincere thanks go to Prof. Novoselac and Prof. Brook from the Civil Department who dedicated their time to provide me guidance and perspectives. Also, I wish to thank Prof. Garrison, my advisor, who believes in me and supports me during my Master study, as well as, my thesis. Finally, I'd like to express my sincere gratitude to Prof. Whitsett who taught me a new perspective toward architecture and sustainability. I am so thankful to him for his motivation, immense knowledge and insightful comments.

Oct 2012

Abstract

Energy Analysis of Toplighting Strategies for Office Buildings in Austin

Sara Motamedi, M.S.S.D.
The University of Texas at Austin, 2012

Supervisor: Michael Garrison

The purpose of this study is to determine the energy impacts of daylighitng through toplights in a hot humid climate. Daylight in the working environment improves the quality of the space, and productivity of employees. In addition, natural light is a free energy resource. On one hand, a proper design of daylight such as distributed toplights can reduce the electrical lighting consumption. On the other hand, in a hot climate like Austin heat gain is a major concern. Therefore, this thesis is shaped around this question: *Can toplighting strategies save energy in Austin despite the fact that buildings receive more direct heat gain through toplights?*

The importance of daylighting is more revealed since electrical lighting takes up a significant portion of the total building energy use (21%). In this thesis I investigated the reduction of lighting electricity and compared that with the total effects of toplights on external conductance, lighting heat gain and solar gain. The results of my thesis show that regarding the site energy a proper toplighting

strategy can save electrical lighting up to (70%) with smaller impact on heating and cooling loads. This means that toplights generally can be energy efficient alternatives for a one storey office building. Developing my research I studied which toplights are more efficient: north sawtooth roofs, south sawtooth roofs, monitor roofs or very simple skylights. I compared different toplighting strategies and provided a design guide containing graphs of site energy, source energy, annual cost saving per square feet, as well as light distribution of each toplight. I believe this can accelerate implementation of efficient toplighting strategies in the design process.

Concluding how significantly efficient daylighting is over heat gain, I finalized my research by comparison of skylights with different visible transmission (VT) and solar heat gain coefficient (SHGC). The major result of this thesis is that proper toplighting strategies can save energy despite the increased solar gain. It is anticipated that the thesis findings will promote the implementation of toplighting strategies and higher VT glass type in the energy efficient building industry.

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Chapter One: Introduction*

1.1. OBJECTIVES: DAYLIGHT

According to the U.S. Energy Information Administration, EIA, lighting consumes (19%) of energy in a commercial building (see figure1). This amount of energy is increased to (22%) for office buildings since electrical lighting is more crucial in office buildings than any other types of commercial buildings. This number is getting even more significant if the cost of source energy or the utility cost is considered, where for one unit of electricity three unites of fuel are burned in power plants (see figure 2). A simple and effective solution for reduction of electrical lighting is to integrate natural light with the design.

For centuries daylight have been the center of architects' attention. The great architect Louis Kahn once said, "A room is not a room without natural light." Natural light gives mood to space

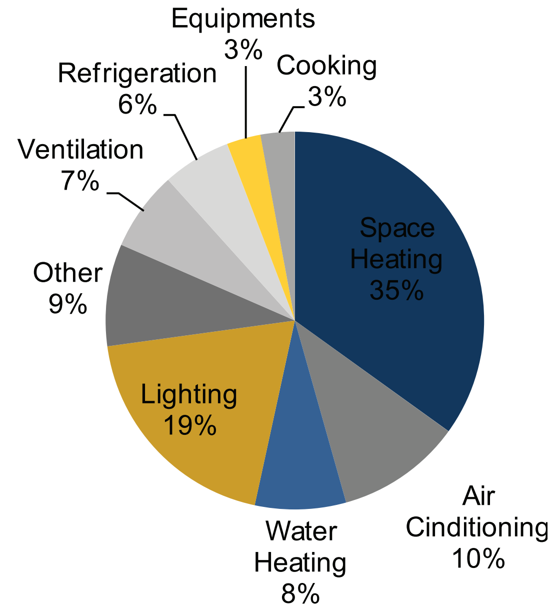

Figure 1: Lighting role in site energy use of commercial buildings in 2003, (U.S. Department of Energy)

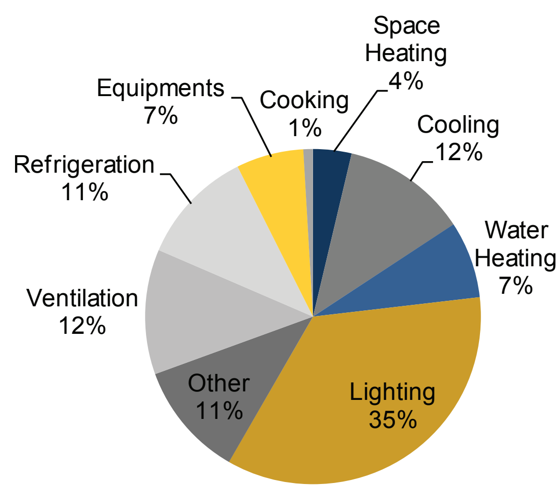

Figure 2: Lighting role in Source energy use of commercial buildings in 2003, (U.S. Department of Energy)

* Part of this thesis was published at World Renewable Energy Forum conference, WREF, Denver, 2012
Motamedi, Sara. Energy Analysis of Different Toplights for Office Buildings in Austin, World, Renewable Energy Forum Conference, 2012

by the nuances of light in the time of the day and the seasons of the year as it enters and modifies the space.” Renzo Piano is another famous architect who always incorporates daylight into his designs. Figure 3 and 4 show one of Piano’s master pieces implementing daylight. It is series of north facing skylights at the extension of The High Museum of Art in Atlanta in 2005. Not only natural light can improve the quality of the life in the space but also the productivity of employees. For example, it is shown that natural light can reduce the Seasonal Affective Disorder (SAD) (Wirz-Justice 1996). Even though many researches have been done for the qualitative benefits of daylight, fewer are aware of the quantitative benefits of daylight. In addition to qualitative benefits of daylight, natural light is considered a free energy resource. As a result, with a proper design, it is possible to reduce electrical lighting consumption. Toplighting (apertures in roofs) and sidelighting (apertures in walls) are

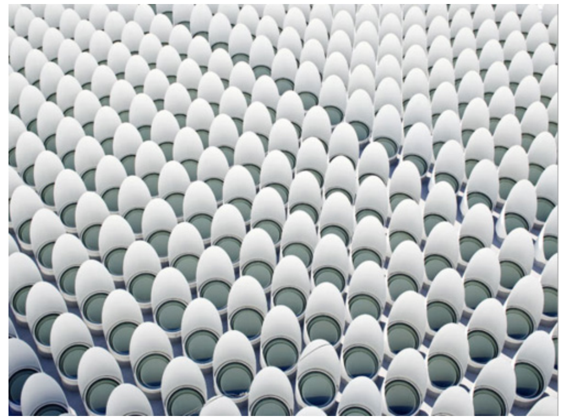

Figure 3: skylights at the extension of The High Museum of Art in Atlanta by Renzo Piano in 2005.

two design strategies to provide daylighting for the space (Boubekri 2008). Lots of research have been done for sidelighting through extensive laboratory experimentations or simulations. However, less research have been conducted about toplights. This is one of my main reasons to choose toplighting strategies as my research question. In addition, toplighting strategies can be an expression of architects and have qualitative benefits. Therefore, as an architect all these benefits motivate me to research about how toplighting strategies can save energy in an office building.

In the following I am going to explain what toplights are and in what condition toplighting is a better design strategy for daylighting.

1.2. TOPLIGHTS

A toplight is any architectural element in a roof that admits natural light to the interior space. Consistent admission of daylight and even daylight distribution are the most important benefits of toplights which provide easy control of glare and easy combination of electric lighting systems. Another advantage of toplights is to provide an opportunity for architectural expressions. In addition, toplight is much more suitable design strategy for deeper spaces, such as big boxes or even big one storey offices. The reason is that big boxes is too deep that daylight from surrounding walls cannot provide enough light for the inner spaces. Despite all these benefits of toplights, there are some unavoidable cautions such as roof leakage, direct solar radiation and heat gain, heat lost and visual disconnection (Lawrence 2008). Regarding the roof leakage today technology is developed enough to prevent that (Lawrence 2008).However, builders may not know how to correctly install toplights. Statistics show that despite the potential of daylighting only approximately (2%) to (5%) of commercial building floor space currently has sufficient skylight area (PG & E 2000). Thus, education among

Figure 4: skylights at the extension of The High Museum of Art in Atlanta by Renzo Piano in 2005.

architects, engineers and builders is the most important step to implement toplights. As a result, the question that I answer in my thesis is that how top-lighting strategies can save energy in an office building. In my thesis I am going to investigate all the energy effects of toplights such as direct solar gain on the buildign loads. Moreover, different types of toplights are studied which are:

- Monitor Roof: A raised section of a roof that has openings, louvers, or windows along the sides to admit light or air (Yoon 2008) (see figure 5).

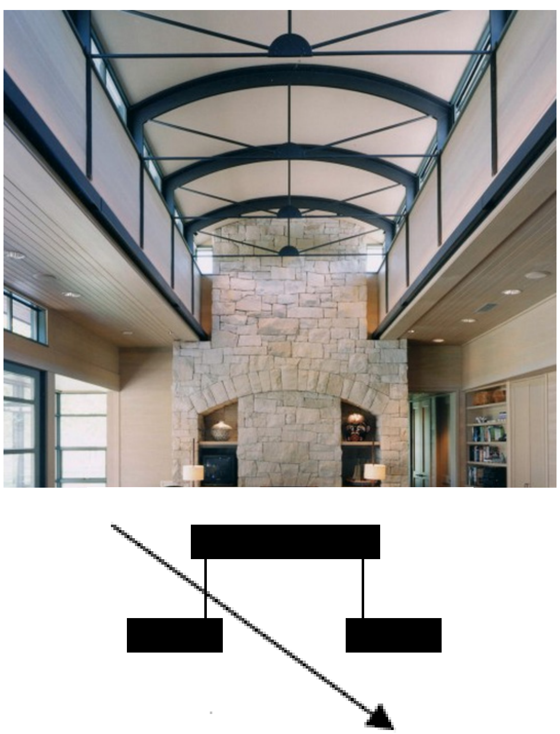

Figure 5: Monitor roofs in a house by Sullivan Conard Architects

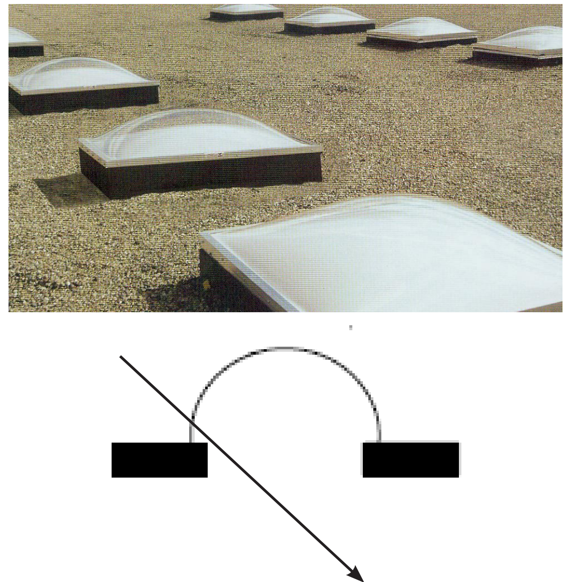

Figure 6: Skylights, C & H Building Specialties Inc.IL

- Skylight: An aperture in a horizontal roof plane which shows in figure 6 (Yoon 2008).
- Sawtooth roof: Vertical roof glass that faces to the same direction to capture light in sawtooth shape (Yoon 2008). Figure 7 illustrates sawtooth roofs.

Although toplights might be energy efficient alternatives, in practice this benefit is often ignored and toplights are mostly considered as an aesthetic element (Lawrence 2008). This is basically due to a common belief that toplights are not able to save energy; and they significantly increase heating and cooling loads. This argument is not necessarily true since the resulted reduction in electrical lighting by toplights hasn't been often considered in previous researches. This lack of consideration is mainly because of the limited capability of software tools which were not able to account for the impact of natural light on the electrical lighting.

In this research I will review the litratures that used advanced modeling software tools to analyze toplights. Then, I will discuss the simulation method and its limitations for litrature reviews and my study. Next, I will compare the efficiency of toplights to side-lighting apertures with different orientations. Then, the base model for the toplighting strategies will be developed based on ASHRAE standards and Austin codes. Skylights will be compared to the base model and all the effects of skylights on the building loads will be analyzed such as external conductance, internal heat gain, solar gain as well as electrical lighting loads. After that, I am going to compare different toplighting strategies for an office building in Austin. Such toplighting strategies include monitor roofs, sawtooth roofs, and skylights. Toplights will be compared based on site energy, source energy, total cost, as well as daylight distribution. As a result of the comparison, an architectural design guide for toplights in Austin will be introduced. Such guidance is the most important

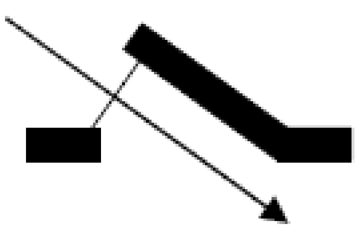

Figure 7: Sawtooth roofs facing to the north, Livestrong, by Lake|flato, 2010

finding of this research. Finally, I will discuss about the importance of Solar Heat Gain Coefficient (SHGC) and Visible Transmission of toplights since these two parameters significantly affect the energy efficiency of the toplights. Another result of this thesis is a 3d graph showing the total cost of building loads for a skylight model with differnet VT and SHGC.

This study will help architects and engineers to implement toplighting strategies in the preliminary stage of design. In addition, this research provides awareness among community that visible transmission is a significant factor in energy efficiency which is usually ignored by standards and professionals in this field.

Chapter Tow: Literature Review

. The qualitative benefits of daylight is the majority of literature body. For example, improvement in student performance and attendance is one of the benefits of natural light in schools. Classrooms with skylights were associated with a 19-20% faster rate of improvement (Boubekri 2008). Research also shows that daylight in a building has a health advantage. For instance, SAD, seasonal Affective Disorder, is a clinically diagnosed condition in which lack of sunlight makes people feel ill (Boubekri 2008). Moreover, natural light can accelerate the healing process in hospitals and increase the productivity of employees (Boubekri 2008).

However, there is not enough quantitative research about the energy analysis of toplights, for instance, how much electericity can be saved and how cooling and heating loads are changed by adding skylights. This gap in the litrature is mainly because of the limited capability of software tools. To consider daylight, software tools have to be able to relate several factors together such as daylight distribution, number of electrical lights, and energy calculations. Tools to account for daylighting and thermal energy demands have been developed recently (Yoon 2008). Most of them were not capable of simulating toplights and were time consuming, complex and inaccurate which makes architects and engineers reluctant to use them.

In 2008 U.S. Department of Energy conducted two reports about the energy efficiency of toplights. Both reports adopted simulation as the method of their research. But they used two different software tools (SkyCalcTM and DOE 2.1 plus Radaince) and each of those tools has their own limitations to expand the research.

In the first report, “Commercial Building Toplighting: Energy Saving Potential and Potential Paths Forward” only skylights were investigated; And the relationship between the cost efficiency and energy savings were addressed. In this thesis number "[1]" always represents this report of U.S. Department of Energy. [1] used SkyCalcTM software to simulate skylights for different building types (offices, schools, warehouses and big boxes) in five cities representing the five ASHRE[1] climate zones in the U.S. (Phoenix, Houston, Chicago, Burlington and Baltimore). The main result of [1] was that skylights can save energy. However, because of the limitation of the software, SkyCalcTM, other types of toplighting strategies were not investigated.

The second report, "How much energy do different toplight strategies save?" discussed energy efficiency of different toplights in several climates (Houston, Phoenix, Seattle, Monopolies and Philadelphia). In this thesis number "[2]" always represents the second report for the U.S. Department of Energy in 2008. [2] coupled a lighting rendering software tool (Radiance) with building energy simulation software (DOE 2.1); This report confirmed that toplights can save energy. However, a problematic assumption in this research was to size the glazing area to meet (2%) daylight factor. The reason to do the research with this basic assumption was because of LEED credit. To get LEED credits in the indoor environmental quality category, (2%) of daylight factor for at least (75%) of occupied spaces has to be achieved. According to [2] comparison of different toplights by (2%) of daylight factor for (75%) of the space is not a reasonable assumption since different toplights introduce natural light to the interior spaces very differently. This report finally concluded that the best strategy is to size the glazing area based on the total energy use.

