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Innovative Fiber Optic/Thin Film Photovoltaic Systems: Adequately Distributing Daylight While Harvesting Energy

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INNOVATIVE FIBER OPTIC / THIN FILM PHOTOVOLTAIC SYSTEMS:

ADEQUATELY DISTRIBUTING DAYLIGHT

WHILE HARVESTING ENERGY

By

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Bachelor of Science – Interior Design
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A thesis submitted in partial fulfillment
of the requirements for the

Master of Architecture

School of Architecture
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ABSTRACT

On any given year, Las Vegas will be exposed to an average of 85% sunlight during typical daylight hours, while averaging seven peak hours a day. That alone makes Las Vegas a prime candidate for renewable solar energy systems (Solar Direct, 2016). By implementing fiber optics into office buildings in conjunction with thin-film photovoltaics, interior spaces have the potential to be adequately illuminated while simultaneously harvesting electricity. The study will be conducted through analysis and experimental field research with the intent of generating physical data, demonstrating that a hybrid fiber optic - photovoltaic system can at minimum match recommended foot-candle values and reduce a building's electricity demand. Supplementary information on United States energy generation and consumption of fuels and the experimental data from this study are cataloged under appendix 1 and 2.

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CHAPTER 1: INTRODUCTION

"A room is not a room without natural daylight."

-Louis Kahn

1.1 GLOBAL WARMING

Climate change can be described as one of the greatest humanitarian crises of the 21st century. It has been linked to rising sea levels and shifts in weather conditions such as drought, heat waves, storms, floods, and a climbing trend in global temperatures. The United States Global Change Research Program states, "global warming is unequivocal and primarily human-induced" and that "climate changes are underway in the United States and are projected to continue to grow exponentially" (U.S. Global Change Research Program 2009, 13)

Manmade refrigerants and aerosol propellants have contributed to changes in the Earth by deteriorating the ozone layer, allowing higher IR and UV rays to enter the Earth's atmosphere. However, the primary pollutant associated with global warming is the greenhouse gas known as carbon dioxide. Research on current climate systems reveals that human induced environmental emissions of greenhouse gases are higher than ever before (U.S. Global Change Research Program 2009). The last thirty years have demonstrated warmer surface temperatures over any previous decades since 1850. Additionally, "the past three decades have been recorded as the warmest period over the last 1400 years in the Northern Hemisphere with a combined land and ocean surface temperature increase of 0.6 to 0.9 degrees Celsius, or 1.1 to 1.6 degrees Fahrenheit" (Core Writing Team, R.K. Pachauri and L.A. Meyer 2014, 8)

(a) Globally averaged combined land and ocean surface temperature anomaly

(b) Globally averaged sea level change

(c) Globally averaged greenhouse gas concentrations

(d) Global anthropogenic CO₂ emissions
Quantitative information of CH₄ and N₂O emission time series from 1850 to 1970 is limited
- Fossil fuels, cement and flaring
- Forestry and other land use

Cumulative CO₂ emissions
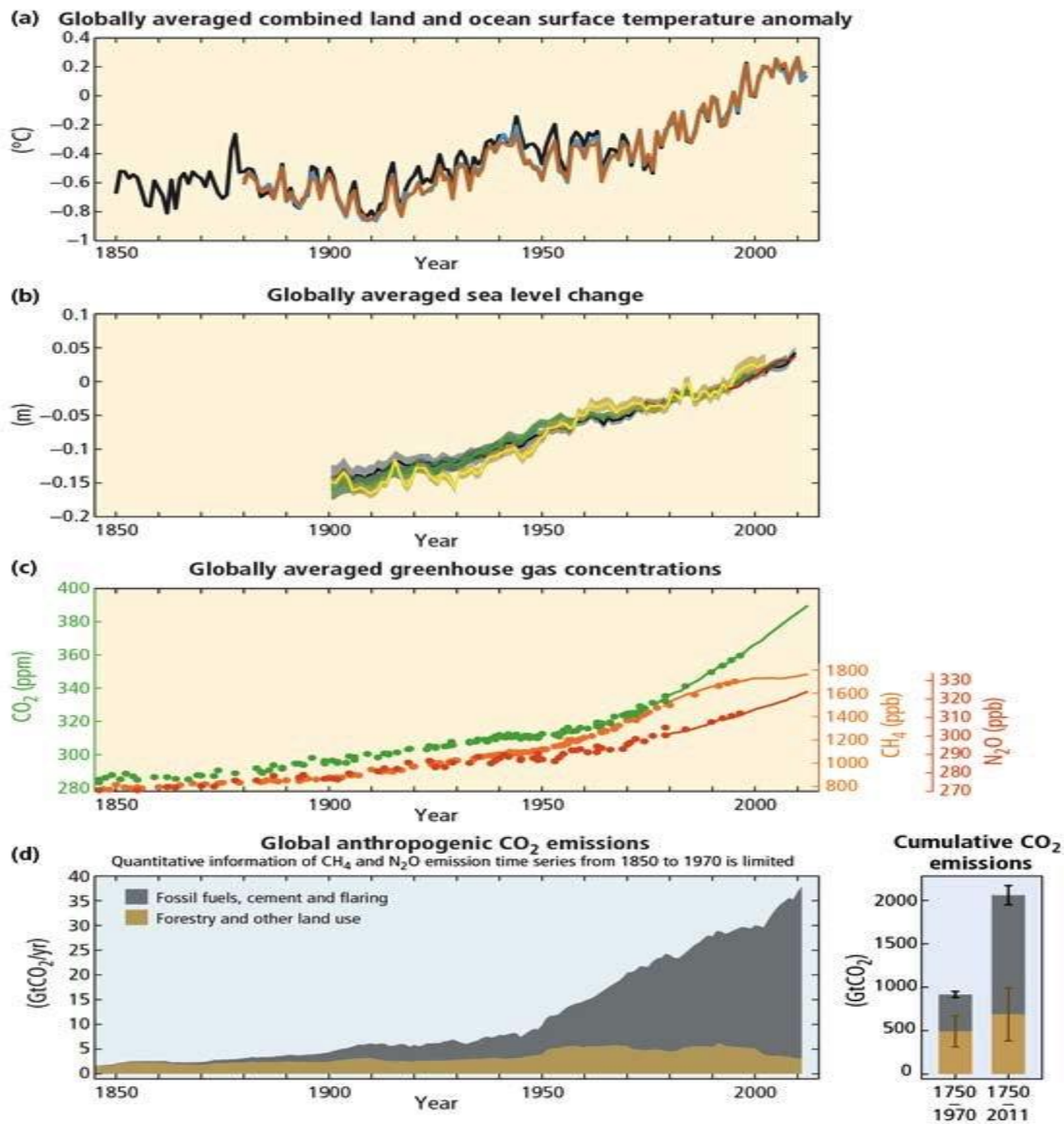
Table 1.1 (NOAA Global Analysis 2015)

Furthermore, the 2014 IPCC Climate Change report states they are "virtually certain that there will be a both higher and lower temperature ranges across most land areas during both daily and seasonal timescales". As the Earth's temperature increases, "it is very likely that progressive heat waves will occur more often and for longer duration,

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while in some areas, extreme cold winters will continue to occur"(Core Writing Team, R.K. Pachauri and L.A. Meyer 2014, 8).

Climate change continues to burden society's ability to meet human development goals while maintaining the growth of natural resources and ecosystems. As a result, governments around the world are taking measures to limit emissions of carbon dioxide and other greenhouse gases. One way is through the Kyoto Protocol, an international agreement linked to the United Nations which proportionally commits developed nations to cut back on carbon dioxide emissions caused by more than 150 years of industrial activities (UNFCCC 2015). Even though the framework set up by the Kyoto Protocol has yet to take precedent around the globe, an impending update may provide a much-needed boost with the conclusion of the 2015 climate change conference held in Paris.

1.2 BUILDING SECTOR IMPACTS

The United States building sector is responsible for 30% of the countries annual greenhouse gases and consumes 40% of the world's total annual energy (United Nations Environment Programme, 2015). This allows the nation to become one of the leading countries in mitigating future climate change through innovative and adaptive sustainable technologies.

According to the U.S. Energy Information Administration's Electric Power Annual 2013 analysis, the United States produced 2388 giga-watts of power by utilizing high carbon emissive resources such as coal, petroleum used for fuel, natural gas, and nuclear power for buildings' electrical generation (Refer to Chart 1.1). In 2014, the United States generated about 4,093 billion kilowatt-hours of electricity. While coal is still the largest source of electric generation with 39% of the overall used resources, the nation's dependence on it has slowly begun to decline as natural gas and renewables continue to enter the market. Currently 67% of electricity has been generated from fossil fuels such as coal, natural gas, and petroleum (U.S. Energy Information Administration 2015).
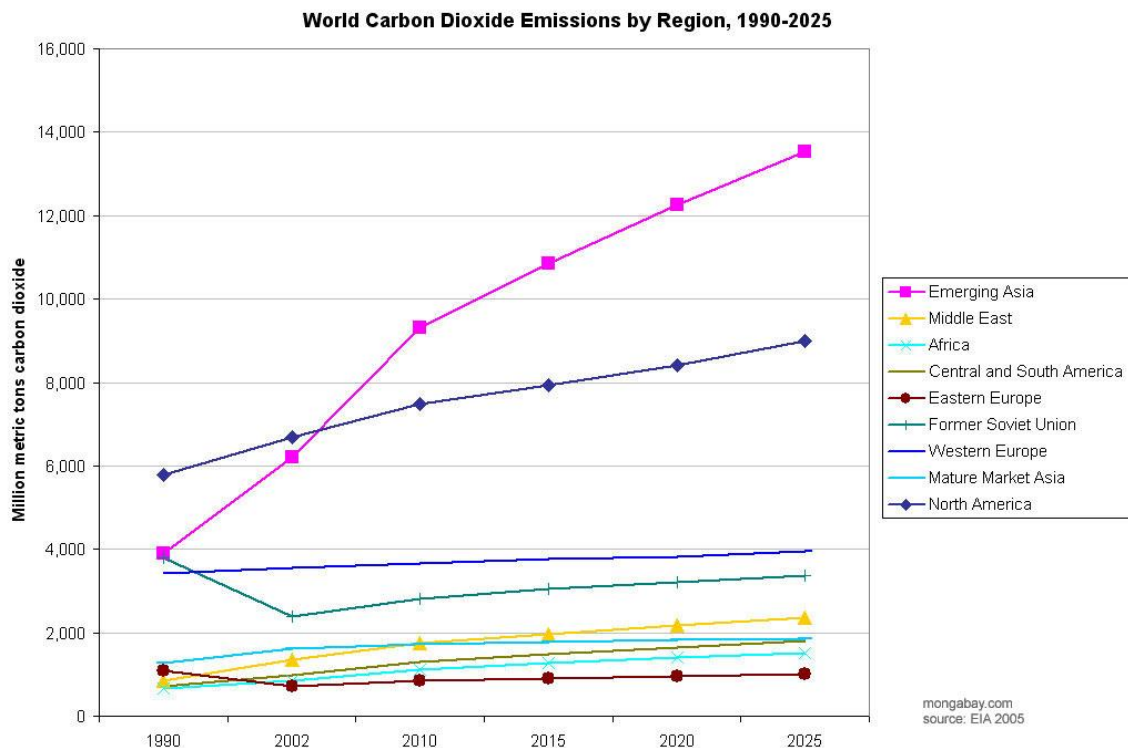
Table 1.2 (1990-2025 World Carbon Dioxide Forecast by the Department of Energy's EIA)

Buildings account for about 47% of the energy consumed in the United States. Heating and cooling systems use about 55% of this energy while lighting and appliances use the other 45% (Zhou and others 2015). In regards to the environment, the effects caused by the building sector demonstrate huge threats to humanitarian, social, and economic ways of life.

"In the buildings sector, an effective energy solution should be able to address long-term issues by utilizing alternative and renewable energy sources" (IEA PVPS Programme, 2014, 5). Buildings alone allow for numerous renewable energy strategies. However, solar energy is a promising and viable option considering that it is both renewable and abundant in nature.

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1.3 OFFICE BUILDINGS

Office buildings require a great deal of energy to deliver comfortable environments for inhabitants. As a passive energy saving strategy, daylighting has the opportunity to play a vital role in the growing industry of renewable energy with regards to reducing the use of electricity. Daylighting greatly impacts the energy consumption incurred by office buildings across the country.

The United States Green Building Council states that buildings consume nearly half of the energy in the United States and contributes 46.7% of the country's greenhouse gases. In 2013, office buildings accounted for 21% of all commercial energy consumption, which averaged 1.4 billion BTU's of energy with a consumption intensity of 97.2 kBTU/ft^2 (U.S. Energy Information Administration 2014b). A decrease in energy use and the increase or utilization of renewable energy sources has been shown to lead to lower production of greenhouse gas emissions.

Due to the growth of today's modern building sector, buildings are the main source of power consumption and greenhouse gas emission, with a growing electricity demand of .07%/year in the United States. The United States Energy Information Administration notes that

Industry 19.9%
(1120 MMT CO$_2$e)

Buildings 46.7%
(2631 MMT CO$_2$e)

Transportation 33.4%
(1881 MMT CO$_2$e)

U.S. CO$_2$ Emissions by Sector

Source: ©2011 2030, Inc. / Architecture 2030. All Rights Reserved.
Data Source: U.S. Energy Information Administration (2011).
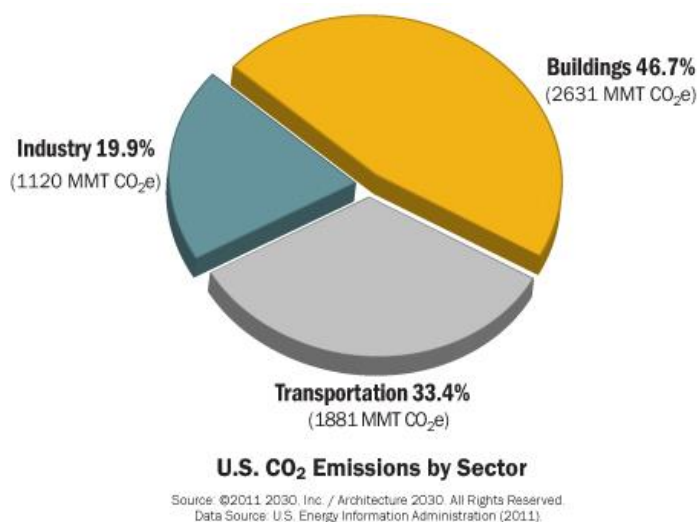
Table 1.3 (2011 U.S. Energy Information Administration)

buildings expel 46.7% of the nation's CO2 emissions (U.S. Energy Information Administration 2014b). Thus, a higher level of consideration has been given to energy consumption due to electric illumination in buildings, which is a major source of energy use. The IPCC reports that energy consumption as a result of electric lights in office settings is approximately 40-50% of the total building energy cost (Hassenzahl 2012). A significant reason for this is that lighting demands are increasing due to rising average luminance levels in buildings suggested by the IES, especially in new construction.

As a way to combat the world energy crisis, "Net Zero" and "Low Carbon Emitting Buildings" have begun to redevelop the framework of architectural thinking. The World Commission on Environment and Development outlines sustainability as, "meeting the needs of the present without compromising the ability of future generations to meet their own needs" (Khamseh 2014, 161-166).

A key component in sustainable design is to maximize solar energy on a given site by utilizing both solar energy capabilities as well as solar illuminating qualities. This is done through the application and use of photovoltaic energy and strategic daylight systems. Well-designed buildings utilizing efficient daylight strategies are estimated on average to reduce electric energy use by 50-80% (Khamseh 2014). Therefore, an appropriate sustainable daylight strategy is encouraged and will lead to a solution to the current rising energy problem.

In sustainable design, the interior of a building is well-lit through the use of daylight coming from exterior fenestration and daylight operating systems. The Illuminating Engineering Society recommends that an office buildings interiors have an average

illuminance of 30 Foot Candles plus task lighting (DiLaura 2016). Depending on the location of the building's fenestration and the size of the glazing, light entering the space will decrease in intensity rapidly, resulting in interior spaces lacking required light levels. As a result, the illumination can sometimes be inconsistent, resulting in dark patches and areas.

It is unrealistic to achieve recommended light levels throughout the entirety of a given day through fenestrations and openings alone. Therefore, society has relied on electric lighting to provide supplemental lighting. In 2014, The U.S. Energy Information Administration estimated about 412 Billion kWh of electricity was used to light residential and commercial sectors in the United States. This was approximately 11% of the total U.S. electricity consumption. (U.S. Energy Information Administration 2014a) (Refer to Chart 1.3)

By utilizing the properties of daylight, we can reduce a building's need for fossil fuel generated energy and lower the cost to sustain a building while simultaneously lessening the associated environmental damages.

1.4 DAYLIGHT METHODS

Based off current technological trends and existing research, advances in daylight strategy usually focus on one of multiple methods at a time. Some strategies focus primarily on a specific daylight catchment strategy while others focus on the improvement of photovoltaic systems. Several daylight-transferring systems already exist in the market today such as light pipes, light guides, and solar collectors, but most of these designs are either bulky in size or require a large area for installation on the project site. While photovoltaics operate in the same manner, different materials can be applied to convert ultraviolet waves and solar radiation into usable energy (Oh and others 2013).

In comparison to photovoltaic systems, fiber optic technology is in its infant stages, but it already provides significant benefits in regards to sustainable daylight design. Fiber optic daylight is an innovative technological system that can transmit harvested daylight to interior spaces using either side lighting strategies or top-lighting designs. Today, daylight fiber optic strategies are categorized as being either passive or hybrid. A passive system typically contains three major components: sunlight collectors (typically a Fresnel lens), optical fibers, and a luminaire to evenly distribute the collected light within a given interior space (ECW 2008) Hybrid systems are similar in design, but also include electric lamps and dimming controls to provide constant light levels. Recent advances to the technology allow for minimal light loss through the cables due to the structure of the fibers themselves. Since the daylight is transmitted through a collector and lens, potential for heat gains within the building are eliminated. Current

developments in the glass fiber technology have allowed for a light transmission of 98.6% per foot at a maximum of 66Ft. (Parans 2016). These strategies will not only, improve indoor environmental conditions, but also conserve large amounts of energy. These systems have the opportunity to not only conserve large amounts of energy, but also improve indoor conditions.

Photovoltaic industries as a whole have experienced rapid growth over the last decade due to environmental concerns. The 2011 World Energy Outlook released by the International Energy Agency provided data denoting that an increased production of solar energy is essential to ensure a steady and secure energy stream while drastically limiting the effects of energy-induced climate change (IEA PVPS Programme 2014). While traditional silicon based PV systems continue to progress, developments in the industry focus on the discovery of new materials that will increase a system's efficiency rate. Recent discoveries have allowed for the development of full spectrum photovoltaic systems. These new systems utilize a new semiconductor material made from indium, gallium, and nitrogen that can virtually convert the entire spectrum of sunlight into electricity (Kim and others 2009). Typical photovoltaic systems have always had an unwieldy and opaque quality to them making it almost impossible for them to be used for any other purpose outside of generating electricity. However, Thin-Film photovoltaic has provided opportunities of transparency while offering the consumer significantly lower cost benefits. Additionally, they require significantly less active materials in comparison to their crystalline silicon counterparts while allowing for unique flexibility, low weight, and lean production processes.

To offset the carbon footprint and energy consumption of buildings, the goal of this research is to develop an integrated Photovoltaic/fiber optic system. This system must be capable of converting collected solar radiation into electricity while also providing necessary illuminance values to an interior space beyond what would typically be achieved through vertical fenestration. A hybridization of the two systems would be a unique prototypical strategy which combines the better of the two systems. The fiber optic system would collect and redirect the daylight into a luminaire coupled with thin-film photovoltaics. By applying the photovoltaics to vertical fins within the fixture, a significant amount of the collected visual spectrum would be able to pass through and illuminate the interior space. Meanwhile, the collected solar radiation would be harvested and converted into energy that potentially allows the system to be self-sustaining and net positive.

Because this specific method of daylight collection has not been tested before, any data retrieved during this process of experimentation will have the potential to provide advancements in modern daylight strategies while assisting in the development of new sustainable lighting technologies. Additionally, this research can lead to large energy savings helping to reduce overall carbon emission output caused by buildings. Adequately increasing the amount of daylight distributed throughout a building will lead to a much more enjoyable user experience that could theoretically lead to increased productivity levels and create more dynamic environments for high-rise typologies.

CHAPTER 2: LITERATURE REVIEW

2.1 PREFACE

Research that references daylight systems tends to focus on the exploration of enhancing key components within an existing strategy. It was essential for my own research to develop an understanding of the most recent advancements as well as current technological developments within the field of solar design. I conducted my research in a manner that analyzed key components of both fiber optic systems and photovoltaic strategies in order to develop validity towards the intended research goals. This also helped to determine the most suitable assembly strategy that would best fit my own research explorations.

2.2 CHARECTERISTICS OF LIGHT

The most natural and abundant source of light comes from the sun. Sunlight plays a fundamental role in the survival of all living things on Earth. By converting solar energy collected from the sun into sugars through the process of photosynthesis, plants are capable of sustaining all life forms on earth.

Solar radiation most resembles that of a black body, with a maximum temperature of 5,800 K (Russel 2012). With a black body diagram, all colors of light can be categorized and accurately labeled. Through the process of nuclear fusion, the sun emits a broad range of electromagnetic radiation in the form of wavelengths in the ultraviolet, visible, and infrared portions of the light spectrum. Electromagnetic radiation can commonly be viewed as a wave defined by wavelengths of frequencies. Wavelengths are the distances between peaks, while frequency is the number of waves that travel past a fixed point per unit of time (Hz). "Visible light consists of
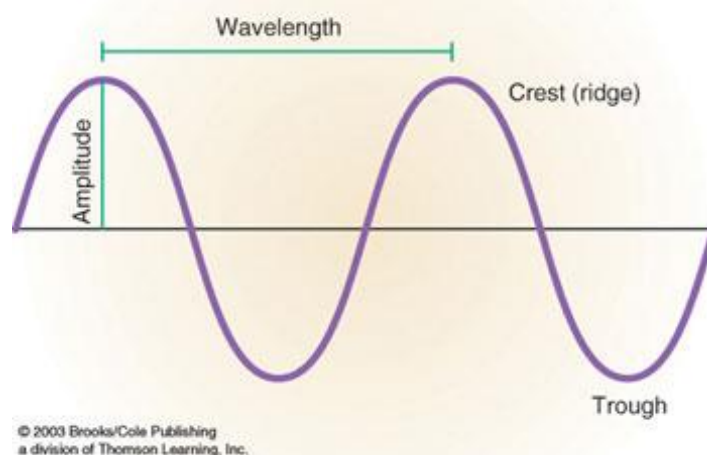
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Figure 2.1 Diagram of a Wavelength taken from CIMSS

wavelengths, between infrared and ultraviolet wavelengths with a range of 380-770 nm, and is commonly the only portion of the solar spectrum of radiation that is visible to the human eye" (Pal 2001, 387) .

In his book, Architecture of Light, Russel best describes the nature of light and the importance of it in reference to the built form:

"In the built environment, it is safe to say that the majority of our experiences are visual. Sound, smell and touch certainly play various roles, but the typical person relies on vision to deliver a very large quantity of information. Vision, by its very nature, is a product of light. It is the result of the creation of light, the reflection of light and ultimately the absorption of light by our visual system. Logic dictates then that if we want to have maximum control of the designed environment we must become intimate with light and learn to make it our ally" (Russel 2012, 115).

