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DESIGN AND CONSTRUCTION EVALUATION OF A PHOTOVOLTAIC DC LED LIGHTING SYSTEM

A Thesis in

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by

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ABSTRACT

The market demand for commercialization of Photovoltaic (PV) systems depends a lot on the reliability, efficiency and performance of various components within the system. PV panels produce DC power when exposed to sunlight, and an inverter converts this to AC power in a typical solar powered building. Though stand-alone PV lighting systems have existed for a long time it hasn't been very efficient in the past. Incandescent light sources were commonly used with traditional PV lighting systems which are inefficient. Today, fluorescent fixtures are mostly used with PV's due to its high efficacy. Light-emitting diodes (LED's) present a new vision to energy efficiency in lighting design with their low energy consumption. Current research predicts improved efficiencies of LED light fixtures and their commercial use is a few years away. LEDs which operate on DC voltages when coupled with photovoltaics can be a simple PV lighting application and a sustainable lighting solution with potential for payback.

This research evaluates the design and construction of a PV DC LED lighting system for a solar house at Pennsylvania State University. A detailed cost and payback analysis of a PV DC LED lighting system is presented in this research. PV array output simulations for the solar house are presented. Results presented in this research indicate that the Solid state lighting market is evolving rapidly and that LED's are a choice in stand-alone PV DC lighting systems. The efficiency and the cost-effectiveness of such systems would improve in the coming years with research and development now focused on photovoltaics, which are an important part of renewable energy systems and on LED's which could possibly be the future of energy efficient lighting.

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Chapter 1

Introduction

1.1 Background

According to the US Department of Energy (DOE), buildings consume nearly 70% of the electricity in the United States (Department of Energy 2001). This figure is due to rise if appropriate measures are not taken to reduce the energy consumption. The industry today is heavily relying on non-renewable fossil fuels such as coal and oil (EIA 2007). Data from the Energy Information Administration (EIA), which provides the official energy statistics from the US government, shows; in 1850, almost 90% of energy consumed in the United States was from renewable energy sources. In 2007, renewable energy sources contribute to only 7% of the total energy, while solar contributes to only 1% of that (EIA 2007 and Department of Energy 2001).

Electricity consumption within the commercial buildings sector has been increasing in the past decade and will continue to rise by nearly 50% by 2025 if appropriate measures are not taken to limit this consumption. US Department of energy aims for net-zero energy homes by 2020 and net-zero energy commercial buildings by 2025 to reduce the electricity consumption. Widespread application of photovoltaic (PV) systems could be one way of achieving this goal (Department of Energy 2008). While the need for “green” concepts in buildings are being emphasized; renewable sources such as wind and solar power are being implemented in buildings a lot more today than they were a decade ago. According to the PV Insider's report, the PV market is growing rapidly, and is projected to grow more than 15% over the next 15 years based on the research and development within the PV industry (PV Insider's Report 1999).

1.1.1 'Green' concepts and sustainability

"Green" or "sustainable" building design is a process of designing, building, operating and demolishing a building in a safer, and a healthier way compared to conventional building design. Potential benefits of the sustainable design process relate to environmental, economic, and social benefits. Green buildings also help reduce operational costs, improving the life-cycle economic performance and improving the occupant productivity, thus contributing towards economic benefits (US Environmental Protection Agency 2006).

Sustainable design when applied to lighting, relates to optimizing the use of daylighting, along with using energy efficient light sources. Currently, lighting alone contributes approximately 22% of the total energy usage within buildings. Using energy efficient lighting and advanced lighting controls can contribute significantly in reducing this energy consumption. Using energy efficient fluorescent lighting also helps reduce this energy consumption. Recent advancements within the lighting industry have resulted in the development of solid state lighting technology, which has the potential to change the traditional lighting scheme mainly due to its low energy consumption. In addition to using the existing technologies for lowering the energy use would be to produce the electricity required to supply these potentially efficient light sources.

One sustainable or renewable method for generation of electricity is using photovoltaics (PV) which make use of the sunlight to produce energy. Using PV panels to generate electricity could not only be an energy efficient alternative, but also environmentally safe. Using light-emitting diodes (LED's) as a light source for lighting applications that make best use of the latest solid state lighting technologies could be another optimistic approach for an overall energy efficient design. Though PV's and LED's belong to two different markets, research indicates they have some strong similarities considering they are two innovative and 'potentially sustainable' technologies.

This research hence seeks to *test a PV system application incorporating LED light sources.*

1.2 Problem Statement

Solar energy is the solar radiation that reaches the earth which is then converted to electricity through various strategies. Solar houses/buildings generally utilize PV panels to produce electricity. PV panels produce DC power when exposed to sunlight, and an inverter normally converts this to AC power, which is the conventional form of electricity in a typical house/building (US Department of Energy 2007). Using DC power directly from PV panels is a challenge as there are not many applications that utilize DC power in a building. Of the possible PV applications utilizing DC power, PV lighting is one such application that has a great potential if efficient light sources are utilized.

PV lighting could possibly reduce the overall energy consumption for lighting in buildings and hence yield cost savings. Although, PV based lighting has existed for a long time, not many PV lighting installations utilizing DC light sources have been efficient. PV lighting, when used with incandescent light sources is inefficient, while using with fluorescent sources require an inverter, which could induce further losses within the system with the DC-AC conversion. LED's, the next generation of light sources, have low energy consumption and hence could contribute in reducing the overall power consumed by a PV lighting system. However, the challenge with LED's is their low lumens/watt (light output for watts consumed) and their high capital costs.

Hence, the intent of this research is *to study the viability of PV lighting systems utilizing solid state lighting technologies (LED's).*

1.3 Research Goal

The main goal of this research is to analyze the ***costs and efficiency*** of a PV LED lighting system. This research also aims to understand PV LED lighting systems better through design and construction evaluation. Another important goal of this thesis is to *understand the advantages and limitations of photovoltaic DC systems.*

A PV DC LED lighting system has been designed and implemented for a solar house at Pennsylvania State University as part of this research. This solar house at Penn state University is called the 'Penn State Solar Decathlon house'.