As a result, in this paper I sized

[1] The American Society of Heating, Refrigerating and Air-Conditioning Engineers

the glazing area based on the total electerical lighting savings. I investigated energy efficiency of different toplights for one storey office buildings in Austin. I analyzed the toplights regarding the heating/cooling loads, as well as lighting savings.

The significance of this research is that, unlike [1], I investigated the energy efficiency of different toplighting strategies such as skylights, monitor roofs, and sawtooth roofs. In contrast with [2], I sized the glazing area based on the electrical lighting savings as well as ASHRAE requirements, e.g. skylight area to floor area (5%). Moreover, Austin is assumed as the location of all the models in this study. City of Austin was not considered in [1] and [2].

Another important point of this research is the extent of details considered in the energy analysis of the toplights. Adding toplights to the roof structure changes heating /cooling loads as well as electrical lighting loads. By distributing daylight evenly in the spaces electrical lighting consumption will decrease. However, other factors directly affecting heating and cooling loads will be changed as well; such as electrical lighting heat gain, solar gain as well as external conductance. Such details were not considered in any of these reports: [1] and [2]. The main direction of this research is to compare the saved electrical lighting versus increased heating or cooling loads. To consider toplighting strategies as energy efficient alternatives, the saved electrical lighting should be bigger than increased heating/cooling loads in Austin.

Proper software for conducting this research should be able to relate the data of daylight distribution to electerical lighting usage and ultimatly to thermal energy demands. In this paper all the simulation were done by Integrated Environmental Solution Software (IES VE PRO).

In the next chapter I will discuss why IES VE PRO is the most appropriate software tool to do the toplighting research.

Chapter Three: Simulation Method

The most powerful tool for daylighting is Radiance which is able to use ray tracing technique. Ray tracing is a computer graphics rendering technique that attempts to simulate the physical behavior of light as closely as possible. It is tracing rays from the virtual camera through several bounces on or through objects. Ray tracing is capable of simulating a wide variety of optical effects, such as reflection and refraction, scattering, and dispersion phenomena (such as chromatic aberration) (Cutler and Durand).

However, this tool is not capable of doing thermal analysis like eQuest and Energy Plus. Energy Plus and eQuest are very recognized tools thermal and energy analysis. But Energy Plus and eQuest are not the most suitable tools for this research as they are currently using Radiosity tool for daylighting analysis. Radiosity is a global illumination algorithm used in 3D computer graphics rendering. Radiosity is an application of the finite element method to solving the rendering equation for scenes with purely diffuse surfaces. Unlike Radiance which handle all types of light paths, typical radiosity methods only account for paths which leave a light source and are reflected

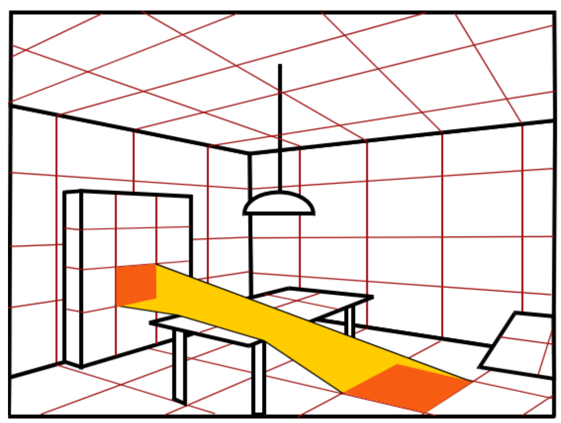

Figure 8:Radiosity (Cutler and Durand, MIT)

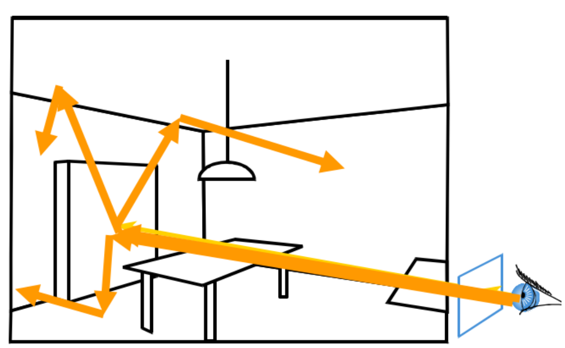

Figure 9:Radiance (Cutler and Durand, MIT)

diffusely some number of times (possibly zero) before hitting the eye (Cutler and Durand). Figure 8 and 9 are diagrams showing the difference between Radiance and Radiosity.

Since the goal of this research is to investigate different toplights with different shapes, bounces of daylight in the space are important. As a result, Radiance or any other software tools adopting Radiance is the best software to use.

IES VE is a software tool that is able to integrate Radiance with energy simulation. Therefore, this software is suitable for toplighting research. IES VE Pro is European software which is also approved by U.S department of energy[2] .

Figure 10 shows the process of energy simulation in IES VE. There are four major engines in this software:

1. ModelIt: This is the geometry engine. The geometry of the model can be shaped in the ModelIt. However, the geometry also can be defined in tools such as Sketchup and Revit and be imported to IES VE. Since the ModelIt is

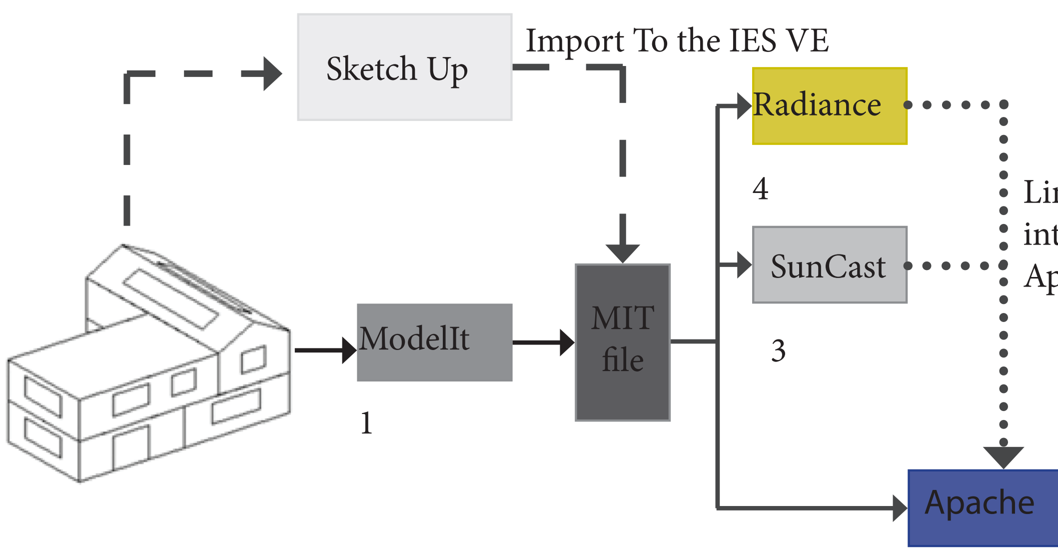

Fig.10: IES VE Simulation Process (IES VE Radiance Guidance)[2]

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[2]http://www.iesve.com/content/downloadasset_2316

not very user friendly, in this research the geometry is shaped in sketchup and imported to the IES VE.

2. Apache: Apache is the energy simulation engine of this software. It simulates the thermal energy flow in the building.

3. Suncast: This engine analyzes the location, solar path, and skin solar gain.

4. Radiance: It is the ray tracing engine of the software which is simulate the daylight pattern in the space.

All the data from Radiance, ModelIt, Suncast is plugged into the Apache system for thermal analysis. According to IES VE website for the Apache calculations within Radiance it performs a set of calculations every hour for one day each month. These calculations are performed on the 15th day of each month (the same day as the default SunCast calculations are performed). Three predetermined sky models are

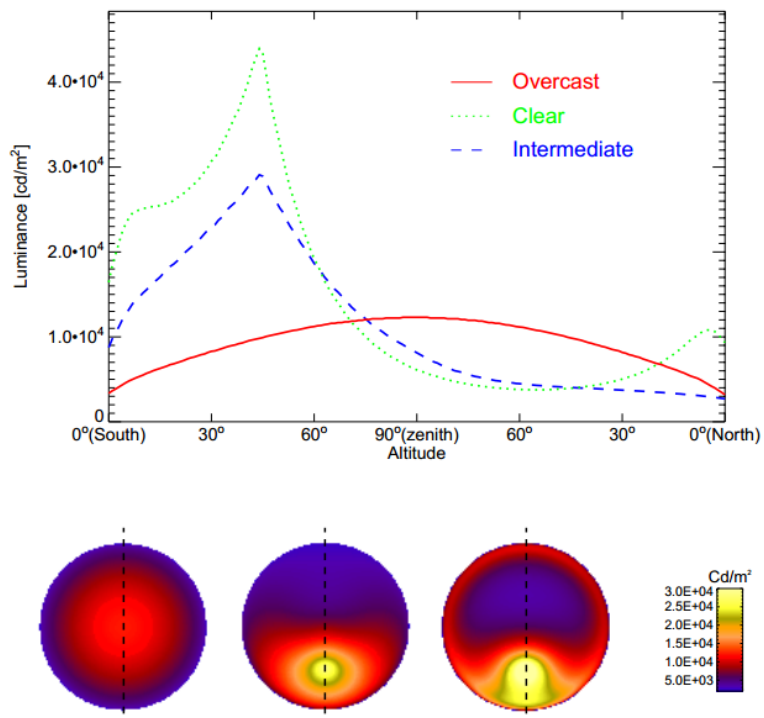


Figure 11: From left to right: Overcast, Intermidiate and Clear Skies, Luminance profile and maps for sky types (Mardaljevic 2000)

used for each time step (See Figures 11, & 12): CIE overcast, clear sky and intermediate sky. When Apache reads in the generated Radiance illuminance file, it then interpolates the 3 figures with the weather data recorded in the climate file to get one illuminance figure. However, the radiance and suncast files have to be linked in Apache calculation. Otherwise, the software will ignore the results from the suncast and radiance simulation.

According to the IES VE website the sky models in this software matched with the Commission International de l'Eclairage (CIE) definitions. CIE has developed a series of mathematical models of ideal luminous distributions under different sky conditions - of which the three most common are CIE, clear and intermediate skies. All these three sky models are shown in figure 11 as well.

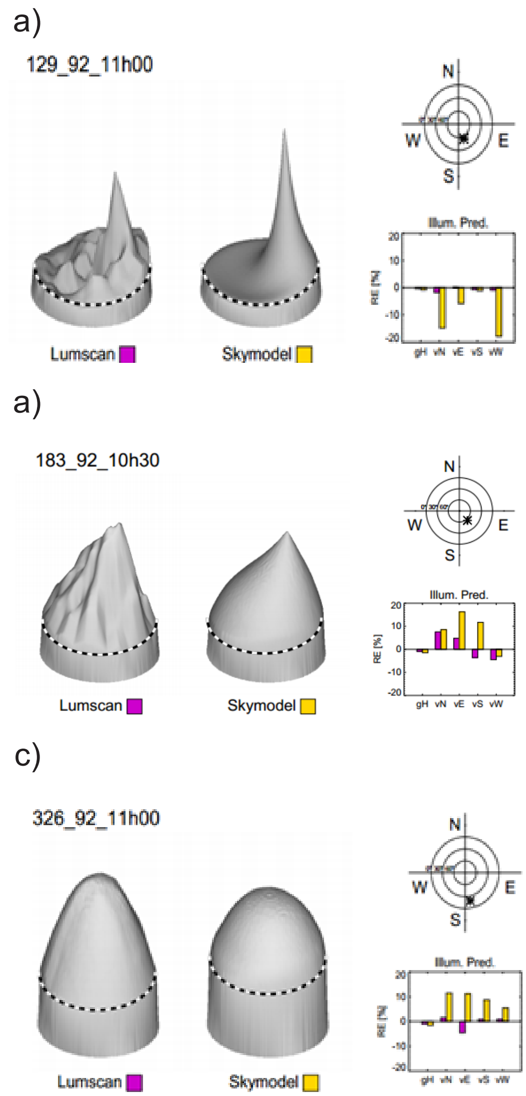


Figure 12: a) Clear sky model b) Intermidiate Sky c) Overcast Sky (Mardaljevic 2000)

- CIE overcast: The Overcast Sky distribution model is based on a completely clouded sky where the Sun and its position are not apparent. The passage of radiation through the clouds usually produces close to white light by mixing as moisture droplets are quite large and affect all frequencies of light.
- Clear Sky : A clear sky assumes

that the Sun is visible, and there is no could. This results in a very non-uniform luminance distribution where the area around the Sun is much brighter than any other area.

- Intermediate Sky: This means partly cloudy. It has between 30 % and 70 % cloud cover. This sky can be combined with sun in some cases.

As a result, for daylight analysis IES VE PRO will read the weather file data and generate appropriate sky model. This results in more accurate electrical lighting usage.

Chapter Four: Daylight and Building Loads

4.1. APERTURE ORIENTATIONS AND ELECTRICAL LIGHTING USAGE

To understand the effect of daylighting through apertures with different orientations, four models were developed: the north window model, south window model, skylight model, as well as no window model These four models are the same regarding the size glazing area, materials and schedule. A graph of electrical lighting usage during a year for each model was provided. This helps to understand the importance of the aperture orientation in electrical lighting. Also by comparison of the four models the best strategy for daylighting regarding energy efficiency will be found. Then, I compare the electric lighting usage of all four models

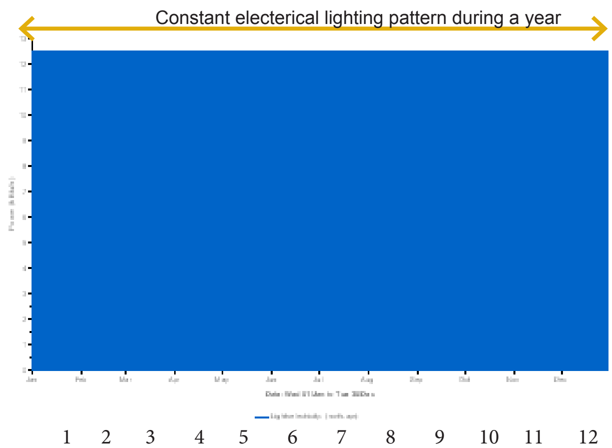
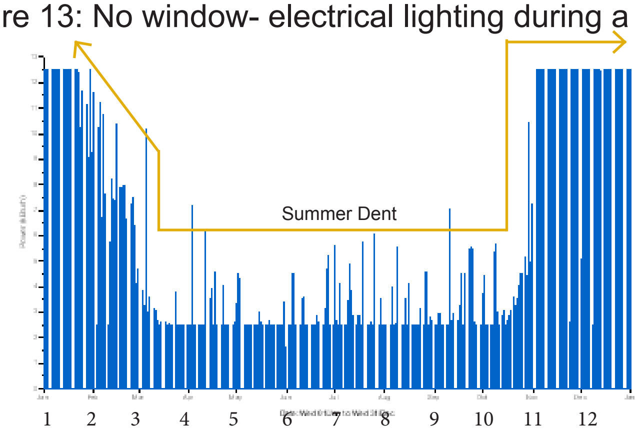


Figure 13: No window- electrical lighting during a year



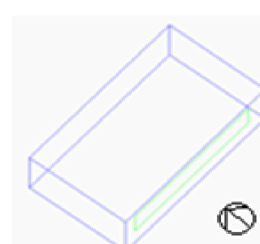


Figure 14: south window- electrical lighting during a year

during a year. This also can provide a better understanding over the aperture orientation and electrical saving.

Figure 13 shows the electrical lighting usage during a year for a base model with no windows. The electrical lighting power is the same amount over the year. Figure 14 illustrates the electrical lighting usage during a year for a south window model. As shown in figure 14, the lowest electrical lighting power for the south window is from March to November. As the sun is due south most of the year, considerable amount of electrical lighting can be saved with a south window.