Sunlight has natural spectral qualities that range throughout the entire visual spectrum. Because of this, sunlight helps to stimulate biological functions within the human body. Typical electric lamps do not compare to the diversity of the sun's light. Fluorescent lamps, the most commonly used fixtures across the country, fit in the yellow to red end of the spectrum. Incandescent lamps, which are becoming less widely used due to their inefficiencies, are concentrated within the orange to red portion of the spectrum.
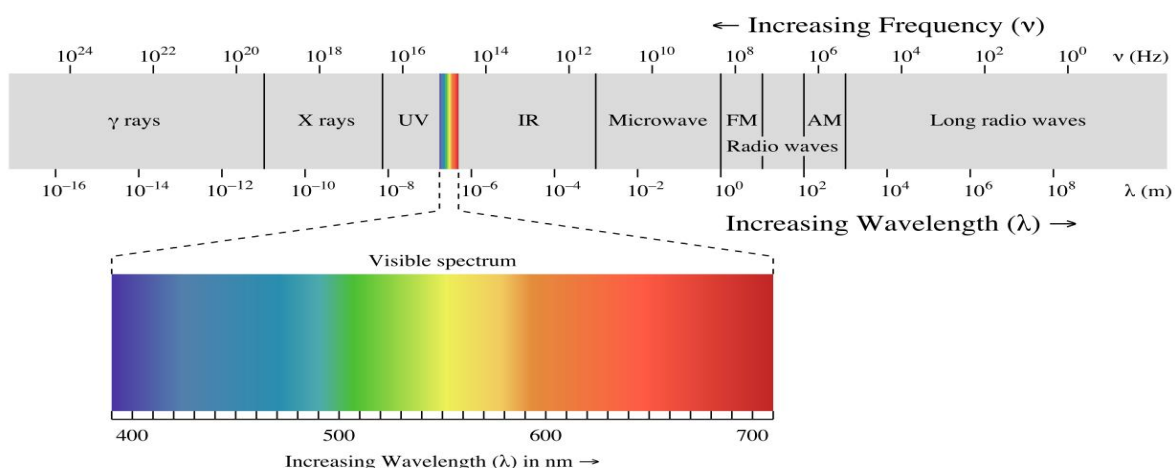
Figure 2.2 Diagram of the Solar Radiation Spectrum taken from Princeton.edu

Recently, companies have attempted to create products that can simulate the sun's spectral range. General Electric has released a new line of fluorescent fixtures including the "Reveal" full-spectrum lamp, which Edwards described as, "the first lamp that closely simulates natural light because it has wavelengths in the blue portion of the spectrum between 400-500 nm" (L. Edwards, and P. Torcellini 2002, 9-10).

2.3 HUMAN HEALTH

Daylight used to light building interiors can improve indoor spaces, human health, lighting quality, and energy efficiency. An electric lighting system often fails to produce comfortable indoor environments, which in turn affects the occupants' health. In office buildings, an average employee will spend most of their workday under an electric light source resulting in complaints of eyestrain and fatigue in 15% of office workers (Hoffmann and others 2008). Both our eyes and skin require direct interaction with sunlight as a way to assist the body in absorbing non-visible wavelengths provided by the sun in order to synthesize D vitamins (A. Dunne 1989). "Daylight provides us the ability to connect with the natural world, while balancing our biological clocks" (National Instiue of General Medical Science 2012, 2).

Well illuminated spaces utilizing daylight often demonstrated "better health, reduced absenteeism, increased productivity, financial savings, and preference of workers" (L. Edwards, and P. Torcellini 2002, 9-10). While exposed to natural light, the pineal gland suppresses melatonin to allow for an alert state of consciousness. Researchers at the University Medical Center in Hamburg, Germany determined that when a space utilizes natural lighting that replicates the 400-500nm spectral range of the sun, building occupants will be calmer and more efficient than those who were exposed only to a typical fluorescent system, which leads to happier and more productive occupants (Wessolowski and others 2014).

Another benefit to introducing daylight into a space is the reduction of headaches and Seasonal Affective Disorder, which has been linked to a deficiency of appropriate light

levels. SAD is a medical condition directly related to sunlight exposure. Research

suggests that SAD is primarily caused by an increase in melatonin levels, as a result of

minimal sun interaction. Treatment to the common office symptom includes increased

interaction with daylight. In severe cases, patients sit in front of a device that replicates

solar wavelengths for a medically prescribed period of time (Franta, G, Anstead, K).

2.4 COMMON DAYLIGHTING STRATEGIES

Daylight was originally the primary source of illumination for indoor and outdoor spaces, while fire by candlelight was used during the evening hours to complete tasks in the darkness. Over the last few decades, the need to rely on daylight drastically declined, as electric lighting became a wide spread technology. Nonetheless, as global warming continues to become an issue, a variety of daylight devices have been designed and improved upon in order to maximize the sun's potential thus increasing occupancy acceptance and reducing negative environmental effects.

There are a multitude of different strategies that can be implemented that will allow daylight to enter the interior of a building. These strategies can be characterized based off their intended operations as well as the type of light they were meant to deliver. Due to conciseness, strategies that are most relevant to the intent of this research are reviewed below.

2.4.1 BASIC DAYLIGHTING – FENESTRATIONS AND SKYLIGHTS

VERTICAL FENESTRATION:

The most commonly used strategy to provide direct daylight across the globe is the use of vertical fenestration applied to the exterior elevations of a building. Vertical fenestration allows all qualities of the sun to enter the interior of a building while drastically reducing the need to use electric light during sun peak hours. Fenestration is strongly encouraged especially in the work place primarily because it provides direct access to daylight as well as views of the outdoors, which is psychologically desired by most building occupants. However, vertical fenestration has its weaknesses and limitations. The use of direct daylight is an attractive way to deliver bright light, but it can also bring glare and contrast which can cause visual discomfort and fatigue. In addition, vertical fenestration is limited to its location and orientation on the building. Daylight entering a space through exterior fenestration is limited to the perimeter of a building, increasing the need for electric lighting to provide appropriate light levels within an interior space. Glazing also requires a great deal of attention due to high heat gains attributed to the materials' low R-value (Walter T Grondzik, Alison G Kwok, Benjamin Stein, John S. Reynolds 2010).
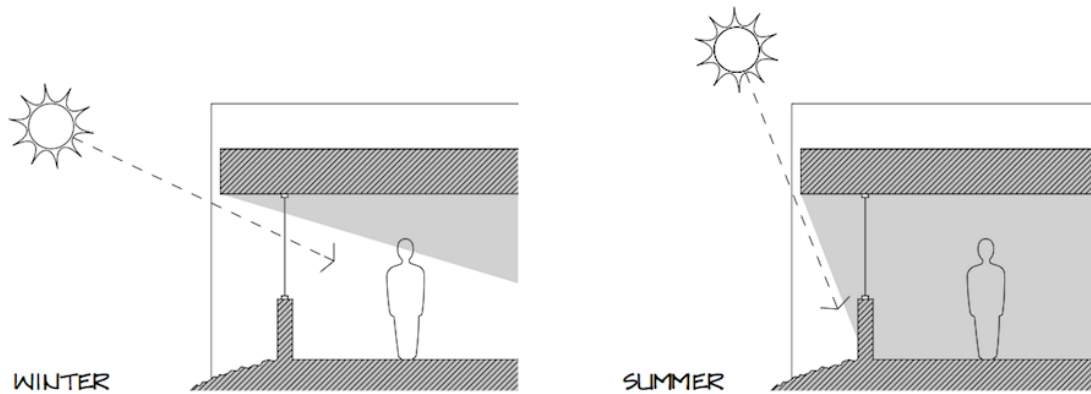
Figure 2.3 Winter and Summer Window Daylight Analysis Taken From DN Architecture

However, manufactures have developed methods to reduce the inefficiencies of glazing and fenestration alike. In the past, the use of tinted or reflective glazing was the primary strategy in controlling heat related variances. Today, the use of light diffusing glass such as frosted or fritted glass is another strategy to diffuse light. These methods drastically reduce the transparency qualities of the glazing.

Recently, spectrally selective films applied to glazing have begun to grow within the market. Spectrally selective films block IR and UV wavelengths while allowing a high amount of light to pass. When comparing tinted films with a spectrally selective window film, researchers found that nearly all the light within 850-1200nm was reflected while having minimal loss of light transmission (R. Padiyath, C. Haak, L. Gilbert, 3M Company)

SKYLIGHTS:

Another common application very similar to vertical fenestration is the skylight. Skylights are essentially fenestration located within the framework of the roof. They provide the advantage of increasing the amount of daylight that enters an interior space past the limits of what a vertical system located on the perimeter walls can offer.

Nonetheless, a skylight is a large opening within the roof system. The opportunity for unwanted drafts and leaks that cause an uncomfortable interior environment to occur

(a)
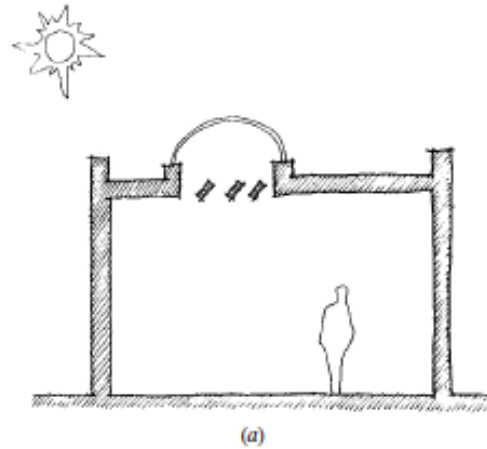
Figure 2.4 Diagram of a Skylight taken from MEEB eleventh edition

are more common due to the implementation of a skylight. Additionally, skylights are expensive systems that can only be utilized in spaces that have a direct connection to the roof. Similar to vertical fenestration, another disadvantage to skylights is the amount of unwanted heat gain and heat loss that will occur in a given space, caused by an R-value that is a fraction of what a roof would be. Because of the inefficiencies of skylights, HVAC systems expend more energy to keep a space at a comfortable temperature causing a higher energy bill. "During the summer months a typical skylight is accountable for as much as four times the amount of heat gains over a standard exterior wall fenestration due to direct contact with the sun's rays. While over the winter months a skylight will lose 35-45% more heat than a vertical window due to the process of convention" (California Energy Commission 2015, 5).

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It has been shown that pyramid and domed shaped skylights have demonstrated a reduction of glare during solar peak hours while diffusing direct light during solar noon hours, thus lowering inefficiencies associated with skylights (McGowan, Desjarlais, and Wright 1998).

Researchers at Southern California Edison constructed and tested a skylight, with design qualities similar to that of the ones found at the Kimball Art Museum by Louis Kahn. The design intent was to analyze the effects of a skylight that utilized a reflector beneath a skylight aperture that would reflect direct sunlight to the ceiling plane in order to spread diffused light across a given space. Results showed that the skylight provided a range of 30-60 fc while delivering "good" uniformity of light within the test space. Test occupants stated broad opinions about their experience in the space, ranging from the space being too bright during certain hours of the day to "indifference" towards the light levels. However, all test subjects thought the change of light throughout the day was "pleasant, nice and friendly" (Lee, ES, Beltran, L.O., Selkowitz, S.E, Lau, H., Ander G.D. May 1996).   These results show that with proper construction and higher rated glazing components, it is possible to minimize the negative aspects of skylights while maximizing the advantages.

2.4.2 SHADING DEVICES – OVERHANGS, LIGHT SHELVES, VENETIAN BLINDS, AND VERTICAL LOUVERS

Exterior fenestration accounts for the greatest direct heat gains entering a building, and therefore applied shading devices play a crucial role in blocking out undesirable light and heat. Buildings will most commonly provide shading to exterior windows through the use of external shading devices. Shading devices such as a basic roof overhang can control sunlight to prevent glare and unwanted heat gains. A benefit to these devices is their ability to substantial increase energy savings by allowing for a reduction in mechanical cooling equipment and cutting the use of electricity, simply by altering the building envelope. There are several devices that can be applied to the exterior of a building in order to control daylight and maximize the benefits.

It is common to see shading devices such as overhangs, screens, light shelves, venetian blinds, and vertical louvers. All of the shading devices mentioned are proven to control daylight to some degree while still allowing the transmittance of light within a space. For example, light shelves are used to bounce light towards the ceiling in order to reflect it deeper into a space, which then minimizes glare on workspaces. In addition to the use of light shelves, blinds can be applied below the shelves as an additional strategy.

Breitenbach, at Cardiff University in the United Kingdoms, found that by implementing variable angle slats to a venetian blind system, the user could have a higher degree of control allowing light to be distributed further into a space (Lawrence Berkley National Laboratory 2008). Beltran, Lee and Selkowitz applied a similar strategy using a curved

reflector that consisted of many small linear grooves used to project the sun's rays onto a room's ceiling at angles between twelve and fifteen degrees. Results revealed that the system could provide a range of 4.6-28 fc throughout the year up to a distance of 27ft. from the face of the vertical fenestration. However, the researchers found that less uniformity occurred frequently when the sun angles were not directly oriented with the face of the glazing (Beltran, Lee, and Selkowitz 1997).

2.4.3 OPTICAL SYSTEMS – LIGHT TUBES

The idea of light tubes were first imagined by William Wheeler. In 1880, he invented a system of light tubes lined with a reflective veneer that brightened a home by using light from an electric arc lamp. With the lamp placed in the basement, light was guided around the home through the use of pipes (Hecht 2004). In an attempt to bring in daylight, the same strategy can be used, by replacing the lamp with the sun. Today a typical light tube consists of a cylinder tube installed in a roof with a concentrating lens on the roof's surface. The interior of the tube is either coated in a reflective material or has the material applied to it so that light can reflect off the surface down into the building. The primary function of the device is to distribute light and reduce glare from direct sunlight for interior occupants. These systems are often better insulated, and are more economically viable than skylights.
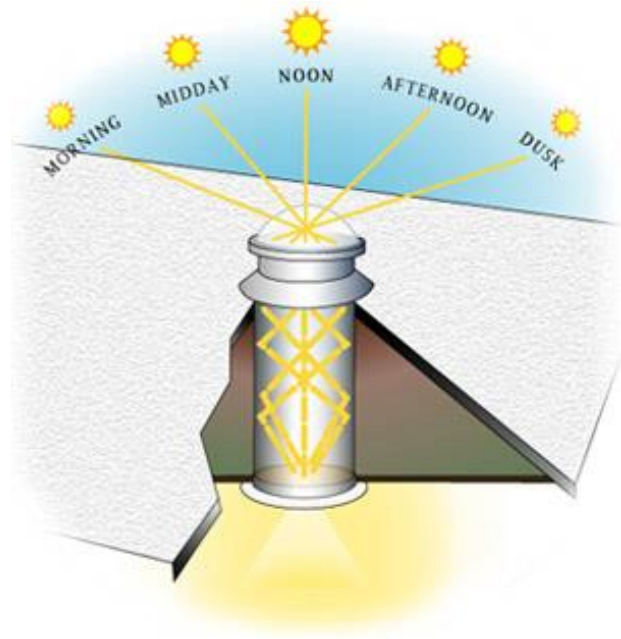
Figure 2.5 Diagram of a Light Tube taken from SolarTubeSkylights.com

Usually a light tube functions vertically, collecting daylight from the roof. However, in some cases a light tube can be applied in a horizontal construction. In this case, the collector would be on the south side of the building, or the side that receives the highest amount of direct sunlight. Researchers applied a horizontal strategy in an office building plenum to determine the functionality of this strategy. Results illustrated that

compared to a vertical application; the horizontal light pipe was significantly less efficient. This was a result of having to reduce the pipe size to maneuver through existing building systems (Beltran and others 1994).

Light tubes in general are cumbersome devices that require strategic planning for proper installment within a building, because they cannot interfere with the structure and mechanical systems. Additionally the flexibility of the system is restricted to a limited degree of rotation before the quality and intensity of light is quickly compromised.

2.4.4 LIGHT TRANSPORT SYSTEMS – FIBER OPTICS

While all systems mentioned are applicable and capable of accomplishing the task of making daylight available to an interior space, they are limited to the constraints of the building's shell. Over the last three centuries, technology has continuously proven Moore's Law through exponential growth. Sustainable systems, with respect to the built environment, are no exception. In recent years, advancements in light transport systems have seen great strides in efficiencies due to the progressive success of fiber optics. Collecting sunlight and funneling it through fiber optic cables is an effective method of harnessing the sun's power to offset electric lighting while simultaneously solving glare, heat gain, controllability, and consistency issues that accompany traditional daylight strategies.

Fiber optics have the ability to extend the distance daylight can enter a given space while providing a diffused output of daylight. As the intent of this thesis is to investigate the potential of a fiber optic system, only fiber optic systems intended for daylight utilization are investigated experimentally.

2.5 HISTORY OF FIBER OPTICS

The application of fiber optics can be defined as the science of data transmission by the passage of light through transparent fibers. Fiber optic technology is one that has been around since the age of the Romans during the end of the first century B.C. The Romans were the first to discover that glass could be manipulated into many different shapes and forms, including that of thin fibers, when inflated from the bottom of a tube. During the early 1800's great strides in optical science occurred when physicist Daniel Collodon, along with Jacques Babinet, demonstrated that light could be directed along jets of water (Tricker 2002). Similarly, John Tyndall
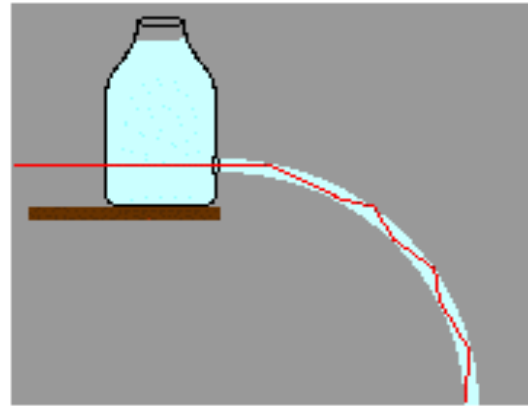
Figure 2.6 Diagram of John Tyndalls experiment taken from Harvard University's science center.

assembled a simple experiment revealing that light could travel through a curved stream, which proved that it was possible to bend the wavelengths of light. Tyndall noted "the laser beam stays internal to the water, continuously reflecting at each boundary" (Hecht 2004, 340). In the two decades prior to the 1900s, Doctors Roth, Reuss, and David Smith all patented bent glass rods used to illuminate the interior of the human bodies within their respective fields. Between 1950 and 1960 research began to revolve around the introduction and advancement of the first laser. Charles Townes and Arthur Schawlow developed the "maser" (microwave amplification by stimulated emission of radiation) or the first interpretation of what was soon to be labeled as the "Laser". Essentially the researchers developed a system that could

reflect light back and forth therefore amplifying the output of light from one point to another.   In 1961, Elias Snitzer demonstrated a laser directed through a thin glass single mode fiber. This discovery found applicable uses in the medical industry but had a light loss too high to be effective for early communication applications. Twelve years later, Bell laboratories developed a method of production that removed impurities and allowed for an ultra-transparent glass fiber that could be easily produced at a reasonable cost. With that came the start of a new telecommunication era. Throughout the 1980s, telecommunication companies such as Sprint have been replacing previously used copper wire lines with glass fibers to rebuild and extend the range of their soon to be globalized infrastructure.

Today, fiber optic technology has allowed the transmission of data, or rapid light signals, over spans as large as the Pacific Ocean. The uses and capabilities of the technology are still growing and can be found in various industries including military, medical, telecommunications, networking, and sustainability. In the medical industry fiberscopes are used as a method of examining the internal aspects of the human body. Within the sustainability realm, studies have demonstrated that a fiber optic system used to transmit daylight is a superior method of design due to its size, maneuverability, and efficiency potential both economically and environmentally.

2.6 FIBER OPTICS AS A LIGHT TRANSPORT DEVICE

Fiber optic daylight systems are either applied as either passive or hybrid systems. A passive fiber optic system is made up of three parts: daylight collector, optical fibers, and a luminaire diffuser to evenly distribute the collected light within a given interior space (ECW 2008). Hybrid systems are similar in design except that they include electric lamps and dimming controls to provide constant recommended illuminance values. Some hybrid systems also utilize a small motor, which allows the solar collector to follow the sun's path throughout the day, providing better daylight collection over the period of a full day.

2.6.1 CONCENTRATORS

Numerous types of concentrators are available for culminating light. These types include Parabolic mirrors, Fresnel lenses, Mangin, and Conic Cassegrain, all of which have different performance and light output potential (Muhammad Arkam C. Munaaim, Karam M. Al-Obaidi, Mohd Rodzi Imail & Abdul Malek Abdul Rahman 2014) . Fresnel lenses and parabolic mirrors are the two most universally used concentrators due to their high solar yields and efficiency differences within commercial daylight applications. Because they are the most commonly used, analysis on system concentrators focused primarily on the parabolic mirror and the Fresnel lens.

PARABOLIC MIRROR:

The principal behind the design of a parabolic mirror relies entirely on the two dimensional shape defined as a three-dimensional object, and has been used as early as 1st century BC. Diocles, a Greek mathematician, is accredited as being the first person to
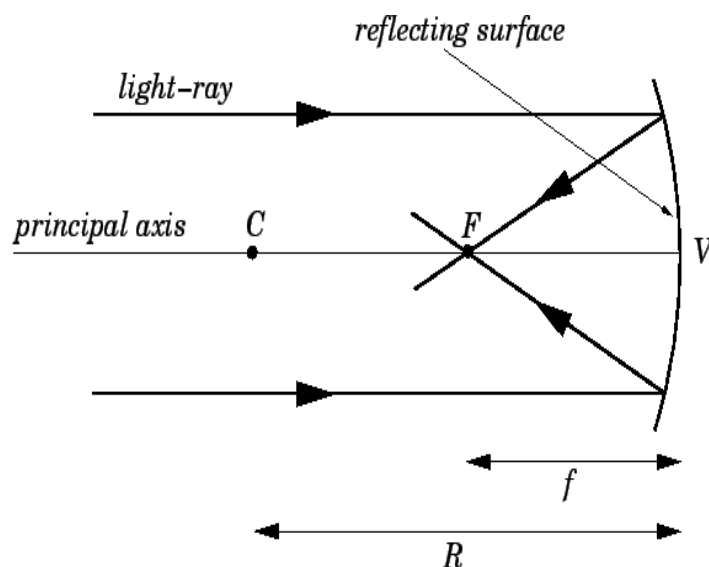
Figure 2.7 Diagram of a Parabolic Mirror Taken From University of Texas at Austin Physics Department

successfully prove the properties of a parabola in his work titled "On burning mirrors" (Michael N. Fried and Sabetai Unguru, Brill 2001, 162-164). A parabolic mirror, or parabolic reflector, is effective because of its inherent shape which can be used to collect or project different forms of energy. With a reflective internal surface wrapped around a central axis, the reflector is capable of forcing a parallel beam of light, sound,

or radio waves to converge to a specific focal point. The strategy can be inversed as well to project the energy out in a specific direction. Today, parabolic reflectors are used in satellite dish designs as well as telescopes. Additionally, parabolic properties are used in many electric lightning devices such as spotlights, headlights, and lamp housing assemblies (Fitzpatrick 2007).