1.4 Objectives

The key objectives of this research are as follows:

(a) To understand the performance and challenges during design and construction of a PV DC LED lighting system

(b) To be able to predict the overall efficacy of a stand-alone PV DC LED lighting system

(c) To understand the performance and output of PV arrays in a stand-alone PV DC LED lighting system operation

(d) To understand the overall costs involved with a PV DC LED lighting system design and construction

(e) To study the payback of a PV DC LED lighting system against a conventional grid LED lighting system

1.5 Scope of work

The *scope of work* for this research is split into three main components;

(a) Design of a PV DC LED lighting system

- The first part of the scope of work for this research involves design of the DC system for the Penn State Solar Decathlon house, also called the “Morningstar House”. (More on the details of this house is presented in chapter 3). The design phase involves conceptual and detailed design including sizing of PV panels, load sizing and calculations, voltage drop calculations, battery bank design, and a working design schematic.

(b) Design Development

- The second phase involves construction of the PV DC LED lighting system for the solar house. This includes investigating compliance with the electrical codes, wiring, and procurement of equipment along with the development of a construction wiring schematic.

(c) Results and Analysis

- The PV LED lighting system designed for the Solar Decathlon house will be evaluated on three main parameters - costs, efficiency, and PV array output production. As part of this analysis, challenges encountered during the design and the construction process would also be presented.

1.6 Summary

Very little research has been done to date on PV system applications and especially on stand-alone PV lighting systems. Of the available literature, research on the use of LED light sources with PV panels is very minimal. *This research hence seeks to analyze the design and construction process of a PV based LED lighting system, while evaluating some of the major factors such as costs and efficiency of the "entire" system.* Some of the results presented in this research will help engineers and designers make better decisions on PV DC LED lighting system design and construction.

This chapter introduced the concept of a photovoltaic DC LED lighting system, while presenting the hypothesis that such a system might prove to be an efficient and cost-effective option when a stand-alone lighting system is desired. Chapter 2 presents a review of the existing literature on PV lighting systems, LED technology, DC systems, and also discusses some photovoltaic applications involving LED's. Chapter 3 presents an overview into the research methodology, research approach and the methods used for research and analysis. Chapter 4 elaborates on the design of the DC LED lighting system for the solar house and includes a design schematic. Chapter 5 covers the construction process for this system. Chapter 6 summarizes the results and analysis of this system.

Chapter 2

Literature Review

2.1 Introduction

This literature review is an attempt to present the most up-to-date information after a thorough investigation into the following main topics; PV system applications, photovoltaic lighting including LED lighting systems, and design and construction challenges with DC systems. This chapter presents information available from findings through research via journals, newspaper articles, internet resources, and books related to the above topics. This literature review presents the most current information available along with an insight into the research application as a probable choice for the future.

This chapter reviews information from these key topics:

1. PV system applications and market
2. Photovoltaic Lighting – Background
3. DC system design and installation- Advantages and disadvantages
4. Battery bank and storage for stand-alone systems
5. PV based DC lighting system concept

2.2 Photovoltaic applications

Making use of sunlight through solar panels is one of the best natural ways to generate electricity and utilize it for various applications such as heating, cooling, and lighting needs in a house/building. Photovoltaic panels can be integrated within the architecture of the building, such as on rooftops, on walls, or can even be stand-alone units to generate electricity during the day-time.

Incorporating the panels within the architecture of the building could mean they form a part of either the façade or the building envelope. Building integrated photovoltaics are getting popular today, as these panels can be a part of the building structure, while also adding to the aesthetics.

Figure 2-1 Photograph of a solar village (Source Inhabitat 2006)

Figure 2-1 shows a green solar village, with building integrated photovoltaic panels, which was featured in “Inhabitat” in 2006. According to the DOE, “worldwide PV manufacturing is growing steadily at an annual rate of more than 20%”, and the demand for research and development of this technology is a lot higher than it was a few years ago (Department of Energy 2004). Building integrated photovoltaic (BIPV) systems are hence one of the most commonly used applications for PV systems.

2.2.1 Basic operation of PV cells

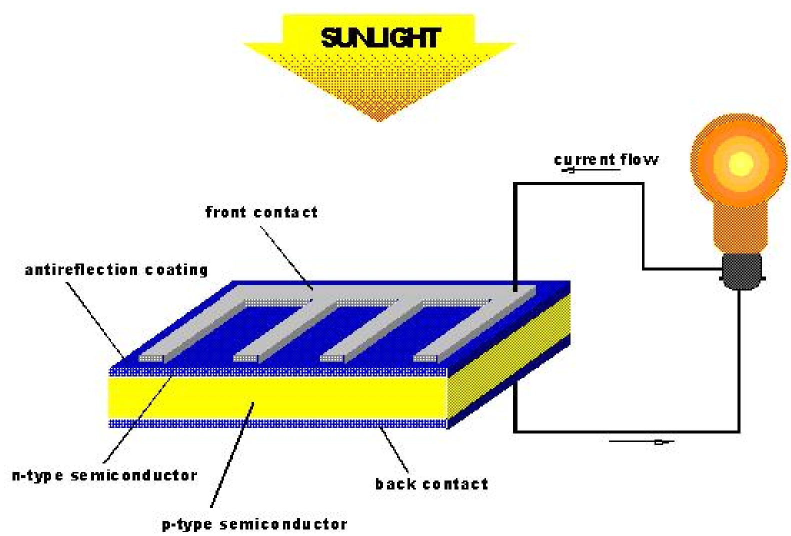


Figure 2-2 Operation of a PV cell (Source School of Photovoltaic and Renewable engineering, New South Wales, 2008)

The basic operation of a PV cell is shown above in Figure 2-2. When sunlight hits the surface of a PV cell, the incident photons are converted to electrical energy. The light source’s photons (sunlight) strike the panel displacing the electrons in the semiconductors within a PV panel, hence causing a voltage to be generated and current to flow if a circuit is connected to the panel's connections. The voltage output of a PV panel is direct current, just like the voltage of a typical battery. An inverter converts this DC power to usable AC power, which is the conventional form of electricity (Messenger and Ventre 2004).

2.2.2 Photovoltaic Systems

A typical PV panel generally consists of a number of small PV cells. A number of PV panels, when wired together in series and parallel connections for a certain voltage and/or current requirement, form an array. The most common material used for a PV panel is crystalline silicon (Messenger and Ventre 2004).

There are two main types of Photovoltaic systems – systems that would be connected to the grid, which is the most common type; and stand-alone systems which are generally small scale (not connected to utility grid). Most residences, or buildings, that have PV panels integrated as part of the façade of a building are usually grid-tied so that during the night –time or during winter months, the electricity is generally taken from the utility grid. During summer months, or during day-time, when excess electricity is generated within the house than required, this power is sent back to the utility company.

