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The thermal effects of daylighting in an energy efficient home

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THE THERMAL EFFECTS OF DAYLIGHTING IN AN ENERGY EFFICIENT HOME

by

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A THESIS

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Approved by

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ABSTRACT

Current trends in building design and construction emphasize the use of natural daylighting to illuminate a building’s interior. This study investigated the energy savings that could be obtained through the use of daylighting compared to additional heating and cooling loads attributed to the glazing required for daylighting. The study, through a combination of experimentation and computer model validation, aimed to determine energy saved from daylighting through illumination metering during a nine-month study period. Energy usage trends during this period were observed using circuit-level monitoring equipment. It was determined that, at select times of the year, energy used to account for additional cooling loads attributed to the glazing were 300% greater than the energy saved from employing daylighting.

ACKNOWLEDGMENTS

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NOMENCLATURE

Symbol	Description
USGBC	United States Green Building Council
LEED	Leadership in Energy and Environmental Design
sDA	Spacial Daylight Autonomy
DA	Daylight Autonomy
UDI	Useful Daylight Illuminance
ASE	Annual Sun Exposure
CFL	Compact Fluorescent
LED	Light Emitting Diode
NIBS	National Institute of Building Science
CBDM	Computer Based Daylight Modeling
DF	Daylighting Factor
ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers
NAHB	National Association of Home Builders
IEQ	Indoor Environmental Quality
IESNA	Illuminating Engineering Society of North America

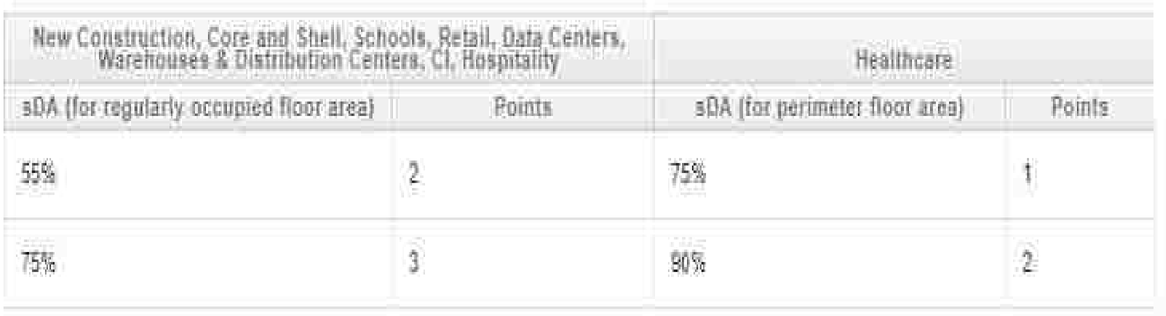
1. INTRODUCTION

Sustainability is defined as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs.” (World Commission on Environment and Development, 1992). The use of sustainable concepts has become prevalent in the construction industry, from recycling materials used in the construction of a building to using environmentally sound techniques in the operations of the finished product. When developing a project, all aspects of the design and construction methods used can be integrated within a “green” process—the goal always being an end product with less environmental impact. One of the major areas in which a building can increase its respective performance is the reduction of total energy used during normal operation. This performance is especially beneficial to building owners as it not only reduces the demands a building imparts on limited natural resources, but it can greatly lessen utility costs associated with the building. Due to these factors, energy reduction has become a major component when considering a sustainable approach.

The reasons behind the need to reduce building energy consumption are numerous. The United States Energy Information Administration (EIA) recently estimated that 39% of all energy consumed in the U.S. in 2014 could be attributed to buildings in the residential and commercial sectors. This accounts for 38 quadrillion British Thermal Units of energy consumption and presents an opportunity for reduction through intelligent, sustainable design and operation. In the commercial sector, heating is the largest end use at 25% of all energy consumed, with ventilation, refrigeration, and lighting accounting for an additional 10% (EIA, 2012). For residential buildings, heating and cooling of occupant spaces account for just below 27%, with lighting just over an additional 9% of all energy consumed (EIA, 2017). Combined, the space conditioning and lighting represent the two largest single end uses of energy in a building, and therefore also the greatest opportunities for reduction.

Daylighting is the introduction of natural light into a building to reduce the need for artificial lighting. This is accomplished with the addition of light through standard windows, skylights, diffuse glazing, and other apertures, all of which allow sunlight into occupied areas of the building, creating an environment that is beneficial to the occupant's well-being, as well as increasing productivity. Research has shown a tangible increase in perceived quality of the indoor environment when utilizing daylighting. A recent study conducted by the University of Illinois at Urbana-Champaign (Boubekri, Cheung, Reid, Wang, &Zee, 2014) demonstrated a correlation between daylight exposure in an office environment with increased activity during the day as well as increases in sleep and reported quality of life. The psychological benefits come from daylight helping to maintain a person's circadian rhythm, an internal mechanism that allows a person to stay in tune with the natural environment. The availability and use of daylighting then becomes even more important in the built environment, not only for energy reduction, but for health benefits as well.

Several building rating programs use daylighting as a quantitative method to partially determine a building's "green" rating. Among these programs is the U.S. Green Building Council's (USGBC) Leadership in Energy and Environmental Design (LEED) rating system, the International WELL Building Institute's eponymous "WELL" Standard, as well as Energy Star, BREEAM, The Living Building Challenge, and many more. These rating programs all incorporate daylighting as a beneficial component of the indoor environment, improving occupant health and reducing energy uses. LEED and WELL, in particular, have specific sections that address daylighting and give additional points towards a building’s score based upon the amount of daylighting received. The LEED system bases the points awarded on a building’s spatial Daylight Autonomy (sDA) as it pertains to naturally illuminated area. The sDA represents the amount of floor area that receives a minimum amount of illumination from natural sources. The LEED v.4 rating system sets a minimum sDA illumination level of 300 lux. The minimum required floor area that meets this illumination level is 50% of the total floor area. These two measurements are shown in the values respective subscript $\left(\mathrm{sDA}_{(300/50\%)}\right)$. LEED awards points on total percentage of occupied floor area that meets this minimum and has point thresholds of 55% and 75% of floor area (Figure 1.1).



New Construction, Core and Shell, Schools, Retail, Data Centers, Warehouses & Distribution Centers, CI, Hospitality		Healthcare	
sDA (for regularly occupied floor area)	Points	sDA (for perimeter floor area)	Points
55%	2	75%	1
75%	3	90%	2

Figure 1.1. LEED v4 Daylighting credit

With the LEED spatial daylight autonomy method, there is also a maximum amount of daylight the measured area is able to receive. This value uses the Annual Sun Exposure metric and indicates the percentage of allowable floor that receives over 1000 lux for a minimum of 250 occupied hours per year; it is denoted as $\left(\mathrm{ASE}_{(1000/250)}\right)$. The maximum percentage allowed to exceed this value and be deemed compliant for the LEED credit is 10% of the measured floor area. This maximum value is used to reduce the possibility of glare conditions that can occur when an area is exposed to increased amounts of direct sunlight, and it helps to avoid increased cooling loads.

All of the rating systems and guidelines mentioned operate on the assumption that utilizing daylighting in a building will reduce total electrical use. But, does it? Many of the rating and certifications justify the electrical reduction using numbers from a study or referencing a time when compact fluorescent (CFL) and incandescent bulbs were still being widely used. For instance, the National Institute of Building Science (NIBS) Whole Building Design Guide references a study from 1997. With today's adoption of Light Emitting Diode (LED) luminaires, and the reduced energy usage of these lights, do the amounts of energy saved from turning off these lights outweigh the increased heating and cooling loads associated with the windows used to obtain all that daylight? This research aims to provide some answers to that question.

1.1. SIMULATION METHODS

The daylighting metrics used for these simulations (sDA, ASE) are examples of Climate Based Daylight Modeling (CBDM). This is a method of computer simulation that uses predictions of the various metrics (irradiance, luminance, and illuminance) involved with solar illumination. The geographical location of the building to be simulated is entered, and this includes the solar values and predicted meteorological conditions. These CBDM simulations are useful in taking into account naturally occurring variances found in daylight. Daylight in a given space is a dynamic parameter, with constantly changing levels of light distribution and intensities as the interaction of the sun and sky conditions shift throughout the day. The simulations also allow for the interaction of the daylighting with the various materials and components used to construct a building. Material reflectance values, building overhangs, window placement, and others can play a significant role in how light enters a building. The CBDM simulations let a designer meet various performance indicators for daylighting contained in the various rating metrics and can account for a vast number of parameters; however, there are no “set” values to be used for the simulation initial data sets. In the LEED rating system, a building must “achieve illuminance levels between 300 lux and 3,000 lux of the floor area” (U.S Green Building Council, 2018). The illuminance levels must be measured at an “appropriate” work plane height and two measurements must be taken at differing times of the year. This is the extent of the instructions given to conduct this measurement; there are no data or parameters for climate or sky conditions. This can introduce extreme fluctuations in measured values depending on what the user decides for the analysis period. In *Daylight simulation: Validation, sky models and daylight coefficients*, John Mardaljevic (2000) describes anecdotal evidence of buildings obtaining the daylight credit while using sky and illumination conditions that cannot occur, such as including a clear sky without the sun, a situation which is impossible to obtain in a real-world setting. This was performed to underline the importance of validation of a model through additional means. These climate-based simulations need quality input in order to produce quality data, and they are very sensitive to the age old “garbage in, garbage out” situation. Plus, the quantity of variables being used can lead to the possible introduction of errors, making the simulation diverge from real-world values. These simulations are based upon many data sets and can be easily performed, sometimes in several iterations, to establish optimal building assemblies and project orientations; but, they do not allow for an easy way to verify the results in the real world. It just would not be feasible to verify the performance of all areas of the building during all hours of the day in a multitude of climate conditions.

A simpler metric, known as Daylight Factor (DF), is also used in many sustainable rating systems. Daylight Factor is a method that measures the illumination provided by the sun at various points inside the structure and then compares this amount to the available outdoor lighting levels. It is expressed as a simple number (2, 3, 5…etc.) and represents the percentage of illumination brought into the building (Eq. 1).

$$Daylight\ Factor\ (DF) = (E_i/E_o) * 100 \qquad \text{(Eq. 1)}$$

$E_i = Interior\ illumination\ level$

$E_o = Exterior\ illumination\ level$

The DF metric was used by earlier versions of the USGBC LEED and WELL Building rating systems and is still used by many rating systems today, including BREEAM. It is also included in the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Standard 189.1, *Standard for the Design of High Performance Green Buildings*. This DF metric is a selectable output on many of the simulation programs available to use for daylighting assessment.

1.2. RESEARCH REASONING

With an increased awareness for environmental concerns, the use of sustainable designs when constructing our built environment has become much more prevalent. Consumer demand for more sustainable/green buildings has increased significantly in recent years, from a $3 billion industry in 2005 to over $80 billion in 2014 (Figure 1.2) (Statista, 2017).

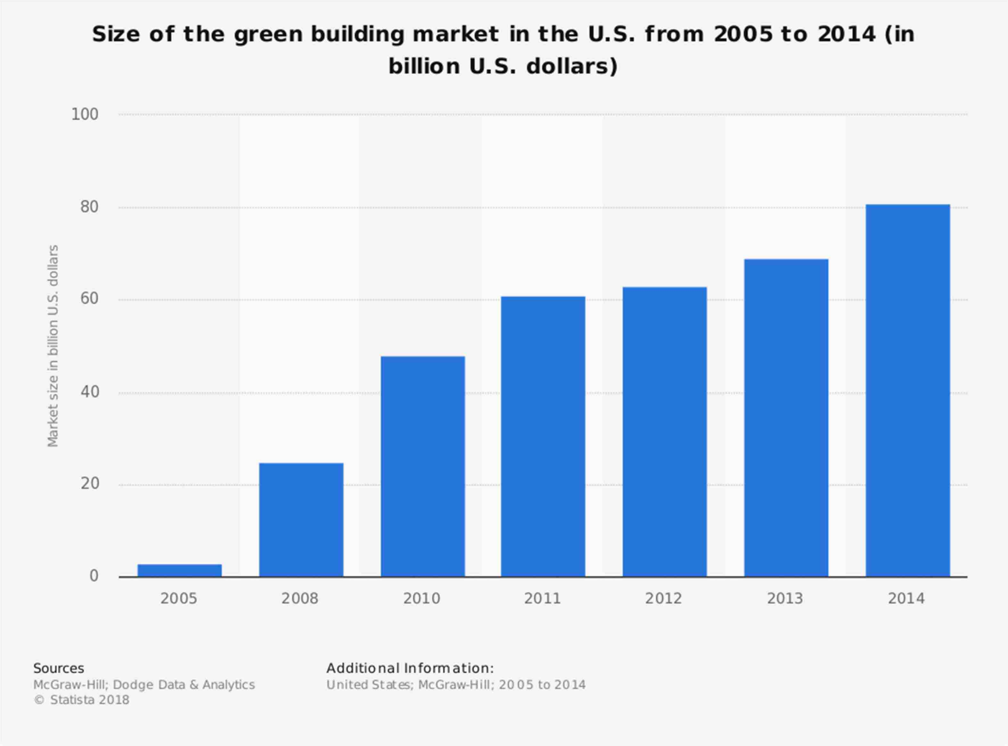


Figure 1.2. Green building market increase

In a 2017 survey conducted by the National Association of Home Builders (NAHB), over one-third of builders responded that "green building" was a significant share of their company's overall activity, and those numbers are expected to continue to rise in the future (Jones & Laquidara-Carr, 2017). With this increase in demand, growth in sustainable rating systems has also occurred. In 2017, there were about 27 different sustainable building rating systems, including some of the more well known, such as LEED and Energy Star.

While the different rating systems do use some differing metrics for evaluating a project, all share some commonality with concern for overall energy reduction and increasing the quality of the indoor environment for occupants. LEED, in particular, established baseline reductions in whole-building energy usage for new construction, renovations, and core and shell projects of 5%, 3%, and 2%, respectively. The proposed building is compared to a baseline project using a simulation in accordance with ASHRAE Standard 90.1 to establish energy usage. The intent of this reduction 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” (USGBC, 2018). The LEED rating system provides guidance on many methods to reduce energy usage in a building during various stages of a construction project. This can start with material selection during the design phase and continue all the way to ongoing commissioning of the building systems, which may occur well into the operational phase of the building.

One of the most-often utilized methods of lowering a building’s energy usage is through reducing the use of artificial lighting. When the LEED 2009 edition was instituted, artificial lighting accounted for approximately 30% of all energy used in a residential setting (EIA, 2013). In the commercial sector, lighting accounted for 18% of energy consumption (EIA, 2011). These numbers, at that time, represented the largest single-use contributor. With the adoption of Light Emitting Diode (LED) lighting systems, the energy use of artificial lighting has dropped significantly. The most recent numbers available from the United States Energy Information Administration (EIA) covers the year ending in 2017. The results indicate lighting now only accounts for 10% in both the residential and commercial sectors, with a projected 1.6% additional drop annually for the foreseeable future (EIA, 2018). This is good news; the problem arises when the sustainable rating systems still treat the lighting as the large contributor to energy consumption when that is no longer the case.