In the case of a daylight strategy, parabolic mirrors are used to reflect sunlight to a secondary optical element in order to significantly lower thermal transfer by collecting only a specified range of wavelengths, including the visible spectrum.
Cold mirrors are used for the secondary element of the system, because they have "an average transmission rate of 85-97% from 750-2500 nm with an average reflectance of 95-97% for the wavelengths from 450-700nm" (Sapia 2013, 18). Cold mirrors are a fundamental part of a parabolic daylight system because they decrease the transmission of undesirable heat caused by infrared wavelengths.

Researchers at the Beijing Institute of Technology tested an experimental sunlight concentrating system that differed from a typical parabolic lens in that the light was focused in a continuous forward progression over typical systems that redirect the light back and forth. The research demonstrated an increase in solar collection with a transmittance of only 17.5% due to a lower reflectance factor within the concentrator (Xue and others 2011). The efficiency increase was accredited to the position of secondary mirrors. Because the light was in a continuous forward direction, the secondary mirrors did not cause shading variances on the parabolic concentrator.

Within the same field of design, researchers at the University of Nottingham compared the efficiencies of a parabolic dish concentrator to a conic shape concentrator. Through simulations, they determined that parabolic mirrors were far more efficient than conic shaped concentrators, which collected fewer daylight hours and had higher light loss through the transmittance process (Han and others 2013).

FRESNEL COLLECTORS:

A Fresnel lens as defined by the Encyclopedia Britannica is a succession of concentric rings, each consisting of an element of a simple lens, assembled in proper relationship on a flat surface to provide a shorter focal length. In 1922, Augustin-Jean Fresnel created what is known to be the first Fresnel lens, assembled as a multi-part lens for early lighthouse beacons. This lens could refract light from a point into horizontal planes while capturing as much as 80% of the original light source. The Fresnel lens is credited for reducing the amount of material required in comparison to a conventional lens by segmenting the lens into concentric annular sections (Calianno 2015)
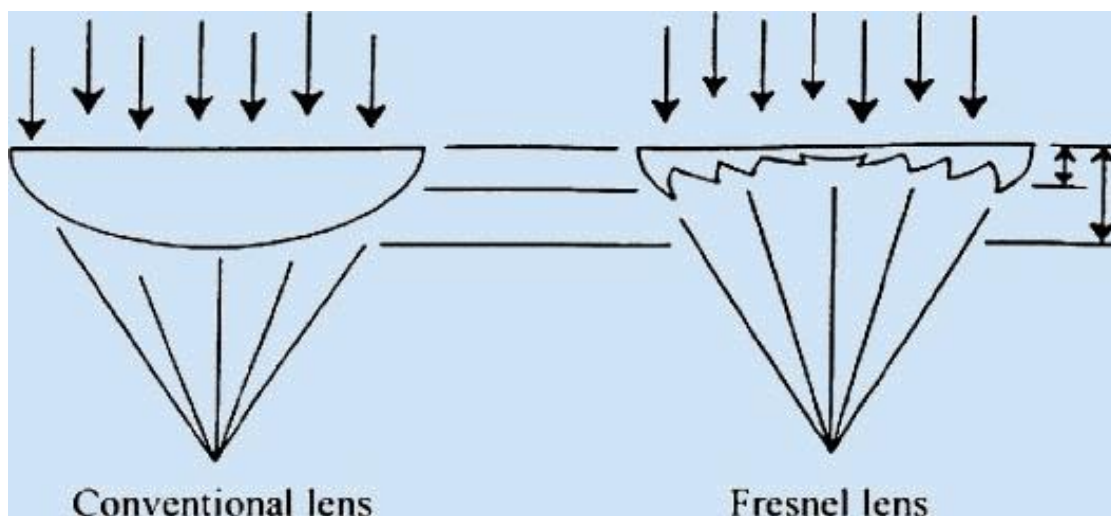
Figure 2.8 Comparison between Conventional Lens and Fresnel lens Taken from William Meehan

The theory behind the Fresnel lens is that the path of the collected light does not change within the lens. Rather, the directions of parallel rays are only altered at the surface of the lens. Because of this, the Fresnel lens can be significantly thinner and more efficient due to less absorption of light through the material. Depending on the orientation of the lens facets, the system will either collect or collimate light. A Fresnel lens can easily collimate a point source by placing it one focal length away from the source. Additionally the lens facets will be oriented away from the point source. This will cause light collected from a single point source to be redirected into parallel rays (Davis 2011, 8) projected in a single direction. As a light collector, the lens facets will face the light source, allowing the collected light to collimate to a specific focal point. Typical Fresnel concentrator systems will orient the facets towards an intended receiving material, such as a Photovoltaic panel. "With the grooves in there is the potential advantage of minimizing the impingement of solar radiation and also to avoid buildup of dirt and debris within the facets" (Davis 2011, 8) .

"A well-crafted lens can concentrate sunlight to a single focal point with a ratio of around 500:1. Due to the physical properties of the lens, the collected light can be concentrated into a beam as narrow as 7 degrees or as wide as 70 degrees" (Boudre 2015, 1) .

Today, Fresnel lenses are used in a multitude of different applications, ranging from lighthouse beacons to theatrical productions. However, the characteristics of the lens show their greatest advantages in the field of solar concentration.

Fresnel daylight collectors utilize several different strategies ranging from a large single lens system to several smaller lenses assembled within a single system.

Ulah and Shin demonstrated that a large lens system was not only equally efficient, but also significantly less costly; due to its size, the system becomes less manageable (Ullah and Shin 2014) . A Fresnel lens magnifies collected daylight while separating a small amount of ultraviolet and infrared portions of the spectrum. Therefore, advances in the system have applied filters to the lenses in order to reduce around 85% of the transferred ultraviolet and infrared radiation (Muhammad Arkam C. Munaaim, Karam M. Al-Obaidi, Mohd Rodzi Imail & Abdul Malek Abdul Rahman 2014) .

However, there are some manufacturers who choose not to apply a filter to the system, thus allowing a spectral range of 400 – 2400 nm. This means that a significant portion of the infrared spectrum is transmittable (Liang and others 1998) . Fresnel lenses are ideal for any application requiring inexpensive, lightweight, and efficient lens.

2.6.2 FIBER OPTIC CABLES
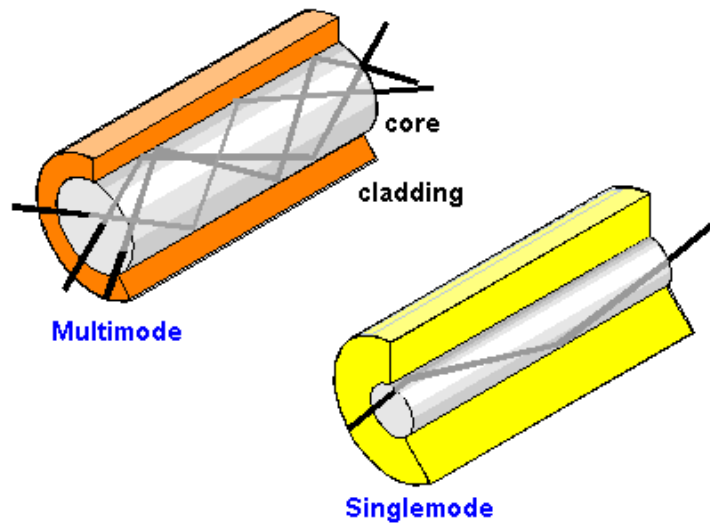
Figure 2.9 Multi-mode and Single-mode graphic taken from the Online Encyclopedia

Fiber optic cables, or optical fiber, are essentially a transportation device that can move waves from one point to another. There are two major types of cables that accomplish this: single-mode and multi-mode. A single-mode fiber allows for a manufactured specific wavelength to enter the fiber and travel with less movement within the fiber. With a diameter ranger of 5-10um, the single mode fiber is used primarily to transfer infrared light signals in Internet and telephone applications. A multi-mode fiber is a bundle of fibers encased within a single cladding material that allow wavelengths to travel through a variety of different paths. This strategy is better used for shorter distances, and can assist in data transfer systems.

An optic fiber is generally made up of either glass or plastic, with each material having different inherent qualities and different outcomes. For example, light transfer systems use silica strands over plastic, because the internal properties of glass can better handle the internal heat associated with daylight. Typically glass fibers have a diameter of 10um (.10mm), while with applied exterior cladding, the fiber's diameter expands to 125um (.125mm). The exterior cladding is essential for light transmittance, as it allows for a process known as total internal reflection. This is a phenomenon that occurs when

a light wave hits the internal cladding wall at an angle that is larger than a given critical angle. "When the internal side of the cladding around a fiber optic cable has a low refractive index and the angle of incidence is greater than the critical angle, the wave of light cannot pass through the medium and is therefore entirely reflected in a forward progression" (Kay 1999, 298).

When a wave of light travels through the fiber, it will begin to lose its intensity through attenuation. In long distance applications, telecommunication companies can install periodic repeaters that receive, amplify, and retransmit the wave. By using a higher quality fiber, attenuation can be limited even after 18 miles (FOA - Fiber Optic Association 2015) . Light waves within a cladded fiber will also experience dispersion caused by the transporting medium, which would be either glass or plastic in this case.

The visual phenomenon of the color spectrum creating a rainbow, best demonstrates dispersion. With regards to fiber optics, dispersion occurs because different wavelengths of light travel through a fiber at different speeds.

Figure 2.10 Light Dispersion Through a Glass Prism taken from Tulane University - Sanelson

Shorter wavelengths will spend more time in the fiber, while longer wavelengths will travel through the fiber at faster and more efficient speeds, resulting in a lower light loss output (Woodford 2015) .

A study by Fiberoptics Technology Incorporated continued to test the transmitting qualities of different optical fibers, determining that the "transmittance is dependent on

the refractive index and that transmitting through glass has a lower acceptance angle compared to the plastic and solid core fibers" (FTI 2014,5).

The solar radiation spectrum begins at around 300nm and ends at 2400nm. Depending on the intended task, a fiber optic cable will be designed to transmit a portion of the solar spectrum. In most cases, fiber optics are either used for passive daylight systems or telecommunications. When used to provide natural daylight, the fiber optic cable is designed to have a spectral allowance between 300-700nm, which allows the visible spectrum to pass through. Telecommunication companies use fibers with a range between 800-1300nm, because this range encompasses the more efficient long wave infrared spectrum of light.

During the 1980's the United States government-funding agency DARPA started a program to develop an ultralow loss infrared fiber for undersea applications. Unfortunately the researchers were unable to develop a new fiber that had lower light loss characteristics than silica fibers. Today infrared fibers are used for broadband purposes as well as transmittance of long wavelength radiation for military purposes. These fibers are not nearly as common due to the lack of applications and the fact that they are brittle due to the toxic material makeup of the fiber. However, IR fibers have been shown to provide a transmittance range that exceeds 20um (Paul Klocek, George H. Sigel Jr. 1989).

In the last decade, researchers have developed unique fibers with specific traits in order to maximize solar radiation collection. The PCS low OH vis-IR fiber is considered a cost effective alternative to fused silica fibers. Its range of wavelength transmission is from 400-2400nm, making it a prime candidate for providing both the visible spectrum as well as solar radiation. Additionally, the researchers demonstrated that a 19-strand bundle was capable of transmitting up to 60W of power with an efficiency of 60% (Liang and others 1998).
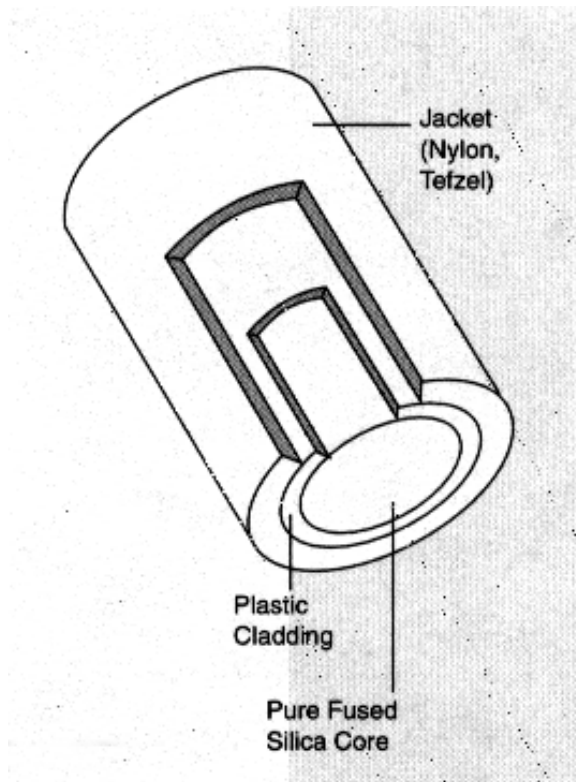
Figure 2.11 Diagram of Anhydroguide PCS Low OH VIS-IR Fiber

Hayman conducted several studies using fiber optic photocells as a model for daylight. Although his experiments resulted in high light losses within the cables, the research led the way to significant advancements in fiber optic technology (Hayman 1990)

2.6.3 LUMINAIRES/DIFFUSERS

The third major component associated with a fiber optic system is the luminaire, or in the case of a Parans system, the diffuser. "The diffuser structure consists of two sheets, the one on the top is plastic with white color to reflect the incoming light and the second sheet is mostly a clear acrylic material which has one attachment hole to terminate the fiber optic end to diffuse the light" (Parans 2016, 5).

2.7 COMMERCIALLY VIABLE FIBER OPTIC SOLAR COLLECTORS

The earliest attempt at a Fiber optic system was in the 1970's when Dr. Kei Mori of the Himawari Corporation developed a prototypical solar collector using a large Fresnel lens to concentrate direct sunlight for interior use. Within nine years Dr. Mori had further developed the solar collecting system into a prototype containing a series of Fresnel lenses mounted in a honeycomb pattern to form a single circular collector that concentrated direct sunlight to optical fibers for transmission. Dr. Mori found that

Figure 2.12 Photo of the Himawari Corporations Solar Collector taken from the Himawari Catalog.

light distribution losses in polymer optical fibers were of significant concern due to internal contaminants within the fiber itself. Additionally, "different portions of solar radiation were attenuating faster than others, making the end product of light look noticeably different from natural sunlight" (Lapsa and others 2007, 7-20). Later updates to the system used progressively more complex arrangements of Fresnel lenses and optical fibers to supply a greater number of light fixtures with brighter and more consistent light. By using circular concentrators over the original hexagonal shape, the collection efficiency increased dramatically (La Forêt Engineering Information Services Inc 2006).

Similarly, Parans, a solar lighting systems manufacturer based in Sweden, developed a collector using a series of Fresnel lenses. Using a slightly different strategy than the Himawari. Parans systems use a collector about 3 ft. wide and 6in. deep, containing a series of sixty-two circular Fresnel lenses mounted across the face of the collector. Each lens is held in place by a small V-shaped metal

Figure 2.13 Photo of the Parans SP3 Solar Collector taken from the Parans webpage.

frame secured to a pivot point at its base. The circular lenses are mounted in a grid across the collector's face, each surrounded by enough open space to accommodate uniform movement as a group in response to changing sun position. Articulation of each Fresnel lens allows for tilt angles of 60⁰ in any direction, forming a 120⁰ active cone capable of capturing direct sunlight for an eight-hour period. Each circular Fresnel lens is mounted above a 0.75-mm optical fiber with the exposed end located at the focal point. The small fiber optic cables are bundled to form four separately large cables, each 6-mm in diameter and capable of supplying a separate luminaire with natural sunlight. Each collector can supply multiple light fixtures or provide four connections to a larger fixture, increasing system flexibility without complicating the optical fiber distribution system. The efficiency of the cable is primarily dependent on the length: for every 6.5 meters, a 20% reduction of the luminous power output occurs. Whatever the collector configuration, newer iterations of Fresnel lens collectors still contain the same

basic components as the original: a series of lenses coupled to dedicated optical fibers

routed out of the collector and into the building (Parans 2016) .

2.8 PHOTOVOLTAIC SYSTEMS: TYPICAL, SEMI TRANSPARENT, QUANTUM DOTS, AND THIN FILM

Since 1990 and as early as the 1970s, concern for energy and the awareness of global warming has encouraged the development of the concept of sustainable design. This development boosted the demand for photovoltaics, allowing them to become a more applicable and desirable system (Dimitri Bigot, Miranville Frédéric, Harry Boyer and Ali Hamada Fakra 2010). Meanwhile, the capacity of global photovoltaics has increased, exponentially, especially in countries like China and the United States, thus influencing the decline in commercial prices and the increase in governmental incentives.

The United States Department of Energy developed an initiative called "Sunshot", which aims to reduce the cost of photovoltaic generated electricity by about 75% by 2020 (Department of Energy 2014). Currently, photovoltaic systems are available ranging from conventional modules and photoelectric membranes to integrated window applications, thin-film cells, transparent photovoltaics, semi-transparent photovoltaics, and the still under development nano-crystalline solar cells.

The photoelectric effect is the direct conversion of light into electricity at a microscopic level. The origin of photovoltaics can be credited to Edmund Bequerel, a French physicist who discovered that certain materials had the ability to absorb photons of light and release electrons in exchange. In 1905, Albert Einstein received a Nobel Prize in physics for defining the nature of light and the photoelectric effects on which current photovoltaic technology is based on. It was not until the 1960's when NASA used solar cell modules to power the spacecraft that the technology became more prevalent. As

the efficiency of photovoltaics increased alongside the demand caused by the energy crisis of 1970, photovoltaics became economically viable (Gil Knier 2002).

A photovoltaic cell consists of several layers of materials sandwiched onto one another in order to create electricity. A photovoltaic cell consists of two layers of semi-conductive material, which is typically chemically treated silicon. The two layers are sandwiched between two electrodes: the top plate (-) and the bottom plate (+). When sunlight hits the surface of the cell, many of the solar photons are reflected or absorbed by the solar cell. Once enough photons are absorbed, they are released through the semi-conductive surfaces to the positive electrode layer, creating enough current to produce between 1-2W. By increasing the number of cells to create an array, the amount of collected solar energy can be vastly increased (Anderton 2015) .

As the global trend of sustainability continues to gain momentum, Photovoltaic technology will continue to progress both scientifically and economically.
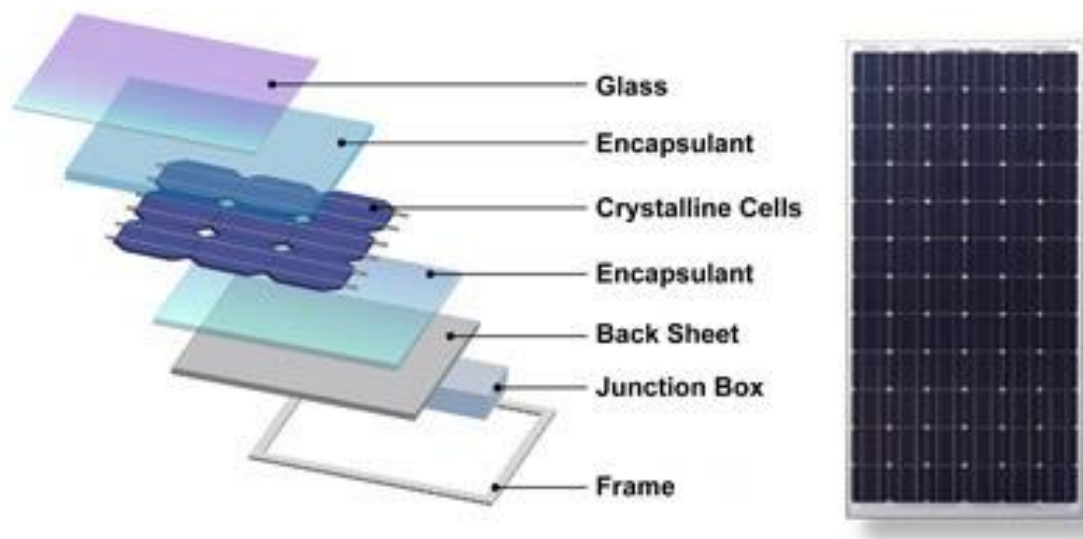
Figure 2.14 Photovoltaic Diagram taken from Dow Corning

2.8.1 SEMI-TRANSPTRANSPARENT PHOTOVOLTAIC

Typically, photovoltaic systems are applied to the roof of a building or structure in order to maximize solar peak hours. However, with the development of semi-transparent building integrated photovoltaics, conventional translucent surfaces can now be utilized as solar collective surfaces.
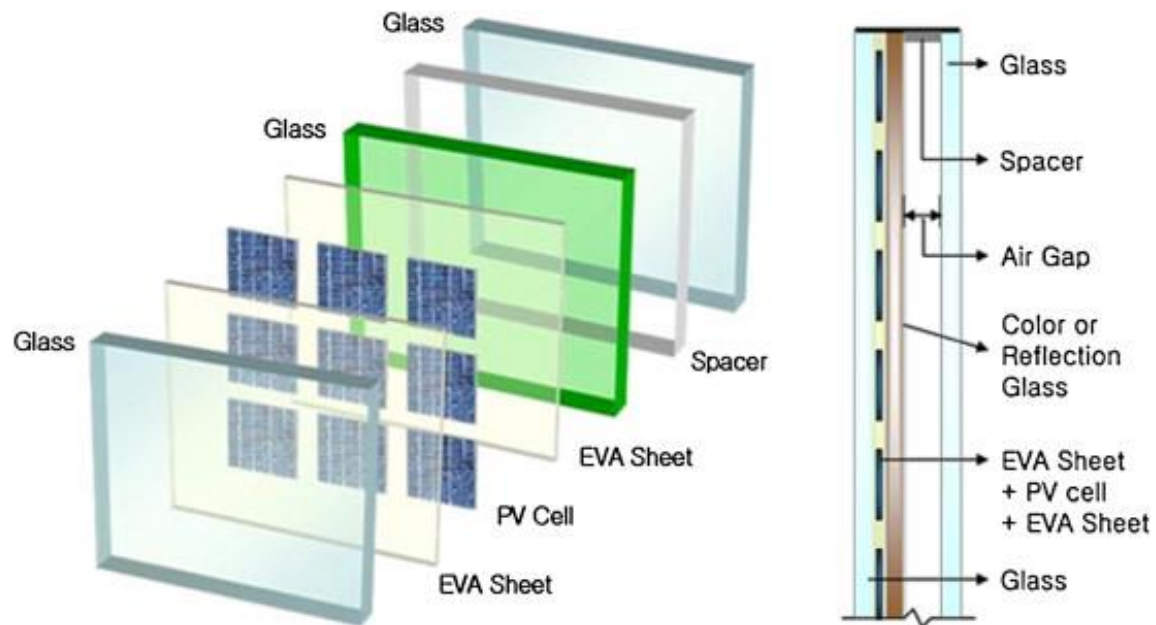
Figure 2.15 Semi-Transparent Photovoltaic Diagram taken from Onyx Solar

Transparent properties can be achieved through two different processes. Small opaque thin-film cells can be inset in between glazing panels in a planned grid arrangement, allowing a majority of light to pass through the glass while still collecting energy. The second and more complex approach is to create a device that utilizes all transparent properties within the cell layers. This approach allows for even light distribution while maintaining a constant flow of solar collection. Today, semi-transparent photovoltaic systems are available for commercial use while researchers search for new ways to advance technology even further.