Stand-alone PV systems

A stand-alone system requires provisions for energy storage, since it is not connected to the utility grid. In this case, the sole source for power is via the solar panels. This system utilizes batteries for power storage, so that the electrical and lighting loads could be utilized during night-time. Batteries are generally required in PV systems as they store energy. Since this energy should be available for use at a later time, batteries utilized in most PV systems must be rechargeable, and hence lead-acid batteries are the commonly used battery type (Northeast Sustainable Energy Association 2001).

The rate of the charging, discharging, and the temperature of the operation of the battery affects its performance. In a typical stand-alone PV system, the rate of charging and discharging of a lead-acid battery is around 90%. It should also be noted that warmer batteries usually hold more charged energy, while if the battery gets too warm, it could also shorten its life (Messenger and Ventre 2004).

Capturing energy from the sun, via the PV panels, requires some equipment in the process. The most common parts of a typical stand-alone AC PV system consists of the PV panel itself, an inverter (to convert the DC energy to AC power), a charge controller (to regulate the voltage and the current from the panels to the loads), an inverter to convert the DC power to usable AC power, batteries for stand-alone systems, and the heating/cooling and lighting loads as required. Figure 2-3 shows a block diagram of a typical stand-alone PV AC system. Some of the known advantages of PV systems are: that it is a renewable energy source, solar energy does not produce hazardous gases within the environment, life of a crystalline cell is more than 20 years and panels require low maintenance (Northeast Sustainable Energy Association 2001).

Typical PV systems are AC based, where an inverter converts the DC power produced by the panels to AC power. Since most of the appliances, lighting, and other loads in a building are AC based, a PV AC system is more commonly used in buildings. An AC system could be either stand-alone or grid-connected. On the other hand, a PV DC system is a stand-alone system only, since it cannot be connected to the local utility grid.

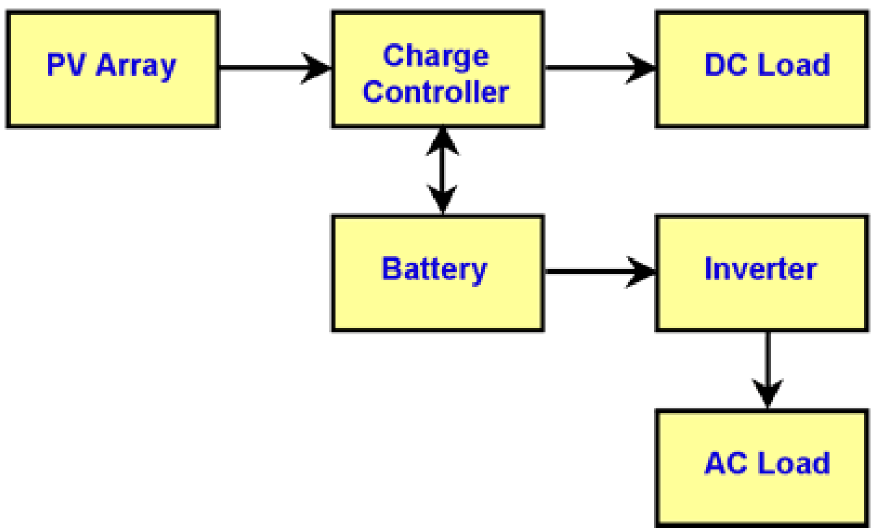


Figure 2-3 Typical PV stand-alone AC system (Source Florida Solar energy center, 2007)

2.2.3 PV Systems Market

<u>The Economics</u>

The photovoltaic industry is growing at a very fast pace considering the need and demand for a cleaner and greener source of electricity generation. According to the Northeast Sustainable Energy Association the maximum record efficiencies in PV cells have reached between 12-22%, a lot higher than they were 15 years ago (Northeast Sustainable Energy Association 2001). It is predicted that it will not be very long until these *highly efficient panels* are actually used in BIPV applications. There also seems to have been a significant improvement in the cost/watt of these panels when compared to a decade ago. Current average cost/watt of a PV array is estimated to be around $5. According to NSEA, the global manufacturing of solar cells was 58 megawatts (58,000,000 watts) per year in 1992 and has risen to over 1,600 megawatts (1,600,000,000 watts) per year in 2005 - an increase of almost 30% per annum over the past 15 years (Northeast Sustainable Energy Association 2001).

An optimistic prediction by economists reveals that, by 2030, photovoltaics will become a widely used commercial source of energy, with sales exceeding over $100 billion (Solar Energy International 2004). With rapid developments in the photovoltaic technology, there is a high probability in the future that sustainable design features may no longer be classified as a 'luxury or option", but rather would be mandatory and may also be standardized into the local codes. California is one of top states pushing the envelope for the use of renewable energy sources. Some of the states are now offering incentives for a PV installation, especially for residential construction. According to an article in the New York Times, California's representation is nearly 75% of the total US solar energy market. The Solar Energy Industries association states that in 2007, nearly

100 megawatts of generating capacity was installed in California which was almost a 50% increase for installations from 2006 (Richtel and Markoff 2008).

In summary, according to analysts, the PV industry will continue to see significant reduction in prices as we further see improvements in efficiencies of PV panels and hence the magnitude of projects implementing these systems will increase. This will *increase the need for innovation and use of "state of art' technologies in PV systems.*

2.3 Photovoltaic Lighting

Photovoltaic based lighting has existed for a long time, mainly using incandescent light sources. This system has not been very efficient, largely due to the inefficiency of the incandescent light source. Incandescent light sources not only consume a lot more energy than fluorescent light sources, but they also do not last very long.

Research in light sources and development in lighting technologies and advanced controls, when applied to green buildings, can reduce the total lighting energy consumption by almost 50% (Environmental Protection Agency 2006). Rapid developments in the lighting industry have seen the use of compact fluorescent sources (CFL) and linear fluorescent (LFL) sources with photovoltaics over the past years. Considering the efficacy of fluorescent sources, it is a good choice in a Photovoltaic (PV) based lighting system. Some of the reasons fluorescent sources are used with photovoltaics are due to the huge energy savings potential when used appropriately. A photovoltaic based lighting system that utilizes fluorescent light sources requires an inverter to convert the DC power to the more usable AC power which is the conventional form of electricity in all commercial buildings. In the past, DC light sources such as incandescent have also been applied with PV systems. Light sources that operate on DC voltages are usually not very efficient. With recent developments in the efficiency of Solid state lighting technology, light-emitting diodes (LED's) which operate on DC voltages could be a likely choice with photovoltaics.