The most widely adopted method of reducing energy consumption from lighting is through the use of daylighting, where natural light from the sun enters into the building's usable floor space, providing illumination for the occupants. All of the sustainable rating systems address daylighting as a favorable metric in some way, awarding points for the levels obtained. In the LEED v4 guidelines from the United States Green Building Council (USGBC), the Indoor Environmental Quality (EQ) category has a Daylight credit, which specifically deals with daylighting as it is related to a building's indoor environmental quality. The credit points are based on the amount of area in the building illuminated through natural means that is regularly used by the occupants. There are multiple methods and thresholds one can use to gain points within this credit (Figures 1.3, 1.4).

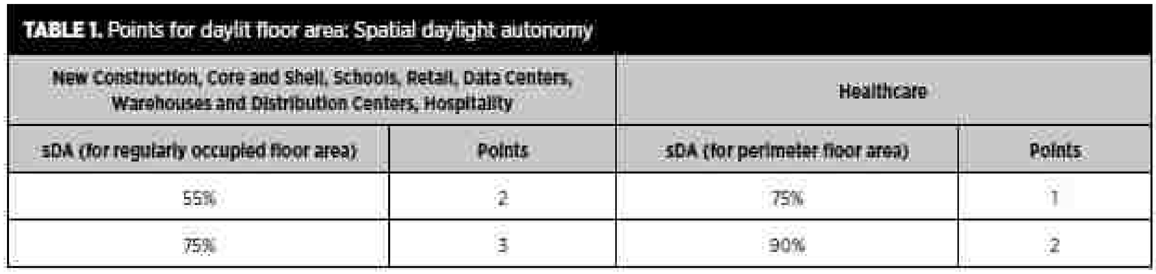


TABLE 1. Points for daylit floor area: Spatial daylight autonomy

New Construction, Core and Shell, Schools, Retail, Data Centers, Warehouses and Distribution Centers, Hospitality		Healthcare	
sDA (for regularly occupied floor area)	Points	sDA (for perimeter floor area)	Points
55%	2	75%	1
75%	3	90%	2

Figure 1.3. LEED v4 Daylighting credit sDA

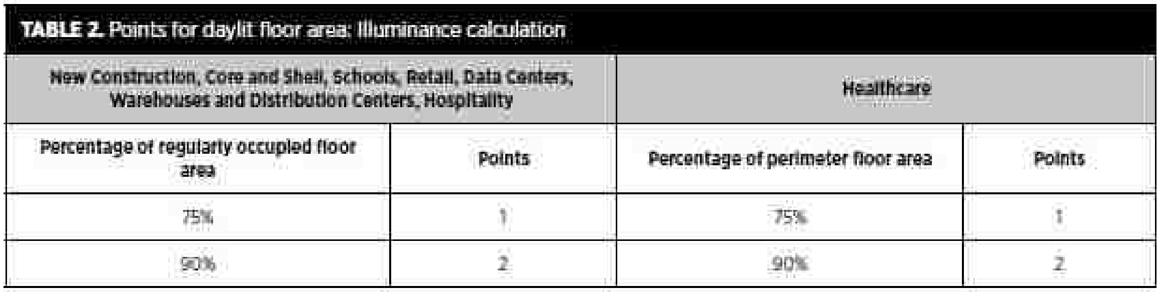
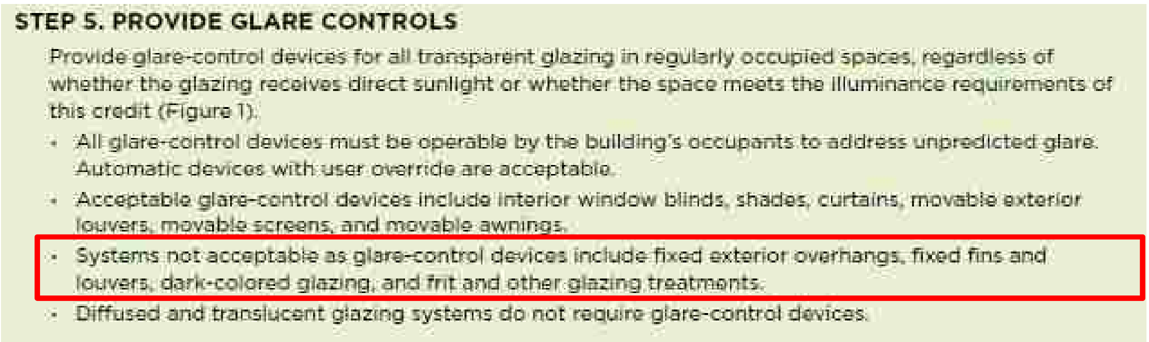


TABLE 2. Points for daylit floor area: Illuminance calculation

New Construction, Core and Shell, Schools, Retail, Data Centers, Warehouses and Distribution Centers, Hospitality		Healthcare	
Percentage of regularly occupied floor area	Points	Percentage of perimeter floor area	Points
75%	1	75%	1
90%	2	90%	2

Figure 1.4. LEED v4 Daylihgting credit calculation method

Both methods require a building to obtain a minimum of 55% or 75% of useable floor area illuminated by daylight to be considered for the credit. While the use of natural daylighting is beneficial to occupants, high levels of exposure to daylight can also have detrimental effects such as increased heating and cooling requirements from the exposure provided by the large amount of glazing, the areas made of glass in building that is necessary. Unwanted solar gain can be mitigated or reduced through the use of shading devices and orientation to control the building surfaces' exposure to the sun; these types of devices are somewhat addressed with the LEED ratings, but only in the context of glare control. In fact, one of the most effective methods of reducing solar heating load is use of a static shading device where a structure is designed in such a way as to shade a building in the hotter months while allowing for solar gain in the cooler times when it is beneficial. This type of static shading device is specifically named by the credit guidelines as NOT being an acceptable form of glare control (Figure 1.5). The method of increasing the amount of daylight area without regard to other attributes needs to be addressed. With current LED technology and its ever increasing efficiency (EIA, 2014), the amount of energy saved by using daylight is decreasing. The amount may now be less than the additional energy used to offset the solar heat gain from exposed glazing needed to allow the ingress of daylight. This could especially be true in highly energy efficient



STEP 5. PROVIDE GLARE CONTROLS

Provide glare-control devices for all transparent glazing in regularly occupied spaces, regardless of whether the glazing receives direct sunlight or whether the space meets the illuminance requirements of this credit (Figure 1).

- All glare-control devices must be operable by the building's occupants to address unpredicted glare. Automatic devices with user override are acceptable.
- Acceptable glare-control devices include interior window blinds, shades, curtains, movable exterior louvers, movable screens, and movable awnings.
- Systems not acceptable as glare-control devices include fixed exterior overhangs, fixed fins and louvers, dark-colored glazing, and frit and other glazing treatments.
- Diffused and translucent glazing systems do not require glare-control devices.

Figure 1.5. LEED v4 Daylighting credit glare control devices

buildings that are more susceptible to fluctuations due to having a smaller overall energy use; even incremental increases can lead to large changes in energy use. This research aims to determine a more holistic approach for energy analysis through the use of daylight modeling and energy consumption rates. This research will also address a more synergistic approach for future standards and rating metrics to be used in designing highly efficient homes.

2. LITERATURE REVIEW

2.1. OVERVIEW

Increasing awareness of reducing a building's energy costs has changed the dynamics in how a building is designed and operated. Current sustainability programs and guidelines such as LEED and WELL encourage the use of daylighting through a points system. With LEED, in the Environmental Quality (EQ) credit, a building can achieve additional value towards certification by illuminating a minimum of 75% of floor area, with additional points available for up to and over 90% of the useable floor area being located in the daylighting zone. While daylighting does provide substantial benefits in occupant comfort and productivity, the large areas of glazing required to achieve high daylighting levels introduce additional heating and cooling loads and possibly mitigate any energy saving achieved through reduced lighting loads. High levels of daylighting are discouraged in the various certification programs, and most include a requirement of some form of manual or automated shading device for occupant comfort; however, these shading devices are used primarily for glare control and not to prevent thermal loading of the exterior fenestrations. The challenge is to balance the beneficial attributes of natural lighting while reducing the unwanted additional heating and cooling loads presented by large areas of glazing.

Previous literature provides insight into several relevant topics concerning the relationship between daylighting as a replacement for electric lighting in the indoor environment and the subsequent energy demand reductions. The employment of static and dynamic shading devices are also common topics in journal articles and peer-reviewed academic papers. There is a distinct lack, however, of a synergistic approach for efficient use of daylighting while being considerate of solar heating loads introduced by increases in the employment of daylighting.

The areas of current research can be separated into three topics: (1) current methods of daylighting as it relates to reduced energy consumption, (2) analysis of static and dynamic type shading devices and structures used to control daylighting ingress into buildings, and (3) review of systems related to glazing and fenestrations controls and automation measures to reduce or mitigate unwanted levels of lighting and non-beneficial performance characteristics.

2.2. DAYLIGHTING

Bellia, Fragliasso, and Pedace (2015) describe the process by which several versions of daylighting modeling programs can be utilized in the analysis of the design process. The use of dynamic daylight modeling takes into account not just the Daylight Factor (DF), which is the percentage of daylight a given surface receives relative to the unobstructed outdoor levels, but also considers the variability with differing times of day, climate conditions, and the reflective values of surfaces in the room. All of these values are used to develop a dynamic model to describe lighting conditions in the room, rather than just an illumination level. While the static approach to analyzing daylighting levels (DF) can be used for verification of a real-world setting, in conjunction with a dynamic modeling result, the limited capabilities of the static method restrict the relevant applications of this method.

The dynamic method, which was instituted for modeling, considered many methods to validate building performance. One method is Daylight Autonomy (DA), in which a scale is used to determine the amount of required illuminance for a particular work plane provided by daylighting. The DA method also employs a range system that has a minimum and maximum light level to incorporate more usability into the model; the maximum level is 10x the minimum task-established illuminance level. The required illumination levels are used in the modeling software to assess the amount of hours per day required by natural methods. A second method, Useful Daylight Illuminance (UDI), determines what constitutes a building's "comfortable" illuminance levels. The acceptable range was established by various studies where building occupants defined at which levels they found lighting to be sufficient to perform tasks, as well as an upper limit of illumination where they found the lighting levels to be uncomfortable. The range of values (100 lx – 2000 lx) is now used in the modeling software to evaluate the acceptable range of time an area should have natural illumination. The UDI method includes many more attributes of the building within the modeling parameters, such as weather data files, the various materials used in fenestration products, as well as user behavior patterns; this allows for a more complete model, taking into consideration the end use of the building.

Bellia et al. then used the dynamic modeling method to conduct a study on a chosen office building in Naples, Italy. They used the Autodesk 3ds Max modeling software for additional material input parameters. The analysis included static shading devices, which incorporated light shelves, showing a demonstrable difference in interior lighting levels. There was an increase in interior lighting levels, but the simulation did not address any increases in solar thermal loading from the proposed fenestration arrangement, with all concerns being centered on illumination levels and glare control.

Bellia et al. considered the incorporation of an automation system including photosensors and performed a simple analysis to judge the feasibility of such a system. The simulations were conducted on the office building using the different protocols, which produced similar results. Areas near the windows received all the required lighting through natural means, and subsequent distances needed additional lightning from artificial sources. The simulation, which utilized the automation through shading device control, required further study and subsequent additional simulations. The various simulations determined daylighting floor areas that diverged up to 15% from initial results. Bellia et al. concluded that further experimentation was needed to improve simulation performance and align the results more with real-world conditions—something this research hopes to address.

Lo Verso, Fregonara, Caffaro, Morisano, and Peiretti (2014) document a case study of daylighting performed on a rehabilitation project consisting of a former industrial area being turned into dwelling units. The project incorporated a synergistic approach to the design, using possible tenant surveys to determine daylighting design aspects early in the design process. Major concern was given to exploiting available daylight throughout the project, and it was broadly implemented in the common areas such as libraries and study rooms. The use of daylighting was incorporated within an approach to improve the indoor environmental quality (IEQ) of the tenants. Other attributes included within the IEQ were thermal and acoustical comfort, as well as indoor air quality and a reduced energy demand from the building systems. Some of the major factors leading to a perceived "good" environmental quality were the size of windows, the views provided, and the amount of daylight brought into the building. This was determined to also affect the perceived cost and value of the proposed dwellings, leading to the incorporation of more glazing surfaces into the final simulation project.

The case study consisted of student and study rooms placed along the perimeter of the repurposed structure, with common areas placed in the central area. The exterior rooms utilized vertical windows to provide daylight penetration into the rooms, with internal shading devices to control glare. The central common areas utilized a transparent panel assembly to increase the daylighting level while controlling direct solar energy, reducing glare, and increasing secondary illumination throughout the area. For the areas employing internal shading devices, a photometric controlled system was used to lower the devices when interior daylighting levels reach a threshold, in this case 50 W/m^2. The shading devices were employed as a means of controlling glare, but nothing was mentioned about using the devices to reduce incoming light due to thermal concerns.

The results of the case study simulations utilized both Daylighting Factor (DF), in which a percentile threshold of daylighting must be achieved in static analysis, and dynamic simulation models using Daylighting Autonomy (DA) and Useful Daylight Illuminance (UDI). The simple static DF process yielded compliance with the required 2% factor for all rooms except one interior area that required elevated lighting levels to comply. Lo Verso et al. noted a discrepancy between standards in which a user would fail to meet LEED specified criteria due to some rooms not meeting other specifications, thus being unable to be counted towards the totals for the project. The dynamic modeling produced mixed results as well, with most areas of the project meeting the criteria for Daylight Autonomy, but all areas but one failing to meet the more stringent design protocols of Useful Daylight Illuminance standards. The discrepancy was attributed to the added complexity of performing the simulation for UDI, with the added criteria of climate-based analysis and other metrics adding to the difficulties. Lo Verso et al. concluded that the prescriptive methods used in the Daylighting Factor would prove adequate for the project, lessening the added complexity dynamic modeling would bring. Also noted was the need to select which modeling procedure to utilize early in the pre-design phase to allow for definition of daylighting strategies. The end result of all modeling was determined to be questionable, as all the simulations relied upon particular occupancy profiles for offices and school use. The proposed project would house college-age students, whose occupancy levels and times are inherently very hard to predict, and could severely change the end results.

Lo Verso et al. called for future research to better integrate perceived value with daylighting features, and described how to best perform analyses containing more variables concerning economic viability of future projects. The adoption of an analysis program that integrates the thermal performance with the visual attributes of daylighting was considered, including the lighting, cooling, heating, and hot water demands in the simulation, which is what this research aims to accomplish.

Cammarano, Pellegrino, Lo Verso, and Aghemo (2015) describe a study in which daylighting use was simulated along with some additional thermal loading. The initial procedures used in the simulation involved several dynamic daylighting performance methods, all using Climate-Based Daylight Modeling (CBDM). The metrics used in the analysis included the commonly used Daylight Autonomy (DA), as well as two sub-sets of DA, which are the continuous model and maximum. The Useful Daylight Illuminance (UDI) matrix was also employed during the simulation processes. This study was recent enough to include two newer metric systems that have been proposed by the Illuminating Engineering Society of North America (IESNA): the spatial Daylight Autonomy (sDA), which builds upon the DA metric by determining the level of daylighting as it relates to sufficient levels in performing specific tasks, and the Annual Sunlight Exposure (ASE) metric, which bases values on potential for glare in a selected area. These two newer methods were employed along with standard metrics in the simulations to enable the researcher to determine more precise results when inputting room usage types.