However, for the north window saving electrical energy is so scattered during a year (see figure 15). The electrical lighting for the north window model is slightly smaller in summer which is because the sun is more intense in summer. In addition, the sun is due north early in the morning and

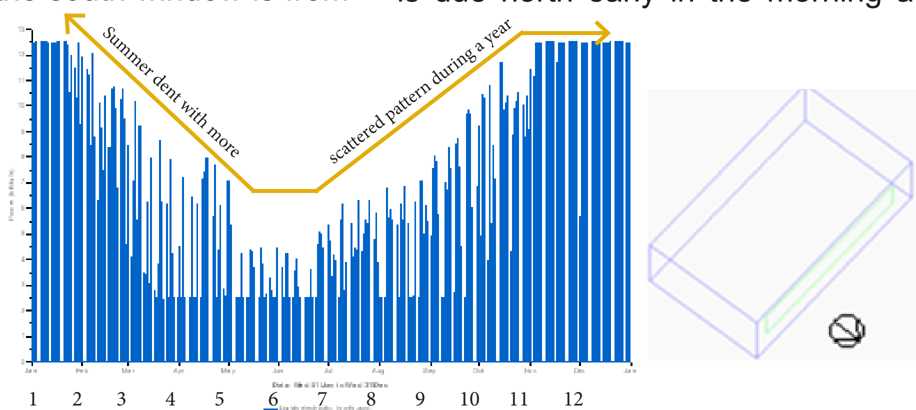


Figure 15: North window- electrical lighting during a year

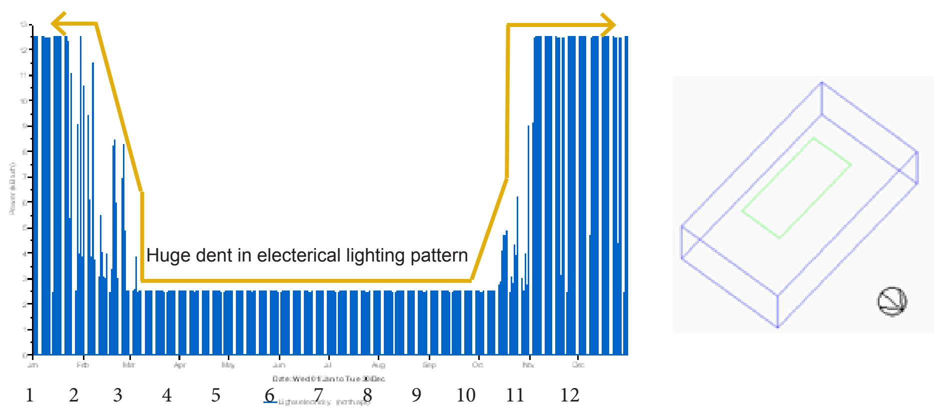


Figure 16:skylights- electrical lighting during a year

late in the afternoon in summer. Thus, this can slightily save electrical lighting for the north window model in summer. This explains a small dent in electrical usage pattern in figure 15. However, compared to the south graph (figure 14) the electrical lighting for the north window is still much scattered and bigger than the one for south window (See figure 17).

Figure 16 shows the electrical lighting for the skylight model. As shown in the figure 16, the electrical lighting usage is in the lowest range in summer days since the sun is high in the sky and skylight provides more even natural light through a day. In addition, the period of time that electerical lighting is saved in the skylight model is longer that the period of time in the north and south models. However, figure 16 also shows that less electrical lighting is saved during winter time. During winter time the sun is pretty low and due south. Since a skylight is flat in this model, it cannot capture enough daylight during winter time.

Figure 17 compares the monthly electrical lighting usage of all four models. As shown in figure 17, apparently the base moedl with no windoe uses ther largest amount of electrical lighting

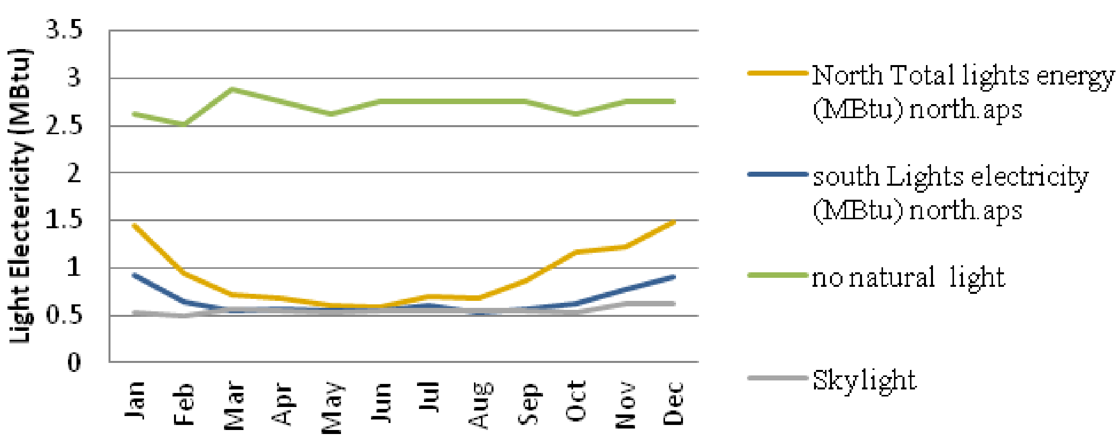


Figure 17: Electrical use skylight v.s. north window v.s. Ssouth window v.s. no window models

among other models. The next larger amount of electerical lighting belongs to the north window model. The electrical lighting use of south model is very close to the skylight model. But skylight model uses the lowest amount of electrical lighting among all four models. This is because skylights can provide more even daylight most of the year.

Since skylights are able to save considerable amount of electrical lighting, they are considered as a possible energy efficient alternatives. Next the energy impact of toplighting strategies will be discussed.

4.2. ENERGY EFFECTS OF TOPLIGHT

Based on the reseach that has been done in this thesis, toplights are considered the most energy efficient daylighting strategies. In this part the effect of toplights on the building loads will be discussed. The total energy consumption of the buildings has several components: heating loads, cooling loads, electrical lights, electrical equipment, infiltration, etc. When daylight is used in the space, it has different, sometimes opposite, effects on each energy component of the building. On one hand, daylight saves electrical lighting. On the other hand, daylight impacts building loads by changing 1) electrical lighting heat gain, 2) solar gain and 3) external conduction.

- Electrical lighting heat gain: Natural light decreases the amount of electrical lights used in the building during a day; and eventually internal heat gain drops since lamps converts (90%) of their electricity to heat. Less internal heat gain has opposite results in different seasons. In summer less internal gain means less air conditioning while in winter less internal gain increases the heating load.
- Solar gain: Daylight increases the solar gain by allowing more direct light into the space. This also has opposite effects in different seasons. In summer solar gain increases cooling

loads and in winter solar gain decreases heating loads.

- External conduction: Since glass has higher conductivity, a toplighting structure decreases the total resistivity of the roof (R value). This increases the heat transfer of the building skin.

All these changes in solar gain, lighting heat gain and external conduction can offset each others' effects and eventually can decrease or increase the energy loads of the building. Therefore, it is extremely important to study toplights while considering these effects simultaneously.

Chapter Five: Base Model

5.1. BASE MODEL DEFINITION

The thesis goal is to evaluate the energy impacts of daylight via toplights verses no natural light. To do so, a base model was developed to represent a one story office building with a square plan that is very deep. This base model was then augmented with different top-lighting strategies to study their energy impacts. In all of the models sidelights (windows in the walls) were avoided since they cannot provide enough light in such a deep space. Construction details such as R value of the envelope, type of electrical lighting and operating schedule were defined according to ASHRAE, [2] or Austin code. These parameters are listed in Table 1.

In order to validate the base model, I computed Energy Use Intensity (EUI) for the base model and compared it with the data provided by CBECS[3] as well as energy star labeled buildings. Results of simulation show the EUI is (68 KBtu/sq.ft) for our base model which is between EUI of CBECS, (92 KBtu/sq.ft), and energy star labeled buildings, (61 KBtu/sq.ft). This approves that our base model has a reasonable total building energy use per area. Note that EUI of CBECS is larger since it accounts for existing buildings while energy star EUI is lower

	Office	Comments and References
Building		
Applicable Building Area	20000 Sq. ft	-
Ceiling Height	17 ft	-
Wall Color	Off-White Paint; Reflectance=80%	[1]
R value	Roof R (38) and Wall R (19)	Austin Code
Operating Schedule	8am to 6pm	AHRAE 8 am to 6 pm no lunch
Electrical Lighting		
Lighting System	Open cell Florescent	US Energy Information and [1]
Lighting Level	35 fc	MEEB and ASHRAE
Power Density	1.2 w/sq.ft	US Energy Information Administration

Table 1: Base Model Parameters

[3]Commercial Buildings Energy Consumption Survey, U.S. Department of Energy

since it is for new energy efficient buildings.

Moreover, to verify the base model electrical lighting assumptions, I compared the base model's Ratio of electrical Lighting consumption to total Energy, RLE, with Energy Information Administration (EIA) data. RLE for our model is (21%) which is close to RLE reported by EIA, i.e. (22%) for commercial buildings. This also confirms the accuracy of our models and it is shown in figure 18 and 19. Figure 20 shows the simple shape of the base model.

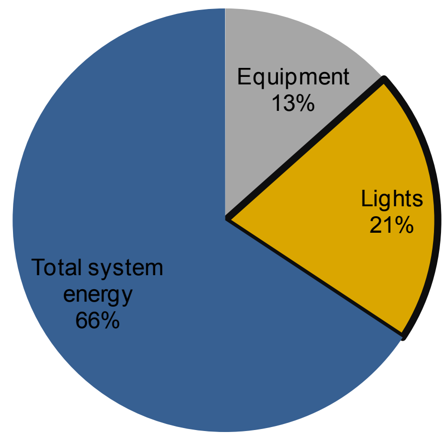


Figure 18: Site energy break down of the base model

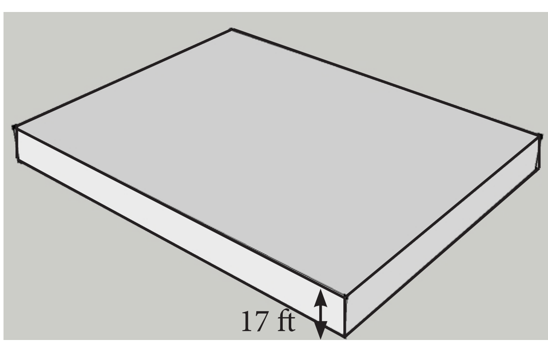


Figure 20: Base model without any daylighting

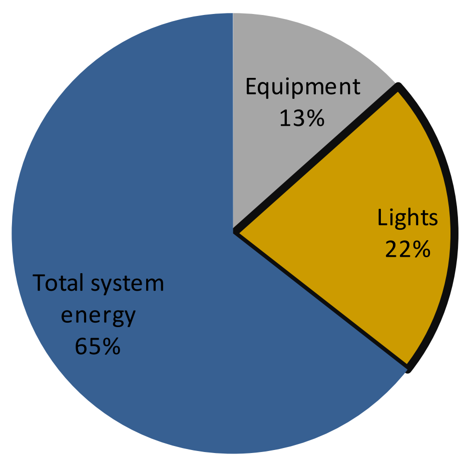


Figure 19: Site energy break down of an office building EIA (U.S. Department of Energy 2003)

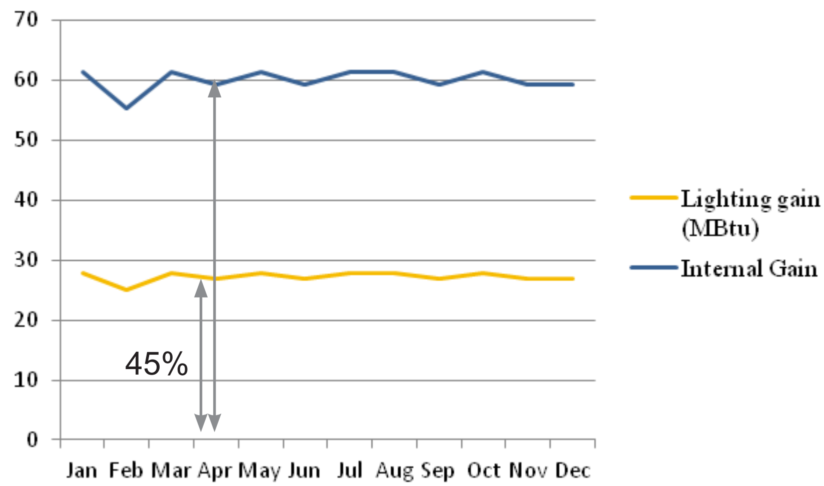


Figure 21: Monthly lighting gain and internal gain in base model

As discussed before toplights have significant effects on building loads by changing internal heat gain, solar gain and external conductance. Next, I will analyze the effects of these factors for the verified base model. Note that in the basic model there is no aperture and daylight; therefore, the base model has no solar gain.

5.2. THE IMPORTANCE OF ELECTRICAL LIGHTING GAIN AND EXTERNAL CONDUCTANCE IN BUILDING LOADS

Internal heat gain includes the heat gain from the occupants, equipments and electrical lighting. The simulation results show that the heat gained by electrical lighting in office buildings is about (45%) of the total internal heat gain in a year (See figure 21). This is a considerable amount of energy playing a crucial role in heating and cooling loads of office buildings. Moreover, external conductance which is based on the resistivity of the skin affects the building loads. Figure 22 shows the monthly amount of these factors along with sensible heating and cooling loads for an office building in Austin, TX.

According to figure 22. during the hot months of the year, from May to September, the ratio of lighting gain to sensible cooling load is in the range of (23%) to (52%) while the ratio of the external conductance gain to sensible cooling load is in the range of (2%) to (31%). Note that in May, Jun and September lighting gain is more than external conductance while in July and August external conductance is bigger. However, considering the whole period of May-September, summation of lighting heat gain is slightly bigger than external conductance gain, i.e. (28%) vs. (24%). This is in particular an important observation since it shows that lighting heat gain is as important as external conductance during hot months in Austin. Note that this is in contrast with common belief that in a very hot climate like Austin external conductance is more important than lighting heat gain. In winter the importance of lighting gain is much clearer since lamps not only provide light for the space but they also produce heat. This is considered as an asset to the heating loads. For

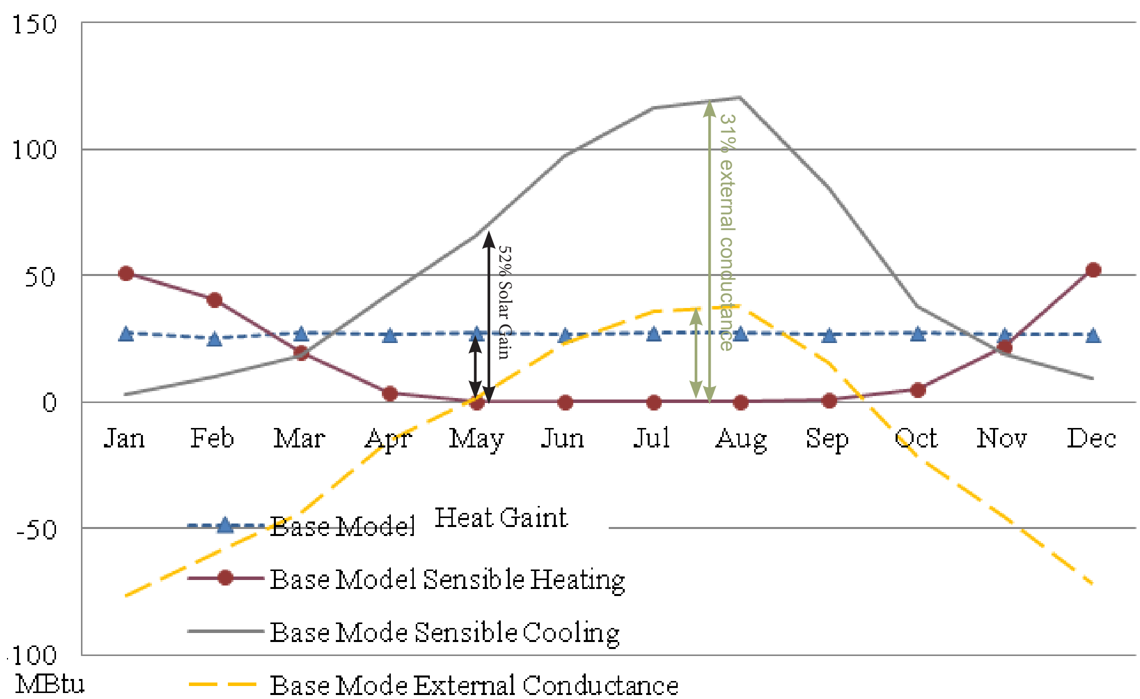


Fig. 22: Monthly lighting gain, internal gain, and conductance in base model

example, in January lighting heat gain can offset the external conductance by (36%).

In conclusion, reduction of lighting heat gain can be an advantage in summer and a disadvantage in winter. In addition, daylight is a kind of strategy to reduce the electrical lighting. In the following I will analyze the impact of daylight trough skylights on the reduction of electrical lighting as well as heating/cooling loads.

Chapter Six: Skylight Model

6.1. SKYLIGHT MODEL SETTINGS

In this section I will add skylights to the base model and review the impacts of natural light on the building energy.