A survey was conducted by the National Lighting Product Information Program (NLPIP) in 2005 to assess the beliefs regarding photovoltaic lighting within the public. Although details haven't been provided with the survey regarding the backgrounds of the respondents, most of the people who took the survey believed light-emitting diodes (LED's) would be the most suitable light source with photovoltaics, followed by fluorescent lamps in the future. Survey respondents felt that incandescent lamps were not suitable for use with photovoltaics in the present generation. Some of the respondents also believed that PV lighting/solar lighting would be more common in residences in the next few years than in commercial applications. Most of the respondents also felt that PV lighting would first get commonly used in simple outdoor applications like pathway lighting, with bollards or low-level luminaires where low-level lighting is desired. A number of survey respondents also believed that PV lighting is good for the environment, and there is a huge savings potential associated with PV lighting when used appropriately in commercial installations (National Lighting Product Information Program 2005).

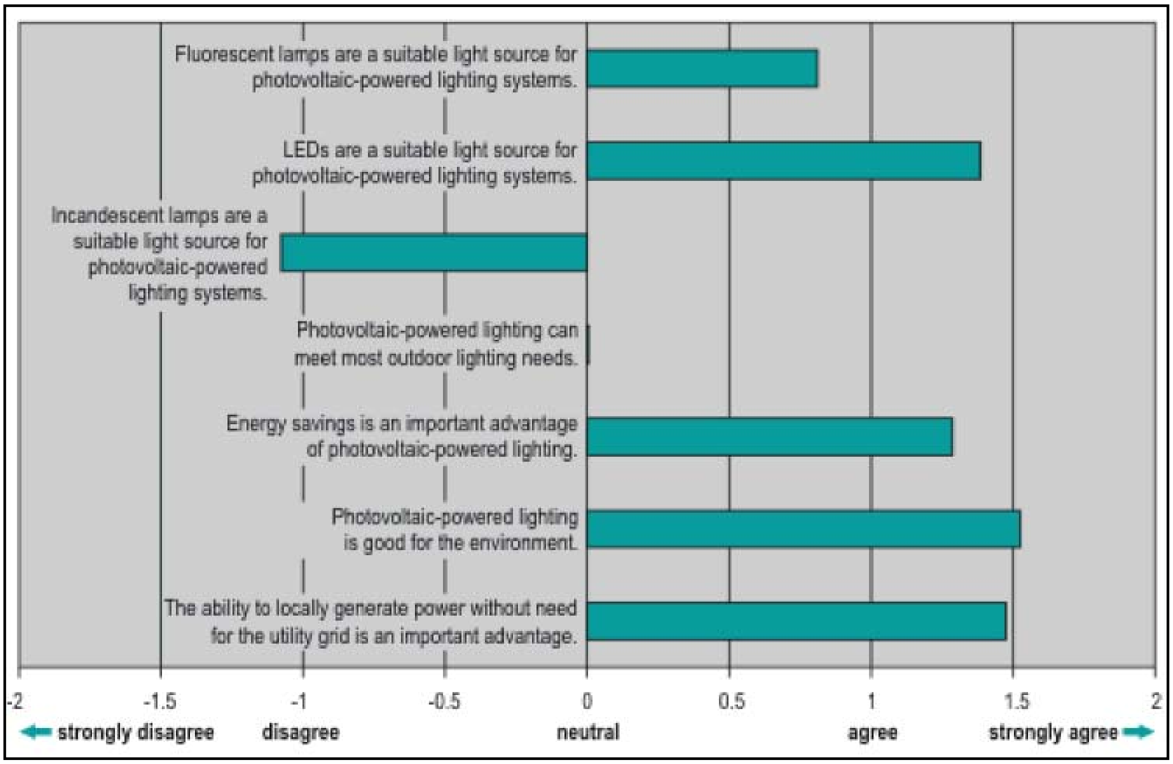


Figure 2-4 PV Lighting survey responses (Source NLPIP publication, 2005)

In summary, though the concept of using “solar lighting” has existed for a while, and there are manufacturers who sell light fixtures that are “solar” based, it hasn’t really been accepted widely yet. Using photovoltaics with LEDs already exists today, though extensive commercialization of this system is dependent on the costs of these two technologies, efficiency, and an intense marketing of the benefits related to utilizing them in buildings. Figure 2-4 highlights some of the responses from the survey by National Lighting Product Information Program and the Lighting Research Center.

2.4 LED Lighting

Solid state lighting technology has been one of the fastest emerging illumination sources in the current lighting market. The prediction is that as building owners, operators and occupants are increasingly aware of this new technology, within the next ten years LED’s will gain popularity within the lighting industry for general lighting application (Craig 2002). With green buildings and the LEED rating system for buildings getting popular, the demand for better energy efficient lighting, which is cost-effective and that which adds to the aesthetics of the space, is increasing. One of the major challenges with light emitting diodes (LED’s), however, has been to keep up with the pace of this ever evolving technology. Anything related to this technology that was prevalent a few years ago, has now become outdated. With researchers and scientists working toward in better improving this technology, it is not long until we see a bigger and a more economic market utilizing LED’s for commercial applications.

About LED’s

LED’s are compound semiconductor devices that convert electricity to light. Some of the main advantages of LEDs are that they last a very long time when compared to their commonly used counterparts, the incandescent lamp, HID light sources or even the fluorescent lamp. The light output of LEDs however, degrades over time and hence reduces the useful lifetime of LEDs (Philips 2006). It is also said that although the lumens per watt of an LED might be higher for the chip itself, but when it is all packaged together as a luminaire, lumens per watt can decrease due to heat buildup. In any case, the long lifetime of an LED luminaire, contributes to very little maintenance over a long period of time. Hence, summarizing some of the key features in utilizing LED's are; a long life-time, very little maintenance, low energy consumption (a few watts when compared to incandescent or even fluorescent sources these days), and that they work well in an exterior environment since LED's can work well in colder temperatures (Alliance for Solid state illuminations and Technologies 2007).

Summarizing some of the most common disadvantages of using LED's in most common applications are; high initial costs (current market), poor color rendering (not an adequate measure for CRI- color rendering index) low lumens/watts (efficacy) for white LED's and that they get very hot. Hence a good heat sink is an essential component of an LED luminaire. LED's are usually known to operate well in colder temperatures. The primary cause of LED lumen depreciation is the heat generated at the LED junction. Without adequate heat sinking or ventilation, the device temperature will rise resulting in lower light output and degradation of its performance over its lifetime. Hence, a heat sink that helps dissipate heat off the LED is an important feature of an LED luminaire (Hong and Narendran 2004).