The simulations used several modeling programs, including Daysim and EnergyPlus, which are both software programs that allow for parametric configurations. The room used for the simulation was a standard office room containing windows on an exterior wall. Standard reflectance values of 70, 50, and 30 were used for the ceiling, walls, and floor, respectively; these values, along with a task illuminance of 500 lux, are very common for simulation exercises. The values used for exterior (0.25 W/m^2K) and interior (1.6 W/m^2K) thermal coefficients also fall in line with commonly used parameters. This simulation was one of the few that listed the Solar Heat Gain Coefficient (SHGC) of the glazing, which in this instance was 0.67. While the initial portion of the study indicated solar heating gain would be analyzed, this was in fact relegated to only monitoring the reduction in direct solar heat gain on the interior surfaces through the use of an automated venetian-type blind system employed on the interior of the glazing surfaces. The energy uses required by lighting, heating, and cooling, along with assumed inter-dependencies, were combined into a single global energy demand value for the various simulation iterations. The simulations produced results approximating several exterior configurations along with the use and absence of shading devices. These results conformed to other similar research studies and demonstrated a reduced energy demand from lighting when a greater amount of daylighting was available. The study concluded the use of daylighting was beneficial in all cases with the greatest savings in global energy use being a reduction of 34% from the baseline, which included the lights always in an “on” position. A full comparison to our research cannot be made because the study did not include the type or wattage of the luminaires used in the simulation or specifics regarding the daylight responsive automation features.

2.3. RESEARCH HOME

The study was conducted on the Missouri S&T Chameleon Home. This building was constructed to participate in the 2013 U.S. Department of Energy Solar Decathlon competition. The Chameleon Home is a 987 ft^2 net-zero energy house designed and constructed by the student-led Missouri S&T Solar House Team. The house was constructed on the Missouri S&T campus during the spring and summer of 2013. After completing construction, it was disassembled and shipped to Irving, California, where it was reassembled to compete in the Solar Decathlon competition. After completing the competition, the house was disassembled again to facilitate shipment back to Missouri, where it remained in storage for 2 years, awaiting the completion of its permanent foundation system. The permanent foundation and related infrastructure was completed in the summer of 2015, and the home was then reassembled on site back to original specifications. The home makes use of a modular steel framework to facilitate relocation for competition and incorporates innovative components to reduce the overall power consumption to less than that which is produced on site by photovoltaic (PV) panels. The exterior envelope of the house is constructed from Structural Insulated Panels (SIPs), which were used to make the walls and the roof of the house. The floorplan of the house is mainly an open-concept design to allow for flexibility during the competition and features a kitchen area, living room, bathroom, and a bedroom area that can be closed off from the main living area by a moveable wall partition as shown in the floorplan (Figure 2.1).

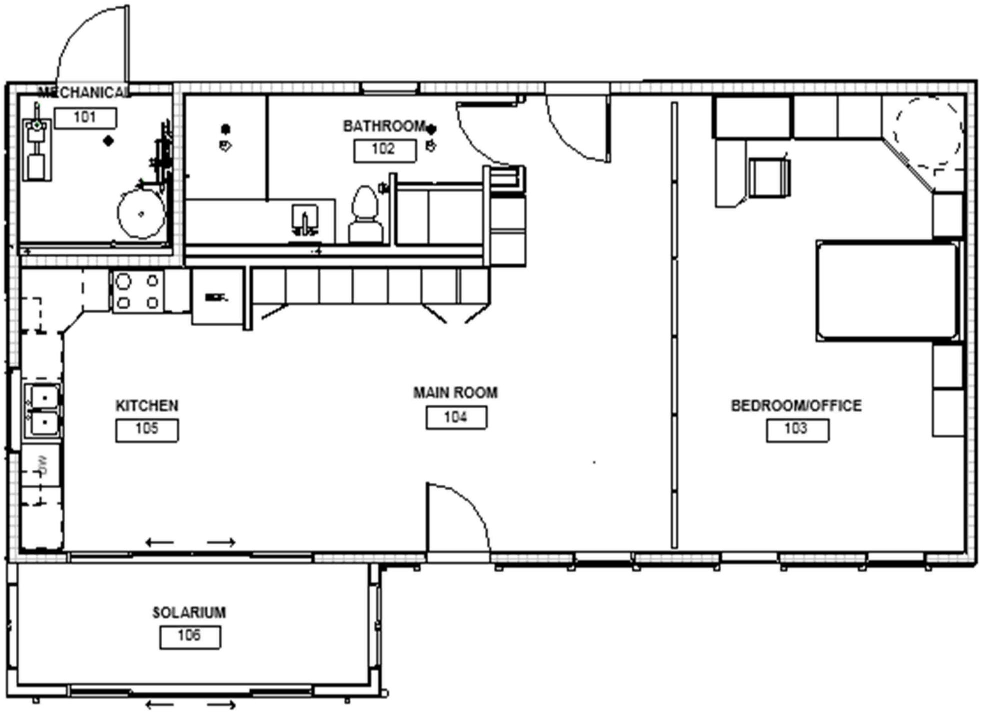


Figure 2.1. Chameleon home floorplan

The house is outfitted with 2 arrays of photovoltaic panels, a 5.8kW system located on the roof of the structure, as well as a 1.9 KW array of bi-facial panels on the south side of the house, serving as an awning.

2.4. BUILDING LOCATION

The location of the Chameleon Home is at 931 West 10th Street, Rolla, Missouri, Latitude 37.9510, Longitude -91.7831. The house sits on the northwest corner of the Missouri S&T Eco Village, a planned community of 6 to 8 net-zero energy homes interconnected through the use of micro and nano-grid technologies. The Eco Village currently has two homes in place, the Chameleon and the 2015 “Nest” House. A third permanent foundation, which was utilized for the construction of the 2017 SILO house, is in place, but the home is currently not located at the village. The site and surrounding area consists of gently rolling terrain with well-manicured grounds due to the area being the former site of the university’s golf course.

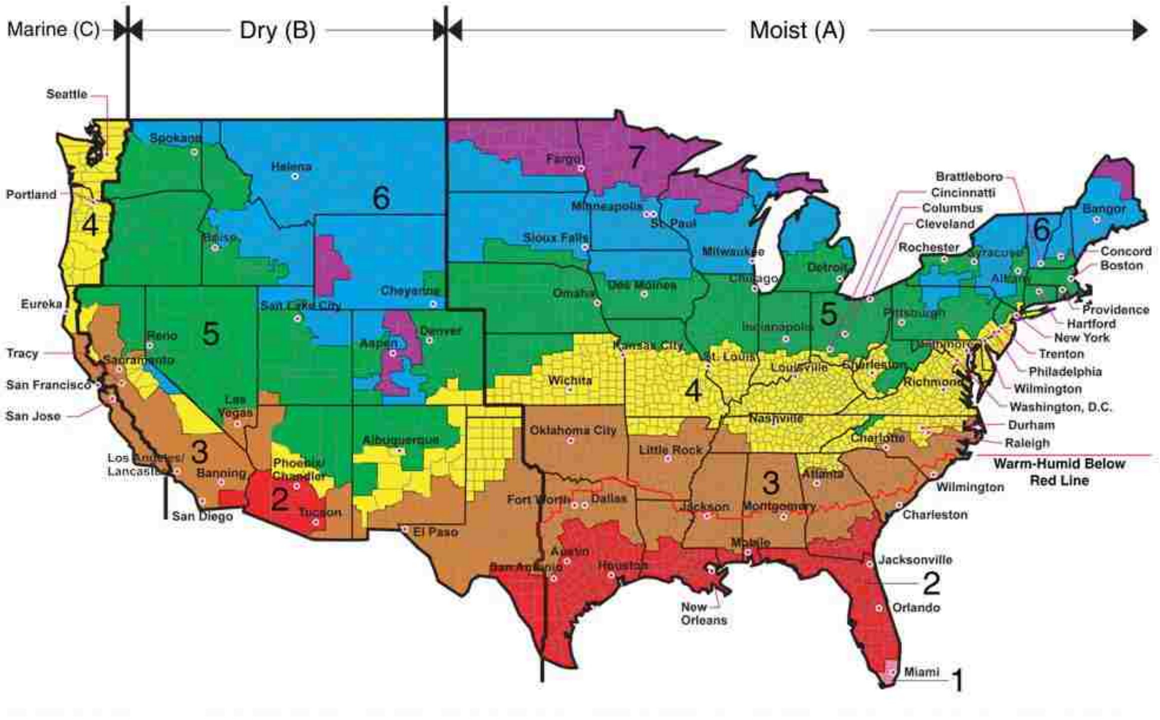


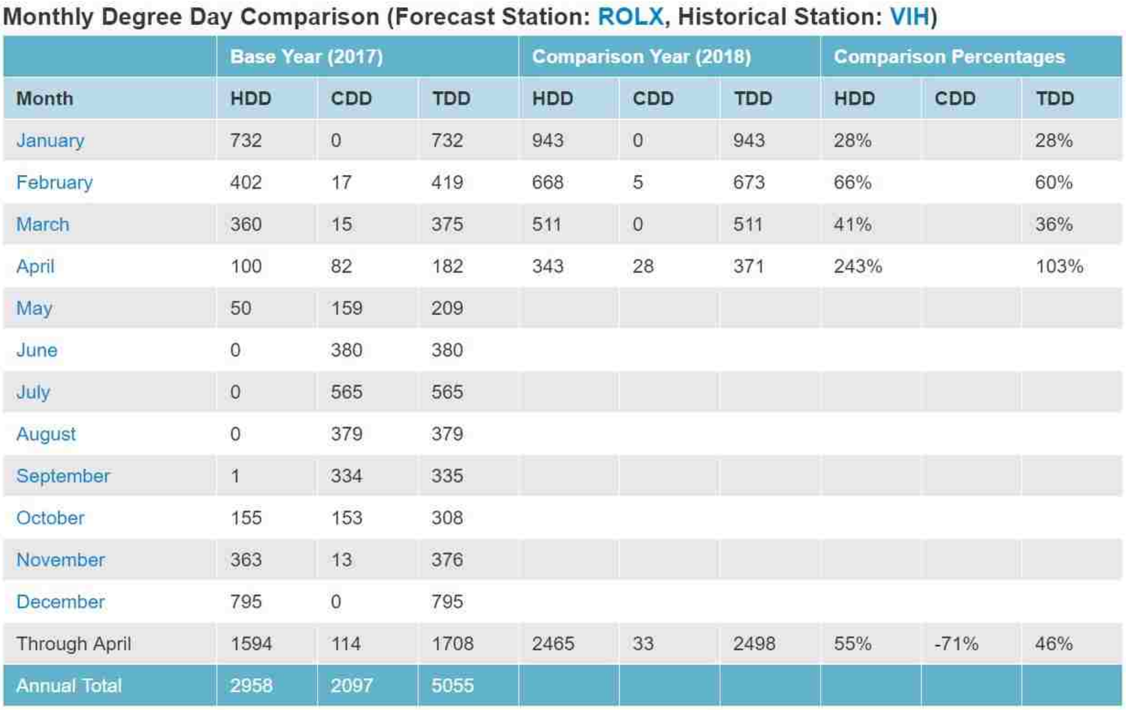
Figure 2.2. ASHRAE climate map

The building site is located in the American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE) climate zone 4A (Figure 2.2). Rolla, Missouri is located in the Ohio Valley (Central) NOAA climate zone and is considered a "Mixed-Humid" climate area. This designation is given to areas that receive rainfall in excess of 20 inches on an annual basis and have less than 5,400 heating degree days per year. The designation also indicates the average monthly temperature goes below 45°F during the winter. A degree day is calculated by determining the average temperature for a given day by taking the mean of the high and low temperatures and comparing it to a normalized temperature (65°). The temperature is considered a "heating" event if the average is below the normalized temperature and "cooling" if determined to be above. This metric is used to determine general climate requirements of a building, and can assist designers in establishing insulation needs as well as heating and cooling equipment sizing.

In 2017, the Rolla area experienced 2,958 heating degree days and 2,097 cooling degree days as shown in (Figure 2.3). The early months of the study period in 2018 demonstrated unusually cool temperatures, with an average increase in heating degree days of 68% per month compared to the observed conditions from 2017. The 2017 local temperature data (Figure 2.4) shows the daily average temps compared to historic trends.

2.5. CHAMELEON CONSTRUCTION

The Missouri S&T Chameleon Home was designed and built utilizing several innovative methods not found in traditional residential construction. Many components



Monthly Degree Day Comparison (Forecast Station: ROLX, Historical Station: VIH)

	Base Year (2017)			Comparison Year (2018)			Comparison Percentages		
Month	HDD	CDD	TDD	HDD	CDD	TDD	HDD	CDD	TDD
January	732	0	732	943	0	943	28%		28%
February	402	17	419	668	5	673	66%		60%
March	360	15	375	511	0	511	41%		36%
April	100	82	182	343	28	371	243%		103%
May	50	159	209						
June	0	380	380						
July	0	565	565						
August	0	379	379						
September	1	334	335						
October	155	153	308						
November	363	13	376						
December	795	0	795						
Through April	1594	114	1708	2465	33	2498	55%	-71%	46%
Annual Total	2958	2097	5055						

Figure 2.3. Rolla, Missouri Degree Days

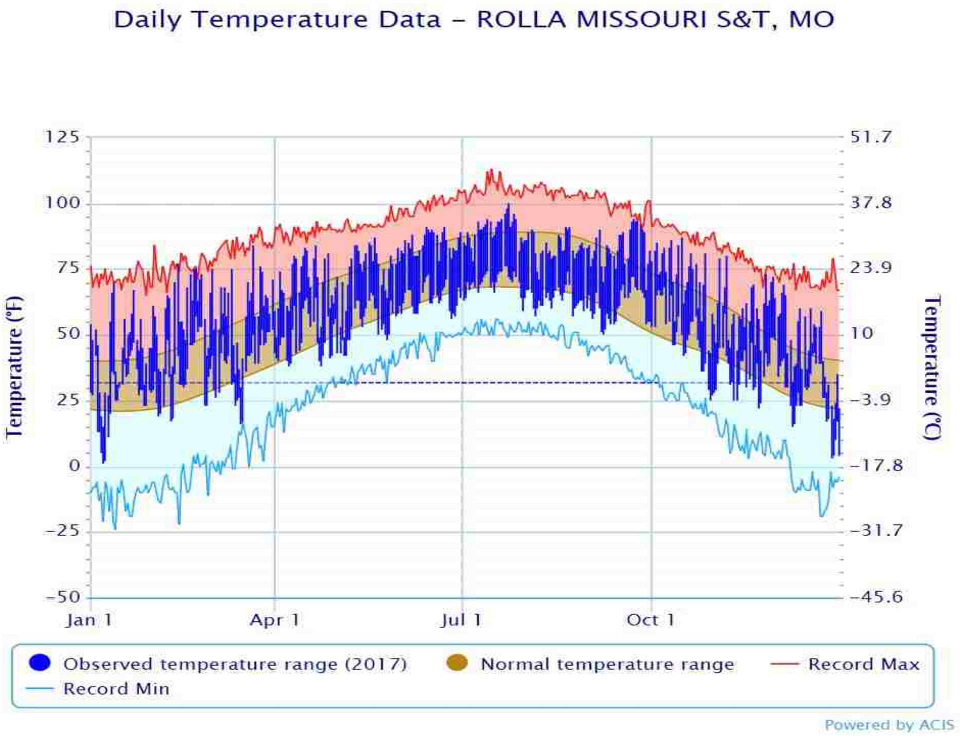


Figure 2.4. Rolla, Missouri 2017 Temperature

and methods were used to reduce the environmental impact of the building through both the building process as well as the operation of the finished home. One such component and method used centered on the exterior framing system. While most homes are constructed in the familiar stick-built fashion using either wood or steel framing, the Chameleon home was built using Structural Insulated Panels (SIPs). This method uses rigid foam insulation panels of varying thickness as the core, which are then bonded with a rigid interior and exterior substrate to form a structural member (Figure 2.5). This construction method has many distinct advantages over traditional stick-built framing, including higher insulating values (in some cases, upwards of R-70), a reduction in thermal bridging along with the system offering a greatly increased speed of construction, and reduced waste of materials. The SIPs were used in constructing all exterior walls and the roof system. The SIPs were designed and manufactured by Energy Panel Structures, Inc., located in Graettinger, Iowa.