In 2003, The Lillis Business Complex at the University of Oregon earned a LEED certification surpassing the minimum code requirements by 40%. The business complex applied a south facing curtain wall made up of widely spaced semi-transparent glazing systems that utilized multi-crystalline solar cells capable of providing 5.9 kW of solar generated electricity (Brown 2004).

Clark, Holt, Schless, and Toevs later investigated the thermal efficiencies of the system, concluding that the photovoltaic array provides a measurable amount of electricity while blocking a significant amount of solar radiation from entering the interior. In some cases, the researchers recorded a difference of 18 degrees between the exterior and interior sides of the glass system (Clark, Edward, Schless, Colin, Holt, Marc, Toevs, Alex 2010) .

Xu, Liao, Huang, and Kang determined that a vertical semi-transparent photovoltaic assembly can provide adequate daylighting while saving up to 30 percent of a room's electric demand, when the optimal photovoltaic cell ratio is applied to each room (Xu and others 2014). Similarly, Cannavale's experiments demonstrated a peak collection rate of 4.22mW/cm2 with an optical transmittance of over 50%, revealing that photovoltaic window systems are capable of increasing indoor natural light levels while converting energy into electricity (Cannavale and others 2013) .

In 2013, advancements in photovoltaic transparency technology have led to fully transparent photovoltaic. Researchers at the University of California Los Angeles developed a transparent photoactive plastic made up of "tandem polymer solar cells"

which utilizes a cell composed of a new infrared-sensitive polymer layer capable of absorbing up to 80% of infrared light with a conversion rate of 7.3% (Chen, Chun-Chao, Dou, Letian, Zhu, Rui, Chung, Choong-Heui, Song, Tze-Bin, Zheng, Yue Bing, Hawks, Steve, Li, Gang, Weiss, Paul S., Yang, Yang 2012) .

Dr. Miles Barr at MIT developed a transparent glass solar cell that absorbs only infrared and ultraviolet light, allowing visible light to pass through the cells unimpeded. The current system transmits more than 70% of the visible spectrum with a power conversion efficiency expected to reach over 12%. Additionally, Dr. Barr believes that the transparent system could be applied to an existing building's framework at very little extra cost (Lunt, Richard, Bulovic, Vladimir 2011). Although the future of transparent photovoltaic technology is

Figure 2.16 Transparent Photovoltaic Diagram taken from MIT Energy Initiative

promising, even the most efficient configuration has too high of a cost for current market use. Additionally the price for a transparent system does not allow for a realistic return on investment.
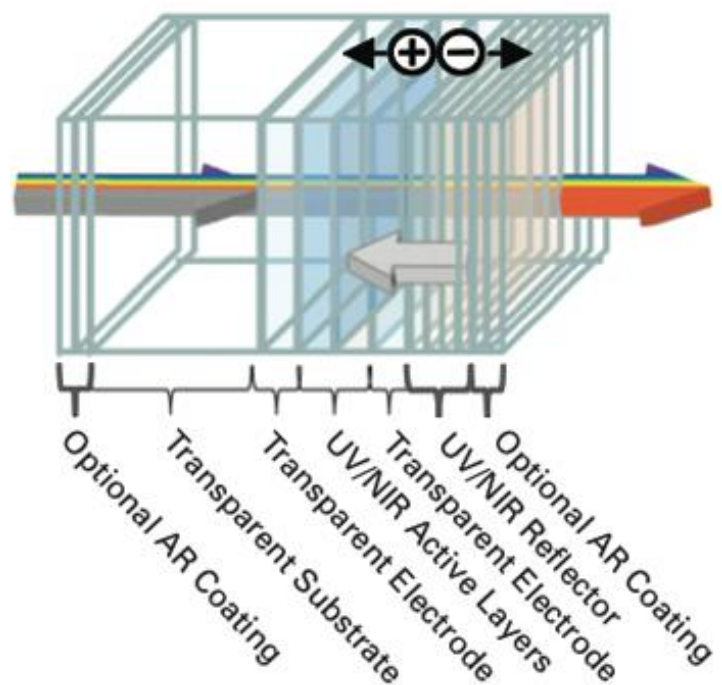
2.8.2 THIN FILM PHOTOVOLTAIC

Thin film technology has received the label as the second generation of photovoltaic. In comparison to the traditional silicon wafer based panels, thin film technology is a cost effective, efficient design. The National Renewable Energy Laboratory released a study forecasting that by 2010 thin film cells would be used to produce 3,700 MW of electricity worldwide (H.S. Ullal 2008) . In 2012, thin film energy generation represented close to 20% of the world's photovoltaic industry with a generation capacity of 28.4GW. The European Photovoltaic Industry Association (EPIA) released the 2013 Global Market Outlook, which revealed a worldwide photovoltaic capacity of 102 GW, with thin film technology accounting for more than 10% of the world's photoelectric capacity (Masson, Orlandi, and Rekinger 2014)

Thin film photoelectric systems are known for the size and scale of the solar cell. Unlike silicon wafer cells, thin film solar cells have light absorbing layers that are just one micron thick. When broken down, the layers consist of several layers of semiconductors on a solid substrate like that of glass or metal. Due to the efficiencies of the applied semi-conductors, the solar cell remains thin and durable. Depending on the type of

semiconductor used, thin film solar cells can be broken down into three types:

Amorphous Silicon, Cadmium Telluride, and Indium Gallium Deselenide silicon cells.
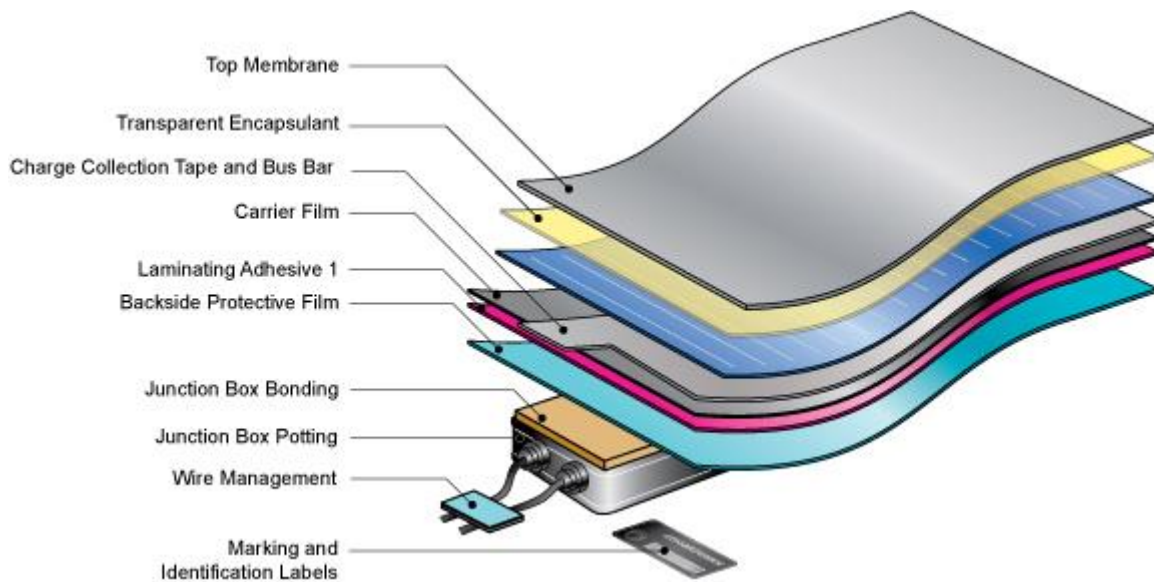
Figure 2.17 Thin Film Photovoltaic Diagram taken from PV Magazine

Research has revealed that these cells lack efficiency when applied to large-scale

projects, and are therefore often limited to smaller applications such as key chains and

small children's toys. This is because the cell is susceptible to significant loss in power

output when exposed to direct solar radiation. Additionally, these cells are a slimmed

down version of the traditional wafer based cells, so the efficiency is equally cut

(Kushiya 2014) .

Researchers at the Department of Architectural Engineering at the Hanbat National

University in the Republic of Korea applied a 48m^2 vertical array of transparent

amorphous silicon thin-film photovoltaics to the front facade (southwest) of a newly

constructed sustainable R&D institute in Yongin city. The researchers were interested

in comparing the thin-film module specifications to the results while measuring the

insulation efficiency of the system with respect to the generation of electricity. An

analysis of more than two years of collected data revealed the system's average monthly electrical energy generation was 1277 kWh/year with an insolation range between 700-900 W/m^2. The system's specifications noted a module efficiency of 7%. However, the tested system resulted in an efficiency of only 3%. The average yearly energy generation per m^2 was 580.5 kWh/kWp/year, which is aggressively inefficient in comparison to other systems. The researchers credit a portion of the systems deficiencies to shading occurrences caused by the building during certain times of the day and year. The data also revealed a direct correlation between the system efficiency and the surface temperature of each module when comparing system efficiencies and system temperatures between the months of August and October (Yoon, Song, and Lee 2011).

In an effort to increase efficiency and lower product cost, non-silicon photovoltaics have grown industry wide. The remaining two thin-film types are defined as a newer generation of thin-film photovoltaics that use either cadmium telluride (CdTe) or copper indium gallium deselenide (CIGS) rather than silicon based electrode layers. In comparison to the wafer based crystalline photovoltaics, which have the current market advantage due to an anticipated higher efficacy, thin-film technologies offer lower production cost with comparable efficiency expectancy. The more expensive traditional wafer cells have an average efficiency of 15-25%, while CdTe and CIGS solar cells have reached similar efficiencies ranging between 10-20% (Kushiya 2014)

CdTe and CIGS thin film cell technologies are economical and currently offer the best approach for significantly surpassing the cost for performance levels of standard

crystalline silicon wafer photoelectric systems. The production of thin film solar systems in the United States has surpassed the first generation crystalline silicone cells. In 1990, NREL began research and development for thin film photovoltaics, since then they have achieved a solar cell efficiency of 19.2% with a three-stage, co-evaporative process (Delahoy and others 2004).

However, the production of CdTe cells is in higher demand over the CIGS cells, primarily due to the complexity of the CIGS manufacturing process such as: "evaporation, metallic precursor deposition by magnetron sputtering and non-vacuum techniques like ink-jet printing, and electroplating" (Dhere 2011, 277-280) . "CdTe is a near perfect material for PV application since it is a direct band gap semiconductor with a high optical absorption coefficient in the visible portion of the photon spectrum, and has a band gap of approximately 1.5eV which is closely matched to the terrestrial solar spectrum for optimum conversion efficiency" (Birkmire and McCandless 2010, 139-142). Additionally, Birkmire's research reveals that the highest performance CdTe cells are heterojunction devices using Cds as a transparent window layer and are fabricated in a substrate configuration where the light enters through the glass. This layering strategy, which is considered to be the most common, demonstrated cell efficiencies between 11-16% (Birkmire and McCandless 2010) .

2.8.3 QUANTUM DOTS
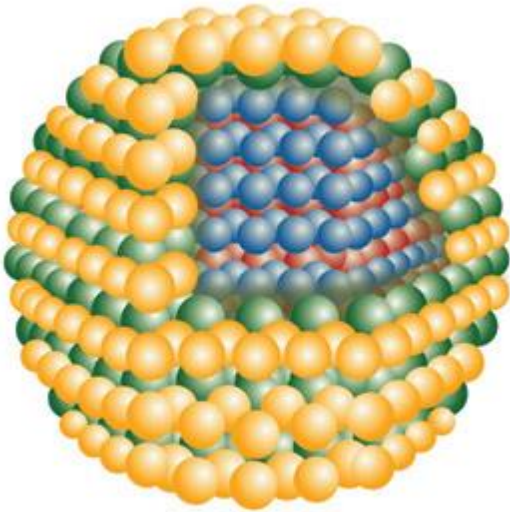
Figure 2.18 Quantum Dot Illustration taken from International Business Today

On a smaller scale, researchers are in the process of further developing nano-crystals known as quantum dots. This progressive technology is being described as the third generation of photovoltaics. A quantum dot is a nanostructure semiconductor with the ability to confine band electrons' valence and band holes, in all three geometrical axis. Small quantum dots, such as colloidal semiconductor nanocrystals, can be as small as 2 to 10 nanometers, corresponding to 10 to 50 atoms in diameter and a total of 100 to 100,000 atoms within the quantum dot volume. "Quantum dot technology allows for manipulation of light absorption, sensitivity to diffused light, and provides the ability to design flexible solar panels" (Kamat 2013, 908-919).

In the field of photovoltaics, a Quantum dot photocell would collect the radiation from the sun in a similar fashion as first and second generation photovoltaics. This technology is expected to lower production cost as well as increase solar efficiencies. Edward H. Sargent, a professor of Electrical and Computer Engineering at the University of Toronto as well as a Canada Research Chair in Nanotechnology, believes that quantum dot technology has the ability to revolutionize solar cell applications as a whole (Sargent 2012) .

Currently the leading researcher on Quantum Dots is Prashant V. Kamat, whose developments have demonstrated 5%-6% efficiencies as opposed to current silicon panels which have efficiencies on average at 10–12%. Comparably, Beijing National Laboratory for Molecular Sciences determined that applying a thin nanoparticle film around a solar cell tube increases the efficiency by 4.16% while still maintaining what is considered to be a viable low cost commercial system (Kamat 2011).

Unfortunately, the technology is in its infant stages and has many deficiencies to overcome before becoming widely available for commercial applications. Once the technology becomes more efficient and cost effective, there is likely to be a place for it within the architectural market.

2.9 HYBRID SYSTEMS: SOLAR COLLECTION

Hybrid daylight systems represent a new and innovative means of bringing direct sunlight into a building while simultaneously taking advantage of the collected solar radiation. Hybrid systems are capable of maintaining the controllability and ease of applications usually reserved for electric lighting by collecting natural light and channeling it through optical fibers to luminaires within a given space. A hybrid solar collection system, can surpass what wall fenestration is capable of providing, in that it will distribute sunlight further into a building's interior without affecting the design of the space or creating glare, lighting variability, and heat gain issues that complicate most daylight strategies.
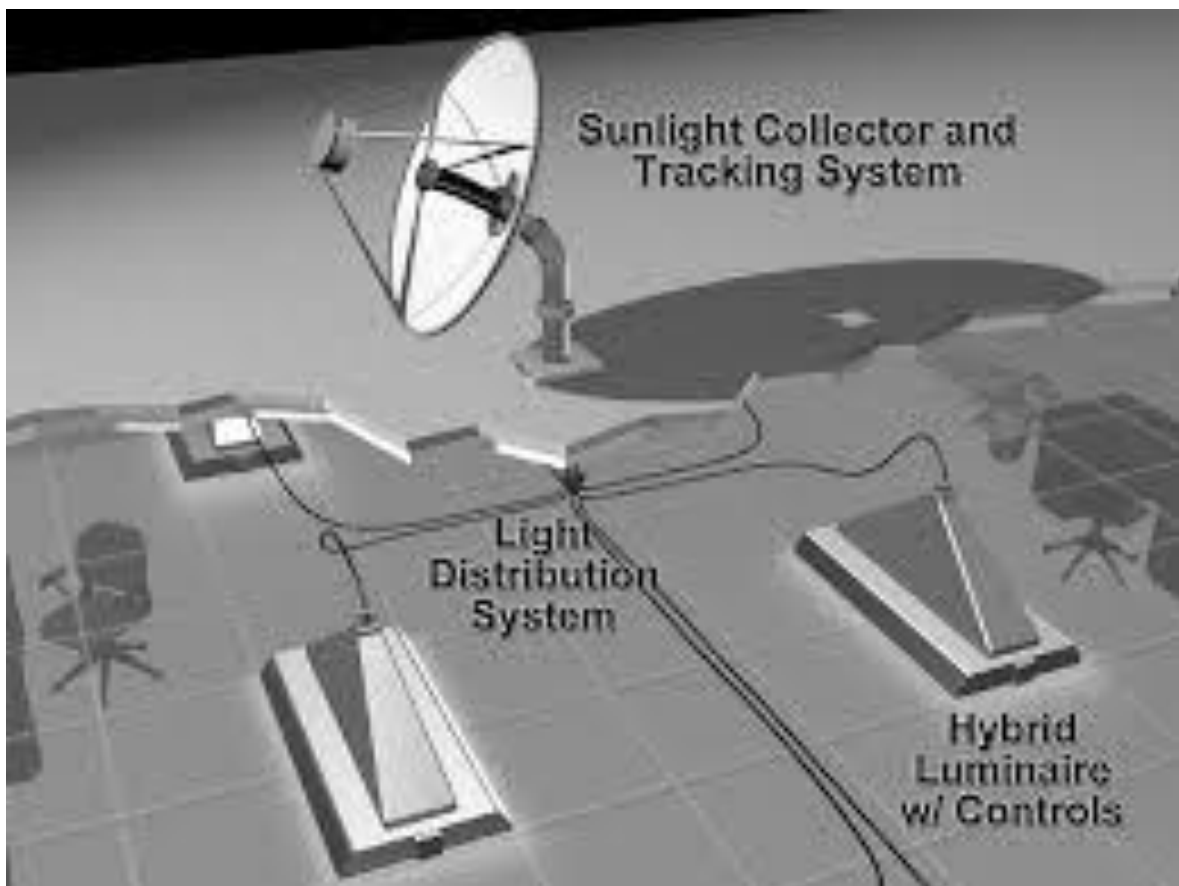
Figure 2.19 Oak Ridge National Laboratory Hybrid Light system taken from ORNL

In 1993, a fiber optic daylight system coupled with photovoltaic technology was under development at Oak Ridge National Laboratory, but the research was discontinued due to technical problems (Wilson 2014) . Six years later, Oak Ridge National Laboratory revealed an updated parabolic system far exceeding the original design. The collector, an acrylic parabolic mirror with a 2 ft. radius, was used over a traditional glass mirror to successfully reduce system cost while upholding collection efficiency. The parabolic mirror reflects direct sunlight onto eight spectrally selective cold mirrors that allow the harvested infrared radiation to be transmitted through the mirror onto a photovoltaic cell mounted behind them while directing the visible spectrum of light into one of eight flexible large-core Polymethacrylate optical fibers. By simultaneously generating power to operate the collector's tracking mechanism, this design further improves end-use efficiency by allowing the collector to deliver 50,000-lm while consuming very little power during operation (Lapsa and others 2007) .

Researchers in the Solar Energy Laboratories at the University of Wisconsin-Madison applied a feasibility and economic analysis of a Parabolic lighting system based off the 2004 Oak Ridge National Laboratory full spectrum hybrid lighting system. The intent of the research was to determine if the technology was applicable for commercial use. The system under investigation was a two-axis system comprised of a circular parabolic mirror, a secondary cold mirror place at the focal point of the parabolic mirror, and flexible large-core Polymethacrylate optical fibers for light transmission. The system utilized a unique strategy where the cold mirror allowed infrared energy to be transmitted while the visible energy is reflected back into a bundle of large-core fiber optics. The otherwise wasted infrared spectrum would be redirected to a traditional

gallium antimonide thermal photovoltaic, which would convert the energy into electricity to be sent back to the local grid. Using the TRYNSYS transient simulation program, the system was simulated in six cities within the United States to analyze lighting, heating, and cooling loads. Results revealed that the system performs significantly higher in a location whose latitude is closest to the Equator because this allows for daylight hours in phase with typical building lighting hours. For example, Hawaii's sun consistently rises by 8am and sets after 5pm. "Although Hawaii is closer to the equator, the high amounts of moisture in the Hawaiian climate leads to smaller amounts of annual beam radiation than drier climates like Reno, NV and Tucson, AZ" (Schlegel and others 2004, 359-368).

Economically, the researchers estimated that a commercially viable system could not exceed a cost of $3,000.00. As a result, the researchers concluded that hybrid lighting systems have the potential for high levels of efficiency. Depending on location and the geometry of the building, hybrid lightning systems could achieve savings as little as 30% in energy usage and in some cases 55% savings in regions with stable sky conditions and high sun peak hours (Mayhoub and Carter 2012) .
Currently the technology is not economically viable due to the fact that it would be considerably challenging to achieve a realistic break even capital cost.

Last year, researchers at Roma Tre in Rome developed a theoretical hybrid sunlight addressing / PV electric lighting system similar to a 1993 system developed by Oak Ridge National Laboratory. The intended system was made up of a sun-tracking primary parabolic collector that was coated with an exceedingly reflective film that would

reflect solar radiation to a set of secondary collectors, which is identical to the Oak Ridge National Laboratory strategy. However, the researchers applied a Cassegrain antenna approach over the original method. The Oak Ridge National Laboratory system reflects light to a specific focal point while the Cassegrain method has a hole at the primary mirrors focal point. This means that the redirected radiation does not have to be focused into a single point but instead the faces of the various fiber optic bundles, permitting for greater flexibility and light collection at the start of the fiber bundles (Balanis 1997) . Through a reverse mathematical analysis, the researchers determined that in order to provide 120lm/W, the reflector would have to have a diameter of 2.6m with a radial depth of 0.79m. It was calculated that the light system would give out about 43,500 lm, equivalent to replacing 12 fluorescent lamps with a luminous efficiency of 60 lm/W. Technical results demonstrate that the system's overall efficiency reached a maximum of 21%. The system would have to collect twelve hours of direct solar exposure a day at a minimum of 320 days a year in order to meet feasible scenarios. With an anticipated cost around $7,028.00 "the proposed solution is not yet fully competitive with traditional lighting systems, but with future developments and refinements as well as the expected dissemination of the technology, should reduce, if not eliminate the gap" (Sapia 2013, 113-121).

As the application of hybrid lighting systems increase, commercial viability will become realistic and even economically viable. A hybrid daylight transferring system can improve a buildings indoor environment, while simultaneously reducing a buildings overall energy footprint.

2.10 APPLICABLE LOCATIONS

Arid regions of the world are known for their abundant supply of daylight, with the southwest desert region being no exception. The National Renewable Energy Laboratory provides a graphic revealing that the southwest geographic region of the United States has a range of 5-6.8 kWh/m2/Day, with Las Vegas at the center of it all (Kristen Ardani, Dan Seif, Robert Margolis, Jesse Morris, Carolyn Davidson, Sarah Truit, Roy Torbert 2013, 1)(Table 1.4),

According to the National Climate Data Center, Nevada has the second highest amount of sunny days, with Arizona having the highest. Nevada's cities experience 153.4 sunny days a year on average, with Las Vegas experiencing an average of 210 sunny days annually. A sunny day as defined by The National Climatic Data Center is when the sky is mostly clear, with cloud covering up to 30% of the sky during normal daylight hours. Throughout a given year however, Las Vegas can anticipate an average of 292 days of sunny days including partly sunny days, where cloud cover exceeds 30%. Based on yearly averages that are again based on years of weather data, the NCDC reveals that Las Vegas is experiencing sunshine 85% of the time between sunrise and sunset with an annual average of seven peak sun hours a day, making Las Vegas the fifth sunniest city in the country (Osborn 2014, 1; National Climatic Data Center -NOAA 2004, 5) (Chart 1.5)

Along with Nevada's inherent geographic location, the state's economy allows for advantageous opportunities in the photovoltaic industry. Nevada was ranked third in solar installations in 2014, behind California and North Carolina (Valasis 2015, 4).