The History

Incandescent light sources were once widely used in most lighting applications, in residences and in commercial applications. Though they are still used in residences, today, they are considered to be inefficient mainly due to their high power consumption. With different light sources such as linear fluorescent, compact fluorescent, halogen, metal halide and LED's currently available in the lighting market, LED's seem to be marching at a fast pace as seen in Figure 2-5 and are considered to be the next generation 'efficient' lighting technology.

Today in 2008, LED's are being widely used in architectural applications such as Exterior Street and parking lot lighting, architectural façade lighting, supplemental lighting, and in some new projects they are also being used for interior lighting applications (Architectural SSL magazine, May 2008).

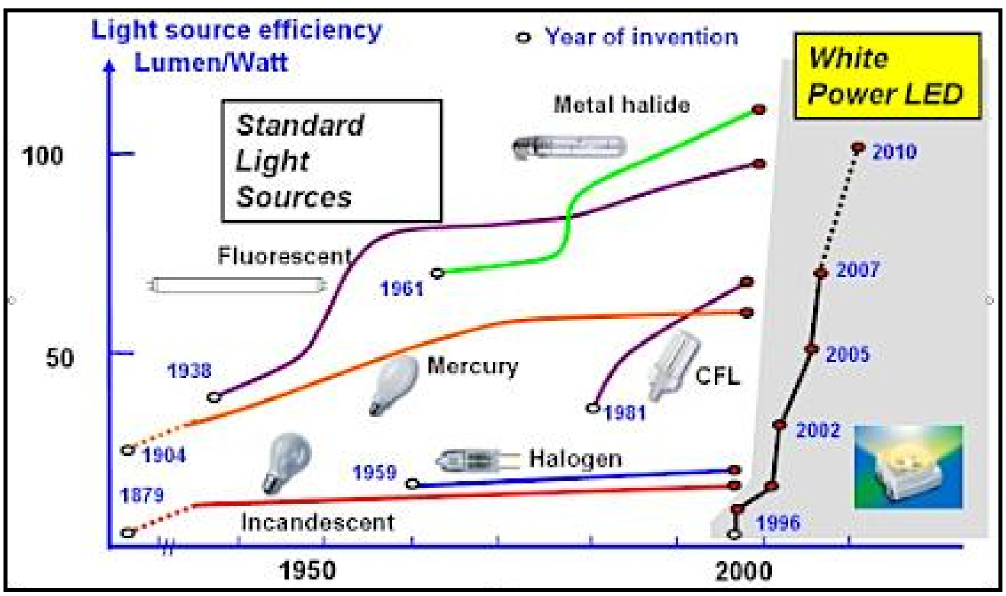


Figure 2-5: History of LED's (Source Osram, History of LED's, 2008)

LED's haven't been used as sources of illumination for a long time because they could not produce white light – only red, green and yellow. "The first 'visible spectrum' LED's producing red light" were created in 1962 by Nick Holonyak of the General Electric company, who used Gallium arsenide phospide. LED's were then adopted as indicator lights. Later in the 1970's Gallium arsenide along with dual Gallium phosphide substrates were used to produce red, yellow and green light. LED's were beginning to be then widely used in applications such as calculators, watches, and other test equipment, until 1980's when brightness' of LED's was further improved and were used in flashlights. The world's first blue LED was developed in 1993. It was discovered by Nichia Corporation that through the use of Indium Gallium Phosphide (InGaAIP) and "adjustments in the size of the energy band gap" LED's with different colors including white could be produced. However, these first 'white' sources produced a harsh bluish light which was unpleasant to the human eye (Marktech Electronics, 2008).

Typically, there are two methods to produce white light from an LED today. The first method is a wavelength conversion method as described previously, where blue LED's are used to excite a phosphor, which emits different colors. These colors are then mixed with some of the blue light 'leaking through' to produce white light. Another process using the wavelength conversion process is to use Ultraviolet (UV) LED's with blue, green and red phosphors. These colors are mixed to 'make white light with the broadest and richest wave-length spectrum". Another method is color mixing, where different LED's, red, green blue or sometime yellow are used in a single lamp, to produce white light. Because no phosphors are used in this method, this process is considered to be the most efficient way of producing white LED today (Sandia National laboratories, 2008).

Rapid developments in research over the years have opened a window of opportunities for this ever-emerging solid state lighting technology. Today, LED's are being used in a wide range of applications, mainly for architectural lighting, where a huge potential exists for energy savings.

2.4.1 A "peek" into the future by industry analysts on LEDs

According to the US Department of Energy (DOE), "the energy consumption for all lighting in the United States is estimated to be 8.2 quads, or about 22% of the total electricity generated in the U.S". Prediction is hence, with the advancement of highly efficient, cost-effective solid-state lighting (SSL) technologies, along with advanced windows and space heating/cooling technologies, we can help reduce total building energy use by 60 to 70 % and that LED lighting could itself cut national energy consumption for lighting by 29% by 2025 (US department of Energy, Lighting Research and Development 2006).

In recent years the lighting industry has seen LED's emerge as a potential source for various interior and exterior applications. Since a lot of energy is spent for enhancing architectural features for retail lighting or hospitality lighting applications, LEDs, when used appropriately for these features can reduce the impact of the total connected load for lighting to a great extent. However, according an article by Kevin Willmorth, a contributing editor of the Architectural Solid State Lighting magazine, LEDs are here to offer much more than just energy efficiency or "white light" in buildings. Considering their form and compactness, color, controllability, efficacy and environmental issues, they can be used for a wide range of applications including those within restaurants, art galleries, healthcare facilities and hospitals, or even residential applications, if specified appropriately (Willmorth 2007).

Today, most efficient white LED light fixtures have efficacies of nearly 30 lumens/ watt, which is nearly twice the efficacy of an incandescent fixture (15 lumens /watt). An efficient fluorescent fixture has luminous efficacy of around 85 lumens /watt. While fluorescent and incandescent light sources are considered to be very mature in terms of research and advancement, research on LED light sources is advancing at a fast pace. In 2006, a prototype white LED having 131 lumens/ watt was produced which was considered to be highly innovative with a record breaking efficiency produced by CREE (Cree 2006). The Department of Energy expects that within the next three years, LED's will have average luminous efficacy of 70 lumens/ watt (James Brodwick, LDA April 2008). In the long-term, with continuous developments in improving this technology, it is said that LED's will have efficacies approaching 150-200 lumens/watt which would be the major breakthrough in this technology. According to the Architectural SSL magazine, major improvements have also been made with the color stability and color temperature of LED's in 2008.