The skylight model extends the base model, described in Table 1, by adding flat skylights on the roof. The main factors of the skylight are glass area and glass properties. Table 2. lists such parameters. The model is adapted to the ASHRAE requirements and Austin Code where the maximum allowed skylight area is (5%) of the gross roof area. This equals to (81) skylights with the size of (3' 6"*3' 6").

In order to control the electrical

	Office	Comments and References
Building		
Applicable Building Area	20000 Sq. ft	-
Ceiling Height	17 ft	-
Wall Color	Off-White Paint; Reflectance=80%	[1]
R value	Roof R (38) and Wall R (19)	Austin Code
Operating Schedule	8am to 6pm	AHRAE 8 am to 6 pm no lunch
Electrical Lighting		
Lighting System	Open cell Florescent	US Energy Information and [1]
Lighting Level	35 fc	MEEB and ASHRAE
Power Density	1.2 w/sq.ft	US Energy Information Administration
Lighting Control	Dimming	It is not step Dimming, it is Continuously Dimming If 0 fc, turn on the whole lamps if 35 fc, turn on 20% of the lamps
GLASS PROPERTIES		
Glass Area	5%(1000 sq.ft)	ASHRAE 90.7, sec. 5
SHGC	0.33	Double Glazed Window
SC	0.5	Double Glazed Window
U value	0.53	Double Glazed Window
VT	0.65	Double Glazed Window

Table 2: Skylight Model Parameters

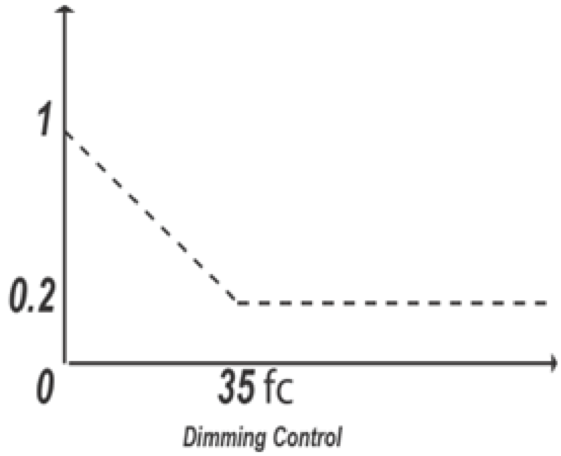


Fig23: The schedule of dimming control system

lighting based on the received natural light, a sensor was defined on the desk level in the middle of the building. The dimming control was scheduled for the sensor. If the sensor receives no natural light, it will turn on all the lamps. If it receives more than (35fc), it will turn off (80%) of the electrical lighting. We set this parameter to (80%) to account for individual side lights. The schedule of control system is shown in figure 23. The threshold of the sensor in this paper was (35fc), which is an adequate amount of light for office spaces according to ASHRAE.

Moreover, the distance between the skylights in the middle of the roof is twice as the distance between the last

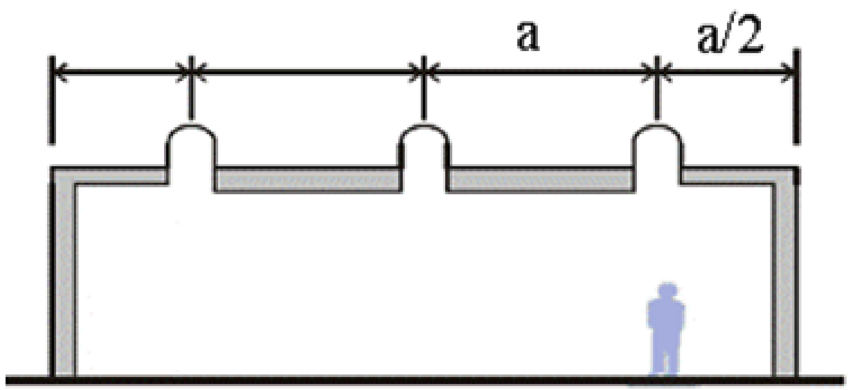


Figure 24: Skylight placement (http://elad.lbl.gov/)

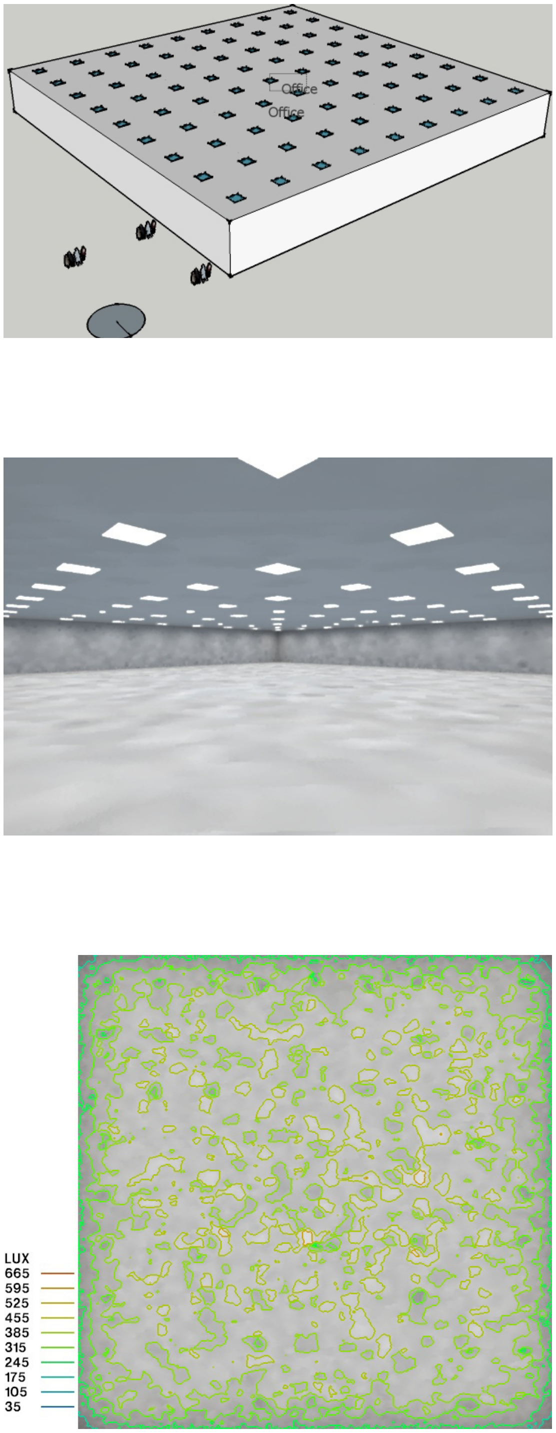


Figure 25: Skylight interior and exterior prespective and interior illuminance map produced by Radiance

skylights and the walls. The reason is that the building edges are darker and the shorter distance of skylights from the edges can create more even daylit space. Figure 24 shows the placement of skylights. And figure 25 shows an interior perspective, exterior perspective, as well as illuminance map for the skylight model. Next I will discuss the impact of skylights on the building loads.

6.2. SKYLIGHT MODEL V.S. BASE MODEL

Toplights affect the building loads by changing these three factors: lighting gain, conductance, as well as solar gain. Figure 26 compares such factors in skylight and base models. Skylights add glass to the roof structure which apparently replaces the conductance of the roof (R38) with the lower conductance of the glass (R2). This seems to be an extra burden for the building loads; however, figure 26 does not show this effect. The reason is that most of the year skylights do not dramatically change the external conductance. Note that external conductance has little increase or decrease in the hottest and coldest months of the year, such as August and January. This change is insignificant compared to the change in solar heat gain and lighting gain. As also shown in figure 26, the lighting heat gain and solar gain change with added skylights. But these can be a burden or an asset to the building loads in different months. Note that in figure 26 the solid red arrows in August and January show the factors that increase the building loads while the blue ones represent the factor that decreases the building loads.

In summer such as August so-

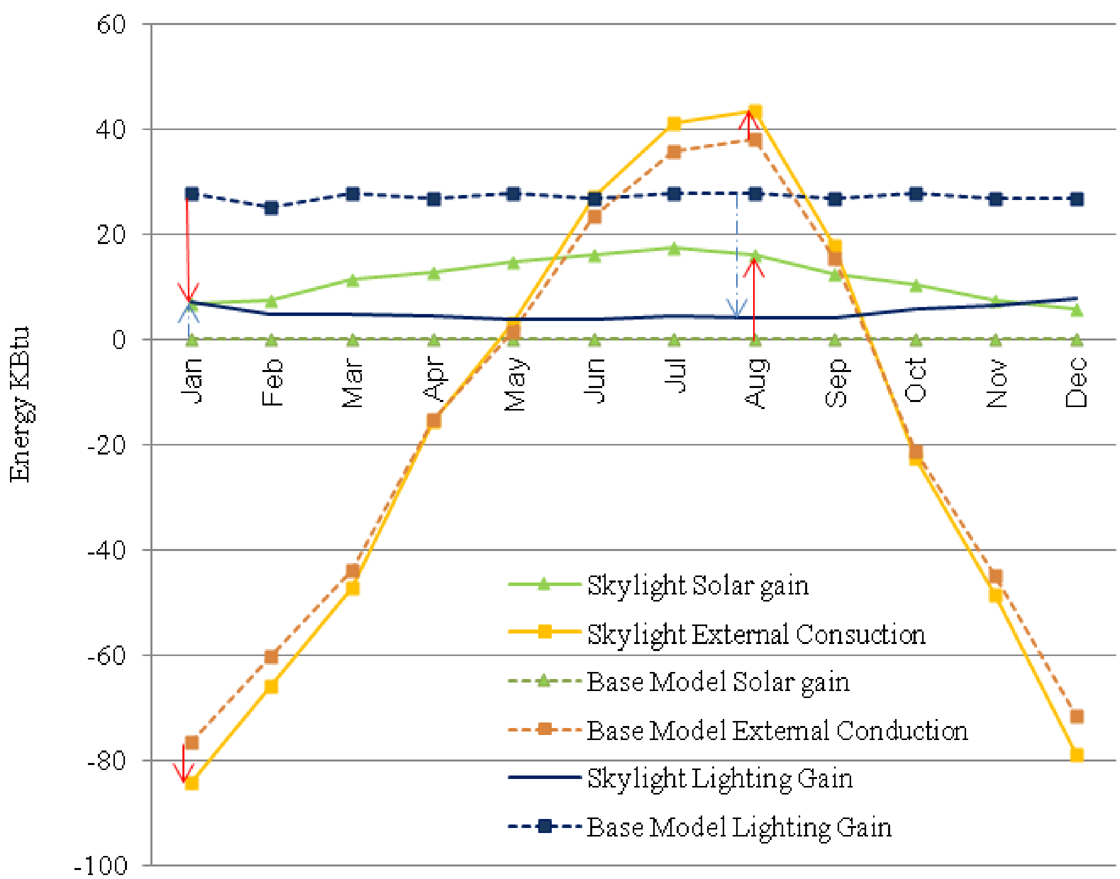


Figure 26: Comparison of solar heat gain, external conductance and electrical heat gain between skylight and base Models. The solid red and the dashed blue arrows indicate increase and decrease in the building energy, respectively.

lar gain and conduce are increased. On the other hand, there is a loss of electrical lighting heat gain offsetting the increased amount of solar gain and conductance. In winter, however, solar gain is an asset to the building loads in contrast with conductance and electrical lighting heat loss which are the burdens. But solar gain in winter is not enough to offset the lighting heat loss and conductance. As shown in table 3, in August, the hottest month in Austin, the skylight slightly decreases the cooling load; and in January, the coldest month, the skylight increases the heating load. In total the heating load is increased by (24%). The reason is that in winter sun is due south and pretty low in the sky during a day. And the defined skylights are flat and are not able to catch the sun.

Moreover, the annual cooling load does not change by adding skylights. The simulation also shows electrical lighting is saved around (73%) which is considerably a larger amount of electricity (table 4).

In conclusion, solar gain and lighting gain are more effective than external conductance in hot climate like Austin. This is because of the small glazing area which is just (5%) of the gross roof area. In addition, the type of the building is important; here we analyzed the offices, which are considered as internally loaded buildings.

August-Cooling Season					
Type	Solar gain (kBtu)	Light gain (kBtu)	External Conductance (KBtu)	The total heat exchange (KBtu)	Is cooling load increased?
Skylight Model	16.111	3.958	43.217	63.286	No
Base Model	0	27.766	38.075	65.841	
January-Heating Season					
Type	Solar gain (kBtu)	Light gain (kBtu)	External Conductance (Kbtu)	The total heat exchange	Is heating load increased?
Skylight Model	6.755	6.89	-84.118	-70.473	Yes
Base Model	0	27.766	-76.484	-48.718	

Table 3: Building Loads Comparison in August and January

	Heating Load natural gas (MBtu)	Cooling electricity (MBtu)	Electrical lights (MBtu)
Basic Model	257.464	531.374	233.77
Skylight	319.581	531.549	64.184
Savings	-24%	0%	73%

Table 4: Comparison of Site Energy between Skylight and Base Models

In this section I discussed the building loads and site energy. In the following I will review the total cost benefit of skylights.

6.3. COST SAVING OF SKYLIGHT MODEL V.S. BASE MODEL

Energy cost simply measures how mcuh a building operator is paying for energy. This definition uses market valuation to account for the relative value of various fuels. Energy cost also reflects, to some extent, the difference between site and source energy. The monthly price of electricity and the natural gas are considered constant in this analysis. By this strategy we don't account for the peak loads as they are very unstable and unpredictable. The average price for (1 kwh) of electricity in Austin is (0.1 $) and the cost of thermal gas is (1 $/therm). This also indicates that natural gas is cheaper; as a result, electrical savings are more important than heating load savings.

Figure 27 illustrates the cost saving of skylight model vs. base model. When skylights are used, they save (0.2 $/sq.ft) by reducing electrical lighting and increase the cost of heating load by (0.03$/sq.ft). Note that there is no cost saving for cooling loads because the cooling change is negligible. Discussing impacts of skylights on the building,

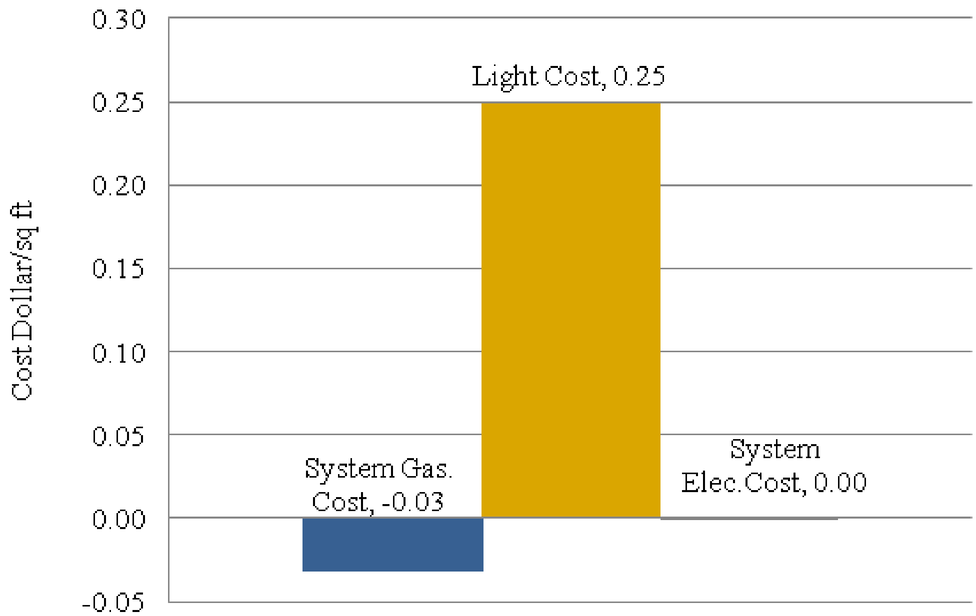


Figure 27: The cost saving per area for heating, and cooling loads as well as electrical lighting

6.4. SKYLIGHT PAYBACK

Saving Energy by skylights decreases fossil fuel usage and ultimately decreases the emissions and green house gases. The environmental benefits of skylights may be very interesting for somebody but it also takes energy to save energy. The term “energy payback” captures this idea. How long does a skylight system over a roof have to operate to recover the energy that went into making the system, in the first place? In the words, energy payback time means the length of time that an energy efficient system will take to produce that same amount of energy that was used to make it (EIA 2004).

Table 5 shows the cost of skylights for each climate zone. This considers cost of skylight, installment as well as dimming lighting control. The data is derived from the report [1] conducted for U.S. Department of Energy in 2008 by TIAX LLC.