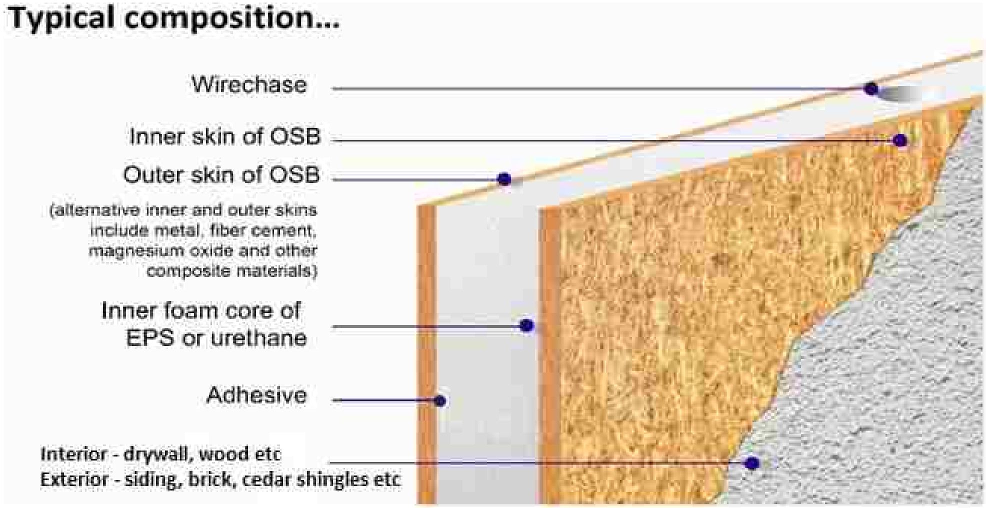


Figure 2.5. Typical SIP construction

2.6. EXTERIOR WALLS

The SIP exterior walls of the Chameleon home are 7-inch nominal structural panels. These panels consist of approximately 5 ½ inches of extruded, closed-cell polyurethane (PUR) styrofoam bonded with structural adhesives to interior and exterior oriented strand board (OSB) sheeting, which act as the "skins" to make up the finished panel system.

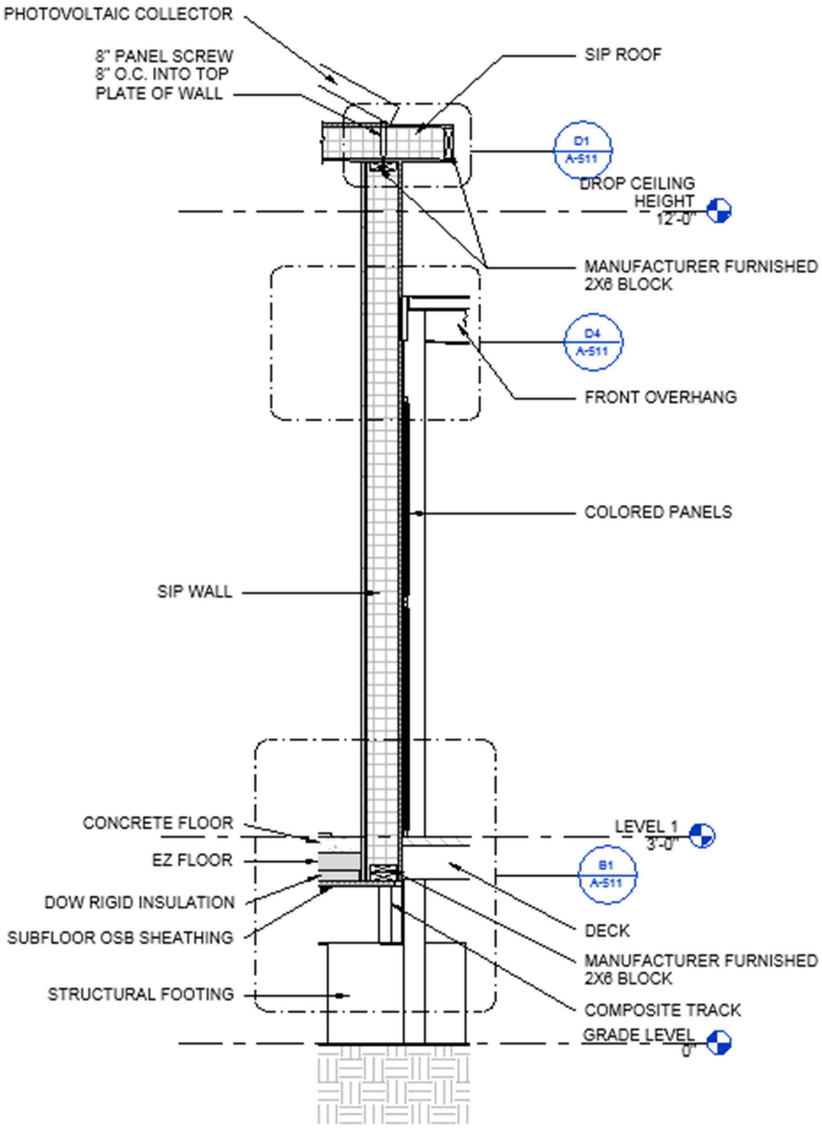


Figure 2.6. Exterior SIP construction

The interior surface of the walls is a gypsum wallboard (1/2 inch thickness) mounted to the interior surface of the SIP panel. The exterior of the SIP panel consists of an exterior insulated finishing system (EIFS) bonded to the face of the SIP panel. The EIFS system for this application consists of a 1 ½-inch rigid extruded polystyrene insulation panel affixed to the exterior surface of the SIPs, which acts as additional insulation, and is finished with a stucco type material that is applied after being mixed with dyes to produce the various colors used on the exterior of the home. This finish also acts as the air and moisture barrier of the exterior walls (Figure 2.6).

2.7. ROOF SYSTEM

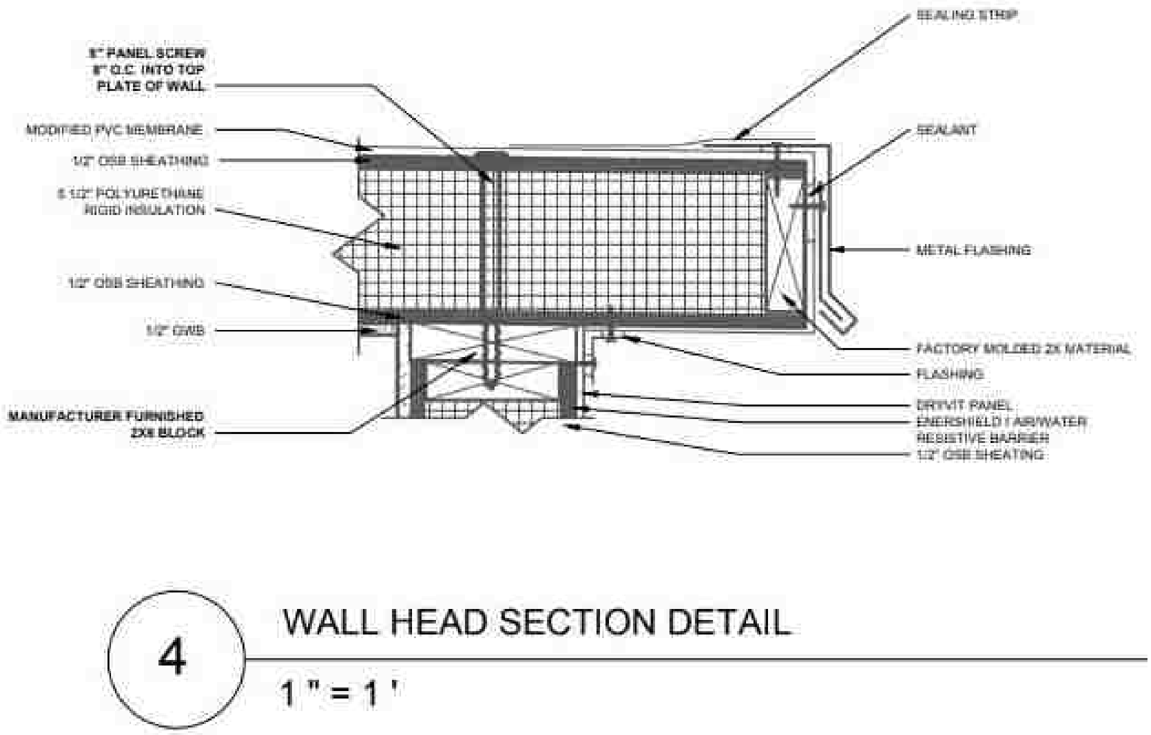


Figure 2.7. Roof construction

The roof of the Chameleon house was also constructed with SIP panels. The roof SIPs used were 7-inch nominal thickness with an approximately 5 ½-inch extruded polyurethane rigid insulation core. On both interior and exterior surfaces, a ½-inch OSB panel was bonded to the polyurethane to form the structural surfaces. On the interior side of the roof system, a ½-inch gypsum wall board was directly installed using construction adhesive and mechanical fasteners. The exterior side, which acts as the roof surface, has a modified poly vinyl chloride (PVC) membrane attached to the SIP panel by means of an adhesive. This membrane acts as the moisture barrier and the roofing surface. The section detail view of the roof and south wall interface can be seen in (Figure 2.7).

2.8. WINDOWS

The widows used in the Chameleon home were designed and manufactured by Crystal Window and Door Systems Ltd., located in Fenton, Missouri. The south face of the home features several glazing assembly types including fixed casing, picture windows, moveable awning types, and operable sliding doors. The fixed casing windows were used in conjunction with operable awning windows in three areas of the south wall. A fourth symmetrical opening was sized the same as the casing openings but provided an exterior egress door in lieu of a window. All four assemblies were provided with respective awning-style clerestory windows at the top portion of the wall. The atrium area on the southwest corner of the house was constructed with a four-panel operable door system, with the middle two panels being movable doors flanked by two fixed panels of the same size. The southern wall elevation can be seen in Figure 2.8. The total glazing area on the south face of the home was calculated to be approximately 115.5 ft^2, with the

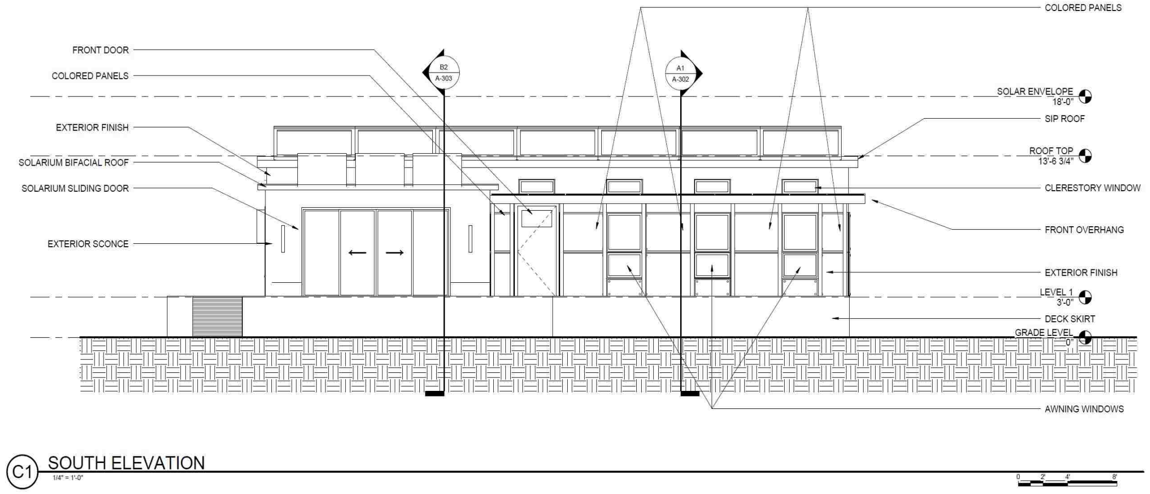


Figure 2.8. South elevation

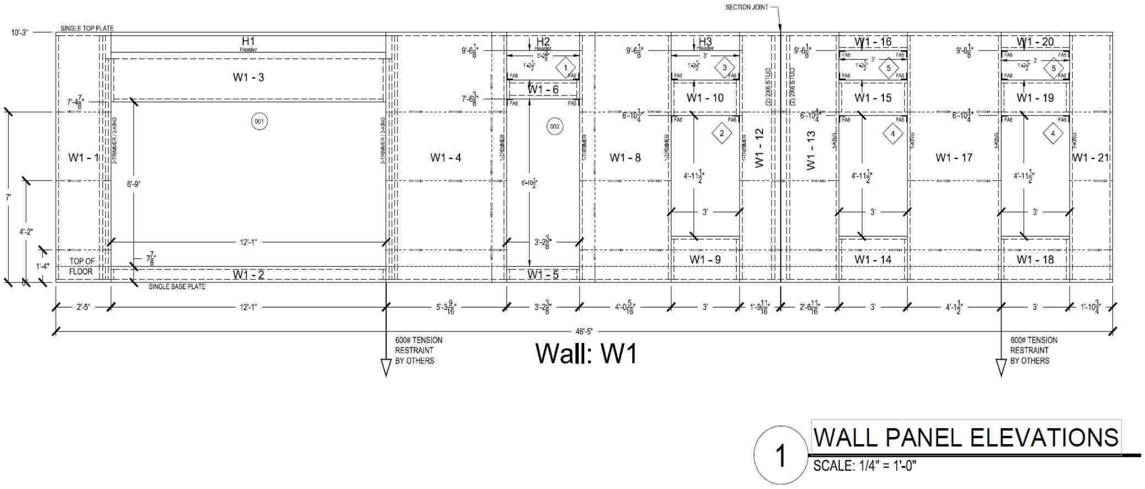


Figure 2.9. South wall fenestration

total southern wall area 475.6 ft^2; this gives the south wall of the home a window-to-wall ratio of 0.24. Dimensions for the various glazing surfaces are shown below (Figure 2.9).