Researchers from the University of California, Santa Barbara predict, widespread deployment of LED lighting could save $115 billion in electricity costs in the US alone by 2025 (McClear 2007). With the Department of Energy along with leading LED manufacturers, focused in developing new research programs and initiatives for further advancements of LED technology, it is not far until we see white LEDs being used in most applications, interior and exterior. Some of the future benefits of using LED's especially in developing countries, and in nations where people still live without electricity, would be applications such as PV lighting.

2.4.2 Photovoltaic LED lighting systems

Solar houses are an important feature of green building design. The LEED rating system has a certain number of points for the use of building integrated photovoltaic panels (BIPV). Solar energy is not only a renewable source of energy, but can also reduce the typical energy consumption within a building. According to preliminary data published within the Earth policy institute in 2007, global PV production in the year 2007 was nearly 12,400 megawatts, while on an average the production has doubled every two years since 2002 (Dorn, Earth Policy institute, 2007). This impressive increase in PV production illustrates the need for more research and application of these systems worldwide. Of the possible research prospects, one aspect on which to focus is to make the 'overall system' more efficient. This means, every system component needs to be chosen to be highly efficient to reduce the overall losses in the creation of light.

Considering that the research and manufacturing developments in LED's is at a sky-rocketing pace; they present a huge potential for use with PV lighting systems. Energy consumption of LEDs is typically very low, and hence if LED's are used, the overall load demand could be reduced heavily, however if the lighting levels are also reduced proportionally. Some likely applications of such a system would be; landscape lighting, exterior façade lighting and street lighting. Colored LED lights combined with photovoltaic panels could also be used to create a glow or set a mood within any given architectural space without consuming a lot of energy.

Photovoltaics and LED's – Two potentially energy efficient technologies

Photovoltaic cells are made up of semiconductor materials such as silicon, which is the most commonly used material. The basic principle of the flow of electrons within the PV cell is applicable to how an LED works as well, as they belong to the same family of semiconductor devices. There are quite a few reasons as to why PVs and LEDs can be combined, or have a lot in similar be it the advantages of using one technology or even the cons of using these technologies. To date, the cost of LED fixtures is a lot higher when compared to CFL lamps. The high cost factor is also true with PV panels. Until there is a rise in the efficiency of PV panels, or the prices to purchase and install a PV system are reduced there is still a long way to go before a PV system is commonly used in many commercial applications.

Figure 2-6 Advanced LED lighting PV –powered streetlight (Source Advanced LED lighting, 2007)

Examples of products and installations using PVs and LEDs

Case-1

LEDs are a small package light source and they work well with the exteriors. They are hence a good source for outdoor lighting applications (Shakir and Narendran 2002). Figure 2-6 shows a commercially available LED product from Advanced LED, a manufacturer of LED lighting products. This product is a streetlight that incorporates a PV panel, along with an LED light source. A product like this could be ideally used on roadways, since it is self-contained, and most of the wiring would also be contained within the unit as well (Advanced LED Lighting 2007).

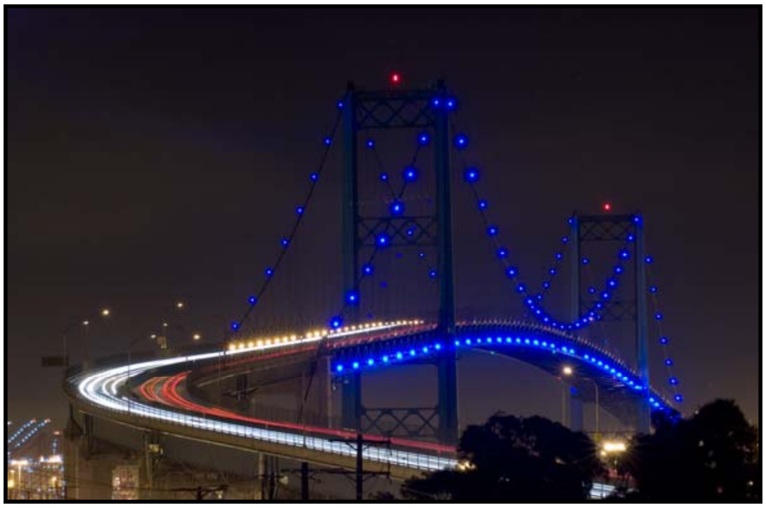


Figure 2-7 Vincent Thomas Bridge in Los Angeles, (Source Renewable Energy Access 2005)

Case-2

Another fine example that used LEDs with photovoltaics is the Vincent Thomas Bridge, located in Los Angeles, which serves as an official landmark to welcome visitors to the city. It is one of the first commercial applications to indicate a successful installation of a PV system that uses LEDs for lighting a bridge. After years in planning, the engineers and designers finally decided to utilize photovoltaic panels to produce electricity. This installation is the first bridge installation in the world that combines LED's with photovoltaics.

LED's not only added glamour to the bridge at night-time, but when combined with PV panels saved a lot more energy. Only a 4.5kW PV array was used to light the bridge using 160 LED lighting fixtures. Initial estimates by the design team revealed that in excess of a 70kW PV array would have been required to light the bridge if traditional light sources had to be used (Broehl "Renewable Energy Access" 2005). Figure 2-7 shows a photograph of the bridge lit at night exemplifying a colorful display of LED lighting. This application is hence one of the best examples to indicate an energy efficient design solution utilizing LEDs and PVs.

To conclude, LED's hold a ***promising future when used with photovoltaic systems***. Using LED's with DC voltages might be an option especially since the inverter is avoided in this case. However, the biggest challenge lies in dealing with DC voltages in this case, which can be used for limited applications in buildings mainly due to the voltage drop with distance, hence requiring larger wires in distribution systems.

2.5 DC power

At first glance, a PV based DC system design can appear to be a simple choice to design and build. The DC power from the PV panels needs to be captured through various equipment and sent to the various loads in a typical residence or a commercial installation. If the loads are required to operate during night-time, a battery storage system needs be considered. Even for installation, at first glance, this system is easy to construct and implement. For a simple design, there would not be too many parts or equipment required to run this system. However, there are some major issues that have to first be overcome before this system can be fully implemented commercially by engineers, designers and manufacturers globally. One of the first concerns would be that not many contractors and engineers have a complete understanding of DC system design and installation.

A hundred years ago, at the beginning of the electric age, DC power was used widely for transmission and distribution of power. However, this transmission of DC power was not without significant power loss over long distances. Later, Westinghouse brought forward the concept of AC power, where electricity could be transmitted over large distances without significant power loss; this could enable large commercial installations enabling efficient power distribution. DC power is generally considered to be much safer than AC, as it is low voltage compared to AC power (Bellis 2007). Systems that have DC voltages are usually at 12V, 24V, or 48VC.