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According to Solar Energy Industries Association reports, the average installed residential and commercial photovoltaic system prices in Nevada have decreased 10% in the last year alone, and that the nation has seen drops between 5% from last year and 28% from 2010. The current NV Energy residential rate is $0.13 per/kWh. Currently, the cost of a solar system over the life of the system is approaching the same cost to produce energy at the rate the utility is charging its consumer. "This decrease in system cost has made, according to the Center for American Progress, the middle class the biggest adopter of solar power in the U.S. with the majority of solar installations occurring in zip codes with median incomes ranging from $40,000 to $90,000. These economic aspects indicate, the timing is right for rooftop solar in Southern Nevada" (Valasis 2015, 4).

The U.S. Energy Information Administration notes that Nevada is the country's leader in solar power potential, making Nevada a prime location for advancements in solar technology.

2.11 BUILDING CODES & STANDARDS

The success of a daylight system is dependent on several factors including cost and performance. With regards to performance, a given system must comply with local and governmental building and energy codes alike. Building energy codes set the lowest expected requirements for resourceful energy design of new and existing buildings. The overall purpose of building energy codes is to save energy, while building codes and standards are put into place to ensure a comfortable and safe environment for the wellbeing of a building's occupants. This is considerably true with building lighting because of the inherent effect lighting can have on human function and capabilities within a space.

> "The requirement for states to adopt and enforce a building energy code is a direct result of the Energy Conservation and Production Act as amended by the Energy Policy Act of 2005. The legislation calls for the U.S. Department of Energy to make a determination of the energy efficiency level of new building energy standard versions of ASHRAE Standard 90.1. Based on this determination, the legislation then typically sets that new building energy standard version as the level of stringency that states must meet."(IEA PVPS Programme, 2014, 6).

Below are relevant codes and regulations that a daylight system must comply with if its intended purpose is to reduce and or replace electric light use during occupied hours of the day.

ASHRAE 90.1:

Standard 90.1 is a United States standard that provides minimum requirements for energy efficient designs for buildings except for low-rise residential buildings. The power consumption of lighting is reduced by setting limits on lighting power density (W/ft2) based on the specific use of the space. ASHRAE 90.1 includes prescriptive requirements for the buildings HVAC, exterior envelope, domestic hot water, electric lighting, power and other equipment. Under the section 9 lighting category, maximum indoor lighting power density expressed in Watts/ Ft^2, minimum lighting controls, exterior lighting, and parking garage lighting are all addressed. The Illuminating Engineering Society of North America provides the LDP baseline recommendations and current efficient technologies proven to be cost effective. According to Standard 90.1, the maximum allowable lighting power density is 1W/ft^2. In reference to lighting controls, the 90.1 standard requires an automatic shutoff control device for buildings more than 5,000 ft^2, and that each room has its own control that also automatically turns off lighting. A control system can meet this requirement by being either time-based or occupancy based.

IESNA LIGHTING HANDBOOK & CIBSE CODE FOR INTERIOR LIGHTING:
The IESNA Lighting Handbook along with the CIBSE Code for Interior lighting provides illuminance criteria for different types of spaces as well as recommendations for different tasks. For example, in an office environment where workstations are present, it is recommended that an illuminance between 27.8FC and 46.4FC is established to ensure a proper lighting design.

2.12 LEED CREDITS

Leadership in Energy and Environmental Design (LEED) is a rating system set in place by the United States Green Building Council in 1994. The Leadership in Energy and Environmental Design Green Building Rating System encourages and accelerates global adoption of sustainable green building and development practices through the creation and implementation of universally understood and accepted tools and performance criteria (2014 Reference Guide V4). The first iteration of LEED for New Construction was released in 1998 as a pilot version of the program and has since evolved and expanded to better meet the needs of construction projects in different market sectors. LEED has evolved through volunteer consensus-based committees of architects, engineers, construction managers, landscape designers, government officials, facilities managers, and others who modify criteria to better meet the goals of the LEED program and expand its applicability to all project types. LEED gives building owners and operators the tools they need to have an immediate and measurable impact on their buildings' performance. LEED promotes a whole-building approach to sustainability by recognizing performance in eight areas of human and environmental health: Location and Transportation, Sustainable Sites, Water Efficiency, Energy and Atmosphere, Materials and Resources, Indoor Environmental Quality, Innovation, and Regional Priority (2014 Reference Guide V4).

The rating system is point based, defining credits under each of the eight concentrations. Each credit is assigned certain criteria that building designers must demonstrate compliance with to obtain the given number of points associated with that credit. LEED has four levels of certification that a project can attempt to achieve. After

meeting the program's minimum requirements, a project must earn at least a total of 40

points to receive certification accolades. (2014 Reference Guide V4)

With proper design and implementation, the utilization of a hybrid daylight system could

earn a project credits towards a LEED certification. Listed below are the applicable

credits based off the most recent version of the V4. LEED Rating System.

APPLICABLE VERSION 4 LEED CREDITS (2014 Reference Guide V4):

EA: Pre-requisite – Minimum Energy Performance

The intent of this credit is to reduce the environmental and economic harms of

excessive energy use by achieving a minimum level of energy efficiency for the building

and its systems. This pre-requisite has three available approaches to meet the credit

intent. Option 1: requires a 5% energy reduction compared to an equivalent baseline

building performance rating, while still complying with all local and governmental codes

and standards. This option is conveyed through a whole building energy simulation and

is highly recommended by the committee as it double dips into other credits. Option 2

and 3 would also be affected by the use of a daylight system, however these options

are obtained by meeting prescriptive standards.

EA: Credit - Optimize Energy Performance

Points: up to 20 points depending on the project type and percentage of energy

reduction.

The intent of this credit is to achieve increasing levels of energy performance beyond

the prerequisite standard to reduce environmental and economic harms associated with

excessive energy use. The greater the reduction of energy use a building has, relates to a larger amount of credits available.

EA: Credit – Renewable Energy Production

Points: 1-3

The intent of this credit is to reduce the environmental and economic harms associated with fossil fuel energy by increasing self-supply of renewable energy. The credit is based off the total percent of renewable energy represented as the equivalent cost of usable energy produced by the renewable energy system divided by the total building annual energy cost.

EQ: Credit – Daylight

Points: 1-3

The intent of this credit is to connect building occupants with the outdoors, reinforce circadian rhythms, and reduce the use of electrical lighting by introducing daylight into the space. To earn this credit, the project team must either demonstrate through annual computer simulations that spatial daylight autonomy of at least 55% is achieved, or achieve an illuminance level between 300-3000 lux for 9 a.m. and 3 p.m., both on a clear sky day at the equinox.

IN: Credit – Innovation

Points: 1

The intent of this credit is to encourage projects to achieve exceptional or innovative performance. To earn this credit, the project team must achieve significant, measurable environmental performance using a strategy not addressed in the LEED green building

rating system. A hybrid daylight system is currently not a strategy defined by the LEED

system and has the potential to provide huge reductions in a building's energy

performance.

RP: Credit - Regional Priority

Points: 1 – 4

The intent of this credit is to provide an incentive for the achievement of credits that

address geographically specific environmental, social equity, and public health priorities.

A hybrid daylight system could possibly assist in earning points within this credit

depending on where the project is located. In the case of Las Vegas, Nevada, a hybrid

system would assist in the earning of this credit, as it fits under the Renewable Energy

Criteria.

2.13 ECONOMIC BENEFITS OF DAYLIGHT

In 2012, the United States commercial sector consumed approximately 274 billion kWh for lighting or about 21% of the commercial sectors electricity consumption using non-renewable materials like coal, natural gas and other carbon emitting fuels to necessitate the required energy. (U.S. Energy Information Administration 2014b) 22% of office buildings' overall energy consumption is strictly dedicated to electric lighting.

Therefore as a strategy to reduce the state's electricity demand, fiber optic daylight systems should be applied to all new and existing office buildings. Studies have demonstrated that office buildings are inherently suitable candidates for this type of system, allowing for several benefits including an increase in office worker productivity and health. The cost of employees in a building will typically be 75-100% larger than the overall rate of utility bills with employee payrolls constituting about 95% of the life cycle cost of a typical office building.

When payroll and a company's revenue are factored in, increased production rates and overall system savings are likely to surpass the cost of a typical buildings energy cost, thus resulting in a rapid payback period.

In 1983, Lockheed Martin increased interaction by integrating daylight into their office layout. Production within the office raised by 15%, which was attributed directly to the integration of daylight within the interior of the building. (Romm 1994) Lockheed Martin reported financial savings due to increased productivity by saying, "every minute less of wasted time per hour represents a 1.67 % gain in productivity, where a 2% increase in productivity is equivalent to 3 million saved per year" (L. Edwards, and P. Torcellini

2002, 9-10) Lockheed Martin officials commented on their increased productivity and financial savings in an article by Burke Miller Thayer:

"The energy savings are over shadowed by the rewards of improved employee productivity…Officials have privately acknowledged that their gains in productivity offset the $2 million extra cost for the building in the first year of occupancy." (Thayer 1995, 26-29)

In 1986, the Reno, Nevada post office was renovated by an architectural firm named Leo A. Daly, who was hired to do everything necessary to reduce energy use. In reference to the lighting design, they allowed for a more dynamic experience within the building by improving the interior light quality and replacing the electric down lights. (Light Corp 2010)   Once again, the quality of light was attributed to an increase in employee productivity levels, this case being by .8%. Once completed, the Reno post office had a record level of productive employees within all the company's branches across the entire western region. Additionally, "productivity gains of 400,000 to 500,000 per annum at the Reno post office paid for the building's renovation in less than a year" (Light Corp 2010, 2)

Although there are sufficient case studies providing data to suggest that simply implementing daylight into a space will increase health benefits, it is difficult to justify. That's why it is important that the daylight system demonstrates definitive results in regards to the substantial reduction of electricity use, thus resulting in a reduction in a building's annual electric bill.

A creative daylight strategy like a fiber optic system must do more that create a suitable indoor environment; it must also demonstrate tangible benefits to the building owner that demonstrate financial offsets. The primary financial validation for a fiber optic daylight system comes from its ability to replace electric lighting and reduce the operating cost of a given space. Office buildings were the second largest market sector in terms of total electrical consumption, accounting for 211- billion kWh of power usage in 2003 (Light Corp 2010) . In any building type there is potential to displace electric lighting with collected sunlight during daytime hours. Because the operational hours of an office building are typically during peak sun hours, there is also a potential to reduce daytime power consumption by considerable amounts.

A fiber optic system being applied in a typical 14,800 square foot office building would cost $735,000 with a payback of 13.2 years. The fiber optic system would consist of 98 separate roof top concentrators distributing daylight to 3 interior luminaires each. On average, an office building uses electric lights 62 hours a week. By simply replacing the need for electric lighting during sun peak hours each day, the system will save over 539,000 KwH each year, resulting in a cost savings of 53,933 dollars each year when the cost of electricity is ten cents per kilowatt hour. Additionally, the cost of saved energy is eight cents per kilowatt-hour, in comparison the current cost of ten cents. The payback period of 13.2 years is accrued by the offset of the system's annual energy savings. There are several other factors that attribute to an even quicker payback period. Using an estimated incremental first cost increase of $0.50 to $0.75 per square

foot of occupied space for dimmable ballasts, fixtures, and controls, daylight has been

shown to save from $0.05 to $0.20 per square foot annually (Ander D. Gregg 2014) .

Because a fiber optic system does not require a lamp, there are no lamp replacement

costs for the system. By offsetting the use of fluorescent lighting, the system will save

another $3,800 dollars over the 13.2 years in bulb replacements at three dollars a bulb,

not including installation cost. With the increase in environmental concerns, rebates are

available through government programs that also reduce the upfront cost.

2.13.1 IPAT

The IPAT attempts to describe the role of multiple factors in determining environmental degradation. The formula is broken down into three terms: population, affluence, and technology.   The IPAT formula suggests that a passive fiber optic system used during sun peak hours 310 days a year in Las Vegas can provide a .11% decrease in an individual's Watt-Hours each year. This system allows an individual to continue with their current way of life since the change primarily occurs due to an increase in the technology used to illuminate an interior space.

The offset of operating costs is beneficial to the owner even when considering a fiber optic system has a significantly larger upfront cost. However, in a broader perspective, we are decreasing power generation and the accompanying environmental pollutants as well by displacing the consumption of electricity.

With the price of electricity continues to rise and climate change concerns continue to Emerge, new technologies, and sustainable strategies will be expected to reduce global energy consumption, while improving overall system efficiencies. Fiber optic daylight systems are as of currently, the best applicable strategy on the market to bring daylight deep into a building's interior. This technology provides better light quality distributed across the entire floor's surface that replaces sizeable amounts of electric light while not requiring other building systems such as the HVAC to compensate for the increased temperature associated with typical electric lighting systems.

Adequately increasing the amount of daylight distributed throughout a building will lead to a drastic reduction in an office building's energy consumption, thus reducing the

nation's energy demands. The increase in daylight will also provide for a much more enjoyable user experience with increased productivity and user happiness level, resulting in an even more profitable and dynamic office environment.

2.14 CONCLUSION

While our knowledge about the earth is expanding, our society is beginning to see global and environmental effects associated with the creation of energy used to meet our daily demands. As our fossil fuels diminish and the effects associated with global warming increase, the desire to meet future energy demands more efficiently have become increasingly relevant.

CHAPTER 3: METHODOLOGY

To determine the feasibility of the proposed fiber optic/ photovoltaic system, a qualitative quasi-experimental approach will be conducted to provide proof of concept data. To appropriately quantify the efficiency of a given system, it will be imperative to test an actual prototypical device under controlled settings. Due to the nature of daylight, it would be ideal to test the system at full scale because the system would demonstrate real scenario data, functionality, and efficiency. This section has been broken down into four sub categories: Materials, Research Set-up, Data Collection Procedures & Metrics, and Product Specifications.

3.1 RESEARCH MATERIALS

PROTOTYPICAL SYSTEM MATERIALS AND ASSEMBLY:

A solar collector must be used in order to gather the sun's energy. For this experiment, a 1'3.5" x 5.5" collector is made to hold 12 Fresnel lenses from Thorlabs. (Refer to product specifications section) The collector is made of solid wood with 2" evenly spaced holes drilled out of it. Each Fresnel lens is 2" in diameter with a focal length of 51mm. Each lens rests on top of a 3D printed PLA frame designed to support the lens and the start of a fiber optic cable. The design of the frame allows for a 51mm air gap, which is required to have the end of the fiber placed at the lens focal point. Literature suggests that glass fiber optics allow for a higher daylight transfer percentage, and can handle higher solar temperatures than that of plastic fiber. However due to budget restraints, plastic fibers are used for this experiment. The Fiber optic cables are 25 strand PMMA multi strand end glow fiber optic cable with a 6.4 active diameter and a black megolon S530 jacket, from Mica Lighting. The cable has an acceptance angle of 75 degrees, with an operating temperature range of 5-248 degrees Fahrenheit. For this prototype, twelve 10' long cables are used.
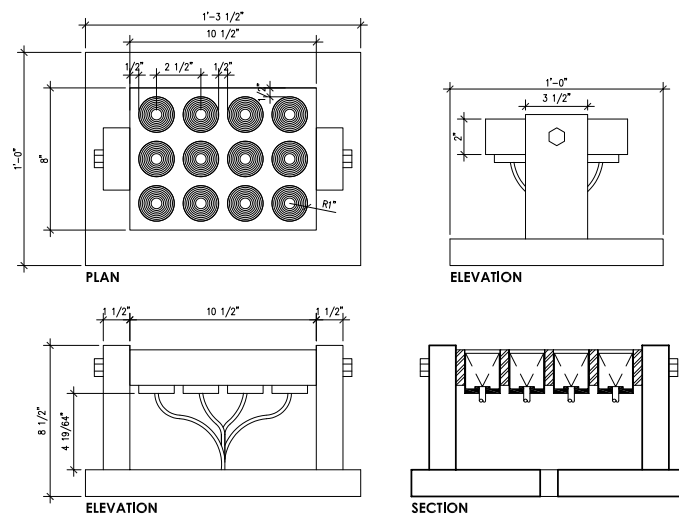
Figure 3.1 Diagrams of Concentrator

Each Fresnel lens concentrates daylight into the receiving end of a 6.4mm fiber cable that transfers the collected light to the distributing end of the cable. At the end of each segment a 20mm hemispherical collimator lens from Luxeon Star LEDs is applied to the face of the fiber. (refer to Product Specifications section) The lens itself has a 180-degree beam spread, which is used to evenly disperse the collected daylight into a modified Lithonia PT2U MV 2x2 T8 Parabolic Multi Volt Troffer. For this study, the
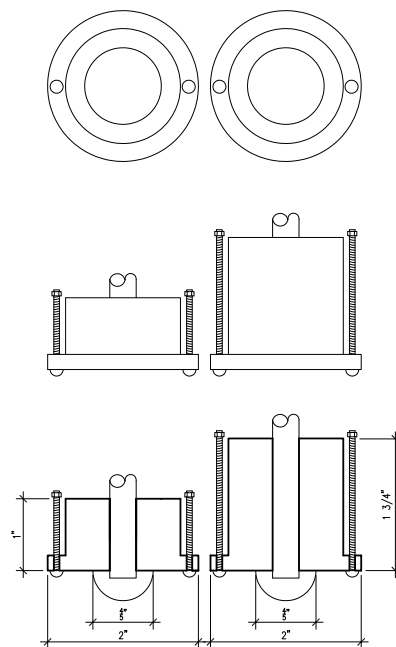
Figure 3.2 Enlarged View of Hemispherical Collimator

Lithonia fixture has been stripped of its lamps and ballasts. A custom 3D printed mount is created to hold the collimator lens flush with the end of the fiber, while allowing it to be mounted within the fixture. The selected fixture utilizes aluminum louvers to reduce glare and evenly distribute light leaving the luminaire. 2.5" x 1.5" SP3-36 6V Thin Film photovoltaics from PowerFilm are secured vertically to the internal louver faces. Using a single circuit strategy, all the Thin Film photovoltiacs are wired in series with the end wires left available for testing. Connecting the Thin Film photovoltaics in series, allows

the array to generate a max capacity of 24V. The entirety of the system is placed into a

testing module described below.
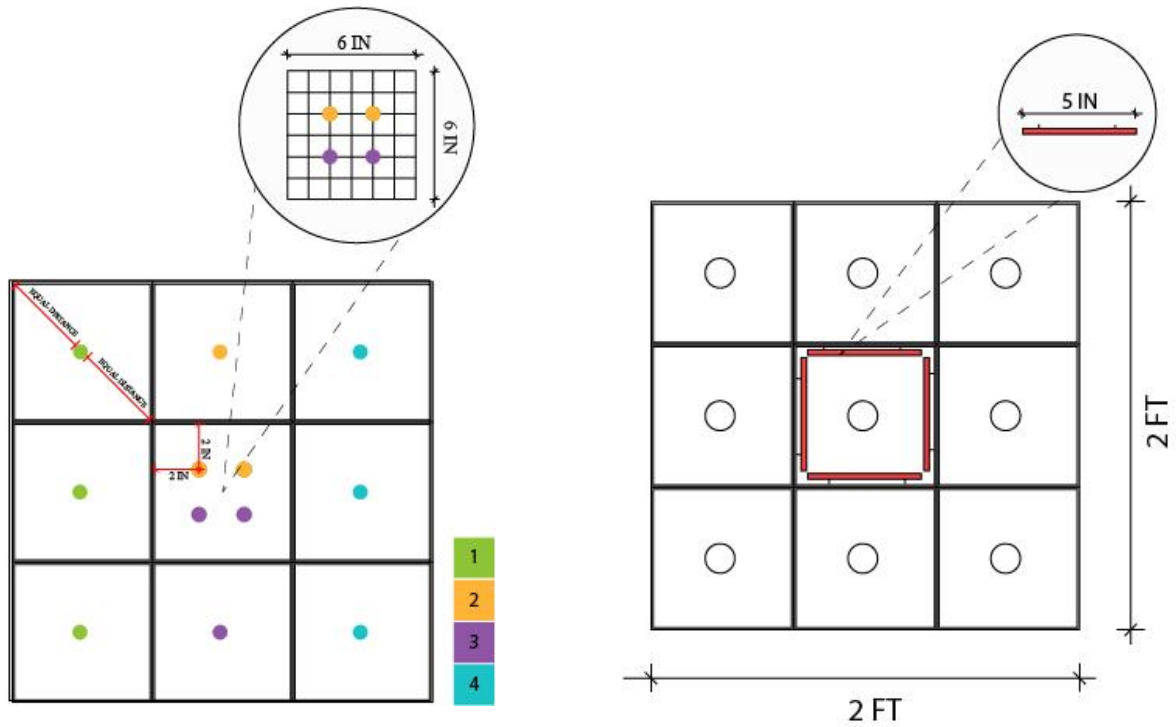
Figure 3.3 Collimator Arrangement And Photovoltaic Placement Within the Lithonia Fixture

3.2 TESTING MODULE ASSEMBLY

A testing module provided by the UNLV School of Architecture, NEAT LAB, houses the experimental system in question. The testing module dimensions are L8' x W5'-4" x H10'-2". Built out of lumber, the module is constructed using 2x6 nominal beams (1.5"x5.5") spaced 1'4" apart on center. The module is insulated with 5 ½" of Batt insulation, providing an R-Value of 15. The test module is located at the University of Nevada Las Vegas, Paul B. Sogg Architecture Building. (36.14548° N, -115.137° E). The module is located on the South East corner of the school lot.
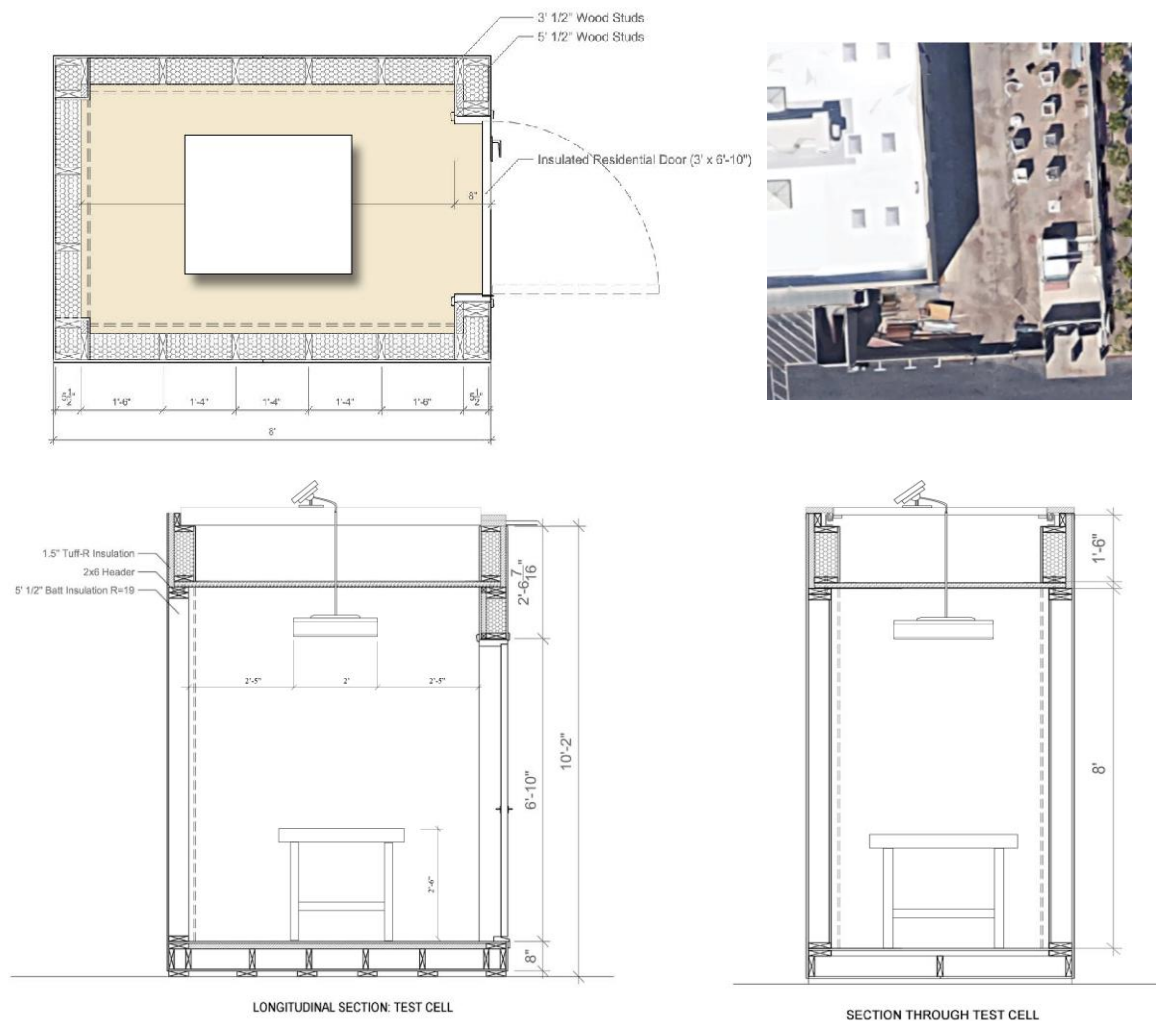
Figure 3.4 Module Drawings with Prototype Placement and Site Map