3. RESULTS AND DISCUSSION

3.1. METHODOLOGY

The primary focus of this study is to determine the correlation between daylighting and heating and cooling loads in an energy efficient home. To investigate this, several types of testing and data collection were carried out on the Missouri S&T Chameleon Home over a nine-month period from September 2017 through June 2018. The testing and monitoring included daylighting levels, circuit-level energy usage, and interior and exterior temperature and humidity. These testing methods were used to determine the building's energy usage when using daylighting to offset artificial lighting use. These energy usage patterns were compared with consumption rates of the heating, ventilation, and air-conditioning (HVAC) equipment to determine what net energy savings occurred. The testing and monitoring methods were categorized into three types: daylighting levels, energy consumption, and environmental factors. The methods and instrumentation used in the respective categories are discussed in this section.

3.1.1. Daylighting Levels. To determine daylighting levels within the building, testing was conducted in accordance with the parameters in the USGBC LEED v4 Daylight credit, option 3: Measurement. The procedure calls for illuminance testing to be done in occupied spaces at work plane height (30 inches) between the hours of 9 a.m. and 3 p.m. When conducting the sampling, all shades were removed from the windows and doors and all artificial lighting sources were turned off. The LEED testing parameters call for a sampling size of the floor space as a grid with the maximum spacing of three feet. To meet this parameter, a grid was placed on the floors in all occupied spaces with spacing of 30 inches, as shown in Figures 3.1, and 3.2.

Figure 3.1. Living room grid placement

Figure 3.2. Bedroom grid placement

To acquire illuminance levels at the proper work plane height, a testing apparatus was constructed to provide placement of the illumination meter at the correct 30-inch height with minimal horizontal obstructions.

Figure 3.3. Testing apparatus

Figure 3.4. Testing being conducted

The apparatus top was constructed of aluminum and was approximately 7 inches by 7 inches to provide adequate room for the meter while remaining small enough to minimize unwanted albedo effects. The illumination meter apparatus is shown in Figure 3.3. During illumination monitoring, the meter apparatus was placed within the floor grids to determine daylighting levels (Figure 3.4).

Figure 3.5. Tondaj LX-1010B meter

The illuminance meter used for daylighting measurements was a Tondaj LX-1010B (Figure 3.5) digital lux meter. The meter features a digital readout handheld portion with range and function selectors, in addition to a tethered sensor unit. This meter was selected to allow for readings to be taken while minimizing user interference with the illumination levels (e.g., casting a shadow).

Manual illuminance testing was conducted on four distinct dates during the study to determine baseline daylighting levels in the home. The tests occurred in September and December of 2017, as well as March and June of 2018. The testing consisted of placing the illuminance meter apparatus within the grids on the floor and collecting the Lux reading. The testing was done from 9 a.m. until 3 p.m. Central Standard Time. The dates selected corresponded with the occurrences of the solar equinoxes and solstices to find daylighting levels during the major solar geometry events. These dates also allow for two distinct pairs of measurements that meet the parameters of the USGBC LEED v4 daylighting credit found in “Table 4” (Figure 3.6).

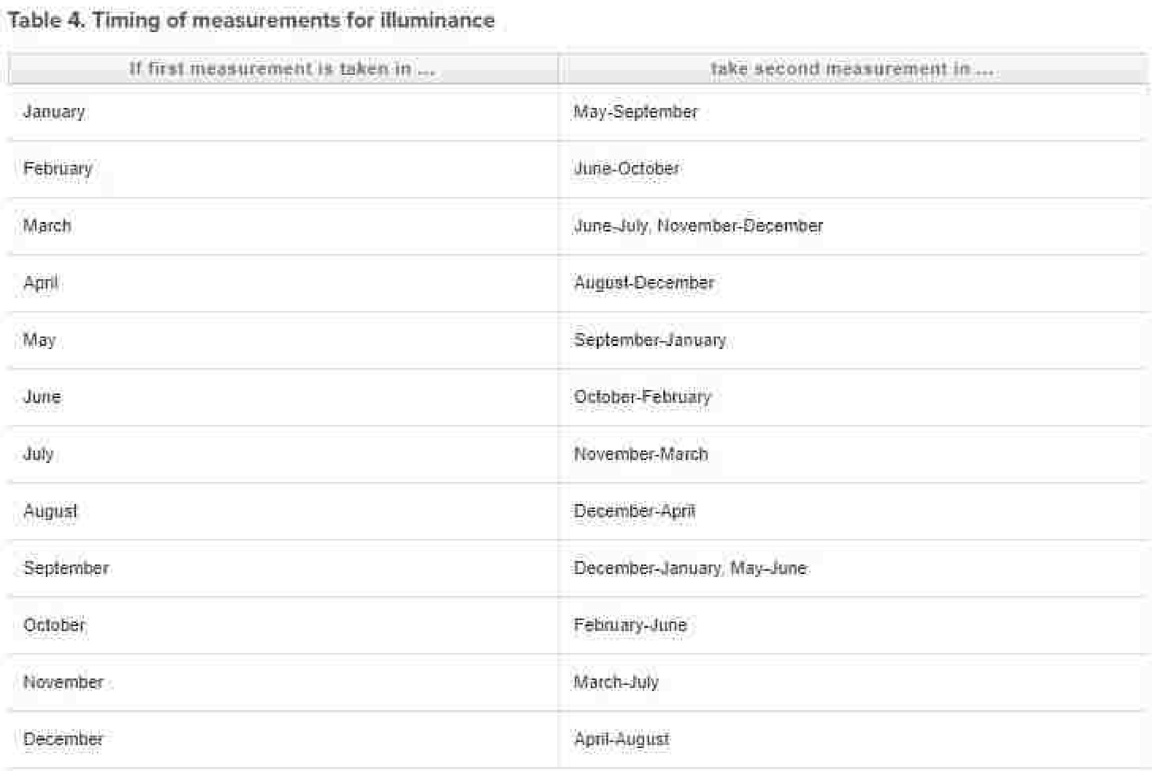


Table 4. Timing of measurements for illuminance

If first measurement is taken in ...	take second measurement in ...
January	May-September
February	June-October
March	June-July, November-December
April	August-December
May	September-January
June	October-February
July	November-March
August	December-April
September	December-January, May-June
October	February-June
November	March-July
December	April-August

Figure 3.6. USGBC LEED Table 4

Daylighting levels were also collected using Extech Instruments SDL400 Light Meter/Data Loggers (Figure 3.7). These devices feature a traditional light meter and, in addition, integrated data logging equipment to take measurements at set intervals without user input. Two of these units were deployed in the Missouri S&T Chameleon Home in ceiling-mounted configurations to monitor daylighting levels in the areas indicated on the floorplan in Figure 3.8. The light meter/data loggers were set to take samplings of the illumination level at 30-minute increments from 9 a.m. until 3 p.m. in accordance with USGBC LEED v4 testing parameters.

Figure 3.7. SDL400 Meter

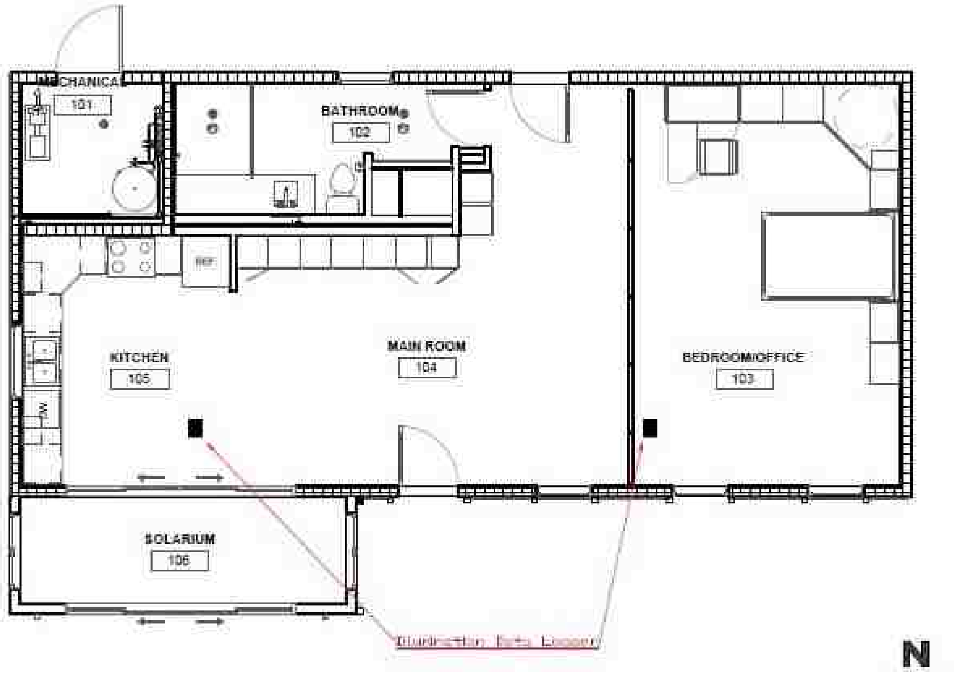


Figure 3.8. Illumination meter placement

The meters were placed face-down on the underside of the drop ceiling mount (Figures 3.9 and 3.10). This placement caused the meters to be in a manner such that they were not at the specified "work plane" height of 30 inches from the floor. To account for this, multiple measurements were taken directly under the ceiling-mounted meter with the Tondaj LX meter placed at work plane height. These corresponding measurements were then entered into an Excel spreadsheet to determine the error caused by the improper placement with respect to illumination level readings. The various readings from the ceiling-mounted data logger (observed) and the work plane height meter (actual) can be seen in Figure 3.11. To determine the error caused by placement, several sets of corresponding measurements were taken under differing outdoor lighting conditions and various times of year. The observed error in illumination levels were found to be approximately 15-26%, with the ceiling-mounted meters reading lower illumination levels than the actual levels observed at work plane height.

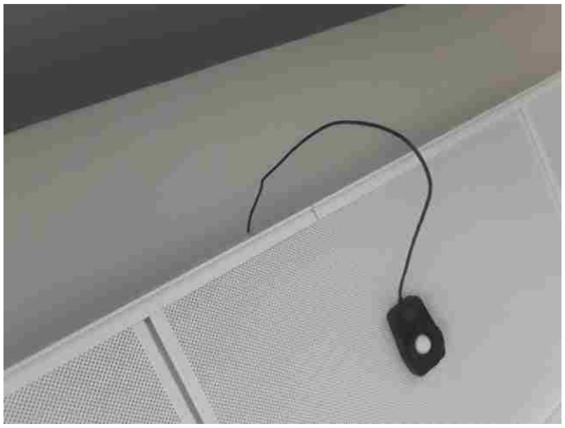


Figure 3.9. Light meter receptor

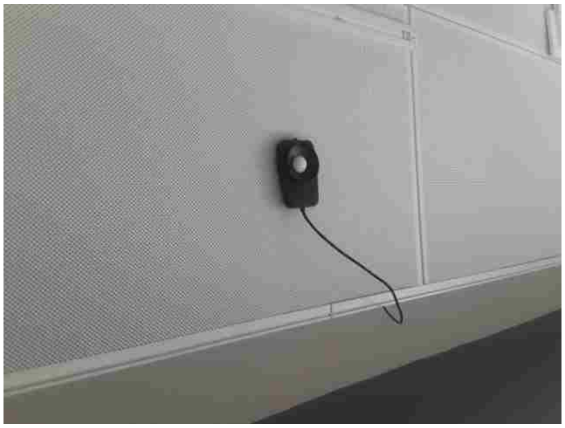


Figure 3.10. Light meter receptor

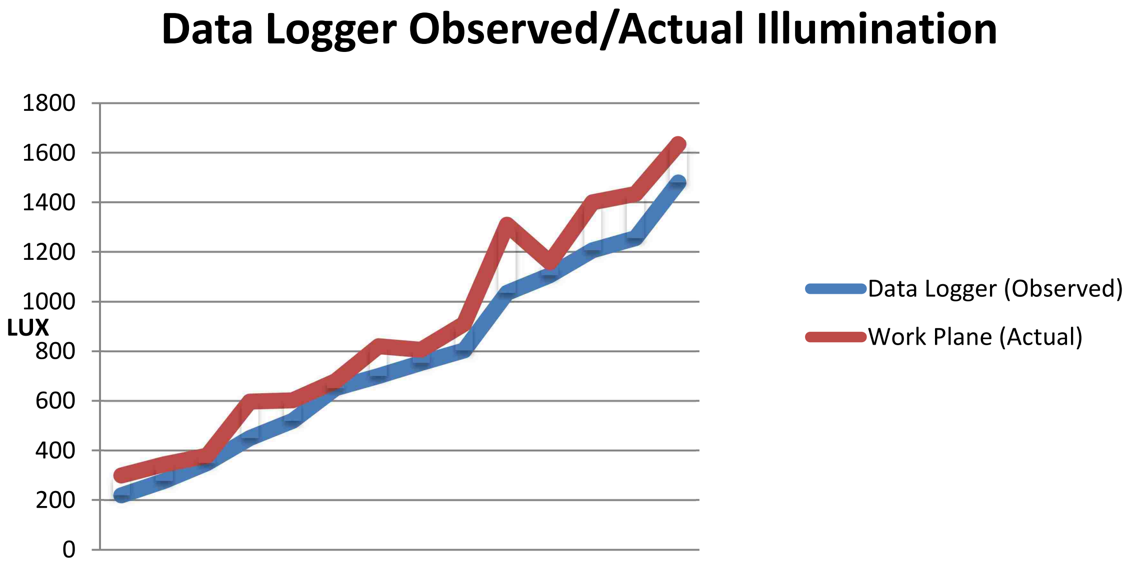
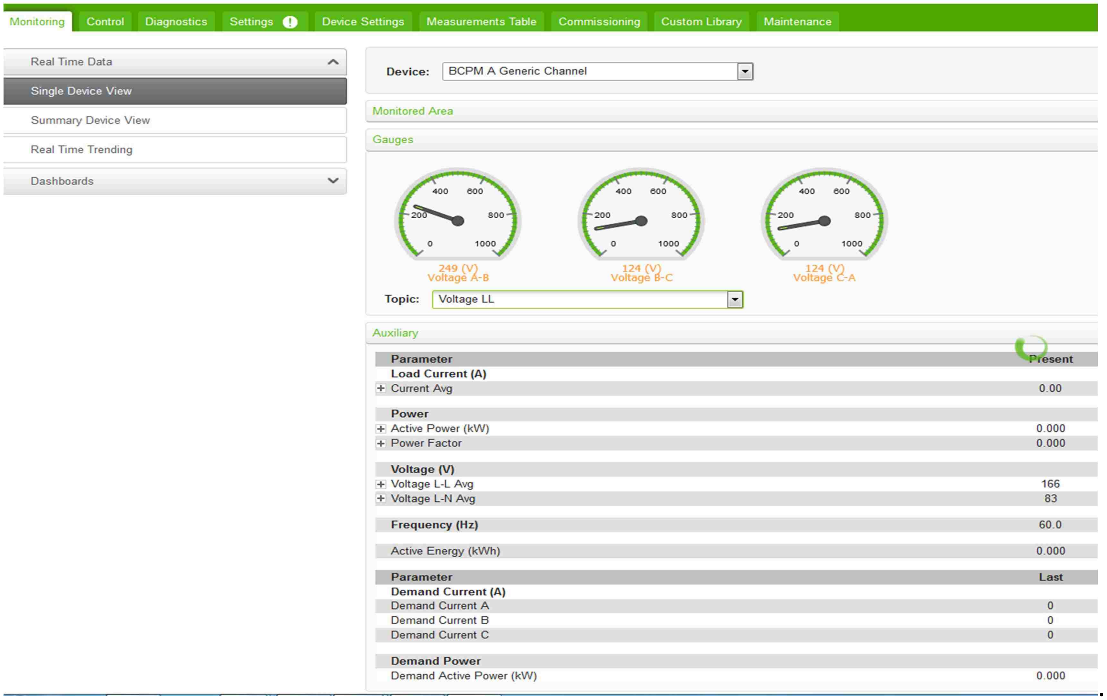


Figure 3.11. Illumination data logger results

3.1.2. Energy Consumption. The energy usage of the Missouri S&T Chameleon Home was monitored throughout the study period with the use of a Schneider Electric Branch Circuit Power Monitor (BCPM; Figure 3.12). This device utilizes current transducers (CTs) mounted within the home's power distribution panel (Figure 3.13) to collect data on amperage flow through the various circuit conductors. Sensors monitor the energy flowing through the individual circuit's wiring and collect the data to show real-time power usage. The system allows for multiple energy analysis methods, including real-time, demand measurements, accumulated energy measurements, and energy snapshots. Demand measurements were used for some portions of the energy analysis and give the user the average values of energy use over a specified time interval. The remaining data was acquired using the accumulated energy measurement feature of the Schneider BCPM system which is shown in Figure 3.14.