2.6 Summary

While LED's can be a potential choice as energy efficient loads for PV lighting systems, they also present another interesting take to the system design. As seen earlier, PV panels run at low voltages, i.e. produce DC power when sunlight strikes them. LEDs usually operate at low voltages as well. For most LED light fixtures, an external DC-AC power supply converts this DC power to AC power for use of LED light fixtures in a typical commercial installation.

As seen in chapter 1, the hypothesis is that a PV DC LED lighting system can be potentially a simple design and a cost-effective alternative to an AC PV DC LED lighting that requires an inverter. To test this hypothesis and to be able to predict the performance of such systems, a PV based DC LED lighting system has been implemented within the Penn State solar house, also called "The Morningstar Home". More information on the design details is presented in chapter 4, while details on the features of this house are available in Appendix A.

This chapter showed the current state of the available literature on PV lighting systems and information on PV systems and LED light sources in general. While LED's open an opportunity of research with PV lighting systems, not much information is available within the existing literature on these kinds of systems and their overall performance measures. This thesis hence aims that the implementation of such a system will most likely present some answers on the performance of these systems.

Chapter 3

Research Methodology

3.1 Research Question

The main goal of this research, as seen in the previous chapter, is to study and evaluate the performance of a stand-alone LED lighting system. Through this research, the following research questions are expected to be answered:

(a) Is the performance of a stand-alone DC LED lighting system comparable to an AC LED lighting system or an AC lighting system with mixed light sources (fluorescent and LED's) ?

(b) Is a stand-alone DC LED lighting system cost-effective when compared to a similar AC LED lighting option or an AC lighting system with mixed light sources (fluorescent and LED) ?

To explore the answers to these research questions, a full-scale photovoltaic DC LED lighting system has been designed and built at Pennsylvania State University for a solar house called the "Solar Decathlon house" in 2007.

<u>About the Penn State Solar Decathlon house</u>

Morningstar is an 800 sq-foot one bedroom modular house. The house is divided into two main components: the living space, and the technical core. The living space consisted of the living room and the bedroom; while the technical core consisted of the kitchen, the bathroom and the mechanical room, which housed most of the electrical, mechanical and PV equipment. Another essential feature in the house was the breezeway, which connected the living space of the house to the technical core of the house.

This house was designed and built by Penn State students to be displayed for a solar house competition, the "Solar Decathlon competition" in Washington DC. The house is stand-alone, with batteries providing back-up supply when required. This house also consisted of two PV systems; 1.AC PV system that supplied power to all essential components within the house 2. DC PV system that supplied only the LED lights within the house. (More information on the design and construction of the two PV systems within the house is presented within Chapters 4 and 5).

3.2 Research Approach

To evaluate the performance of a stand-alone DC LED lighting system, this research takes a two step approach, as listed below for evaluating its performance.

(1) Application – System development

(2) Research and Analysis

3.2.1 System development

A. Conceptual/Schematic design phase

The following steps were taken to approach the design of this system;

1. *Review existing literature*

Before a design schematic for this system could be developed, a thorough investigation into the available literature on LED lighting systems, PV stand-alone system applications, battery bank design and DC system operation was first carried out. Chapter 2 presented a review of the current literature.

2. *Conceptual block diagram developed*

An approach to any electrical system design requires an initial schematic/block diagram to be developed first before final details of the system can evolve. This is critical to the success of the design and construction process for any project. A conceptual basic design block diagram was developed to identify the main elements within the system to proceed to the next phase.

3. *Advice sought from experts within the industry*

Advice was sought from industry experts to obtain guidance on the conceptual design schematic, best industry design practice methods, and guidance with stand-alone system design.

4. *Lighting design concept*

A schematic lighting design concept is essential for an effective lighting design. A concept of what spaces within the house were to be lit by LED's, and how this is to be achieved was the next important step within the development of the system.

5. *Estimated load requirements*

As part of the conceptual design phase, an initial lighting load estimate was calculated. The lighting load was estimated to be approximately 250Watts.

6. *PV Array design*

PV Array design requires an understanding of how PV systems work in general. A basic understanding of stand-alone systems is important to be able to size the array adequately. For this step, the PV array was sized to fit in with the architecture of the house, along with ensuring the array was sufficient to meet the estimated load demand. Comprehensive design details of the PV array are covered in chapter 4.

7. *PV Equipment*

The PV Equipment and associated electrical equipment were then selected and approximately sized in accordance with the load demand estimate.

8. *Battery bank design*

Battery bank design requires an understanding of what batteries are commonly used with PV systems, their charging and discharging capabilities, and their voltage and current requirements.

9. Develop working schematic

Steps 1 to 7 are typical in the development of a conceptual/schematic design for a stand-alone PV system application. Once a schematic design is developed, final details on the wiring, final load estimates, and equipment sizing can occur. These steps are described below in detail.

B. Design development and Construction

The following steps were taken to approach the design development and the construction phase of this system;

1. Review codes

The National Electric Code (NEC) has a section (Article 690) devoted to code compliance issues related to PV systems. Although some of the code compliance issues for PV system applications are discussed within the NEC 2005, appropriate guidance from an industry expert regarding any further safety measures should be considered. This system was designed to be in full compliance with the NEC standards. Design and construction details along with challenges that the code presented are included in chapter 5 and 6.

2. Detailed load calculations

Detailed load calculations, including actual load sizing and voltage drop calculations were carried out in compliance with the standards.

3. Wiring details and equipment sizing

Wiring details and equipment sizing were finalized upon completion of all calculations in compliance with the codes.

4. Develop final schematic – Design development

A final design schematic was developed once all equipment sizing, battery bank sizing, load calculations and wiring details were finalized.

5. Procurement

Once the final design schematic was developed, most of the equipment including PV panels, batteries, charge controllers, and light fixtures were procured. Some of the equipment was procured at a discounted rate while some was donated by the manufacturers for the project. A list of the manufacturers can found in chapter 4 under the specifications section.

6. Construction

Upon completion of the design and procurement of the equipment, the system was then built, again in compliance with the standards. Details on the construction phase are presented in chapter 5.

Design Summary

The PV DC LED lighting system was stand-alone and DC power based i.e it did not have an inverter, and supplied only the LED lights. Two PV arrays were installed integrated to the solar house, one facing east and the other west. The total PV array output was 1.2kW. More on the design description of this system is detailed in chapter 4.