As Austin is in climate zone 2, skylights cost (4.24$) for each square feet. Table 6 shows all the data to calculate the pay back for the skylight

Climate Zone	City	Office	School	Warehouse	BB Retail
1, 2	Phoenix, AZ	$4.26	$4.26	$0.96	$1.25
3	Memphis, TN	$4.68	$4.68	$1.25	$1.25
4	Baltimore, MD	$4.68	$4.68	$1.25	$1.25
5	Chicago, IL	$4.68	$4.68	$1.25	$1.25
6, 7	Burlington, VT	$4.68	$4.68	$1.25	$1.25

Table 5: First Cost of Toplights in New Buildings, $/ft^2, by Climate zone and Building Type [1]

which is estimated to be around 19 to 20 years. Since the life of the skylight is 20 to 25 years, skylights for an office building is energy efficient and the savings from the skylights can pay back the initial cost of skylight installment.

I also used another reference to calculate the skylight cost. According to "Energy and Construction Cost Estimate," report conductade for U.S. Department of Energy the average skylight cost is around (500$) and the labor cost to install is (40%) of the skylight cost. Moreover, the dimming light control cost is (1.15$) per square feet which is ultimately results in investing huge amount of money compared to the cost of skylights. Table 7 shows all the calculation and the final result of pay back.

I calculated the skylight payback based on two different methods from different resources. The results for the initial cost of skylights and ultimately the payback are the same (Table 6 and 7) which means the skylight cost will be recovered by the skylight' energy saving during its life.

So far I have investigated that skylights are energy efficient and they have a reasonable payback. This

Total First Cost(Skylight, Installment, Dimming Control)$	Saving Energy$	Pay Back Years	Life of Skylight	Does Saving pay the Skylight cost in its life?
85200	4313.9	19.75	20-25 years	YES

Table 6: Payback of Skylights in Austin Texas (First Calculation)

means that the investment in skylights makes sense. So the next question is that what about other types of toplighting strategies. In the following, I will analyze the energy efficiency of different toplight toplights.

Skylight Price(500$ each)	Installment, labor(40%)	Dimming Control(1.15$/ft^2)	Total
44550	17820	23000	85370

Table 7: Payback of Skylights in Austin Texas (Second Calculations)

Chapter Seven: Different Types of Toplights

Based on the research that has been done in this thesis the saved electricity through skylights are much bigger than the increased heating loads in a hot climate like Austin. The next questions are 1) how much energy can be saved by different toplighting strategies, and 2) which of them can save more in this climate. The toplights that are compared in this chapter are: Skylights, Monitor roofs, north sawtooth roofs, and south sawtooth roofs.

7.1. DEFINITION OF TOPLIGHT MODELS

To compare different alternatives, we had to first determine the fixed and variable factors. In report [1] it is claimed that (2%) daylight factor is not a good criterion in order to size the glazing area. Report [1] also suggests that glazing area needs to be sized by energy saving results. Based on thee

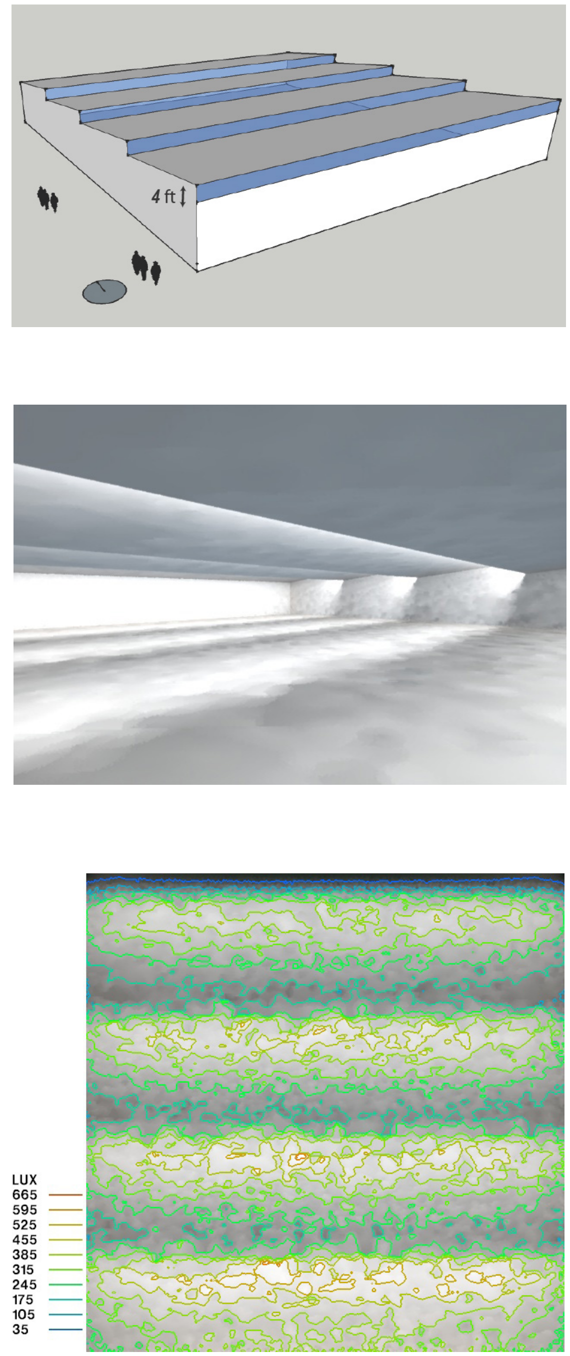


Figure 28: South sawtooth roof: interior and exterior prespective and interior illuminance map produced by Radiance

research has been done so far electrical lighting saving is bigger than increased heating loads in Austin climate. As a result, saved lighting electricity was the constant factor to size the glazing area of the toplights in this research. In the other words, I changed the aperture size or ratio of the glazed area to the wall area for each toplight in order to achieve almost the same electrical lighting savings. Then, I was able to analyze how much cooling/heating loads were changed for various toplights with different glazing area while the electrical lighting saving is constant.

IES VE is plugged into another software, sketch-up, for a geometrical shape, and there is no optimization programming. Thus, to change the glazing area, I needed to go back and forth between sketch-up and IES VE. This made it difficult to save exactly the same amount of electrical lighting. However, after iteration in the process I achieved almost the same amount of electricity electerical lightign for each

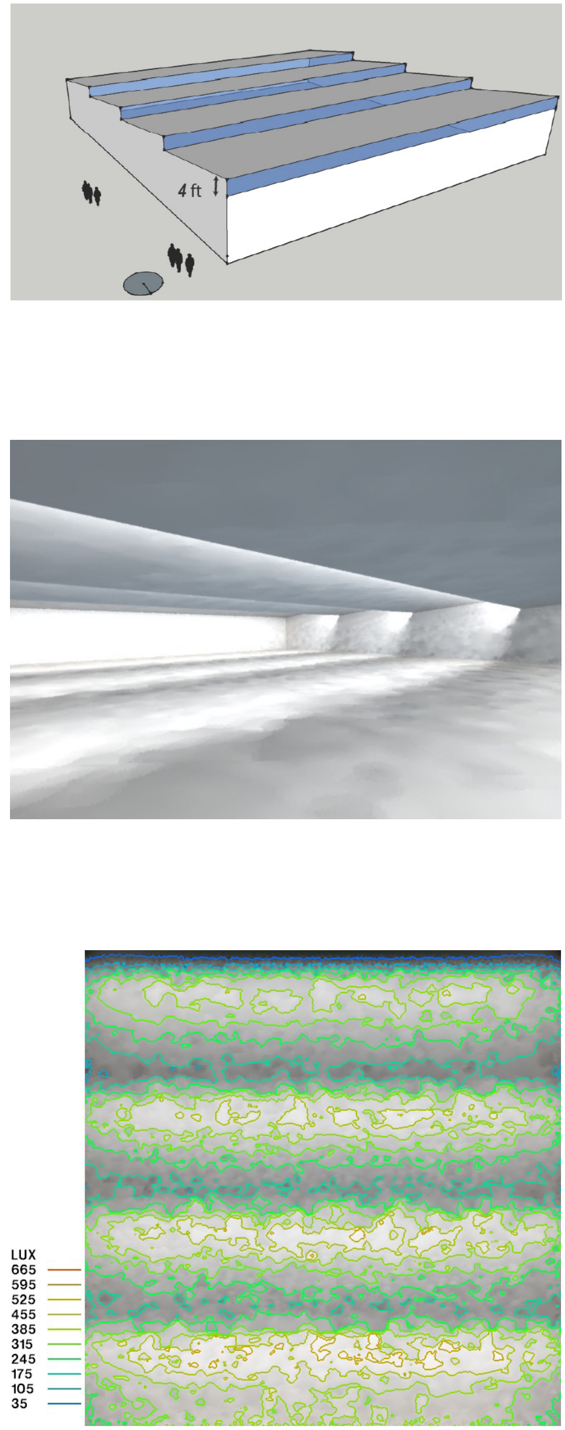
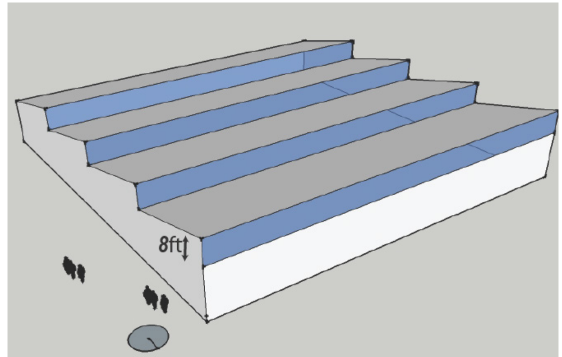


Figure 29: Nouth sawtooth roof with the same area: interior and exterior prespective and interior illuminance map produced by Radiance

top light which is about (0.25) to (0.24 $/sq.ft) or (73%) to (72%) electrical energy compared to the base model.

Figures 29, 30, 31, and 32 illustrate different type of toplights. Four rows of monitor roof and sawtooth roofs are defined to distribute the natural light evenly into the space. In designing the toplights we considered these facts: 1) It should save the same amount of electrical lighting 2) Distribution of natural light should be evenly in the space 3) The glazing area should not exceed 30% of the wall area which is based on the Austin code.

I also rotated the south facing sawtooth roof to the north with the same amount of glazing. I found that in order to save the same amount of lighting for the north facing sawtooth roof, the height of sawtooth roof should be doubled, from (4 ft) to (8 ft). This is because of north diffuse light compared to south direct light. In addition, south facing windows always have daylighting most of the time in a day or in a



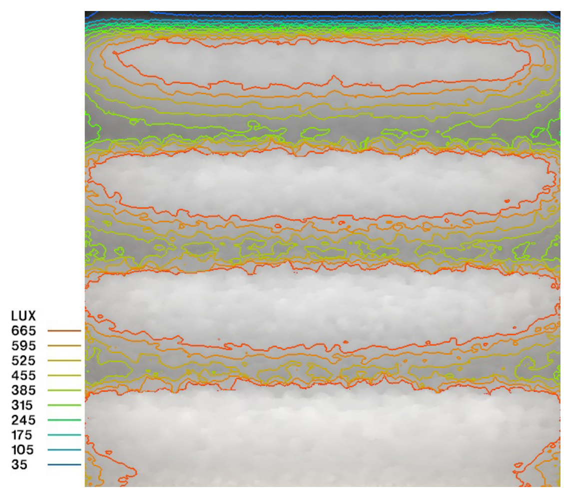


Fig 30: Nouth sawtooth roof with a double hight of window: interior and exterior prespectives and interior illuminance map produced by Radiance

year compared to the north windows.

Next, I' ll discuss how much energy each toplight can save and what kind of toplight is the best strategy for decreasing the energy cost.

7.2. RESULTS AND DISCUSSIONS

In this paper, all toplighting strategies were compared to the base model scenario. As shown in the figure 32 and table 8, the total amount of energy saved by skylights is bigger than any other types of toplights. There are several reasons for that: 1) the sun is high in the sky most of the time during a day except for the early morning and afternoon 2) the sun is high in the sky most of the time during a year except for the winter that is slightly due south 3) skylights distribute daylight evenly into the space without leaving any dark spot 4) finally with even daylight distribution the glazing area or the number of skylights decreases which directly affects heating and cooling loads.

Another interesting result is that

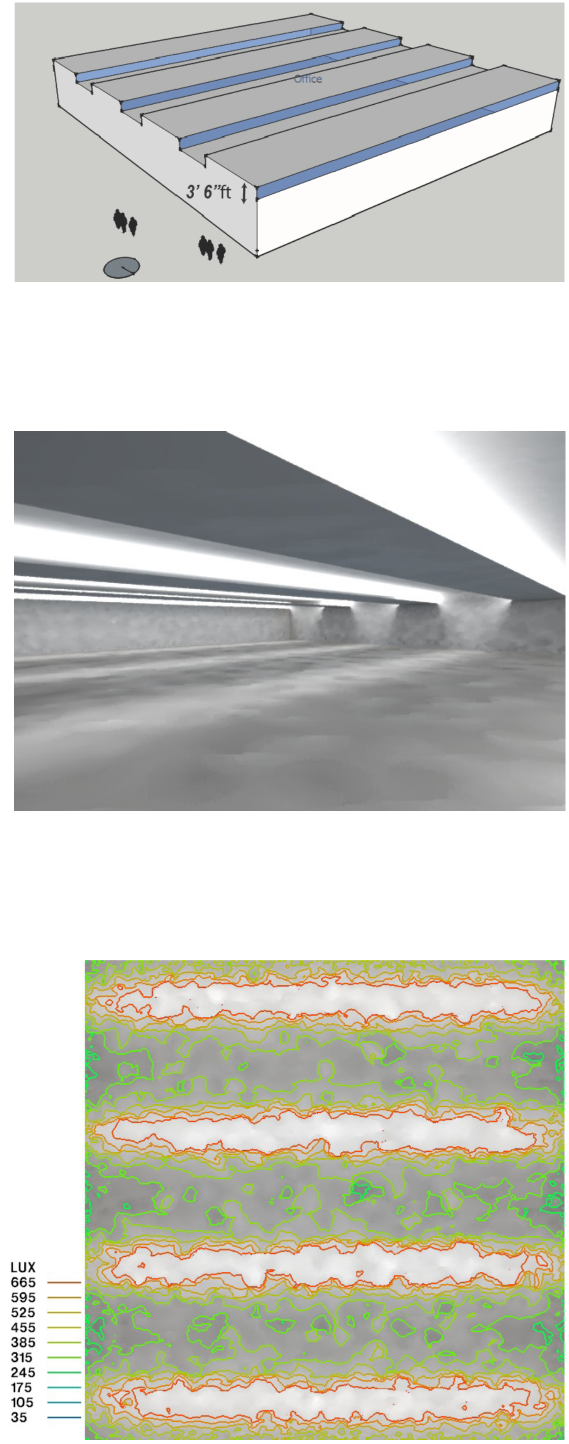


Figure 31: Monitor Roofs: interior and exterior prespectives and interior illuminance map produced by Radiance

the height of the north facing sawtooth roof had to be twice as the height of the south facing sawtooth roof to save the same amount of lighting. Table 7

Type of Toplight	Heating Load natural gas (MBtu)	Cooling electricity (MBtu)	Electrical lights (MBtu)
Skylight	-24%	0%	73%
North Sawtooth Roof, Same Area	-36%	0%	49%
South Sawtooth Roof	-29%	-2%	72%
Monitor Roof	-56%	-7%	71%
North Sawtooth Roof, Bigger Area	-43%	1%	72%

Table 8: Site Energy Comparison for Each Toplight

shows all the changes in building loads and electrical lighting for each toplight.

The heating loads of the north and south sawtooth roofs are increased (43%) and (29%) respectively. The cooling load is decreased about (2%) for the north and increased about (1%) for the south sawtooth roof. Both scenarios save almost (72%) of lighting. If the cost of natural gas and electricity considered, the total cost savings of double height north facing sawtooth roof is almost the same as south facing sawtooth roofs, slightly bigger (table 8).

The reasons for the increase in heating loads are generally because of the direct solar gain from the south as well as the high conductivity value of the glass (U value). Moreover, the decrease in cooling loads in the north facing sawtooth roof is based on the reduction of lighting gain in office buildings which is almost (45%) of the internal gain. Another reason is the lack of direct solar gain compared to south facing sawtooth roof.