3.3 EXPERIMENTAL SET-UP

The testing module houses the system's modified fluorescent luminaire as well as the bottom end of the fiber cables, while the solar collector remains on the exterior fastened securely to the roof of the testing module. The solar collector remains in a fixed position facing south, with the collector face tilted to match the position and solar altitude of the sun in Las Vegas at the time of data collection. Within the module, the fixture is fastened securely to the corrugated steel roof using metal chains and hooks. It hangs 7 feet off the ground and 4 feet 6 inches above a given work surface.
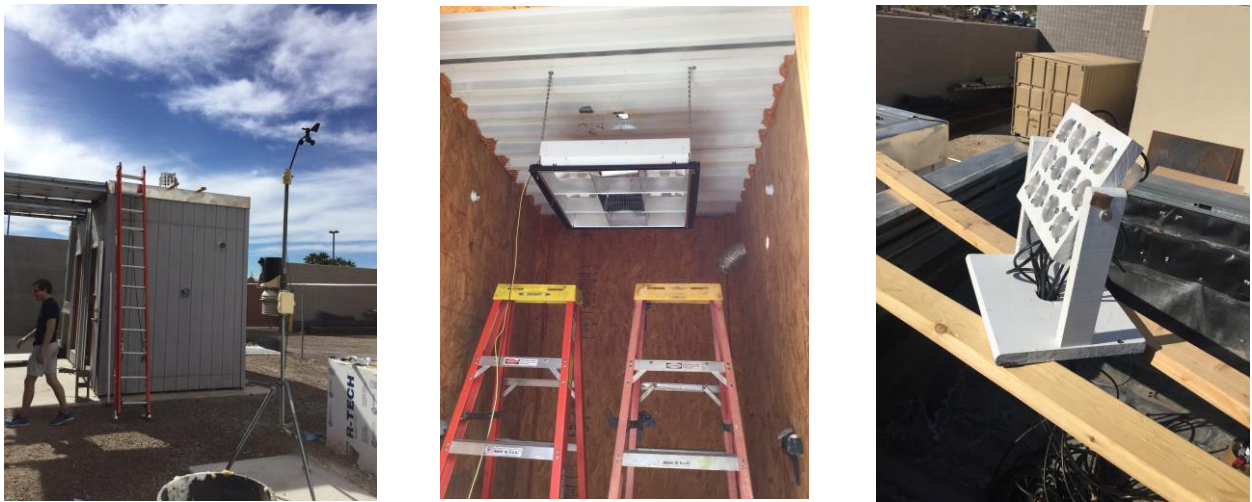
Figure 3.5 Experimental set up, (Left) Module (Middle) Hybrid fixture (Right) Concentrator

3.4 DATA COLLECTION PROCEDURE AND METRICS

Over a period of 7 days, data is collected manually at 9a.m., 12p.m., and 3p.m. in order to get an understanding of how the system would function throughout Las Vegas' solar peak hours. During each interval the solar concentrator must be prepped for the upcoming test. The plastic fibers used in this experiment have an operating temperature allowance of 5-248 Fahrenheit. Simple tests revealed that the temperature at the focal point of the 2" Fresnel lens exceeded 320 degrees Fahrenheit. Because of this after every test, each fiber must be removed from the 3D printed frame and clipped back up to ¼", revealing a clean non obstructed point of entry for the daylight to enter. The solar concentrator will be orientated to align directly with the Suns azimuth and altitude.   An Ajax scientific dual scale thermometer is placed in the interior and exterior of the test module. Recording the temperature differences between the two thermometers will determine the internal temperature difference caused by the system. Using a thermal imaging camera, photos of the module's interior are taken daily to determine if any solar radiation passes through the fiber. Internal light levels are tested and recorded both manually and electronically. Using a Konica Minolta light meter, six different points within the module will be measured. The first point is located one foot below the luminaire, while the remaining five points will be located on a surface simulating a work surface. Using the hand held light meter, measurements will be recorded at 7am, 12pm and 3pm throughout the course of the experiment. In addition to point testing, battery powered hobo data loggers will be placed at the exact 5 measure points, taking lumen readings every two minutes over the length of the testing period. Both sets of data will

provide comparative readings that will illustrate the fixtures light output potential as well as the beam spread of the fixture.
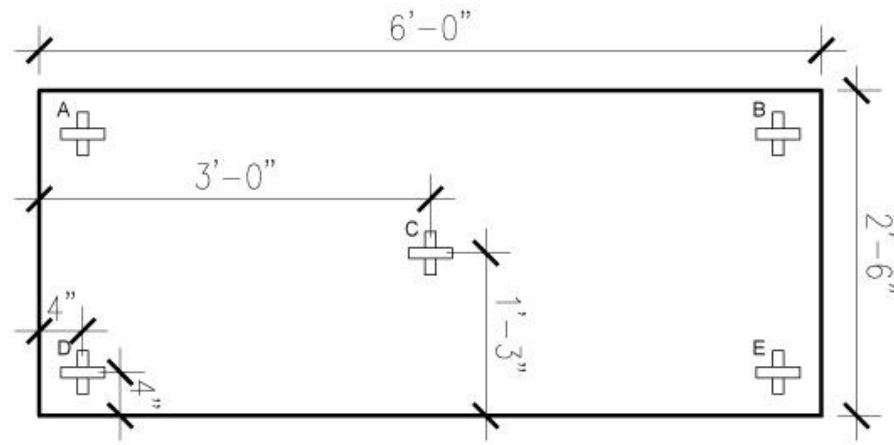
Figure 3.6 Plan view of work surface table with measurement point locations

To measure the amount of electricity that is generated by the system, a Fluke 87 III True RMS multi-meter is used to record both the voltage (V) and current (A) generated by the photovoltaic film components. Using data provided by the National Oceanic and Atmospheric Administration, along with weather data from the Las Vegas, McCarran International Airport weather station, solar altitude for the month of February, 2016, Daily outdoor Temperature, PSM Direct Normal Irradiance levels, and daily weather conditions will all be recorded during each test day. By testing and recording the light levels, thermal difference, Daily variables and electrical potential, it can be determined if the system can adequately provide recommended light levels while simultaneously generating natural energy in Las Vegas.

3.5 TESTING SCHEDULE CHART

A larger version of this chart can be found in the Appendices.

Daylight Collection and Electricity Generation Analysis 2016

UNIVERSITY OF NEVADA LAS VEGAS

Location: Las Vegas, Nevada
Researcher: Sean Zurko

Start Date of Experiement: 02.21.2016
End Date of Experiement: 02.27.2016

	21-Feb			22-Feb			23-Feb			24-Feb			25-Feb		
	9 a.m.	12 p.m.	3 p.m.	9 a.m.	12 p.m.	3 p.m.	9 a.m.	12 p.m.	3 p.m.	9 a.m.	12 p.m.	3 p.m.	9 a.m.	12 p.m.	3 p.m.
Solar Altitude (Degrees)															
PSM Direct Normal Irradiance Levels															
Daily Outdoor Temperature (F)															
Weather Conditions															
Internal Temperature (test cell)(F)															
Baseline Illuminace (FC)															
Internal Light Levels - at 1ft off fixture face (FC)															
Internal Light Levels - Point A (F)															
Internal Light Levels - Point B (F)															
Internal Light Levels - Point C (F)															
Internal Light Levels - Point D (F)															
Internal Light Levels - Point E (F)															
Current Generated by PV (A)															
Voltage Generated by PV (V)															
Thermal Temperature (Fixture)(F)															
Thermal Temperature (Ceiling)(F)															

	26-Feb			27-Feb		
	9 a.m.	12 p.m.	3 p.m.	9 a.m.	12 p.m.	3 p.m.
Solar Altitude (Degrees)						
PSM Direct Normal Irradiance Levels						
Daily Outdoor Temperature (F)						
Weather Conditions						
Internal Temperature (test cell)(F)						
Baseline Illuminace (FC)						
Internal Light Levels - at 1ft off fixture face (FC)						
Internal Light Levels - Point A (F)						
Internal Light Levels - Point B (F)						
Internal Light Levels - Point C (F)						
Internal Light Levels - Point D (F)						
Internal Light Levels - Point E (F)						
Current Generated by PV (A)						
Voltage Generated by PV (V)						
Thermal Temperature (Fixture)(F)						
Thermal Temperature (Ceiling)(F)						

Data Analysis

	9 a.m.	12 p.m.	3 p.m.	Average
Average Illuminance - Point A (FC)				
Average Illuminance - Point B (FC)				
Average Illuminance - Point C (FC)				
Average Illuminance - Point D (FC)				
Average Illuminance - Point E (FC)				
Overall Average Illumiance (FC)				
Average Voltage Recorded by Time (V)				
Overall Average Recorded Voltage (V)				
Average Current Recorded by Time (A)				
Overall Average Recorded Current (A)				
Max Temperature at Focal Point (F)				
Max Recorded Illuminance at work surface (FC)				
Max Recorded Voltage (V)				
Max Recorded Amps (A)				
Work Surface Area (SQ. FT)				
Max Lumens per SQ. FT.				
Max Voltage per SQ. FT.				
Total Surface area of Lens' (SQ. in.)				
Average Lumans Per lens				
Max Watts (W)				
Max Lumens per Watt (lm/W)				

Table 3.1 Testing Schedule Chart

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3.6 LENS SPECIFICATIONS

Ø 50.8mm
[2.00in]

1.5mm
[0.06in]
REF

Total Transmission of Fresnel Lenses

NOTES/SPECIFICATIONS:

1. Nd= 1.49 Vd= 55.3
2. CLEAR APERTURE: >90% OF DIAMETER
3. FOCAL LENGTH: 51 ±2.5mm
4. GROOVE SPACING: 0.33mm
5. PITCH: 10°
6. THICKNESS TOLERANCE: ±0.25 mm
7. DIAMETER TOLERANCE: ±0.125 mm
8. PARALLELISM: <3 arcmin
9. SURFACE QUALITY: 80-50 SCRATCH-DIG

DRAWING PROJECTION			THORLABS
	NAME	DATE	www.thorlabs.com
DRAWN	DS	14/AUG/13	Ø 2" POSITIVE FRESNEL LENS, EFL = 51mm
APPROVAL	DD	09/SEP/13	MATERIAL
COPYRIGHT © 2013 BY THORLABS			OPTICAL QUALITY ACRYLIC REV A
VALUES IN PARENTHESIS ARE CALCULATED AND MAY CONTAIN ROUNDOFF ERRORS		ITEM # FRP251	APPROX WEIGHT 3.39 g

Figure 3.7 *2" Diameter Fresnel Lens by THORLABS*

ISS.	DATE	E.C.N.	DESCRIPTION
1	25-Feb-09		FIRST ISSUE

© 2006 CARCLO
ALL DIMENSIONS IN mm

CUSTOMER DRAWING

SECTION A-A
SCALE 2:1

Ø 19.7

0.7

1.5

7.0   7.0

DIAMOND DOWEL
DETAIL C
SCALE 10:1

1.60

2.40

3.0
GATE WIDTH

Ø 11.0

10.0
MAX GATE
LENGTH

7.3

Ø 2.40

A   A

0.85

3D GENERAL VIEW
SCALE 1:1

DIAMOND DOWEL
SEE DETAIL C

MATERIAL: POLYCARBONATE

carclo
technical plastics

CARCLO TECHNICAL PLASTICS (SLOUGH)
111 BUCKINGHAM AVE, SLOUGH
SL1 4PF, ENGLAND
TEL: +44 1753 575011   FAX: +44 1753 811359
e-mail: design@carclo-optics.com}

GENERAL TOLERANCES (UNLESS STATED)

LINEAR	ANGULAR
X +/- 0.25	X +/- 1°
X.X +/- 0.1	X.X +/- 0.5°
X.XX +/- 0.05	X.XX +/- 0.1°

CUSTOMER

CARCLO

TITLE

UNIFORM HEMI-SPHERICAL
EMITTER BUBBLE OPTIC

DRAWN	AJD	DATE	25-Feb-09
CHK'D		DATE	
APP'D		DATE	

SCALE	CARCLO PART No.
2:1	10620

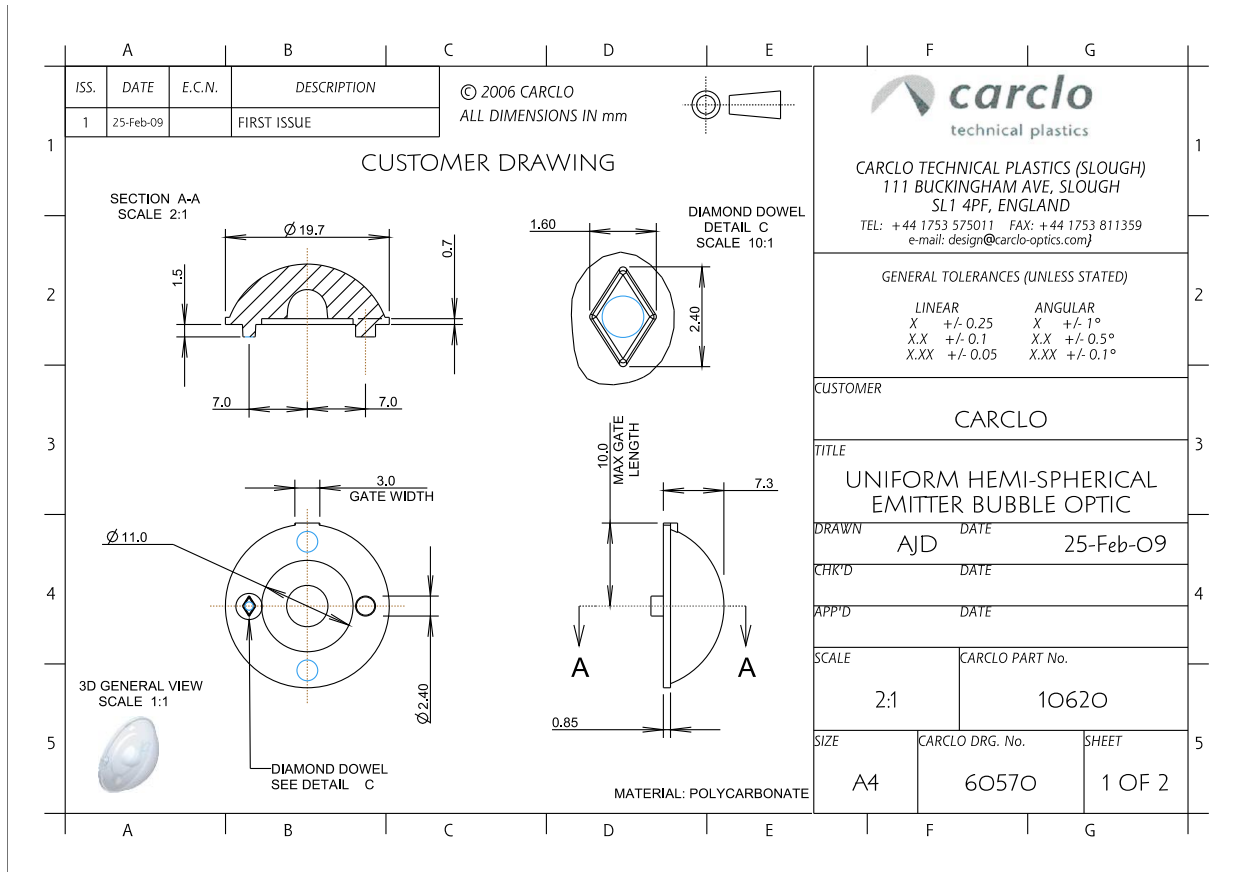| SIZE	CARCLO DRG. No.	SHEET
A4	60570	1 OF 2

Figure 3.8 *20mm hemispherical collimator lens from Luxeon Star LEDs*

CHAPTER 4: RESULTS

Over a period of seven consecutive days, data was recorded to determine the feasibility of a hybrid fiber optic daylight system that provided both code required internal light levels and generated enough electricity to be at minimum self-sufficient. The system in question consists of three major segments working in tandem to allow for a continuous path for daylight to travel through. Daylight is collected using a twelve lens concentrator to collect and transmit the harvested daylight into fiber optic cables. Those cables then function as a vehicle for the light to travel through until it reaches a modified fluorescent fixture. The fixture utilizes twelve collimator lenses to evenly distribute light down into a given space. Additionally the fixture contains vertically oriented thin film photovoltaics that uses a small portion of the collected light in order to generate electricity. Over the testing period, during the times of 9 am, 12 pm, and 3 pm, the solar concentrator was manually oriented to align with both the sun's altitude and azimuth. During each of the mentioned intervals, interior light levels, indoor and outdoor temperatures, voltage, amperage, and both internal and external conditions were all recorded.

RECORDED ILLUMINANCE:

A	1.04 LM/FT^2					.87 LM/FT^2	B

C
6.0 LM/FT^2

D
1.03 LM/FT^2

E
.74 LM/FT^2

FIXTURE ABOVE
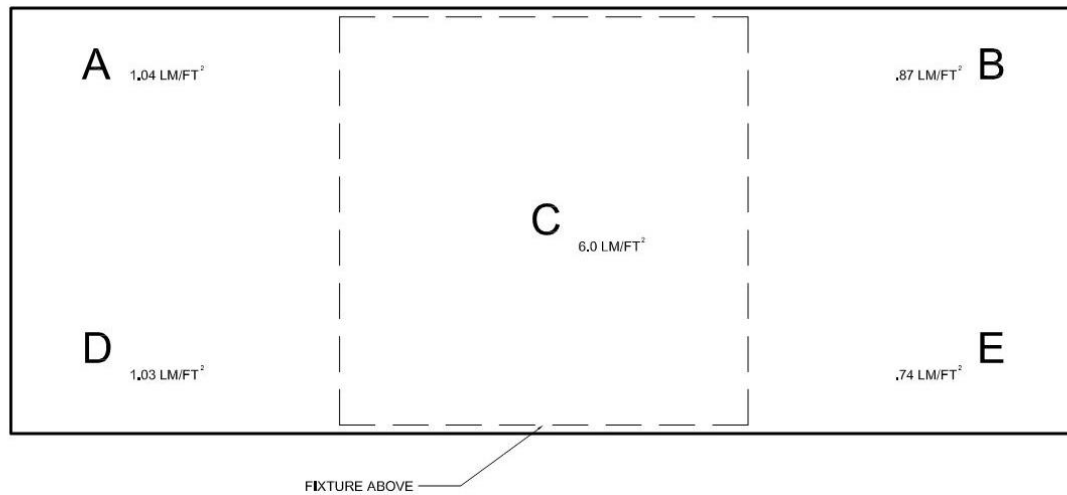
Table 4.1 Average illuminance values at each recorded point on the simulated work surface

Table 4.1 provides the overall average illuminance values at each of the recorded points within the test cell at work surface height (2.5' above the finished floor). Point C, located directly below the fixture produced the highest average illuminance value of 6 lm/ft^2, with a recorded range of 1.3 -15.06 lm/ft^2. While the surrounding points remained consistent with an average range between them of .12-2.45 lm/ft^2. At the end of the test period, the fixture produced an average illuminance of 1.94 lm/ft^2. At one foot below the fixture face, recorded measurements fluctuated from 6.28–39.1 lm/ft^2, with an overall average value of 29.44 lm/ft^2.
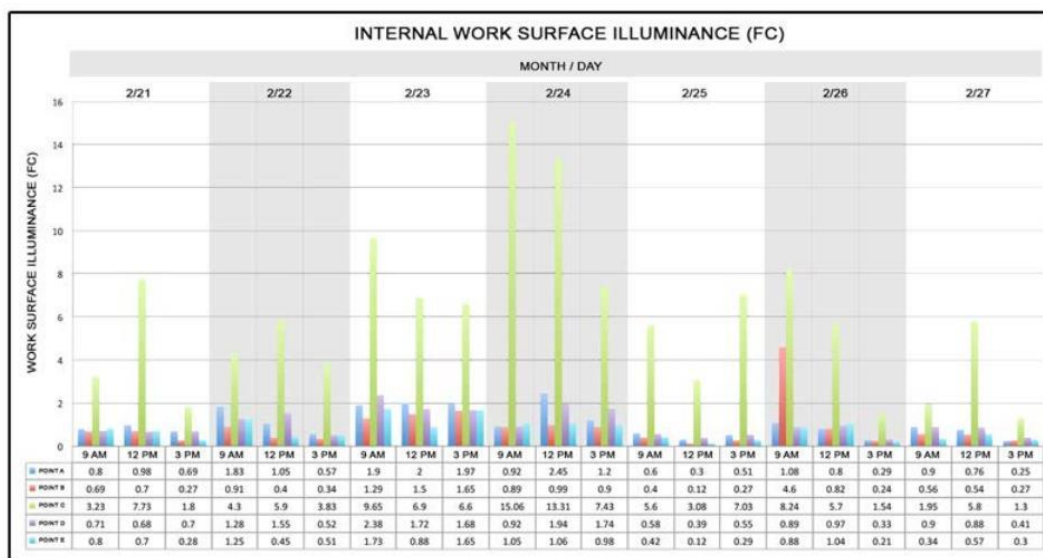
Table 4.2 Internal work surface Illuminance Values at each tested interval

Table 4.2 provides results of all recorded data points at each daily interval. With a work surface area of 10ft^2 within the test module, the maximum surface illuminance was 1.5 lm/ft^2. While each of the twelve lenses within the concentrator provided 1.26 lumens per lens. Results revealed that during this experiment, the highest transmission of daylight occurred at noon with an average illuminance of 6.92 lm/ft^2, followed closely with 9am intervals with an average of 6.86 lm/ft^2. Figures 4.3 and 4.4 provide an analysis in weather conditions and outdoor temperatures and the effects they have on the amount of daylight that was harvested. Table 4.3 suggests that during times of the day with higher cloud cover in the sky, the amount of harvested daylight is significantly reduced. This is primarily due to the fact that less daylight is available to make contact with the face of the concentrator lenses. Table 4.4 reveals that when the outdoor temperature is below 65 degrees Fahrenheit, a higher percentage of daylight can be collected. A prime example of this can be seen on February 24, at 9 am. During this interval the National Oceanic and Atmospheric Administration (NOAA) observed the Las

Vegas sky as "Few Clouds" with a temperature of 54 degrees Fahrenheit. Over the

testing period this was the lowest temperature interval recorded, resulting in the highest

yield of daylight within the test cell recorded at 15.06 lm/ft^2. On February 27, at 3p.m.