Figure 3.12. Schneider monitor

Figure 3.13. Chameleon home circuit panel



Device: BCPM A Generic Channel

249 (V)
Voltage A-B

124 (V)
Voltage B-C

124 (V)
Voltage C-A

Topic: Voltage LL

Parameter	Present
Load Current (A)	
Current Avg	0.00
Power	
Active Power (kW)	0.000
Power Factor	0.000
Voltage (V)	
Voltage L-L Avg	166
Voltage L-N Avg	83
Frequency (Hz)	60.0
Active Energy (kWh)	0.000

Parameter	Last
Demand Current (A)	
Demand Current A	0
Demand Current B	0
Demand Current C	0
Demand Power	
Demand Active Power (kW)	0.000

Figure 3.14. Schneider BCPM dashboard

3.1.3. Artificial Lighting Energy. To determine the amount of energy reduced by employing daylighting, testing was performed to find the amount of artificial lighting needed to achieve comparable illumination levels. The Tondaj LX meter (used in the daylighting method) was placed in the same respective grid positions with the room in non-day-lit conditions (i.e., nighttime). The home is outfitted with a combination of whole-room and task lighting consisting of 38 track-mounted lights and LED linear lights suspended in the ceiling. All track-mounted lighting was equipped with EUFY Lumos tunable soft white bulbs (Figure 3.15). These bulbs are rated at 9W of power usage with a lumen output of 800 lm. The lights were separated into eight distinct groups, which were

Figure 3.15. Lumos tunable soft white bulb

individually controlled through the use of an installed Amazon Alexa personal assistant and a Wink Hub 2 smart device hub. The various lighting groups were individually activated during the nighttime test to find the LUX levels they produce (Figures 3.16 and 3.17). The lighting grouping was adjusted until illumination levels, which were comparable to the daylighting levels, were encountered. This involved grouping the light activation to achieve four levels of lighting intensity: 300, 400, 500, and 600 LUX. The lighting groups associated with the intensity levels were then activated and remained on for a full 30-minute cycle to determine the energy consumed by accessing the Schneider BCPM system. The energy use data was then used to find the amount of energy offset through the use of daylighting (Table 3.1).

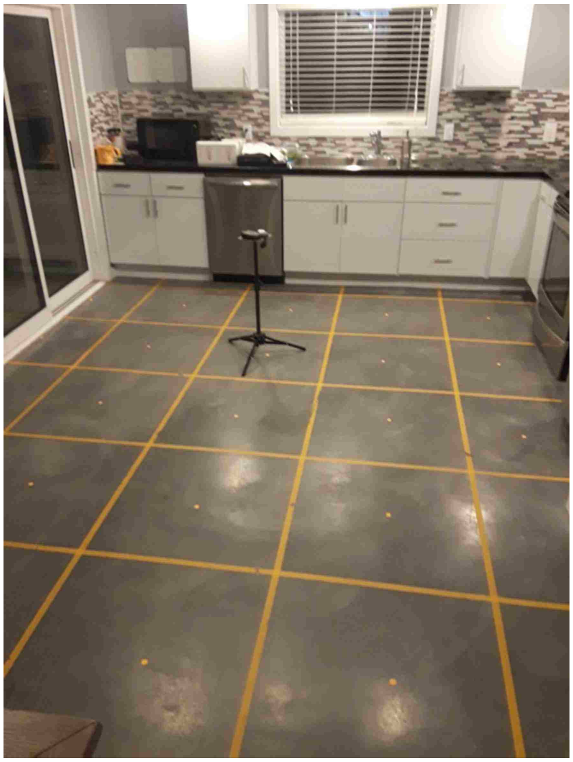


Figure 3.16. 600 LUX level

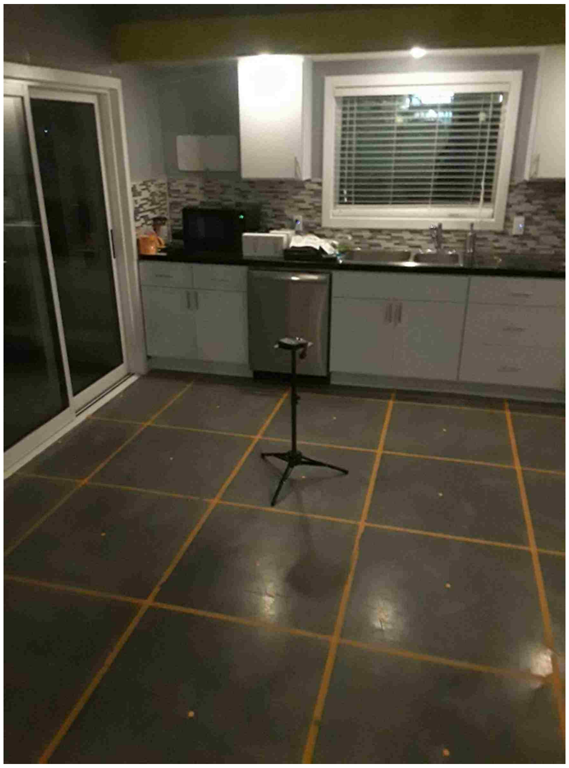


Figure 3.17. 300 LUX level

Table 3.1. Artificial lighting level power usage

Artificial Lighting Equivalent Power Usage	
300 LUX	0.13 kW
400 LUX	0.18 kW
500 LUX	0.23 kW
600 LUX	0.27 kW

3.1.4. Environmental Factors. There were seven environmental factors to be taken into consideration for this study: internal and external temperatures, orientation of the building, local weather conditions, ambient sky conditions to determine solar insolation levels, and the insulating and conductive properties of the various building assembly components.

The internal and external temperature was obtained using Eitech GSP6 temperature and humidity data loggers (Figure 3.18). To determine heating and cooling

Figure 3.18. Eitech GSP6 data logger

loads of the building, design values and procedures from the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) 2013 Handbook was used to calculate R-Values for individual components and the envelope assemblies. These values were used along with the indoor and outdoor ambient conditions to define the loads attributable to the glazing surfaces. The equations and values can be found below.

Table 3.2. Wall assembly R-Values

Wall Assembly Component R-Values (ASHRAE 2013 Handbook: Table 5-12, 5-14, 5-15)	
Assembly Component	**R-Value**
Inside Air Film	0.68
½" Gypsum wall board	0.45
½" OSB Interior sheathing	1.47
5 ½" Polyurethane insulation	19.25
½" OSB Exterior sheathing	1.47
1 ½" Exterior finish	4.82
Outside Air Film (15mph wind)	0.17
Total R-Value ($R_{assembly}$)	**28.3**

$$U_{assembly} = 1/R_{assembly} = 1/28.3 = 0.0353 Btu/h * ft^2 * °F \qquad \text{(Eq. 2)}$$

$$\text{Exterior Door (no glazing)} \quad U = 0.16\, Btu/h * ft^2 * °F$$

$$\text{Exterior Door (with glazing)} \quad U = 0.52 \frac{Btu}{h} * ft^2 * °F$$

$$\text{Exterior Windows} \quad U = 0.49\, Btu/h * ft^2 * °F$$

Table 3.2 indicates the assembly components which make up the exterior wall assembly. The thermal transmittance values for other components which were used in the exterior include exterior doors with and without glazing, along with window assemblies. The roof assembly consisted of a similar construction method, and the respective component values are shown in Table 3.3.

Table 3.3. Roof assembly R-Values

Roof Assembly Component R-Values (ASHRAE 2013 Handbook: Table 5-12, 5-14, 5-15)	
Assembly Component	**R-Value**
Inside Air Film	0.68
½" Gypsum wall board	0.45
½" OSB Interior sheathing	1.47
5 ½" Polyurethane insulation	19.25
½" OSB Exterior sheathing	1.47
3/8" PVC roofing membrane	0.64
Outside Air Film (15mph wind)	0.17
Total R-Value (R_{roof})	**24.2**

$$U_{roof} = 1/R_{roof} = 1/24.2 = 0.0413\, Btu/h * ft^2 * °\mathrm{F} \qquad \text{(Eq. 3)}$$

The overall thermal transmittance of the exterior envelope was calculated using the following equation from ASHRAE (2013):

$$\boldsymbol{U_o = \sum U_i A_i / A_o} \qquad \text{(Eq. 4)}$$

Where

$$U_o = \text{area} - \text{weighted average of thermal transmittance}$$

$$U_i = \text{thermal transmittance of individual component}$$

$$A_i = \text{area of individual component}$$

$$A_o = \text{total area of envelope assembly}$$

$$U_o = (0.0353)(937\text{ft}^2) + (0.16)(40.4) + (0.52)(41.3) + (0.49)(186.4) + (0.0413)(1048.5)/2253.6 = 195.65\ Btu/h * {}^\circ F$$

The U-values were utilized along with the respective square footages of assembly components to find the heating and cooling load attributable to the glazing surfaces through convection. This “attributable” portion of loads would then be entered along with energy usage amounts from the HVAC system to find the energy demand from the heating and cooling loads imparted from heat transfer on the glazing surfaces needed to allow daylighting into the interior occupied spaces.

3.2. RESULTS

The data were collected from the various testing methods and compiled to determine results. The measurements, along with the respective tables and graphs, can be found in the following section.

3.2.1. Power Demand from Heating and Cooling Equipment. Data collected from the Schneider BCPM were analyzed to determine usage patterns of HVAC equipment. In the graph (Figure 3.19), the hourly demand averages from the HVAC are shown. The individual lines indicate a single week of the study period and allowed for the investigation of whether higher or lower use patterns correlated with differing temperatures or solar insolation levels. No large-scale outliers were found; all documented periods had usage rates that roughly correlated with respective temperatures or solar energy data.

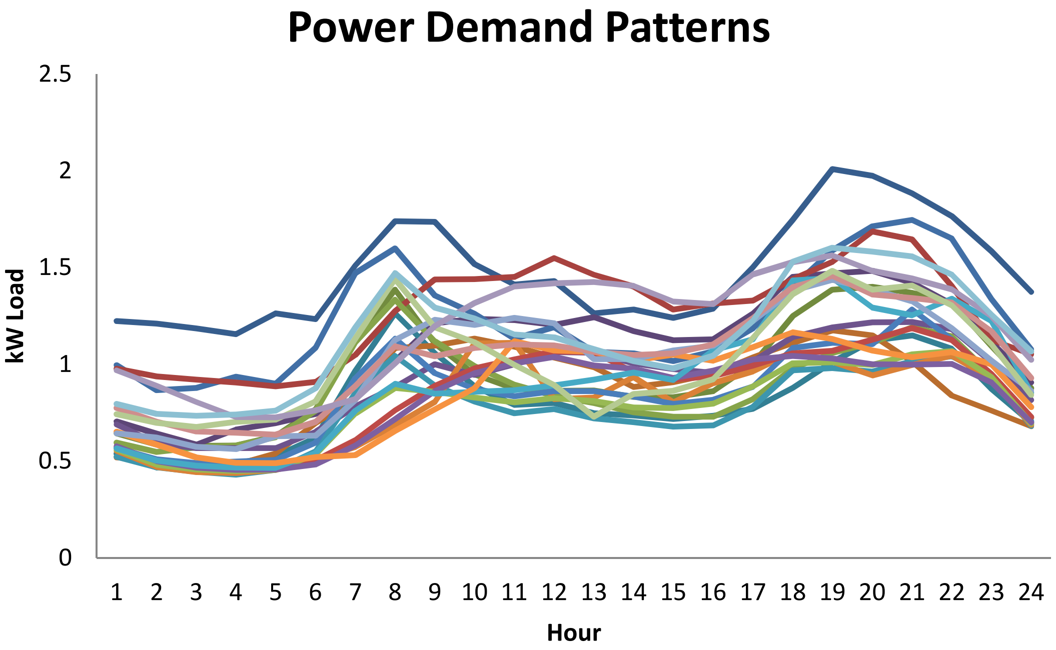


Figure 3.19. Weekly power demand

3.2.2. Daily Power Usage. To determine power usage from individual days, the Schneider BCPM dashboard was utilized to identify specific days chosen for analysis, and the data was downloaded and placed in an Excel spreadsheet. The initial data encompassed the entire 24-hour period, but as the study was only concerned with the times between 9 a.m. and 3 p.m., only that data was used. The results are reported by the software in 10-minute increments (Figure 3.20); these results were then averaged over a

30-minute period to determine overall demand for that period. This process was repeated for all individual days selected for manual daylight measurements, and the results are shown in Table 3.4.