In addition, the results show that monitor roofs are not as efficient as

Type	Skylights	North Sawtooth	South Sawtooth	Monitor Roof	North Sawtooth the same area
Glazing Area to	Roof, 5%	Wall, 30%	Wal,18%	Wall, 20%	Wall, 18%
Total Cost Saving: $/sq.ft	0.22	0.20	0.20	0.12	0.13
Total Cost Saving : $	4343.99	4064.11	3951.12	2309.67	2524.02

Table 9: Cost saving Comparison for Each Toplight

other types of toplights. The reason is that the distributed light of the monitor roof is not as even as other types of toplights (see figure 32). In this type of toplights some parts of the roof are elevated and some are not for the raised parts of the roof natural light is brought from both sides to the area beneath which may causes overlit spaces. On the other hand, the un-raised parts of the roof have no contribution to brighten the space beneath. Thus, this causes dark spot in the space. To avoid that, I had to increase the glazing area, increase the width of the raised parts of the roof, as well as decrease the un-raised parts of the roof. This amount of glazing area facing to both south and north directions increases both heating and cooling loads. Our conclusion for monitor roofs is that such roofs are not as energy efficient as other types since they create dark spots in a space because of their specific forms.

According to figure 32 the most energy efficient toplights are in this order: skylights, north facing sawtooth roofs with double height of window, south facing sawtooth roofs, north facing sawtooth roofs with the same height, and monitor roofs. Figure 33 summarizes all the results as an architectural design guidance illustrating the comparison of different toplight strategies regarding the energy as well as the daylight distribution in a space.

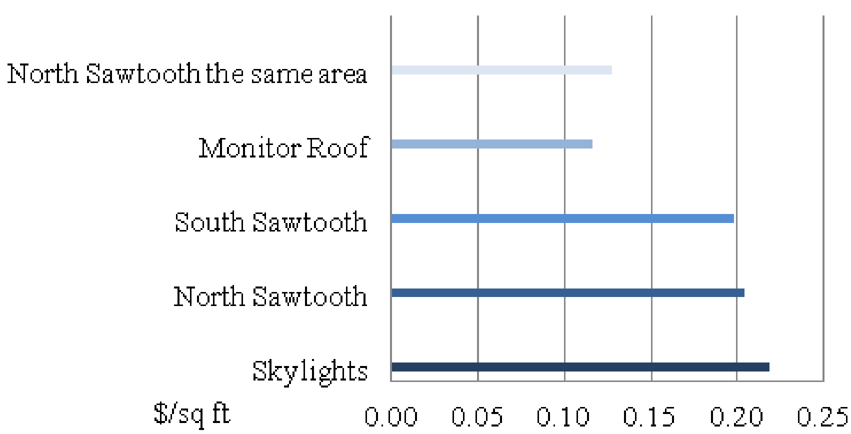


Figure 32: Comparison of different toplights regarding the cost saving

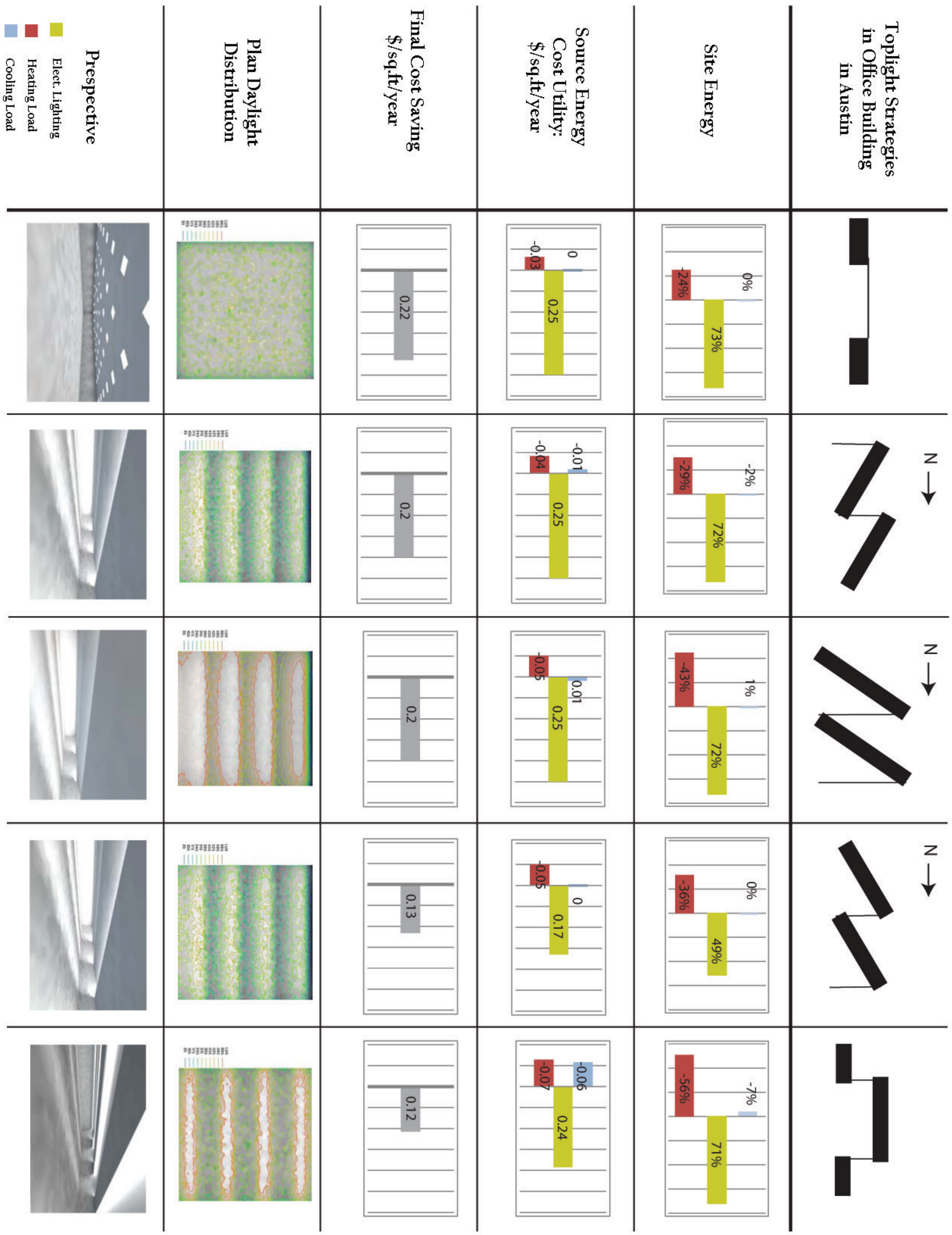


Figure 33: A design guide containing site Energy, cost analysis, and daylight distribution for different toplighting strategies

Followings are general conclusions comparing different toplighting strategies:

- Any toplighting strategies distributing daylight evenly into the space are able to reduce the total energy. In this research the glazing area, however, is a very important factor.
- The saved electrical lighting is much bigger than the increased cooling/heating loads for different toplighting strategies. Regarding the building loads it seems toplights have a bigger impact on the heating loads than the cooling loads in this climate. The reason is that toplights decrease more amount of electrical lighting heat gain than increase solar gain or external conductance.
- Skylights are the best energy efficient alternative. In a sunny location like Austin, small apertures in the roofs can bring enough daylight into the space and have a smaller effect on HVAC loads.
- South facing sawtooth roofs can save the same amount of total energy as the north facing sawtooth roofs with bigger glazing area can save.
- Monitor roofs are not as efficient as the other types of toplights because such toplights creates dark spots in the space.

Since any kinds of toplighting strategies can save energy, any factors that affect the efficiency of toplights can compromise the energy efficiency of the building. Two important factors that significantly affect the efficiency of toplights are Visible Transmission (VT) of glazing area and the allowed glazing area.

To optimize the glazing area another software tool such as MATLAB (matrix laboratory) has to be used in the research. MATLAB is a numerical computing environment that is able to manage all the data generated by IES VE pro. The approach will be going back and forth between two tools: 1) IES VE for 3d modeling, radiance, and energy consumption, and 2) Matlab for execution control, geometry input, data storage and optimization engine. Although the optimization of the glazing area is not a material for this master thesis, it has a great potential as a research topic for future studies.

Regarding the Visible Transmission (VT) of the glazing area, Standard and codes ignore this important property of the glass. Or they don't emphasis on it as much as they do on the Conductivity (U value) or Solar Heat Gain Coefficient (SHGC) of the glass.
In the next chapter I will discuss the importance of VT versus SHGC in toplighting strategies.

Chapter Eight: The importance of Visible Transmission (VT) V.S. Solar Heat Gain Coefficient (SHGC)

8.1. THE IMPORTANCE OF VISIBLE LIGHT

The transparent, ethereal nature of glass allows for extraordinary creations in the world of architecture. From a crystalline pyramid of light to a clear balcony 1,300 feet in the sky, glass is truly a versatile material for the creative architects .Generally the rationale to use glass in the architecture is: 1) aesthetic purposes and creativity, and 2) functional purposes including views to the outside and daylighting for health and psychological reasons (Boubekri 2008). Despite such benefits, the use of glass in the building may increase the cooling and heating loads. This is mainly because glass has a higher Conductivity (U value) compared to the walls and it increases solar heat gain as well. To prevent the thermal impact of daylighting on the cooling and heating loads national or international standards such as ASHRAE regulate a very low Solar Heat Gain Coefficient and very low conductivity for the glass in a hot climate. In a hot climate like Austin such regulations also motivates practitioners to choose the glass based on the very low Solar Heat Gain Coefficient. But lower Solar Heat Gain Coefficient (SHGC) may cause very low visible light transmission (VT) as well. And very low visible transmission makes the view to the outside obscured. In addition, it makes a very dark interior space. As a result, a glass window with very low visible transmission may lose its functional benefits: clear views to the outside and daylighting. Low visible transmission may not affect the the appeal of the glass structure. However, some may questions why we should use glass in the first place if it loses its functional benefits.

In addition to the importance of VT in functional purposes of windows, in chapter 7 through intensive simulations I proved that daylighting through toplights can save energy. The saved electrical lighting is bigger than thermal impact of toplights. And the efficiency of toplights significantly depends on VT. As a result, visible light transmission through the glass not only can affect the views, and daylighting but it also can compromise the energy efficiency. In other words, visible transmission can significantly affect three functional benefits of the glass: 1) views to the outside 2) daylighting for health and psychological reasons, and 3) energy efficiency.

The topic of the research in this master thesis is about toplights. And toplights generally don't provide views to the outside but toplights can provide enough daylight into the space. However, in a hot climate like Austin practitioners have a concern about solar heat gain through the glass (SHGC) and they don't pay attention to the amount of visible light passing through the toplights (VT). Either of Higher visible light and lower SHGC can save energy. Therefore, the question that I intend to answer in this chapter is that which of Solar Heat Gain or Visible Light can save more energy. But first I will discuss the definitions of SHGC and VT.

8.2. THE DEFINITIONS OF VT AND SHGC

To understand the limitations of the software and find solutions for the challenges of the research, in this part I explain the definitions of common terms in glass industry.

Most input of the Earth energy is received from the Sun. The solar energy is short-wave radiation. The incident solar energy (shortwave) may be reflected and absorbed by the Earth's surface or the atmosphere. And Earth's surface and atmosphere also emit the radiation which is longwave radiation (National Science Digital Library) (See Figure 34).

Shortwave radiation or solar radiation is a term used to describe radiant energy with wavelengths in the

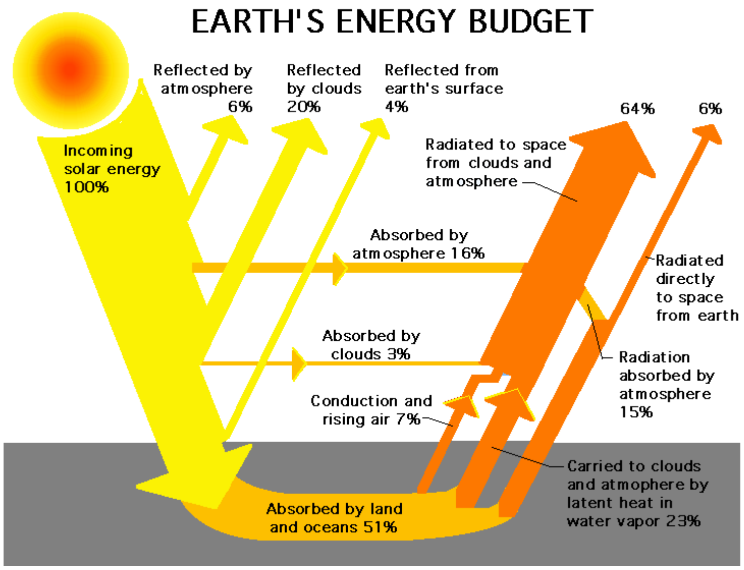


Figure 34: Solar radiation and earth longwave radaition

visible (V), near-ultraviolet (UV), and near-infrared (NIR) spectra. Longwave radiation is a part of radiation spectrum that has a longer wavelength and is infrared radiation. Figure 35 shows the different types of radiation.

Moreover, figures 36, 37, and 38 shows that Austin receives considerable amount of shortwave and longwave radiation (National Science Digital Library). Since shortwave radiation length is short and it has a higher

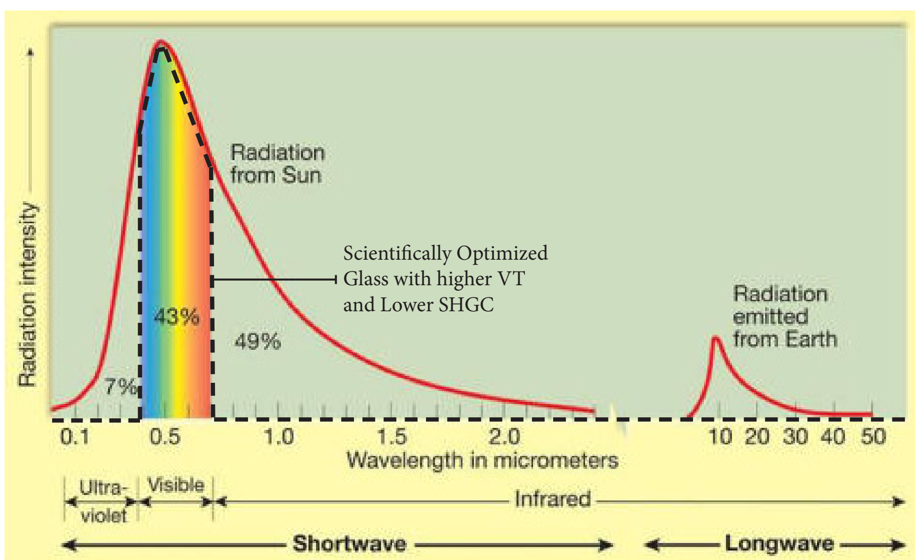


Figure 35: Longwave and shortwave radiation (Pearson Prentice Hall, inc 2007)

frequency, shortwave radiation has higher energy than longwave radiation. And glass can pass most of the shortwave radiation and casue over heating. Then, in a hot climate like Austin it is better to block the lower shortwave radiation though the windows. As shown in figure 35 visible light is almost (40%) of the shortwave radiation. And lower shortwave radiation can decrease the amount of visible light passing through the toplights. The scientific terms of Solar Heat Gain Coefficient (SHGC), Solar Shading (SC) and Visible Transmission (VT) are widely used in glazing industry. According to National Fenestration Rating Council (NFRC) these terms mean:

- Solar Heat Gain Coefficient: (SHGC) measures how well a product blocks the heat of solar radiation or shortwave radiation. SHGC is expressed as a number between (0) and (1). The lower the SHGC, the better a product is at blocking unwanted heat gain. Therefore, he lower SHGC is

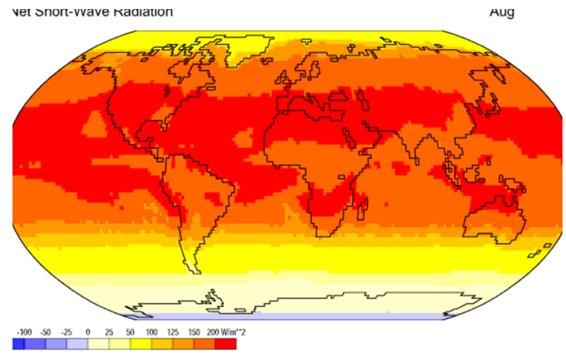


Figure 36: Shortwave radiation in Aug (University of Oregan 2000)

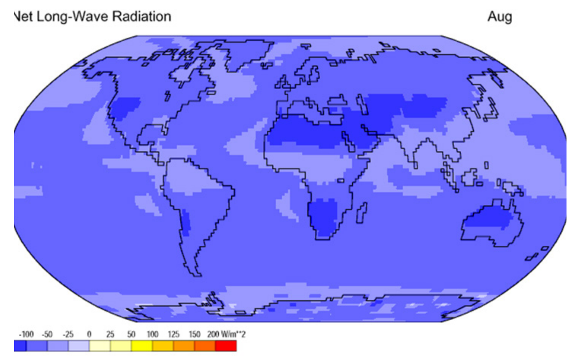


Figure 37: Longwave radiation in Aug (University of Oregan 2000)

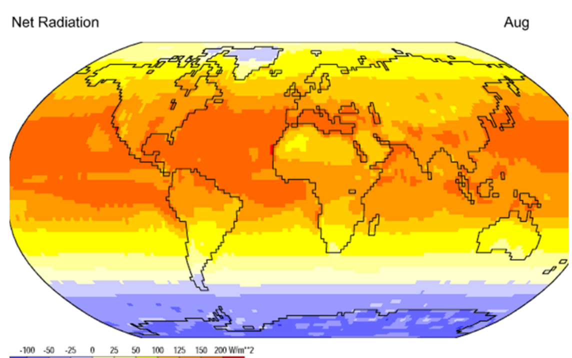


Figure 38: Net radiation in Aug (University of Oregan 2000)

better for a hot climate like Austin.