NOAA observed the sky as "Mostly Cloudy" with an outdoor temperature of 79 degrees

Fahrenheit. At this interval, the lowest yield of daylight was recorded where the

maximum illuminance value was 1.3 lm/ft^2.
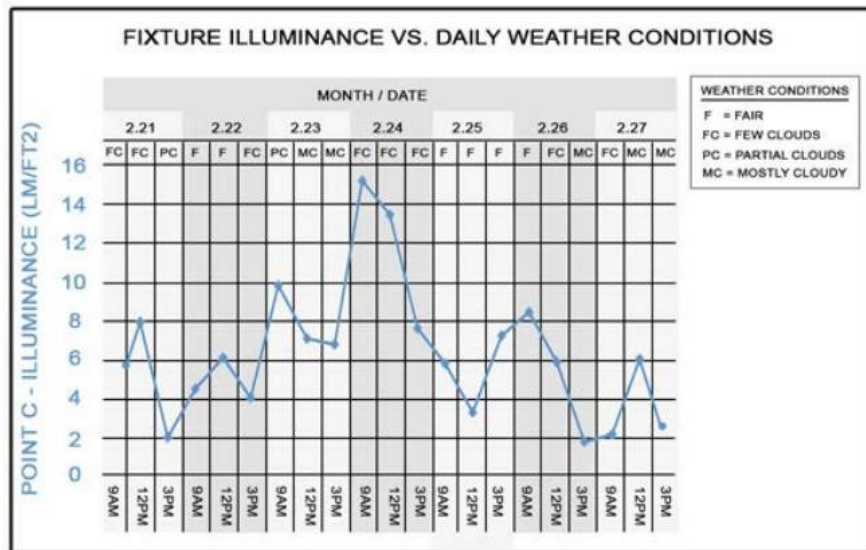
Table 4.3 Internal Illuminance compared with NOAA recorded Daily
Weather Conditions
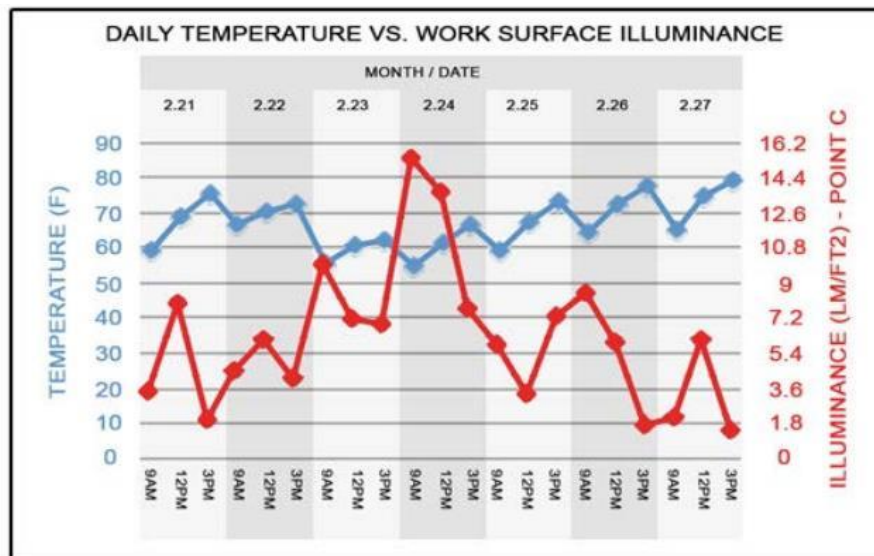
Table 4.4 Daily Temperature compared to the Internal Illuminance

Refer to Figures 4.7a/b and 4.8 for additional lumen values and recorded internal

conditions generated by hobo data loggers placed within the module.

RECORDED VOLTAGE:

At each interval, thin film photovoltaics within the fixture were monitored using a handheld multi-meter, with the highest voltage and amperage being recorded. Results shown in Table 4.5 reveal that 12p.m. intervals on average generated a higher voltage yield over the 9a.m. and 3p.m. intervals. On Average 12p.m. intervals reached up to 10.21V, with a system high of 14.85V on February 24. While 9a.m and 3.pm. intervals reached up to 9.08V and 8.24V, with high of 10.90V and 11.17V respectfully. The four thin film photovoltaic panels were connected in a single series to allow for a maximum capacity of 24V. Over the length of the experiment the four panels averaged a total of 9.18V or 38% of the total system capacity, with a maximum output of 3.95W. The maximum amperage produced by the photovoltaics was .3 Amps with a minimum as low as .1 Amps. Overall the system produced an average of .17Amps, throughout the length of the experiment.
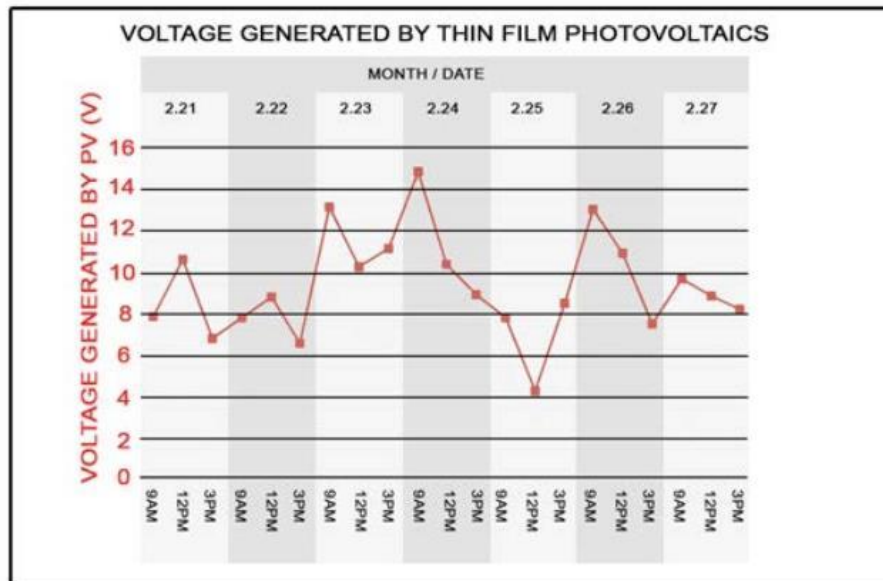
Table 4.5 Voltage generated by Thin Film Photovoltaics

Table 4.6 shows a direct correlation with regards to the daily irradiance and the
generated voltage over the period of the experiment. On days where direct horizontal
irradiance was high, the voltage generated also demonstrated an upward trend, while
on days were the irradiance was low, the recorded voltage yield was lower. However
on February 25, the results were uniquely different, in that while all irradiance levels
were generally normal, the recorded voltage reached the lowest during the length of the
experiment at 4.3V. This is likely to have been the case, due to high daily temperatures
and clear skies causing the tips of the fibers to melt, thus reducing the efficiency of the
overall system.
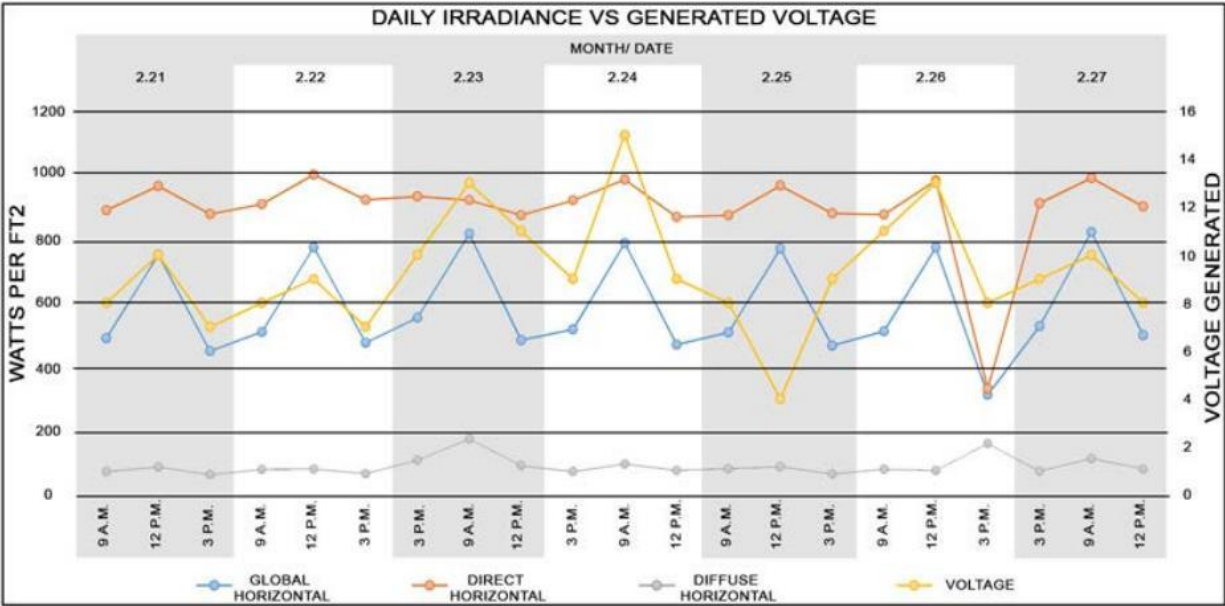
Table 4.6 Daily Irradiance Recorded by NREL in comparison to the amount of voltage generated

Overall, the system demonstrated that the tested assembly can simultaneously redirect
daylight to the interior of a building while simultaneously generating electricity.
However, the system did not provide the 50FC or XX lm/W required by code for office
building settings. Under the best tested conditions the system managed to
produce .2lm/Ft^2, while simultaneously producing .049W/Ft^2, and 1.32V/ft^2.

ADDITIONAL RECORDED DATA AND CHARTS:
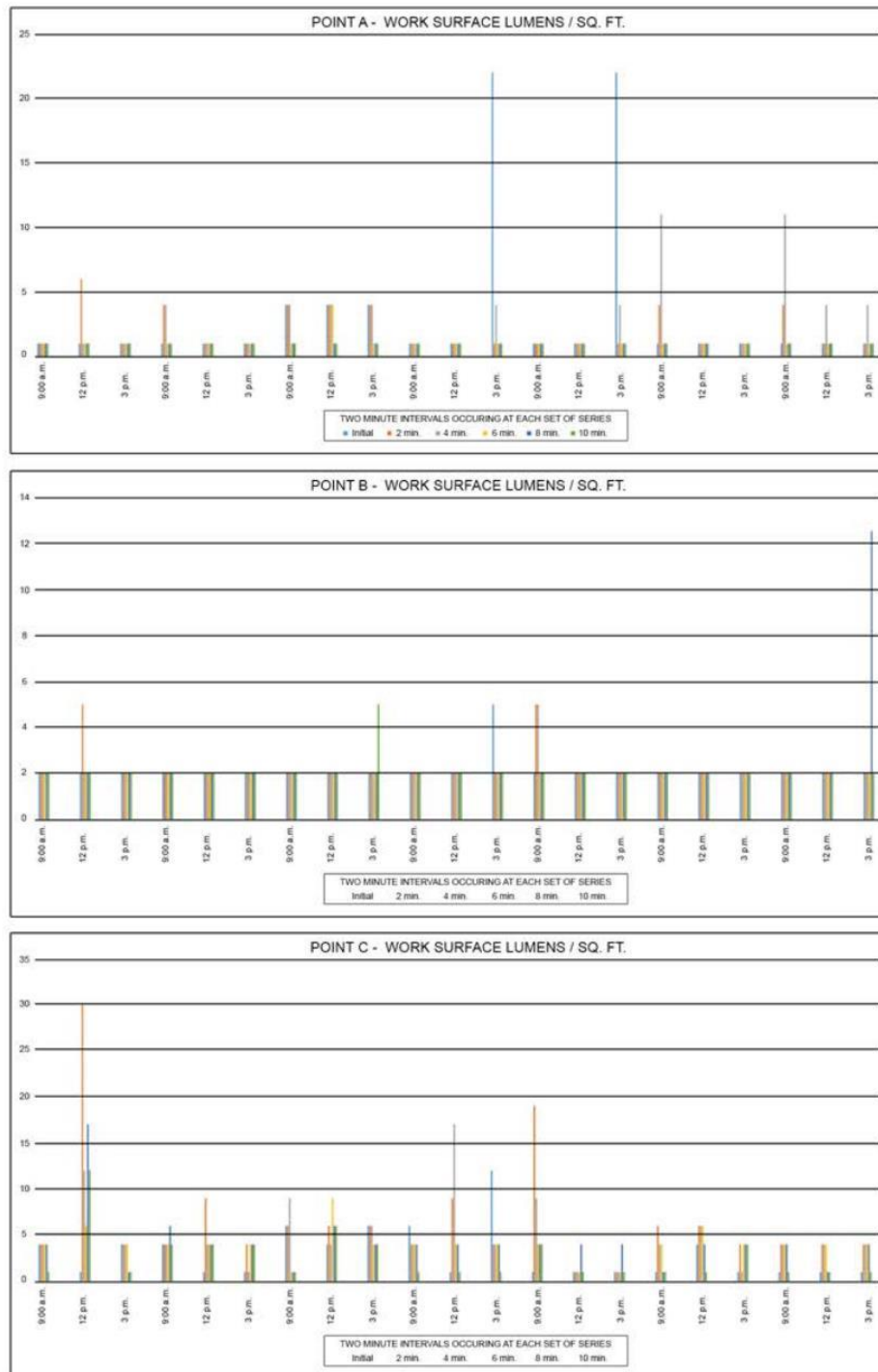
Table 4.7a Internal illuminance values recorded by Hobo data loggers (Points A-C)

93
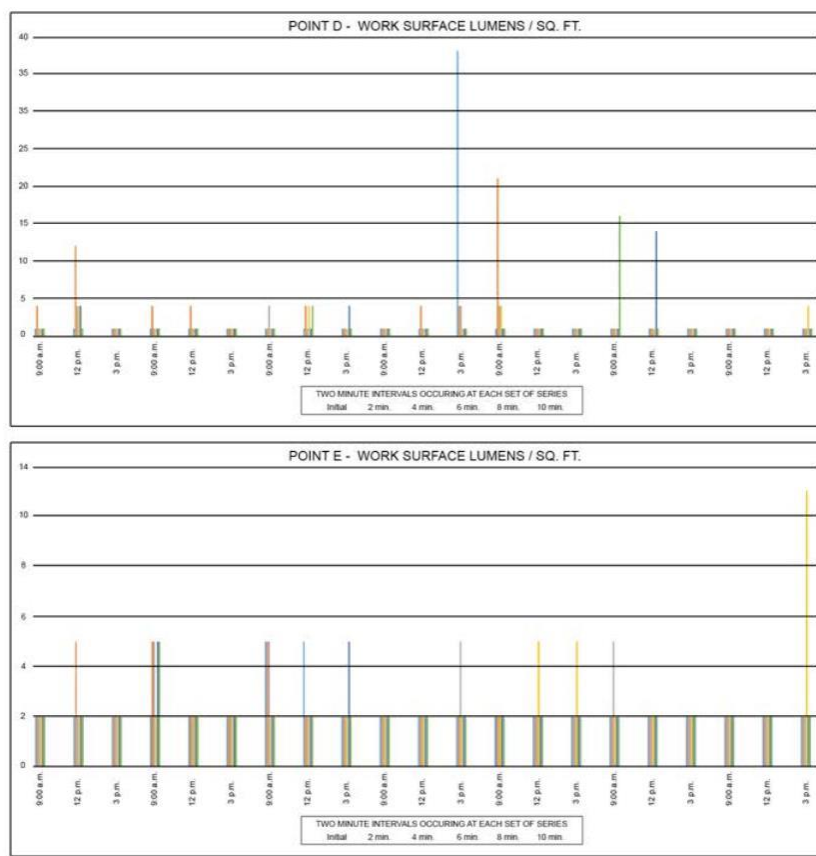
Table 4.7b Internal illuminance values recorded by Hobo data loggers (Points D-E)
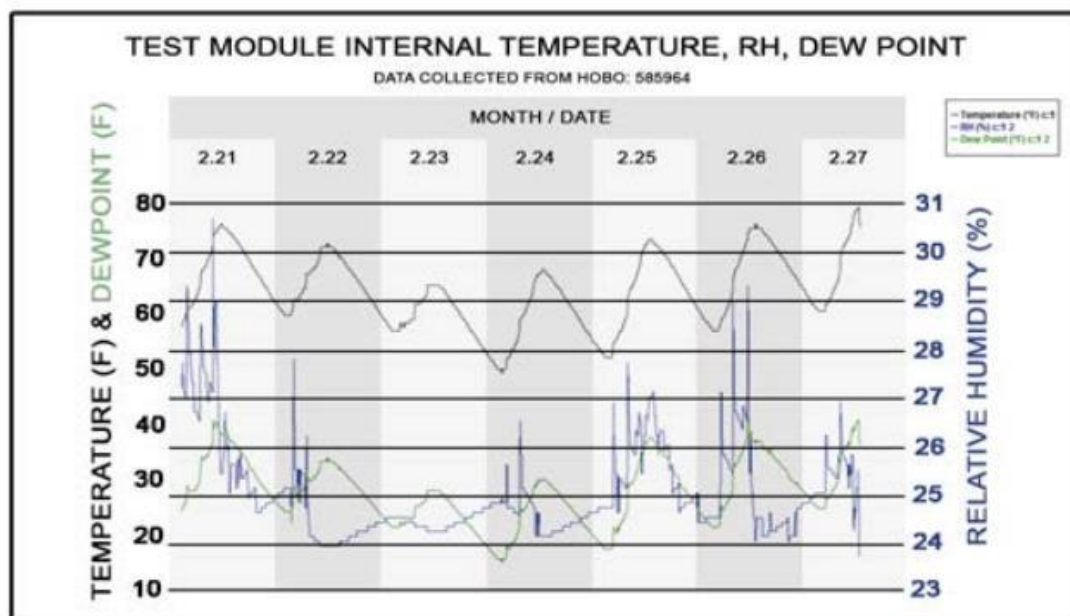
Table 4.8 Internal test cell conditions

94

4.1 DISCUSSION

HUMAN ERROR:

The data retrieved with regards to the system in question, suggests that a passive assembly has the ability to generate a quantifiable amount of daylight at a given time, while simultaneously producing naturally generated electricity. However, human error as well as product materiality contributed to the systems overall inefficiencies. When handling lenses, precision is key. If the face of the lens is not parallel to the face of the fiber optics, then the collected daylight will not enter the fibers. Because the optical grade lenses were mounted and secured within the wooden concentrator frame manually, it's very likely that the faces were not perfectly aligned. During some instances, it was visibly evident that up to 25% of the lenses were not directing equal parts of daylight into the fixture. With the assistance of machine manufacturing these issues can be easily resolved, greatly increasing the overall amount of daylight concentrated into the systems fiber optics. Another factor that affected the amount of harvested daylight was the manual positioning of the concentrator to align with the Suns position. When the lenses are not directly aligned with the Sun, it was common to record less than $1lm/ft^2$ within the test module. By applying a GPS guided solar tracker to the concentrator, human error with regards to proper solar alignment can be eliminated.

MATERIAL INEFFICIENCIES:

For this experiment, plastic fibers were selected over glass fibers due to budget restraints. Although, plastic fibers are economically viable with respects to their glass counterpart, they render the systems overall efficiencies vulnerable to high temperatures. Glass fibers have an operating temperature capacity as high as 900 degrees Fahrenheit, while plastic fibers have a maximum exposure threshold of 158 degrees Fahrenheit. This is the melting point of most PMMA fibers. Over the course of the experiment temperatures at the face of the PMMA fibers far exceeded what the fibers could withstand. A simple test using a digital thermometer was done to determine the temperatures occurring at the focal point of the Fresnel lens. After five minutes the thermometer read as high as 316 degrees Fahrenheit, double what the plastic fibers were designed to handle. It's because of the extreme heat that caused the fibers to melt, thus causing substantial reductions in light transmission. By utilizing glass fibers over plastic fibers, one can speculate that the amount of light entering the test module would be greatly increased, consequently increasing the voltage generated.

FUTURE SYSTEM OPPORTUNITIES:

For this experiment twelve Fresnel lenses were used to concentrate daylight into twelve 6mm PMMA fiber optic strands, which distributed the light into a modified 2'x2' fluorescent fixture containing four 4"x5" thin film photovoltaics. This assembly produced a maximum of 15.06 FC at work surface height, while simultaneously generating 14.85V. Theoretically, by tripling the amount of lenses on the concentrator to 36, and increasing the number of photovoltaic panels to 36, the number of faces within the fixtures louver system, it's possible that it could provide if not exceed 45-50 FC and generate over 125V per fixture. Furthermore, by applying a GPS guided mount the concentrator and replacing the PMMA fibers with suitable glass fibers, the system would be able to collect daylight evenly throughout the entire day maximizing solar peak hours. Simply by utilizing more resilient materials and increasing both the number of lenses and photovoltaic panels, it's possible that a hybrid daylight fixture could produce enough daylight to meet code requirements while generating enough electricity to, at minimum be self-sustaining.

CHAPTER 5: TABLES, CHARTS, AND FIGURES CITATIONS

TABLE 1.1
2015 Globally Averaged Combined Land and Ocean Surface Temperature Anomaly by NOAA
https://www.ncdc.noaa.gov/sotc/global/201509

TABLE 1.2
Carbon Dioxide Emissions by Region, 1990-2030
http://rainforests.mongabay.com/09-carbon_emissions.htm

TABLE 1.3
U.S. CO2 Emissions by Sector
2001 2030 inc. / Architecture 2030 / U.S. Energy Information Administration 2011

Figure 2.1
Illustration of a Wavelength taken from Cooperative Institute for Meteorological Satellite Studies.
https://cimss.ssec.wisc.edu/satmet/modules/3_em_radiation/img/wavelength.jpg

Figure 2.2
Illustration of the Solar Radiation Spectrum taken from Princeton.edu
https://www.princeton.edu/~willman/observatory/oseti/spectrum.jpg

FIGURE 2.3
Winter and Summer Window Daylight Diagram taken from DN Architecture
http://dnarchitecture.com/passive-solar-design-principles/

FIGURE 2.4
Skylight diagram taken from Mechanical and Electrical Equipment for Buildings 11th edition. Page 596

Walter T Grondzik, Alison G Kwok, Benjamin Stein, John S. Reynolds. 2010. *Mechanical and electrical equipment for buildings*. 11th ed. Hoboken, New Jersey: John Wiley and Sons.