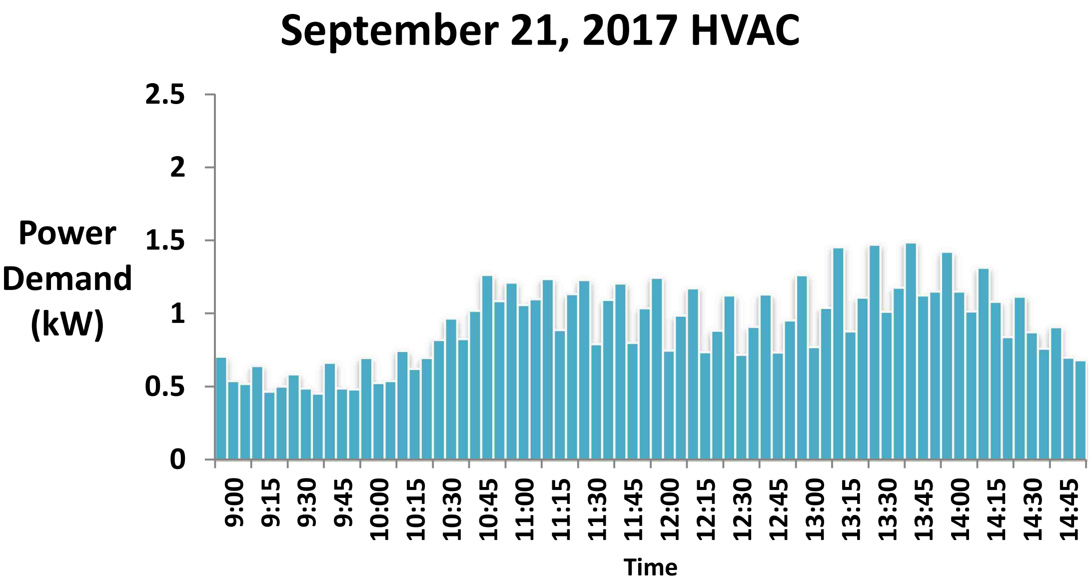


Figure 3.20. September 21, 2017 HVAC power demand

Table 3.4. Total power demand

	Total HVAC Power Demand (kW)												
Time	**9:00**	**9:30**	**10:00**	**10:30**	**11:00**	**11:30**	**12:00**	**12:30**	**13:00**	**13:30**	**14:00**	**14:30**	**15:00**
21-Sep	**1.00**	**0.87**	**0.88**	**0.94**	**0.90**	**1.09**	**1.24**	**1.28**	**1.22**	**1.26**	**1.13**	**1.19**	**1.07**
21-Dec	**1.12**	**1.09**	**1.06**	**1.01**	**0.86**	**0.81**	**0.80**	**0.72**	**0.74**	**0.85**	**0.82**	**0.89**	**0.92**
21-Mar	**1.08**	**0.94**	**0.91**	**0.86**	**0.74**	**0.63**	**0.82**	**0.77**	**0.74**	**0.80**	**0.76**	**0.84**	**0.88**
22-Jun	**0.64**	**0.59**	**0.58**	**0.58**	**0.63**	**0.77**	**1.13**	**1.39**	**1.11**	**0.95**	**0.87**	**0.86**	**0.87**

Once the overall HVAC power use for the daylighting period was determined, this data were utilized with the U-Value calculations (Eq. 4) to ascertain the portion of power attributable to heat transfer through the glazing surfaces of the exterior envelope. The resulting power usage amounts are shown in Table 3.5.

Table 3.5. Glazing power demand

Power Demand Attributable to Glazing (kW)													
Time	9:00	9:30	10:00	10:30	11:00	11:30	12:00	12:30	13:00	13:30	14:00	14:30	15:00
21-Sep-17	0.63	0.55	0.53	0.50	0.43	0.37	0.47	0.45	0.43	0.46	0.44	0.49	0.51
21-Dec-17	0.37	0.34	0.34	0.34	0.36	0.45	0.65	0.80	0.64	0.55	0.51	0.50	0.50
21-Mar-18	0.63	0.55	0.53	0.50	0.43	0.37	0.47	0.45	0.43	0.46	0.44	0.49	0.51
22-Jun-18	0.37	0.34	0.34	0.34	0.36	0.45	0.65	0.80	0.64	0.55	0.51	0.50	0.50

Table 3.6. Temperature

Temperature (°F)													
Time	9:00	9:30	10:00	10:30	11:00	11:30	12:00	12:30	13:00	13:30	14:00	14:30	15:00
21-Sep-17	78.5	79.2	83.1	85	86.1	87.2	88.5	89.6	90.2	93.8	91.5	91.6	91.3
21-Dec-17	41.9	45	48	48.2	51.6	52	54	54.1	54.9	54.8	56.3	55.8	56.7
21-Mar-18	35.9	37.1	38.2	38.5	40.1	40.8	41.4	42.2	43.2	43.5	44.7	44.2	45.8
22-Jun-18	70.2	70.8	71.7	73.8	74.5	77.4	78.6	80.4	81.5	81.2	80.5	79.7	80.2

The results from daylighting illumination level testing using the Tondaj LUX meter were determined for the days selected. These test were conducted between the hours of 9 a.m. and 3 p.m. (Table 3.7).

Table 3.7. Daylighting levels

Daylighting Level (LUX)

Time	9:00	9:30	10:00	10:30	11:00	11:30	12:00	12:30	13:00	13:30	14:00	14:30	15:00
21-Sep-17	**389**	**460**	**534**	**664**	**685**	**671**	**697**	**702**	**730**	**700**	**693**	**662**	**516**
21-Dec-17	**286**	**298**	**312**	**368**	**382**	**418**	**442**	**438**	**398**	**386**	**365**	**324**	**286**
21-Mar-18	**414**	**462**	**590**	**634**	**708**	**714**	**668**	**580**	**742**	**701**	**625**	**583**	**534**
22-Jun-18	**457**	**530**	**605**	**638**	**680**	**630**	**590**	**572**	**553**	**521**	**485**	**435**	**410**

Table 3.8 demonstrates the power usage required to achieve measured respective daylighting illumination levels through artificial lighting use.

Table 3.8. Equivalent lighting power usage

Artificial Lighting Equivalent Load (kW)

Time	9:00	9:30	10:00	10:30	11:00	11:30	12:00	12:30	13:00	13:30	14:00	14:30	15:00
21-Sep-17	**0.18**	**0.21**	**0.24**	**0.30**	**0.31**	**0.30**	**0.30**	**0.32**	**0.33**	**0.32**	**0.31**	**0.30**	**0.23**
21-Dec-17	**0.13**	**0.13**	**0.14**	**0.17**	**0.17**	**0.19**	**0.20**	**0.26**	**0.18**	**0.17**	**0.16**	**0.15**	**0.13**
21-Mar-18	**0.19**	**0.13**	**0.14**	**0.17**	**0.17**	**0.19**	**0.20**	**0.20**	**0.18**	**0.17**	**0.16**	**0.15**	**0.13**
22-Jun-18	**0.21**	**0.24**	**0.27**	**0.29**	**0.31**	**0.28**	**0.27**	**0.26**	**0.25**	**0.23**	**0.22**	**0.20**	**0.18**

Combining the data obtained from HVAC power usage (total and attributable to glazing) with temperature data (Figure 3.21), this demonstrates relationships between outdoor ambient temperature and the required energy to operate the HVAC system. Figure 3.22. shows the correlation between daylighting levels and HVAC energy use.

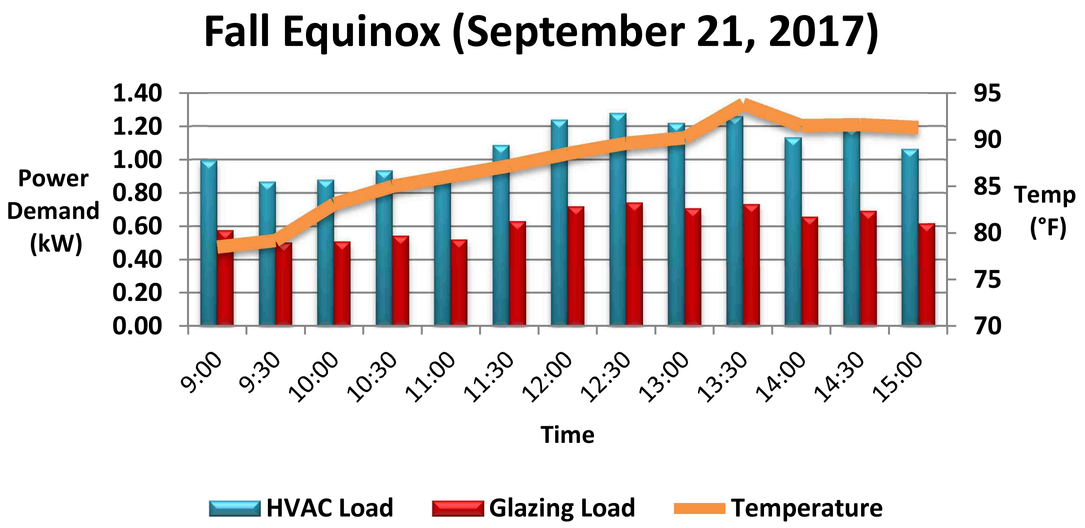


Figure 3.21. September temperature and HVAC power usage

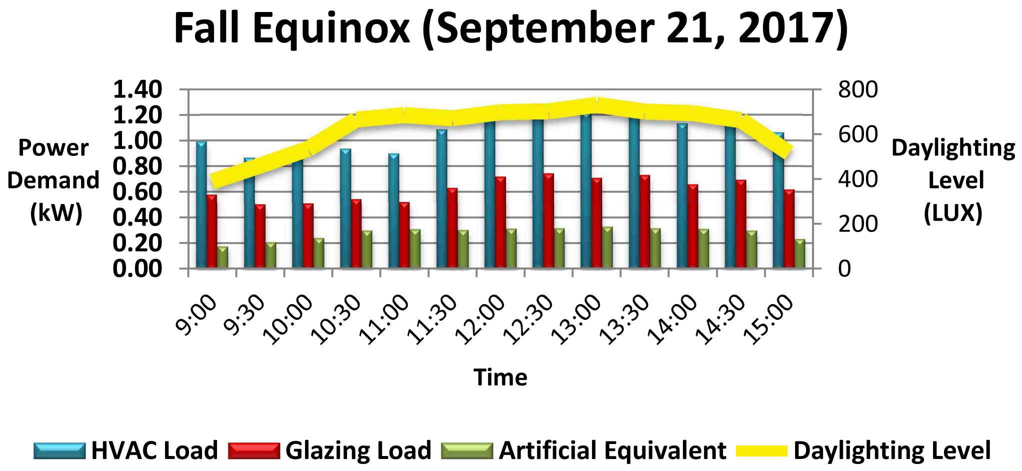


Figure 3.22. September power usage and illumination levels

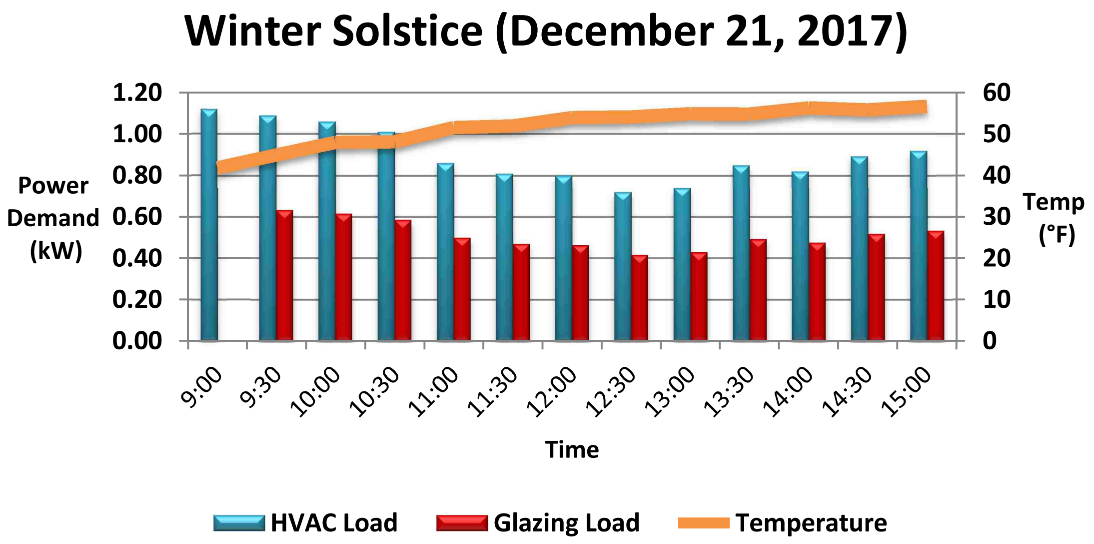


Figure 3.23. December temperature and HVAC power usage

The correlations between temperature and HVAC power levels are also prevalent during cooler months such as December (Figure 3.23). The relationship between HVAC energy use and daylighting levels is also shown (Figure 3.24.)

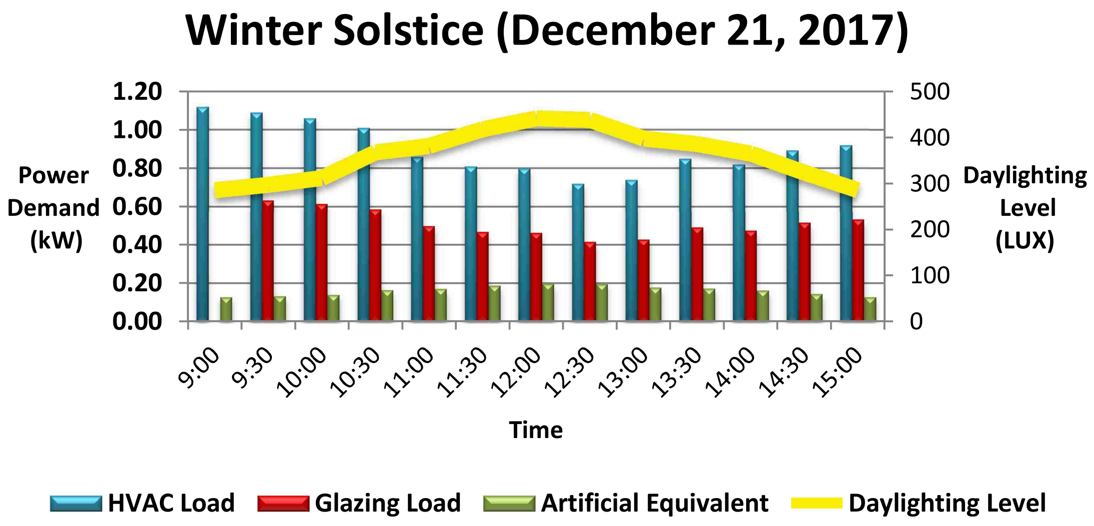


Figure 3.24. December power usage and illumination levels

The power usage and daylighting illumination levels for the March 21, 2018 measurement period (Figure 3.26) shows a distinct reduction in daylighting level at 12:30 p.m. This was due to localized clouds in the area that obstructed lighting levels for a significant portion of the day.