• Shading Coefficient: Until recently, the shading coefficient (SC) was the primary term used to characterize the solar control properties of glass in windows. Although it is being replaced by the solar heat gain coefficient (SHGC), it is still referenced in books and product literature.

The shading coefficient (SC) represents the ratio of solar heat gain through the system relative to that through (1/8-inch) (3 mm) clear glass at normal incidence. The shading coefficient is expressed as a dimensionless number from (0) to (1). A high shading coefficient means high solar gain, while a low shading coefficient means low solar gain.

For any glazing, the SHGC is always lower than the SC.

• The visible transmittance (VT): is also referred to as visible light transmittance (VLT) which is the amount of light in the visible portion of the spectrum that passes through a glazing material. A higher VT means there is more daylight in a space which, if designed properly, can offset electric lighting and cooling loads due to daylighting. Visible

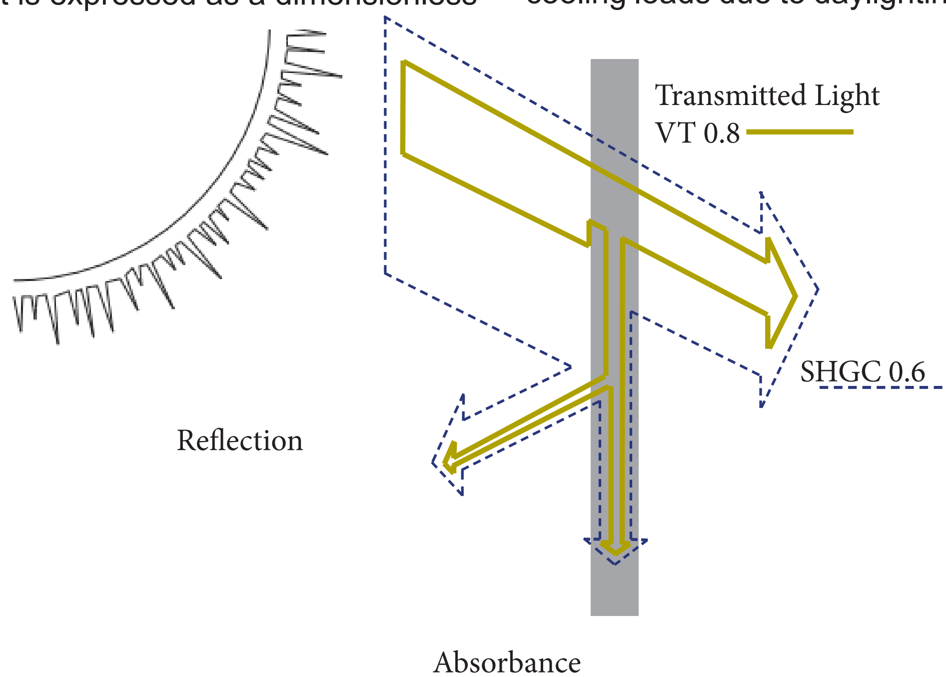


Figure 39: SHGC V.S VT

transmittance is influenced by the glazing type, the number of layers, and any coatings that might be applied to the glazings. Visible transmittance of glazings ranges from above (0.9) for water-white clear glass to less than (0.1) for highly reflective coatings on tinted glass. In addition, most values among double- and triple-pane windows are between (0.30) and (0.70).

All these terms are illustrated in figure 39. Next, I will develop a series of models with different VT, SC, and SHGC for the skylight model.

8.3. SIMULATION

In chapter 7 through series of simulations and scientific reasoning I concluded that skylights are the most energy efficient toplighting strategies in Austin. To compare a wide range of VT with SHGC, I developed the same skylight model from chapter 6. The model is a one story square shape with (20000) sqft area. And the skylight area is (5%) of the gross roof area. For more details about the skylight model, I refer you to part 6.1.

The range of SC for the double glazed Low-E glass is (0.2) to (0.6) which are the available glass options in IES VE. According to NFRC the maximum VT for double glazed window is (0.7). Therefore, the range of VT in this analysis is (0.2) to (0.7).

As shown in figure 35 , VT is about (40%) of the shortwave radiation. As a result, glass with lower than 0.4 SHGC cannot have VT of 1. However, IES VE only uses input data of VT for daylgihing and illuminance map; It only implements SHGC of the glass for thermal calculations. Therefore, IES VE is not able to recognize that VT of (1) is not possible for the glass with SHGC of lower than (0.4). To be sure that IES VE is the proper software to use, I also used EnergyPlus. Confirmed with the Energy Plus “InPut and OutPut” document, VT is an optional data input for the glass property and EnergyPlus uses this data for just

	SC	0.2	0.3	0.4	0.5	0.6
	SHGC=SC*0.84	0.168	0.252	0.336	0.42	0.504
science	IF SHGC>=0.4, VT=1 , Otherwise VT=SHGC*1/0.4	0.42	0.63	0.84	1	1
Double Glazed Windows	IF VT>=0.7, VT=0.7	0.42	0.63	0.7	0.7	0.7

Table 10: Calculating SC, SHGC and VT

daylighting, not thermal calculations. I did a series of simulation through EnergyPlus as well. Ifound out even EnergyPlus is not able to understand that the glass with SHGC of (0.3) and lower cannot have VT of (1). This is a bug in software simulation tools that even though theoretically and scientifically SHGC of (0.3) and lower cannot have VT of (1), they can still run the simulations for these impossible alternatives. However, this is the researcher responsibility to know the software, be aware of software bugs and verified the simulation results. Thus, I myself calculated the maximum of possible VT for each SHGC.

Next, I will conduct a matrix showing models with different VT and SHGC; Then, I compare the total energy cost of different models. I will prepare a design guid for the selection of energy efficient glass.

8.4. COMPARISON OF DIFFERENT VT VERSUS SHGC

In this chapter I will develop a design guide for the selection of energy efficient glass based on SHGC, VT and SC. 30 models were simulated with VT in the range of (0.2) to (0.7) and SC in the range of (0.2) to (0.6). According to NRFC to perform an approximate conversion from SC to SHGC, the SC should be multiplied by (0.87). However, in IES VE software this factor is (0.84). Since simulation via IES VE software is the method of my research, I adopted (0.84) factor to convert SC to SHGC. Table 9 shows the glass properties of simulated models in this study including SHGC, SC and maximum possible VT for each SC.

Shown in table 9 , skylights with SC (0.3) and (0.2) scientifically cannot have VT of (1). On the other hand, skylights with SC (0.6), (0.5), and (0.4) scientifically can have VT of (1). This means that the glass with those SC can block all types of radiant energy with different wavelengths except the visible light wavelength (see figure 35). As a result, the scientifically optimized glass with higher VT and lower SHGC is the glass with VT of (1) and SHGC of (0.4).

However, based on the limitation of technology double glazed window cannot have VT bigger than (0.7) (NFRC). As a result, I considered VT (0.7) for skylights with SC (0.4), (0.5) and (0.6) that scientifically can have VT of more than (0.7).

I calculated the total energy cost of the skylight models including heating, cooling and lighting cost. Table 10 is a matrix shows the total cost of each scenario. The dark blue colored cells are representatives of scenarios that can be simulated by software but scientifically it is wrong. The light gray cell is the skylight with the lowest total cost which means that it is the most energy efficient glass alternative for toplighting strategies in Austin. The most energy efficient skylight has the glass with SC

	SC	0.2	0.3	0.4	0.5	0.6
	SHGC	0.166	0.249	0.332	0.415	0.498
VT	0.2	23897	24112	24341.49	24584	24838
	0.3	22812	23024	23250	23489	23739
	0.4	21953	22162	22385	22620	22867
	0.5	21077	21283	21502	21734	21978
	0.6	20577	20780	20996	21225	21465
	0.7	19910	20108	20319	20543	20778

Table 11: Total Energy Cost of Skylights with different VT and Different SC
Dark Blue shows the unreal alternatives that software is able to simulate and dark orange is the 10 most energy efficient alternatives. The light grey cell shows the most energy efficent glass type in Austin.

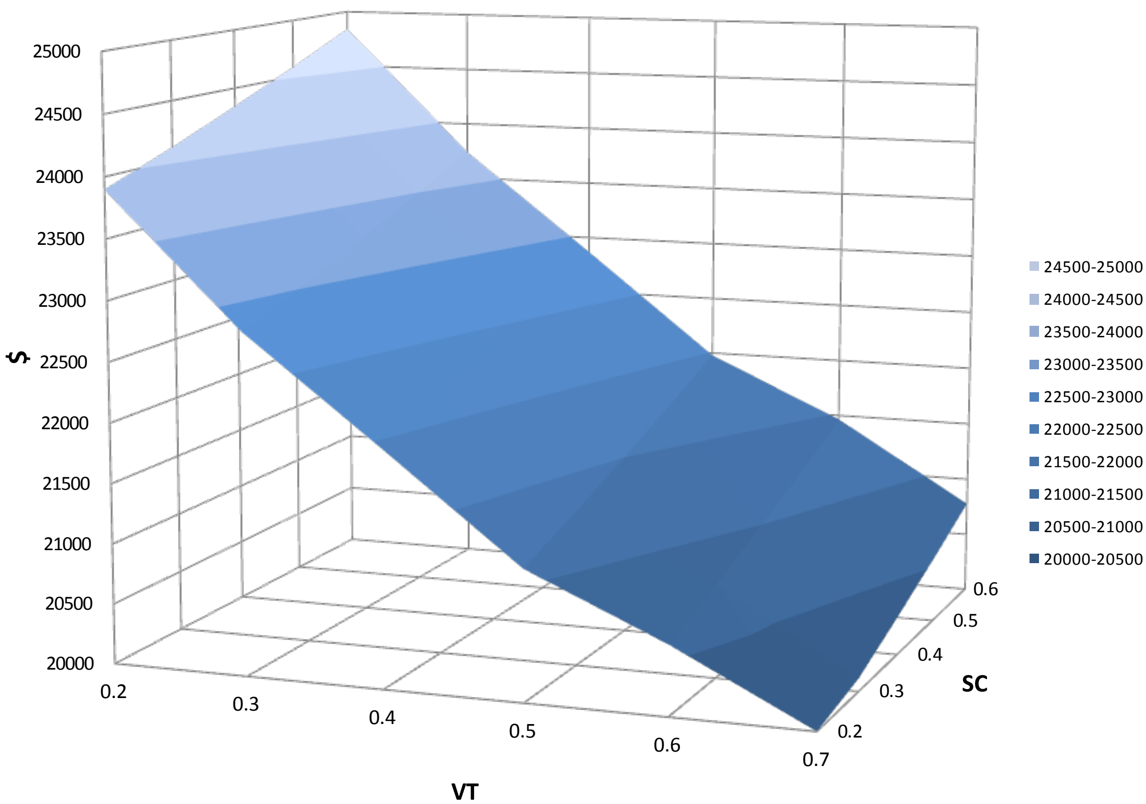


Figure 40: 3D graph of SC v.s. SC

(0.4), VT (0.7) and SHGC of (0.34). The dark orange cells with thick solid boundaries show the (10) most energy efficient glass scenarios.

For better understanding Figure 40 illustrated the 3d graph of table 9 . As shown in this figure , the highest VT and lowest SC results in lowest total cost.

To understand how much VT and SC contributed in saving energy, I developed tow charts showing the total energy cost saving of models with different SCs but fixed VT (figure 41, as well as models with different VTs but-fixed SC (figure 42).

All curves are parallel in figures 41 and 42. The linear equation for each curve is shown in these figures. For different SCs with fixed VT curve (figure 41) the slope is about (235) which means that for one unit of increased

						Energy Cost ($)
	SC	0.2-0.3	0.3-0.4	0.4-0.5	0.5-0.6	0.6
	SHGC	0.17-0.25	0.25-0.34	0.34-0.42	0.42-0.5	0.504
VT	0.2	215	229	242	254	24838
	0.3	212	226	239	250	23739
	0.4	209	223	236	247	22867
	0.5	206	219	232	243	21978
	0.6	203	216	229	240	21465
	0.7	198	211	224	235	20778

Table 12: Cost Saving ($) for an Increased Unite of SC

SC total cost will be increased by the factor 0f (235$).

The saving energy by the factor of (235) also is noticeable in table 11. In this table each row has a fixed VT. It shows the total saved energy by increasing a unit of SC. As shown in this table 11, all the numbers showing the energy saving are around (200$).

In figure 42 the slope is about (800) which means that for one unit of increased VT total cost will be decreased by the factor of (800$). This also is shown in table 12. In this table each column has a fixed SC. It shows the total saved energy by increasing

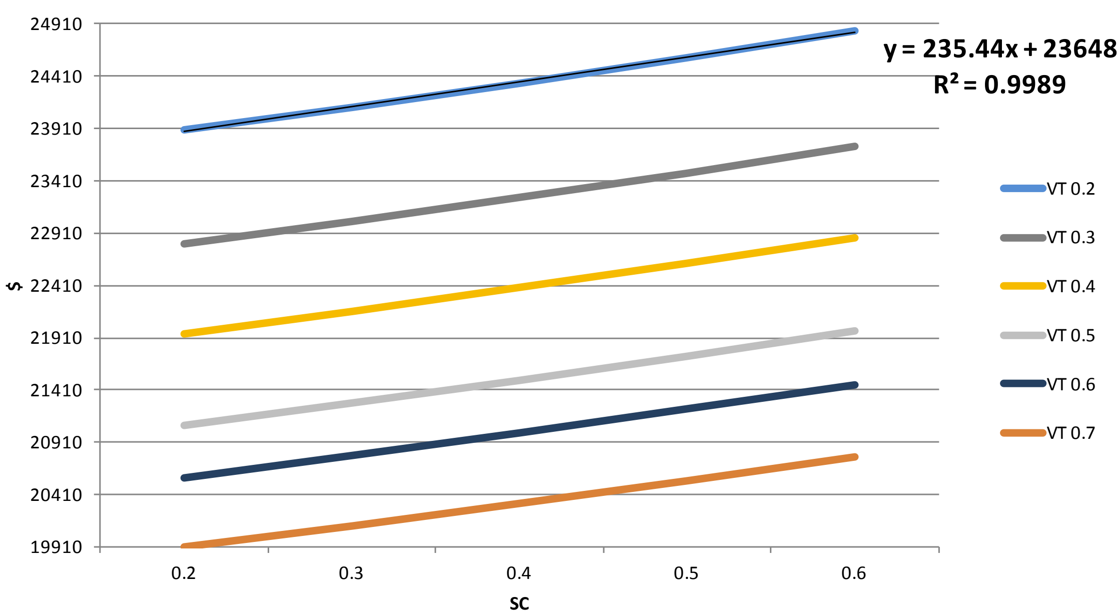


Figure 41: Curves with different SC and Fixed VT

	SC	0.2	0.3	0.4	0.5	0.6
	SHGC	0.168	0.252	0.336	0.42	0.504
Energy Cost $	0.2	23897	24112	24341.49	24584	24838
VT	0.3- 0.2	1085	1088	1092	1095	1099
	0.4-0.3	859	862	865	868	871
	0.5-0.4	876	879	883	886	890
	0.6-0.5	501	504	507	510	513
	0.7-0.6	667	671	676	682	687

Table 13: Cost Saving($) for an Inceased Unite of VT

a unit of VT. The average numbers in this table is about (800$). However, the saved amount of energy reaches its maximum while VT changed from (0.2) to (0.3). This amount of energy is almost about (1000$).

As shown in all these graphs and tables, skylights with higher VT can save more energy than skylights with lower SC. This fact is also demonstrated in the table 13 which is a matrix shows the order of energy efficient glasses.