FIGURE 2.5
Diagram of a Light Tube taken from Solar Tube Skylight website
www.solartubeskylight.com

Figure 2.6
Diagram of John Tyndalls laser through water experiment taken from Harvard
University's Science Center
http://scictr.fas.harvard.edu

Figure 2.7
Diagram of a Parabolic Mirror taken from Richard Fitzpatrick, Professor of Physics at
the University of Texas at Austin
http://farside.ph.utexas.edu/teaching/302l/lectures/node136.html

Figure 2.8
Diagram comparing a conventional lens with a Fresnel lens taken from William Meehan.
http://laser.physics.sunysb.edu/~william/journal/

Figure 2.9
Multimode and Single mode graphic taken from the online Encyclopedia
http://encyclopedia2.thefreedictionary.com/Chromatic+dispersion

Figure 2.10
Light Dispersion demonstrated through a glass prism taken by Tulane University-
Sanelson
http://www.tulane.edu/~sanelson/eens211/proplight.htm

Figure 2.11
Diagram of Anhydroguide PCS Low OH VIS-IR Fiber taken from SYS Concepts
http://www.sys-concept.com/Large_Core_Fiber.htm

Figure 2.12
Photo of the Himawari Corporations Solar Collector taken from the Himawari Catalog.
http://www.himawari-net.co.jp/e_page-index01.html

Figure 2.13
Photo of Parans Inc. Solar Collector taken from Parans SP3
http://www.parans.com/eng/sp3/

Figure 2.14
Photovoltaic Diagram taken from Dow Corning
http://www.dowcorning.com/content/solar/solarworld/solar101.aspx

Figure 2.15
Semi-Transparent Photovoltaic Diagram taken from Onyx Solar
http://www.onyxsolar.com/standard-photovoltaic-glass.html

Figure 2.16
Transparent Photovoltaic Diagram taken from MIT Energy Initiative
http://mitei.mit.edu/news/transparent-solar-cells

Figure 2.17
Thin-Film Photovoltaic Diagram taken from PV Magazine
http://www.pv-magazine.com/news/details/beitrag/north-america--hosiden-and-hisco-sign-distribution-partnership-agreement-to-meet-growing-pv-demand-_100000431/#axzz3rroZFQ2P

Figure 2.18
Quantum Dot Illustration taken from International Business Today
http://www.ibtimes.co.uk/nasa-tech-miniaturised-allow-integration-quantum-dot-spectrometers-into-smartphones-1509147

Figure 2.19
Oak Ridge National Laboratory Hybrid Light System taken from ORNL
http://web.ornl.gov/~webworks/cppr/y2001/pres/117989.pdf

Chart 1.1
U.S. Energy Information Administration 2013 Electric Power Annual
https://www.eia.gov/electricity/annual/html/epa_01_01.html

CHAPTER 6: CHARTS AND DIAGRAMS

| | Total (All Sectors) | | | Electric Power Sector | | | | Commercial | | Industrial | |
| | | | | Electric Utilities | | Independent Power Producers | | | | | |
Fuel	Year 2013	Year 2012	Percentage Change	Year 2013	Year 2012	Year 2013	Year 2012	Year 2013	Year 2012	Year 2013	Year 2012
Net Generation (Thousand Megawatthours)											
Coal	1,581,115	1,514,043	4.4%	1,188,452	1,146,480	379,270	354,076	839	883	12,554	12,603
Petroleum Liquids	13,820	13,403	3.1%	9,446	9,892	3,761	2,757	118	191	495	563
Petroleum Coke	13,344	9,787	36.3%	9,522	5,664	1,780	1,758	5	6	2,036	2,359
Natural Gas	1,124,836	1,225,894	-8.2%	501,427	504,958	527,522	627,833	7,154	6,603	88,733	86,500
Other Gas	12,853	11,898	8.0%	798	0	3,524	2,984	0	0	8,531	8,913
Nuclear	789,016	769,331	2.6%	406,114	394,823	382,902	374,509	0	0	0	0
Hydroelectric Conventional	268,565	276,240	-2.8%	243,040	252,936	22,018	20,923	44	28	3,463	2,353
Renewable Sources Excluding Hydroelectric	253,508	218,333	16.1%	32,417	28,017	189,045	160,064	2,956	2,545	29,091	27,707
... Wind	167,840	140,822	19.2%	26,436	22,926	141,306	117,822	61	54	37	19
... Solar Thermal and Photovoltaic	9,036	4,327	108.8%	943	639	7,782	3,525	294	148	17	14
... Wood and Wood-Derived Fuels	40,028	37,799	5.9%	2,534	1,836	9,768	9,214	34	24	27,691	26,725
... Other Biomass	20,830	19,823	5.1%	1,499	1,472	15,419	15,084	2,567	2,319	1,346	948
... Geothermal	15,775	15,562	1.4%	1,005	1,143	14,770	14,419	0	0	0	0
Hydroelectric Pumped Storage	-4,681	-4,950	-5.4%	-3,773	-4,202	-908	-748	0	0	0	0
Other Energy Sources	13,588	13,787	-1.4%	615	603	6,742	7,030	1,118	1,046	5,113	5,108
All Energy Sources	4,065,964	4,047,765	0.4%	2,388,058	2,339,172	1,515,657	1,551,186	12,234	11,301	150,015	146,107
Consumption of Fossil Fuels for Electricity Generation											
Coal (1000 tons)	860,729	825,734	4.2%	638,327	615,467	217,219	205,295	513	307	4,670	4,665
Petroleum Liquids (1000 barrels)	23,231	22,604	2.8%	16,827	17,521	5,494	4,110	328	272	582	702
Petroleum Coke (1000 tons)	4,852	3,675	32.0%	3,409	2,105	779	756	1	1	662	812
Natural Gas (1000 Mcf)	8,596,299	9,484,710	-9.4%	3,970,447	4,101,927	3,917,131	4,686,260	66,570	63,116	642,152	633,407
Consumption of Fossil Fuels for Useful Thermal Output											
Coal (1000 tons)	18,350	19,333	-5.1%	0	0	2,416	2,790	843	1,143	15,090	15,400
Petroleum Liquids (1000 barrels)	3,456	3,097	11.6%	0	0	1,050	992	498	122	1,908	1,984
Petroleum Coke (1000 tons)	1,486	1,346	10.4%	0	0	96	113	11	11	1,379	1,222
Natural Gas (1000 Mcf)	882,385	886,103	-0.4%	0	0	303,177	322,607	51,057	47,883	528,151	515,613
Consumption of Fossil Fuels for Electricity Generation and Useful Thermal Output											
Coal (1000 tons)	879,078	845,066	4.0%	638,327	615,467	219,635	208,085	1,356	1,450	19,761	20,065
Petroleum Liquids (1000 barrels)	26,687	25,702	3.8%	16,827	17,521	6,544	5,102	826	394	2,490	2,685
Petroleum Coke (1000 tons)	6,338	5,021	26.2%	3,409	2,105	875	869	12	13	2,041	2,034
Natural Gas (1000 Mcf)	9,478,685	10,370,812	-8.6%	3,970,447	4,101,927	4,220,309	5,008,867	117,626	110,999	1,170,303	1,149,020

Sales, Revenue, and Average Retail Price for January through December								
Total U.S. Electric Power Industry								
	Retail Sales (million kWh)			Retail Revenue (million dollars)			Average Retail Price (cents/kWh)		
Sector	Year 2013	Year 2012	Percentage Change	Year 2013	Year 2012	Percentage Change	Year 2013	Year 2012	Percentage Change
Residential	1,394,919	1,374,515	1.5%	169,113	163,280	3.6%	12.12	11.88	2.0%
Commercial	1,344,207	1,327,101	1.3%	138,224	133,898	3.2%	10.28	10.09	1.9%
Industrial	978,352	985,714	-0.7%	66,909	65,761	1.7%	6.84	6.67	2.5%
Transportation	7,625	7,320	4.2%	805	747	7.7%	10.55	10.21	3.3%
All Sectors	3,725,103	3,694,650	0.8%	375,050	363,687	3.1%	10.07	9.84	2.3%

NM = Not meaningful due to large relative standard error.
W = Withheld to avoid disclosure of individual company data.
Displayed values of zero may represent small values that round to zero. The Excel version of this table provides additional precision which may be accessed by selecting individual cells.
Coal generation and consumption includes anthracite, bituminous, subbituminous, lignite, waste coal, refined coal, synthetic coal, and coal-derived synthesis gas.
Petroleum Liquids includes distillate fuel oil, residual fuel oil, jet fuel, kerosene, propane, and waste oil.
Petroleum Coke includes petroleum coke and synthesis gas derived from petroleum coke.
Natural gas includes a small amount of supplemental gaseous fuels that cannot be identified separately.
Other Gases includes blast furnace gas and other manufactured and waste gases derived from fossil fuels.
Wood and Wood-Derived Fuels include wood, black liquor, and other wood waste.
Other Biomass includes biogenic municipal solid waste, landfill gas, sludge waste, agricultural byproducts, and other biomass.
Coal stocks include anthracite, bituminous, subbituminous, lignite, refined coal, and synthetic coal; waste coal is excluded.
Retail sales and net generation may not correspond exactly for a particular month for a variety of reasons (e.g., sales data may include imported electricity).
Net generation is presented for the calendar month while retail sales and associated revenue accumulate from bills collected for periods of time that vary depending upon customer class and consumption occurring during and outside the calendar month.
Note: Values are final. Percentage change is calculated before rounding.
See technical notes for additional information including more on the Commercial, Industrial, and Transportation sectors.

Chart 1.1 U.S. Energy Information Administration 2013 Electric Power Annual

In 2014, the United States generated about 4,093 billion kilowatthours of electricity.[1] About 67% of the electricity generated was from fossil fuels (coal, natural gas, and petroleum).

Major energy sources and percent share of total U.S. electricity generation in 2014:

- Coal = 39%
- Natural gas = 27%
- Nuclear = 19%
- Hydropower = 6%
- Other renewables = 7%
    - Biomass = 1.7%
    - Geothermal = 0.4%
    - Solar = 0.4%
    - Wind = 4.4%
- Petroleum = 1%
- Other gases < 1%

[1] Preliminary data.

Learn more:

Monthly Energy Review: Electricity

Last updated: March 31, 2015

Chart 1.2 U.S. Energy Information Administration 2013 Electric Power Annual

Growth in electricity use slows, but still increases by 29% from 2012 to 2040

percent growth (3-year compounded annual growth rate)

Period	Annual Growth	
	Electricity use	GDP
1950s	9.8	4.1
1960s	7.3	4.4
1970s	4.7	3.2
1980s	2.9	3.0
1990s	2.4	3.2
2000-2012	0.7	1.8
2013-2040	0.9	2.4

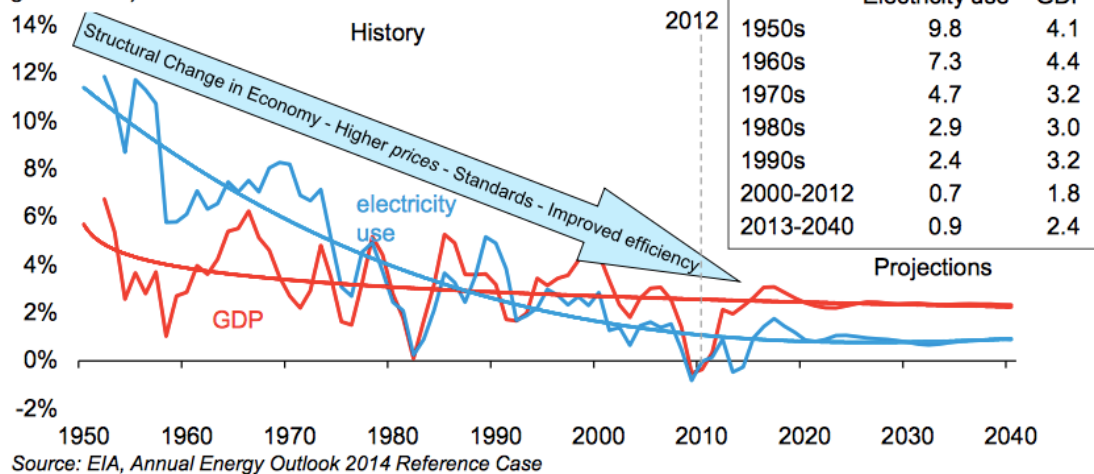Source: EIA, Annual Energy Outlook 2014 Reference Case

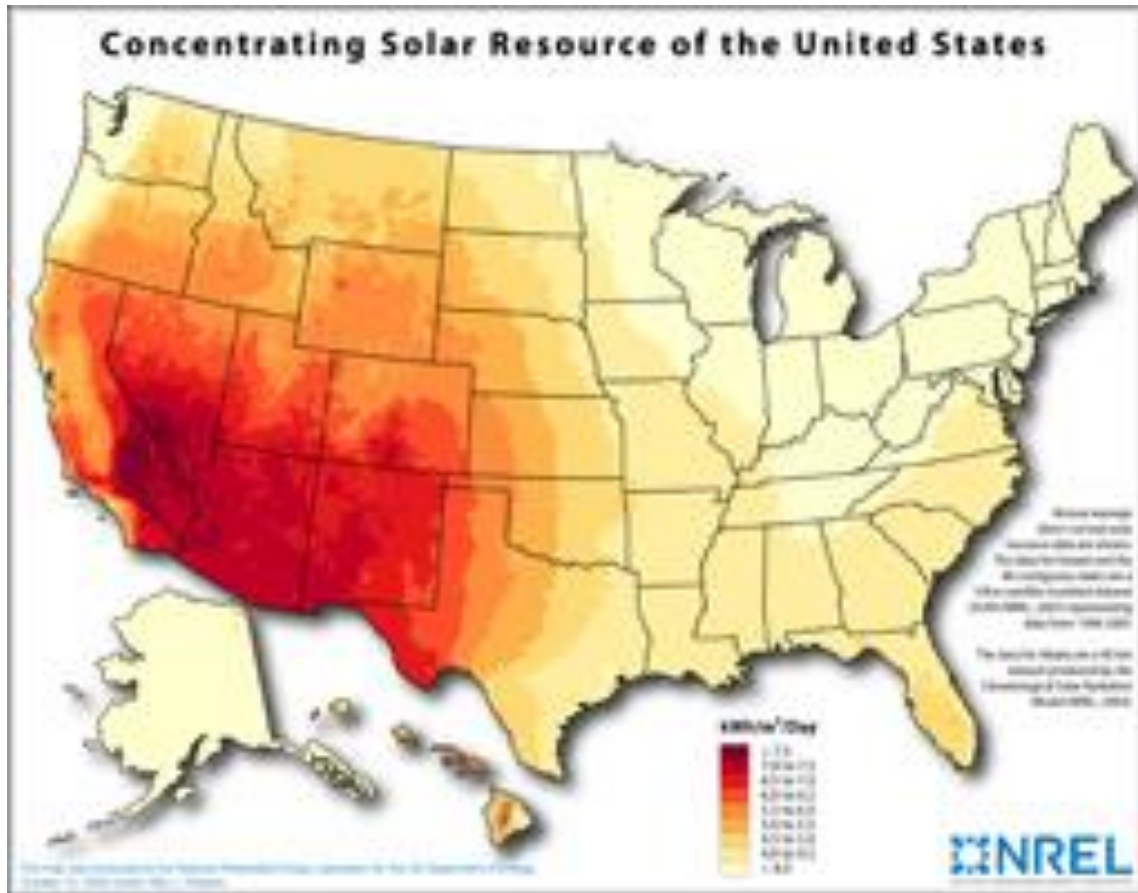*Chart 1.3 U.S. Energy Information Administration 2013 Electric Power Annual*
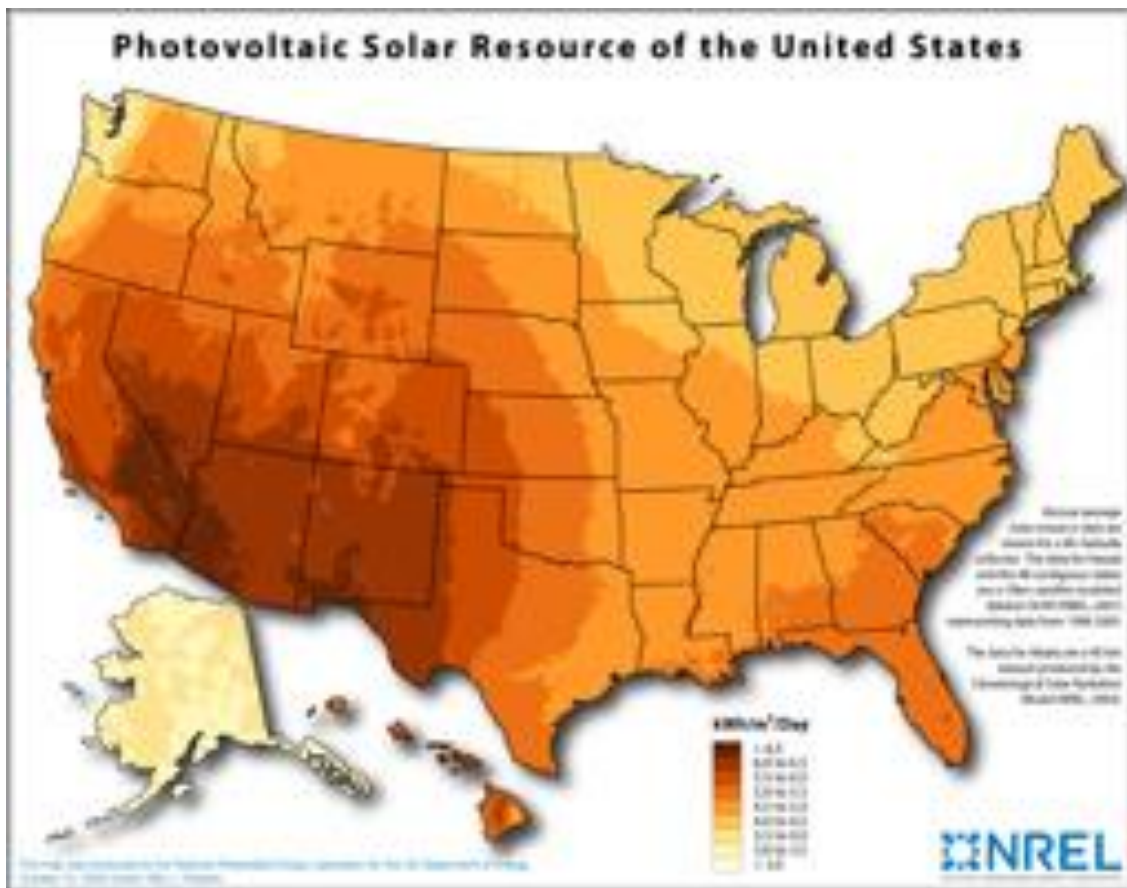
Chart 1.4 NREL solar resource maps

Chart 1.4 NREL solar resource maps

Annual days of sunshine

City	Sunny Days	Partly Sunny Days	Total Days With Sun
Elko	130	99	229
Ely	131	109	240
Las Vegas	210	82	292
Reno	158	93	251
Winnemucca	138	89	227

Percent sunshine yearly

City	% Sun
Ely	73
Las Vegas	85
Reno	79
Winnemucca	68

State	Place	% Sun	Total Hours	Clear Days
Kentucky	Louisville	56	2514	93
Louisiana	New Orleans	57	2649	101
Maine	Portland	57	2513	101
Maryland	Baltimore	57	2582	105
Massachusetts	Boston	58	2634	98
Michigan	Lansing	51	2392	71
Minnesota	Minneapolis	58	2711	95
Mississippi	Jackson	61	2720	111
Missouri	Springfield	60	2690	115
Montana	Helena	59	2698	82
Nebraska	Lincoln	61	2762	117
Nevada	Reno	79	3646	158
New Hampshire	Concord	54	2519	90
New Jersey	Atlantic City	56	2499	94
New Mexico	Albuquerque	76	3415	167
New York	Syracuse	46	2120	63
North Carolina	Greensboro	60	2651	109
North Dakota	Bismarck	59	2738	93

Chart 1.5 National Climatic Data Center – Annual Sunshine and Solar Hours analysis

	Total Electricity Consumption (billion kWh)									
	Total	Space Heat-ing	Cool-ing	Venti-lation	Water Heat-ing	Light-ing	Cook-ing	Refrig-eration	Office Equip-ment	Com-puters	Other
All Buildings*	890	34	116	113	15	335	6	104	19	43	105
Building Floorspace (Square Feet)											
1,001 to 5,000	113	5	13	5	3	27	2	40	2	3	11
5,001 to 10,000	77	4	10	5	2	24	1	16	2	3	10
10,001 to 25,000	119	6	14	13	2	44	1	15	3	6	16
25,001 to 50,000	103	4	16	15	3	35	(*)	10	2	5	12
50,001 to 100,000	119	5	17	19	2	46	1	9	2	5	13
100,001 to 200,000	141	5	18	23	1	57	(*)	7	Q	9	16
200,001 to 500,000	106	2	15	16	1	48	(*)	3	2	6	13
Over 500,000	112	2	14	16	1	53	(*)	4	2	7	13
Principal Building Activity											
Education	109	4	22	24	3	33	(*)	5	1	9	6
Food Sales	61	2	4	2	Q	14	1	35	1	1	3
Food Service	63	3	8	7	3	12	4	20	(*)	1	4
Health Care	73	2	10	12	1	31	(*)	2	1	3	11
Inpatient	52	1	7	11	1	22	(*)	1	1	2	6
Outpatient	20	1	3	1	(*)	8	(*)	1	(*)	1	4
Lodging	69	4	7	4	3	36	1	3	Q	2	7
Retail (Other Than Mall)	62	2	7	5	1	33	(*)	6	1	1	6
Office	211	10	30	18	2	82	(*)	10	9	22	27
Public Assembly	49	1	10	18	(*)	8	(*)	3	Q	1	7
Public Order and Safety	17	1	2	3	1	5	(*)	1	(*)	(*)	3
Religious Worship	18	1	3	2	(*)	5	(*)	2	(*)	(*)	5
Service	44	2	4	7	(*)	18	Q	3	(*)	1	8
Warehouse and Storage	72	1	4	6	1	39	Q	10	1	1	9
Other	39	1	5	3	Q	17	Q	3	Q	1	6
Vacant	4	(*)	(*)	(*)	Q	1	Q	(*)	Q	(*)	2
Year Constructed											
Before 1920	26	1	2	3	Q	10	(*)	5	1	1	4
1920 to 1945	61	1	5	9	1	26	(*)	7	1	2	9
1946 to 1959	68	2	8	10	1	26	1	8	1	3	8
1960 to 1969	96	3	13	15	2	33	(*)	12	2	5	11
1970 to 1979	168	8	21	22	3	65	1	17	4	8	20
1980 to 1989	184	8	27	19	4	69	1	19	4	11	21
1990 to 1999	202	7	29	26	4	72	2	25	5	10	23
2000 to 2003	86	3	13	9	1	34	1	11	1	3	9

Chart 1.6 EIA – Commercial Energy Consumtion break down, 2003

CHAPTER 7: APPENDICES

APPENDIX 1: Table 3.1 Testing Schedule Chart is located in attachment one of the supplemental material

APPENDIX 2: Chart 2.1 U.S. Energy Information Administration 2013 Electric Power Annual is located in attachment two of the supplemental material

CHAPTER 8: REFERENCES

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