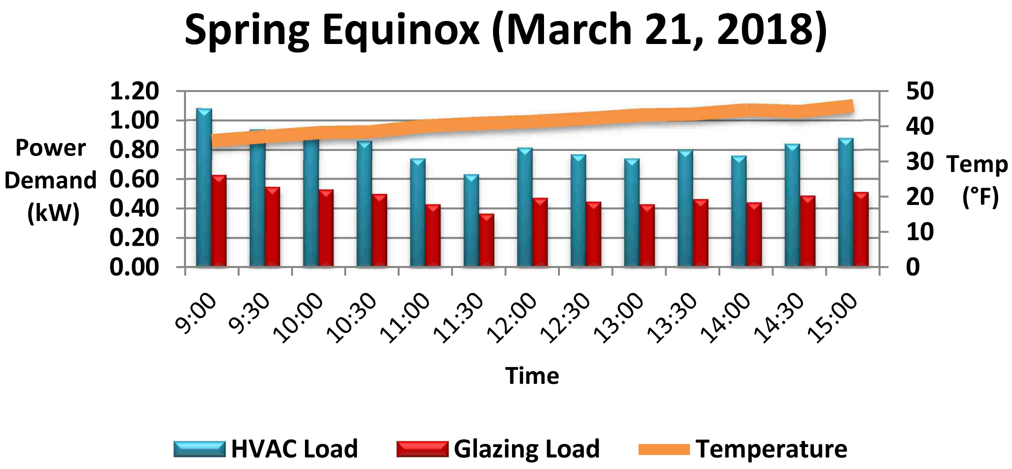


Figure 3.25. March temperature and HVAC power usage

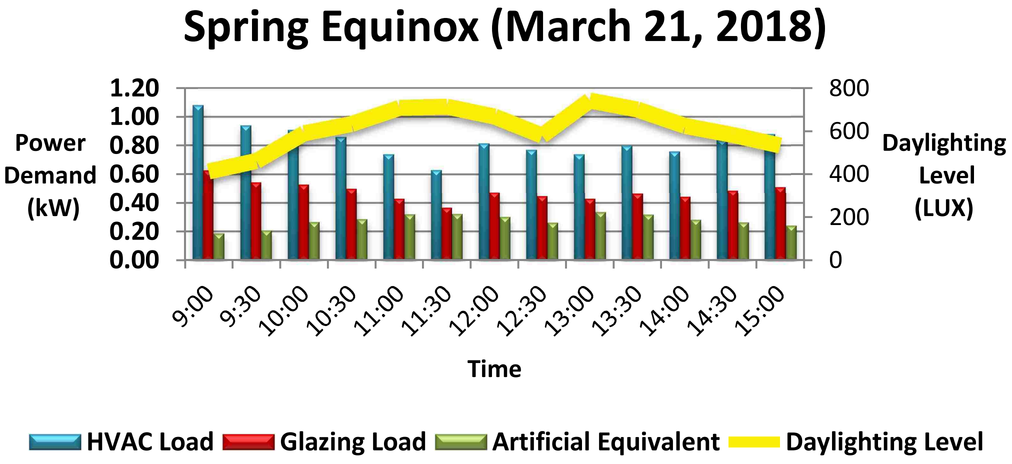


Figure 3.26. March power usage and illumination levels

In Figure 3.27, the correlation between outdoor ambient temperature and HVAC energy usage is demonstrated. This day was cool for the season (high temperature, 81°F). This is shown in the lower usage rates of the cooling system.

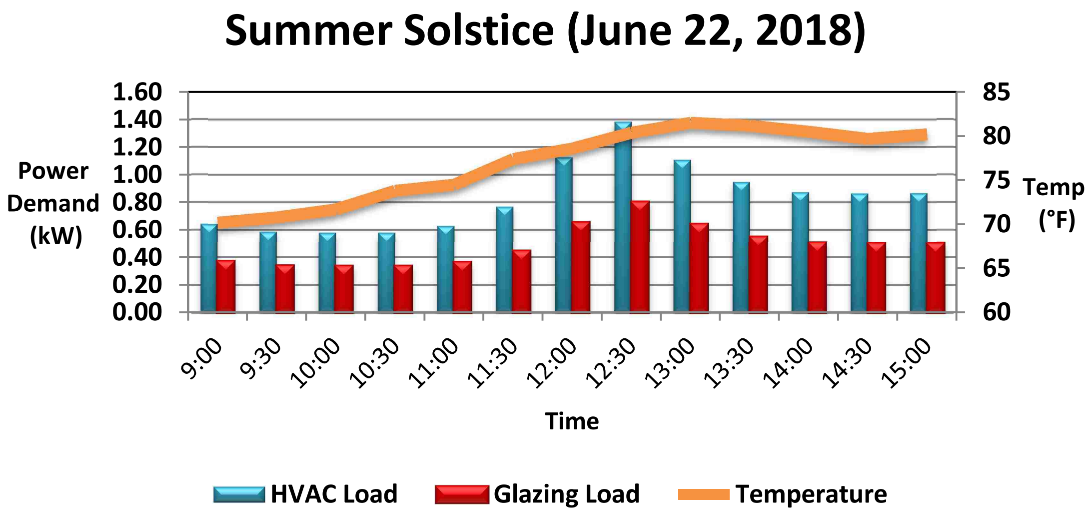


Figure 3.27. June temperature and HVAC power usage

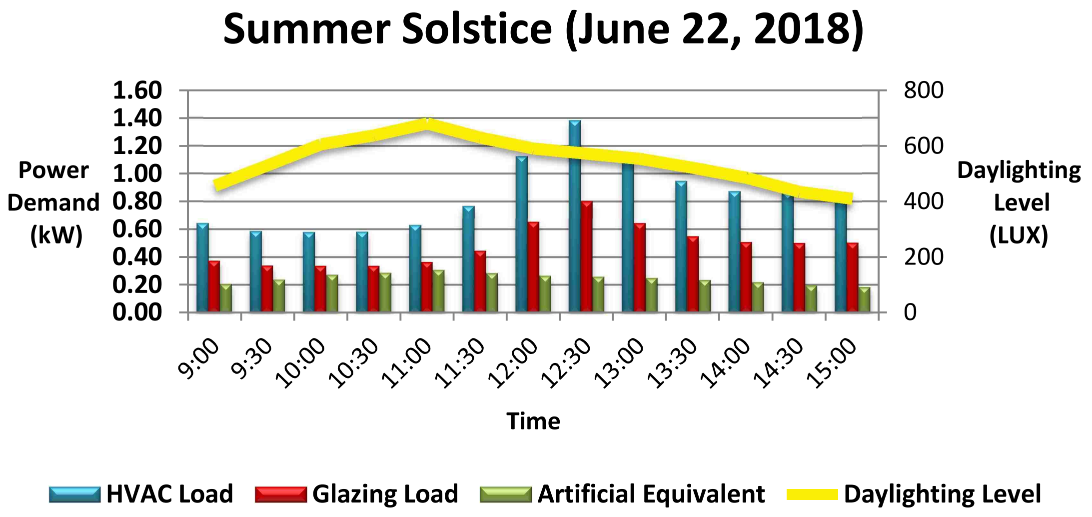
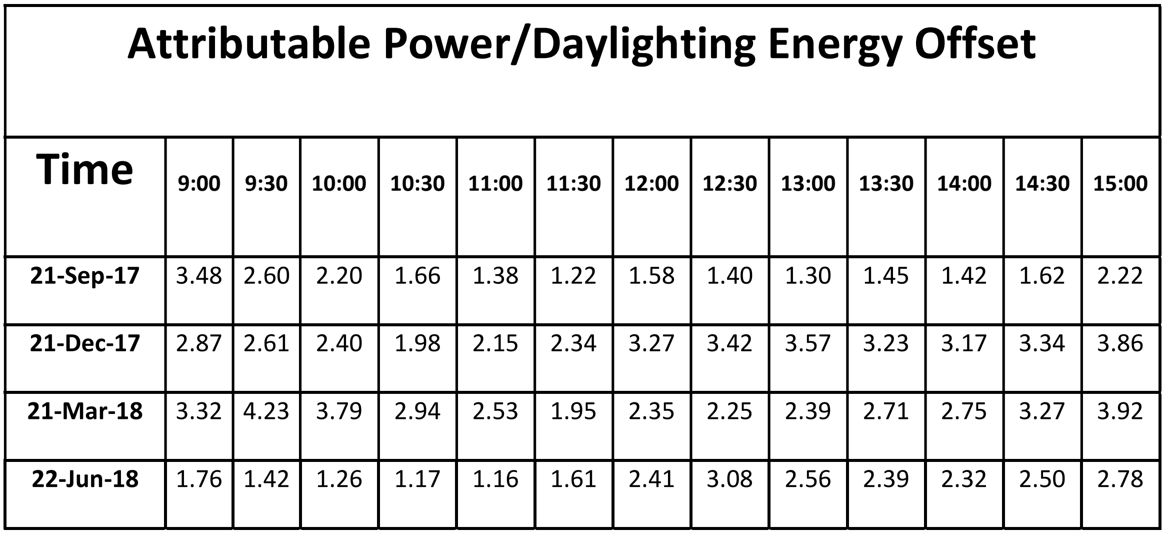


Figure 3.28. June power usage and illumination levels

The measured amounts of power for energy offset and energy levels attributable to glazing were compared for all times throughout the study period. When consumption for all days is summed, the results are the energy used by the HVAC system in the house, which was attributable to the glazing, was 25.21 kW. The amount of energy offset during the same period through the use of daylighting was 11.16 kW. This indicates the amount of energy used is 226% larger than the amount saved by not using artificial lighting. With respect to individual days, the greatest difference between HVAC energy attributable to glazing and offset energy from daylighting occurred in the afternoon of December, which was due to increasing HVAC load from cooling outdoor ambient temperatures along with reduced daylight illumination levels at 3:00 p.m. The smallest difference occurred in the morning of March 2018. This was due to lower energy usage from the HVAC due to high levels of solar energy assisting in warming the house as well as high levels of daylighting, which would require larger amounts of energy to replicate



Attributable Power/Daylighting Energy Offset

Time	9:00	9:30	10:00	10:30	11:00	11:30	12:00	12:30	13:00	13:30	14:00	14:30	15:00
21-Sep-17	3.48	2.60	2.20	1.66	1.38	1.22	1.58	1.40	1.30	1.45	1.42	1.62	2.22
21-Dec-17	2.87	2.61	2.40	1.98	2.15	2.34	3.27	3.42	3.57	3.23	3.17	3.34	3.86
21-Mar-18	3.32	4.23	3.79	2.94	2.53	1.95	2.35	2.25	2.39	2.71	2.75	3.27	3.92
22-Jun-18	1.76	1.42	1.26	1.17	1.16	1.61	2.41	3.08	2.56	2.39	2.32	2.50	2.78

Figure 3.29. Attributable HVAC power usage/Daylight energy offset ratio

with artificial lighting. Respective individual ratios of power attributable to glazing and energy offset from daylighting are shown in Figure 3.29. These represent the amount of energy attributable to glazing divided by the amount of energy offset by utilizing daylighting instead of using artificial lighting to obtain the illumination level at that measurement time.

4. CONCLUSIONS

The recent technological advancements in lighting technology have changed the dynamic of energy use within the built environment. Current sustainable building programs along with recent research still view daylighting as a definitive method of saving energy. While this may be true in a pure definition (it does offset the use of electrical lighting and therefore saves energy), when all aspects of how solar energy effects a building are examined, daylighting does not appear to be a net saver of energy. The amount of glazing needed to effectively illuminate an interior with daylight can, in many cases, create thermal loads for the building that require larger amounts of energy to account for than is offset by the daylighting. This is further compounded by some building rating systems that encourage very high percentages of the interior spaces to be illuminated with daylight. If a knowledgeable designer or builder uses daylighting to enhance a building's interior environment, it has benefits beyond energy savings, but the main driver behind utilizing daylighting is still energy savings, which with the much lower energy use of modern luminaires, these savings may never materialize. The energy use of artificial lighting is the main contributor of the change in daylighting's usefulness as an energy saving method. As recently as 2008, it was common to see incandescent lighting still in use. These types of bulbs require vastly larger amounts of energy to operate, so when these bulbs were commonly in use, daylighting saved large amounts of energy. This is no longer true if a building is utilizing LED lighting. Some of the LED bulbs currently being used only consume 8% of a comparable incandescent bulb to produce the same illumination levels.

The way daylighting is presented needs to be looked at in a critical manner. While it does pose benefits outside of energy savings, it is still sold as a great way to lower a building's energy use by huge amounts. If a building is using LED lighting and the fenestrations are designed in a way to maximize daylight without considering other effects of glazing placement, those energy savings will never materialize. The synergy between the different systems within the building should allow daylighting to be an important part of a way to improve the occupants' experiences, but no longer as a means to reduce energy use by large amounts.

5. FUTURE RESEARCH

This study looked at energy flow through the exterior envelope as heat transfer only. In reality, the way solar energy works with a building is a complex, multi-faceted interaction involving a myriad of different coefficients. To accurately predict this level of performance, the use of advanced computer modeling is necessary. These are commonly used in industry but are rarely verified. Building upon the research done in this study, adding more data acquisition methods would allow for the development of a model which not only would more accurately predict energy use in a small-scale construction but would allow for verification of the results. This would enable a better model to be produced through successive iterations, further improving the model.

The main driver of the energy use in the studied building was heat transfer through the glazing surfaces. Even when using an advanced construction method like structural insulated paneling, the high insulating values of the assembly were mitigated by poor performing windows. This further emphasizes how the windows in a building are almost always the “weakest link” in energy performance. Research into better performing windows, even small incremental improvements, could eliminate huge amounts of energy use from buildings. Also along the lines of window research would be investigating the benefits of better suited panels in non-viewing positions. The upper windows in the studied home were of traditional design and featured minimally performing glazing. These windows were placed at a height that did not allow for traditional viewing, so why were they clear, viewable windows? Research into replacing these types of windows, or others located in non-favorable viewing areas with better performing types of panels, could be highly productive for energy reduction. Several manufacturers produce opaque type panels that offer insulating values vastly higher than most standard windows while still allowing daylight to enter the building. This could realize the benefits of daylighting to the occupants while eliminating most of the drawbacks. This is, after all, the original goal of using daylighting—improving the occupant comfort while reducing energy use.

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VITA

Thomas Glenn Yarbrough II was born in Tucson, Arizona. Growing up within an engineering family, he developed a strong interest in buildings. To follow this interest, he attended architecture school at Drury University in Springfield, Missouri and gained a passion for sustainable buildings. He worked at several architecture and construction firms in the Midwest before returning to further his education. In 2012, he received a Bachelor of Arts degree in Architectural Design, as well as an Associate's degree in drafting from East Central College in Union, Missouri. It was in this time he became interested in the area of engineering, and began pursuing a degree in civil engineering. He graduated Magna Cum Laude in 2016 with a BS in Architectural Engineering, as well as a BS in Civil Engineering from Missouri University of Science and Technology in Rolla, Missouri. He continued on to graduate school, graduating with a Master's of Science degree in Civil Engineering from Missouri University of Science and Technology in December of 2018. He was appointed the senior researcher for the Missouri S & T Center for Research in Energy and Environment in 2016 where he conducted research on sustainable construction and the built environment. He received several sustainable certifications, including LEED accredited professional status in both building design and construction, and neighborhood development. He also became a certified building envelope commissioning process provider, and commissioning authority. He has been a member of multiple state and national councils, including the National Institute of Building Sciences, USGBC, and National Council of Building Codes and Standards.