To select a proper glass, it is important for practitioners to know if it is worthwhile to invest on the specific

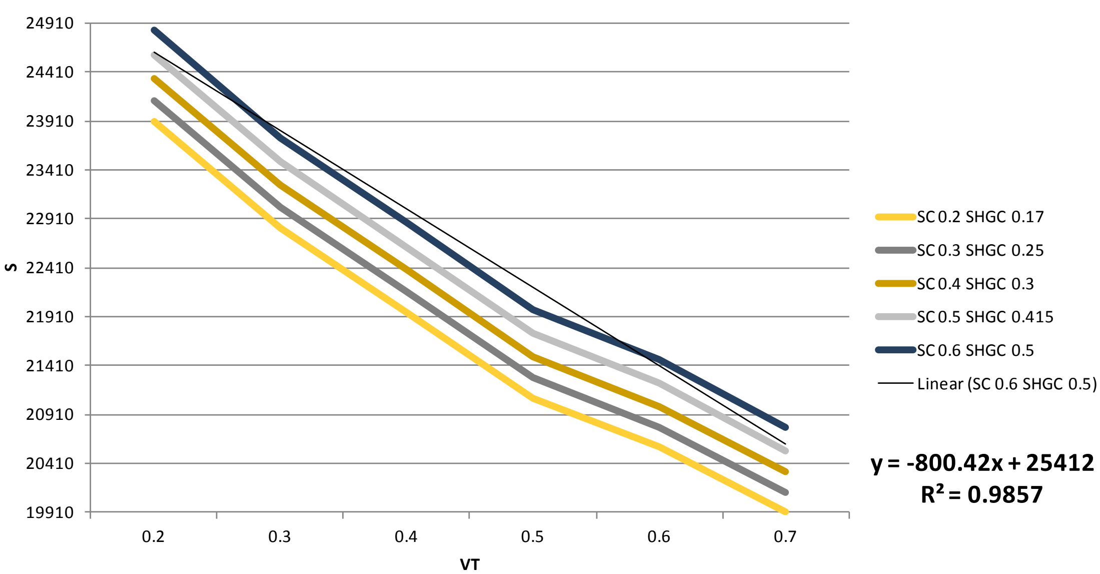


Figure 42: Curves with different VT and fixed VT

SC	0.2	0.3	0.4	0.5	0.6
SHGC	0.168	0.252	0.336	0.42	0.504
VT 0.2	22 19-20: 215$	23 23-24: 229$	24 24-25: 242$	25 25-26: 254$	26
VT 0.3	16 16-17: 55$	18 19-20: 226$	19 19-20: 239$	20 20-21: 250$	21 21-22: 158$
VT 0.4	11 11-12: 25$	13 13-14: 223$	14 14-15: 236$	15 15-16: 192$	17 17-18: 157$
VT 0.5		7 1-2: 181$	9 9-10: 232$	10 10-11: 219$	12 11-12: 185$
VT 0.6		4 4-5: 216$	5 5-6: 229$	6 6-7: 59$	8 8-9: 38$
VT 0.7			1 1-2: 224$	2 2-3: 235$	3 3-4: 2$

Table 14: The order of Energy Efficient Glass Types for Skylights in in Austin and the Total Cost Saving $

alternative. So it can be very useful to prepare a guide that helps the practitionars to compare the energy efficiency of different glass alternatives. Table 13 shows how much will be saved by each scenario compared to the next energy efficient scenario. In this table each cell is a representative of specific glass type. The big bold number in each cell shows the order in energy efficiency of that glass type. Each cell also shows how much can be saved by each type of glass compared to the next energy efficient one. For example the best scenario is alternative number (1) with SC (0.4) and VT (0.7), the next energy efficient one is alternative number (2) with SC (0.5) and VT (0.7). The amount of cost that can be saved by selecting alternative number (1) over number (2) is shown in cell number 1 which is (224$) per year. This is an example for two glass types in a row reagarding energy efficient.

But table 13 can also be used to compare any differnt alternatives. For instance, to compare the energy efficiency of alternative (1), SC (0.4),&VT (0.7), over alternative (16), SC (0.2) and VT (0.3), the practitioner needs to add all the cost from alternative (1) to alternative (15) which is shown in equation 1 below:

$$(224+235+2+216+229+59+38+181+232+219+185+223+236+192+157)\$= 2628\$$$

Equation 1 based on Tale 13 the cost saving ($/year) of alternative 1 over alternative 16

This example shows a very typical decision over the glass type in a hot climate like Austin. Practitioners and Standards like Energy Star don't pay attention to the importance of VT over SC or SHGC. As a rule of thumb practitioners will choose a glass with lower SC or SHGC. For this example, practitioners will choose alternative (16) over (1) because alternative (16) has lower SHGC. However, as shown in the equation above, alternative (1) is more energy efficient than alternative (16)and saves (2628$) per year compared to alternative (16).

For the final result, I prepared another table demonestrates the order of energy efficiency of glass types for skylights in Austin without mentioning the amount of money that will be saved. This table is very simple and it just shows the glass with SC, SHGC and VT, as well as its order in energy efficiency. Table 14 can be used by architects and engineers which can accelarate the design decision about the glass types in a hot climate like Austin. Table 14 is shown in the next page.

In the final chapter, I will summarize all the findings of my master thesis; I will also discuss over the importance of standards and the wrong beliefs among practitioners over toplighting, daylighting and glass types.

	VT	SHGC	SC
1	0.7	0.336	0.4
2	0.7	0.42	0.5
3	0.7	0.504	0.6
4	0.7	0.504	0.6
5	0.6	0.336	0.4
6	0.6	0.42	0.5
7	0.5	0.252	0.3
8	0.6	0.504	0.6
9	0.5	0.336	0.4
10	0.5	0.42	0.5
11	0.4	0.168	0.2
12	0.6	0.42	0.5
13	0.4	0.252	0.3
14	0.4	0.336	0.4
15	0.4	0.42	0.5
16	0.3	0.168	0.2
17	0.4	0.504	0.6
18	0.3	0.252	0.3
19	0.3	0.336	0.4
20	0.3	0.42	0.5
21	0.3	0.504	0.6
22	0.2	0.168	0.2
23	0.2	0.252	0.3
24	0.2	0.336	0.4
25	0.2	0.42	0.5
26	0.2	0.504	0.6

Table 15: The Order of Energy Efficient Glass in a Hot Climate Like Austin

Chapter Nine: Conclusion

9.1. SUMMARY AND DISCUSSION

Daylgiht is a traditional design strategy that can improve the quality of the life and the productivity of the office building. Architects and engineers appreciate the beauty of toplights but they are doubtful to actually implement them in a hot climate like Austin because of heat gain. In the modern world, that architecture is moving fast toward energy efficiency and reducing the foot print, daylighting through toplights is disgraced especially in a hot climate because of the concern over the direct solar heat gain and thermal impact. The goal of this master thesis was to analyze how daylighting through toplights impacts the building loads. In most of the research that have been done the importance of daylight in decreasing electrical lighting loads, as well as lighting heat gain is taken out of the equations. Even the software was not that developed to consider the impact of daylight in lighting loads and lighting heat gain. In this research through series of simulation by advanced energy software tool, IES VE, I proved that daylight can save the total energy loads of building. In fact, the saved electrical lighting is much bigger than increased heating/cooling loads. In this study the impacts of toplights on electrical lighting, cooling and heating loads were investigated. Different toplight strategies such as skylights, monitor roofs, and sawtooth roofs were compared regarding the site energy and cost. I prepared a design guide comparing different toplighting strategies regarding energy efficiency, as well as illuminance. Such a design guide can accelerate the implementation of toplights in design decisions.

Since my simulations show that daylighting can significantly save energy, I hypothesized that visible light of the glass should have an important role in saving electrical lighting. However, in a hot climate like Austin very low Solar

Heat Gain Coefficient (SHGC) is recommended for the glass by different standards and codes. This may significantly decrease the Visible Light (VT) and ultimately the energy efficiently of the building. To understand which of VT or SHGC is more important in saving energy, I compared different Visible Transmission (VT) of the skylight glass with different Solar Heat Gain Coefficient. The results show that Visible Light should be more important factor than SHGC when it comes to choose the type of the glass. I prepared another design guide which shows what types of the glass save more energy in Austin. The optimum glass type for skylights in Austin is a glass with SHGC of (0.33), SC of (0.4) and VT of (0.7). The higher the VT the more energy will be saved.

Inadequate understanding and awareness about the benefits of toplights can affect codes and regulations which fail to encourage energy savings. Regulations such as Austin code and ASHRAE should incorporate toplighting requirements in certain circumstances such as big shopping mall boxes. Most state codes discourage, however, skylights due to their thermal impacts. For example, 2006 IECC (International Energy Conservation Code) limits skylights to (3%) of the roof area. This is in contrast with results of my thesis which shows skylights with (5%) of the roof area in a hot climate can save considerable amount of energy.

In addition to limitations of skylight area, most of the codes prescribe a very low Solar Heat Gain Coefficient (SHGC) and they don't require higher Visible transmission. Low SHGC may limit the Visible Transmission (VT) of efficient skylights which can decrease the energy benefits of toplighting.

My conclusion is that codes and standards should not only focus on thermal properties of toplights but also address the electrical lighting savings of toplights and encourage the community to implement toplights. The regulations should address both VT and SHGC. Importantly VT of toplights needs to be redefined in regulations since my results show that higher VT can save more than lower SHGC.

9.2. FUTURE STUDIES

In this study I analyzed the energy efficiency of toplights in a hot climate like Austin. I didnot consider different locations. Therefore, rmre research needs to be done for different climates. In a cold climate daylight can save electrical lighting and provide passive solar heat gain most of the year while it will decrease electrical lighting gain. Extensive research with monthly analysis is necessary to understand if daylighting is an energy efficient strategy in a cold climate as well.

In addition, it is also important to indicate that the glare issue was not the material of this study. Excessive daylighting can cause glare in the space and irritates the human eye. The glare issues can calibrate the future study in this field.

Moreover, the type of building has a key role in energy efficiency of toplights. My study was for an office building which is considered as a highly lighting loaded building. For other types of buildings like residential ones more research has to be done. In a residential building the lighting load is (11%) compared to an office building with (21%) electrical lighting loads. This may jeopardize the energy efficiency of daylighting in residential buildings.

In this paper I presented that toplights with (5%) of the roof area can save energy in a hot climate. However, in my research I did not calibrate the area of the toplights. Hence, more research needs to be done to optimize the aperture size of different toplights in order to get the most benefits out of toplighting strategies.

In the long run, in this thesis I come to this conclusion that daylighting through toplights can play an imperative role in energy efficiency if toplights distribute the daylight evenly into the space. Factors such as glazing area and visible transmission of toplights which affect the daylighting can change the efficiency of toplights and ultimately the energy efficiency of the building.

References

Moek, Yoon. How much energy do different toplighting strategies save?, US Department of Energy, 2008

Lawrence, Tyson. Commercial building toplight: energy saving potential and potential paths forward, US Department of Energy Report, 2008

Michaels, Joelle Davis. Energy for Commercial Buildings. US Department of Energy, CBECS, 2005 http://www.eia.gov/emeu/consumptionbriefs/cbecs/pbawebsite /office/office_howuseenergy.htm

ASHRAE. 2005. Handbook of Fundamentals. American Society of Heating, efrigerating and Air-Conditioning Engineers, Inc., Atlanta, Georgia

Mohamed Boubekri and Ebooks Corporation, Daylighting, Architecture and Health: Building Design Strategies, Burlington:Elsevier, 2008

Wirz-Justice, Anna, Peter Graw, Kurt Kräuchi, Asita Sarrafzadeh, Judie English, Josephine Arendt, and Lothar Sand, Natural Light Treatment of Seasonal Affective Disorder, Journal of Affective Disorders 37, no. 2–3 (April 12, 1996): 109-120

Gagnon, Alec. High Museum Expansion – Atlanta, Georgia. AEWORLDMAP.COM (1,647 Posts), n.d http://aedesign.wordpress.com/2009/08/31/high-museum-expansion-%e2%80%93-atlanta-georgia/

Sullivan Conard Architects. Houzz, 2009 http://www.houzz.com/photos/22150/ Sullivan -Conard-Architects-contemporary-living-room-seattle

Unit Skylights. C and H Building Specialist, n.d http://candhbuildingspecialties.com/ index.php?id=397

Lance Armstrong Foundation Headquarters / Lake|Flato Architects and The Bommarito Group. ArchDaily, 2011 http://www.archdaily.com/105042/lance-armstrong-foundation-headquarters-lakeflato-architects-and-the-bommarito-group/

Culter, and Durand. MIT Computer Graphics. Issuu, 2001 http://iss uu.com/ examzone/ docs/ computer-graphics20.

Mardaljevic, John. Daylight Simulation: Validation, Sky Models and Daylight Coefficients. De Montfort University, 2000.

Radiance Overview. Integrated Environmental Solutions, IES, 2008 http://www. iesve .com/ content/download asset_2316.

Tax Deduction Qualified Software. US Department of Energy, Energy Efficiency and Renewable Energy, 2009

Trocellini, P, B Griffith, and R Judkoff. Evaluation of the Energy Performance and Design Process of the Thermal Test Facility at the National Renewable Energy Laboratory. National Renewable Energy Laboratory NERL, 2005 http://www.nr el.gov/docs/fy05osti/34832.pdf.

Eugene, M, K Burn Jay, and Olsen. Energy Consumption Series, Energy End-Use Intensities in Commercial Buildings. Energy Information Administration Office of Energy Markets and End Use U.S. Department of Energy, 1994. http://apps 1.eere.energy.gov/buildings/publications/pdfs/corporate/ns/qs_iesve_ v6_1.pdf

Ghatti, Vinay. "Section Design." eLADwiki, 2011 http://elad.lbl.gov/index.php/Section Design.

Winiarski, D., J.Hail Shankle, B. Liu, and A. Walker. Energy and Construction Estimates. Pacific Northwest National Labratory and National Renewable Energy Labratory, n.d. http://www1.eere.energy.gov/femp/pdfs/buscase_appendixb.pdf.

Yuri, Mun. Earth Radiation Budget, Earth Radiation Budget/Environmental Science/Rutgers, The University of New Jersey 1998 http://marine .rutgers. edu/ mrs/education/class/yuri/erb.html.

Longwave and shortwave radiation Pearson Prentice Hall, inc 2007

Global Climate Animation. Department of Geography, University of Oregon, 2003 http:// geography.uoregon.edu/envchange/clim_animations/.

Versage, Rogerio, Ana Paula Melo, and Roberto Lamberts. Impact of Different Daylighting Simulation on the Prediction of Total Energy Consuption. Energy efficiency in building laboratory, Federal University of Santa Catarina, 2010 http :// www.ibpsa.us/pub/simbuild2010/technicalPresentations/SB10-PPT-TS01A-01-Melo.pdf.

Lighting Level. Chartered Institute of Building Servise Engineers, 2002http://www. Arca 53.dsl.pipex.com/index_files/lightlevel.htm.

Grondzik, Walter, Alison Kwok, Stein Benjamin, and John Reynolds. Mechanical and Electrical Equipment for Buildings.Chapter 14 &15, 2010

Lighting, Integrated Environmental Solutions, IES Forum, 2012http://forums. iesve.com/ viewforum.php?f=186&sid=c6ce2c74bad0311631bdaa7332ff3ba2.

Stefan Bader, High Performance Façades for Commercial Buildings, Austin,: University of Texas, 2010

Dariush Arasteh et al., Window Systems for High-Performance Buildings, W. W. Norton & Company, 2003

Nancy Ruck et al, Daylight in Buildings: A Source Book on Daylighting Systems and Components, Washington: International Energy Agency, 2000

Gregg D Ander, Daylighting Performance and Design New York: Van Nostrand Reinhold, 1995

Edward Dean, Daylight Design in Libraries, U.S. Institute of Museum and Library Services, 2005

Mary McAuliffe, The erasure of the canopy: spatial definition at the Menil Museum [Houston], Crit, no. 19, 1987

Alison G Kwok, The Green Studio Handbook: Environmental Strategies for Schematic Design, Oxford: Architecture Pressl, 2007

Mark Frankel and Cathy Turner, How Accurate is Energy Modeling in the Market? (ACEEE, 2008)

McHugh, Jon. Modular Skylight Wells:Design Guidelines for Skylights with Suspended Ceilings. California Energy Commision, 2003

Daylighting Guide for Canadian Commercial Buildings. Public Works and Government Services Canada, 2002

Galasiu, A.D. Application of Daylighting Computer Modeling in Real Case Studies. International Energy Agency, 1998

Leslie, Russell. Patterns to daylight schools for people and sustainability. Rensselaer Polythecnic Institute, 2010

Motamedi, Sara. Energy Analysis of Different toplights for Office Buildings in Austin, World Renewable Energy Forum Conference, 2012

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