3.2.2 Research and analysis

This system has been designed as a *"proof of concept" or rather a first prototype version* within a solar house at Penn State. The house is called the "Morningstar" build for the Solar Decathlon competition in 2007. Hence, the intent behind the design and construction of this system was to learn and evaluate the pros and cons on the concept of having a PV system that supplied LED lighting loads and operated on DC power. As part of the evaluation and to answer the research questions stated previously, two main aspects will be presented within the analysis:

(A) Performance of the system

(B) Cost –effectiveness

(A) Performance of the system:

To study the performance of any PV system, it is first important to understand the intent behind the operation of the system. Understanding this from the initial phase would result in a better design and better operation of the system.

The intention behind the implementation of this system as said earlier was to test the feasibility of a PV DC lighting system. Another aspect with this design was to also test its performance with LED light fixtures. With the increasing demand for energy efficient lighting, LED's are a prospective energy efficient light source with very low energy consumption. One important point to be noted as seen in the literature review is that, although, their wattage requirements might be very low, their efficiency, or efficacy (lumens/watt), i.e the amount of light let out through the light fixture for the wattage consumed is also very low. Though the scope of this research does not extend in the quality of light aspect, efficiency in design, in construction and in output have been a major part of this analysis. Some of the parameters used to analyze this system performance are listed below:

(1) *PV output simulations:*

PV arrays have been placed on the east and west walls of the solar house. Simulations to study the output from these arrays on a day-to-day basis along with a monthly analysis have been carried out. The goal of these simulations was to test the output from both the arrays, and to analyze this against the load demand throughout the year. This is presented in detail within part 1 of the analysis in chapter 6.

(2) *Efficacy of this PV lighting system*

Efficacy of this stand-alone lighting system has been calculated by taking into account the individual efficiencies of each system component. Some of the efficiency ratings have been obtained by the manufacturer of the product, while some equipment efficiencies have been calculated and/or estimated. Efficacy of the LED light fixtures has also been taken into account. Details of these are presented in part 3 of chapter 6.

(3) Design and construction process

The design stages, and the construction process with this system, will also be a major part of this analysis. Designing a PV DC system which is to be stand-alone imposes certain challenges as briefly discussed in chapter 2. Using LED's as lighting loads, which are not fully established within the current lighting market also adds to the complexity of the design and construction. As part of this analysis, challenges encountered during design, and system implementation, along with issues related to code compliance, will be presented. Certain improvements to design will also form part of this analysis.

(B) Cost analysis

The cost analysis aspect of this research is performed on a comparative basis. Actual costs of the DC system are calculated along with estimated costs of a similar AC system. A spreadsheet tool is produced as a result that could be used to compare cost-effectiveness of a stand-alone AC lighting system versus a DC lighting system. In estimating the costs for the AC system, two aspects to the system are presented; - firstly, changing the DC loads i.e adding more lighting loads (fluorescent and LED fixtures) to the existing array, and secondly, varying the size of the array with the existing lighting loads. By looking at these two aspects, costs of an AC lighting system could be predicted, and hence an analysis on the cost-effective option could be obtained.

As part of the cost analysis, a simple payback of a PV DC LED lighting system with the best configuration of PV panels against a conventional grid-non PV lighting system is also presented. Detailed cost analysis is presented in chapter 6.

3.2.3 Summary

Taking the traditional approach for design and construction of this system, all the above steps have been summarized in a table format in 3-1.

Table 3-1 Research Approach

RESEARCH ASPECT	PHASE OF RESEARCH	TASKS
APPLICATION - SYSTEM DEVELOPMENT **PART-1**	Literature review	Review of existing literature on LED lighting, PV systems, PV lighting, stand-alone systems, DC systems, Write Findings
	Conceptual design	Schematic design, Lighting load estimates Advice from industry experts
	Design development	Design schematic PV array sizing Battery bank sizing Load sizing PV/electrical equipment
	Construction development	Wiring sizing Voltage drop calculations, Procurement Construction,
RESULTS AND ANALYSIS **PART -2**	PV output analysis	PV array output simulations
	PV DC system analysis	Cost analysis, Efficiency analysis, Document design and construction process
	PV AC system analysis	Cost analysis
	Results and conclusions	Summarize findings from evaluations, design and construction challenges limitations with current research and future research ideas

3.3 Data collection method

As part of the research analysis, data will be collected through simulations for the first part of the analysis, to estimate the performance of the PV arrays. The software used to perform these analyses was ‘PV Design Pro-S’.

For estimating the efficiency of the system and for the cost analysis, details were obtained from the respective manufacturers.

3.4 Expected contributions to knowledge

Very little research has been done to date on PV system performance. Of the available research, information on PV lighting systems is not very common. This thesis aims to answers some questions on the performance and affordability of PV DC lighting systems. As traditional DC lighting systems are not very popular and efficient, LED’s have been used due to their potential scope for energy savings.

Through this research, some of the answers to questions related to the cost-effectiveness and efficiency of PV DC systems is presented. This research hence aims to fill in the gaps in understanding PV lighting systems better and to help engineers understand the advantages, challenges, and performance of these systems to be able to make better decisions during design and construction.

Chapter 4

PV lighting system design

4.1 Morningstar Solar house Overview

This chapter discusses the design details of a PV LED Lighting system within the Penn State solar house. As discussed previously, a PV lighting system can be of two types; a grid-connected system where the system is partially powered by the PV panels and tied back to the local utility grid, and a stand-alone system where the system is independent of the utility grid. Some of the main components in a stand-alone PV lighting system are the PV panel, the charge controllers, batteries for storage, an electrical panel for load distribution, and lighting loads. For a typical system, the PV panels collect solar energy and this is usually stored in batteries. This energy is released from the batteries, or discharged to power lighting, electrical and other mechanical loads in a typical house/building, during the night-time. A stand-alone PV lighting system has been designed for the Penn State Morningstar solar house, the details of which are discussed below.

The Morningstar house is a one-bedroom 800 square feet solar house. The house is divided into two main sections; the technical core, and the living space unit. A breezeway connected the living space with the technical core along with providing a flow of air within the space. In brief, the house included a living space, a kitchen, a bathroom, dining space and a bedroom just as any typical house. The house also included a mechanical room, where most of the mechanical and PV/electrical equipment was stored. Details on the architectural design features of this house are included in Appendix A.

4.2 PV System design overview

There are two PV systems within the house, an AC system, and a DC system, which was intended only for lighting.

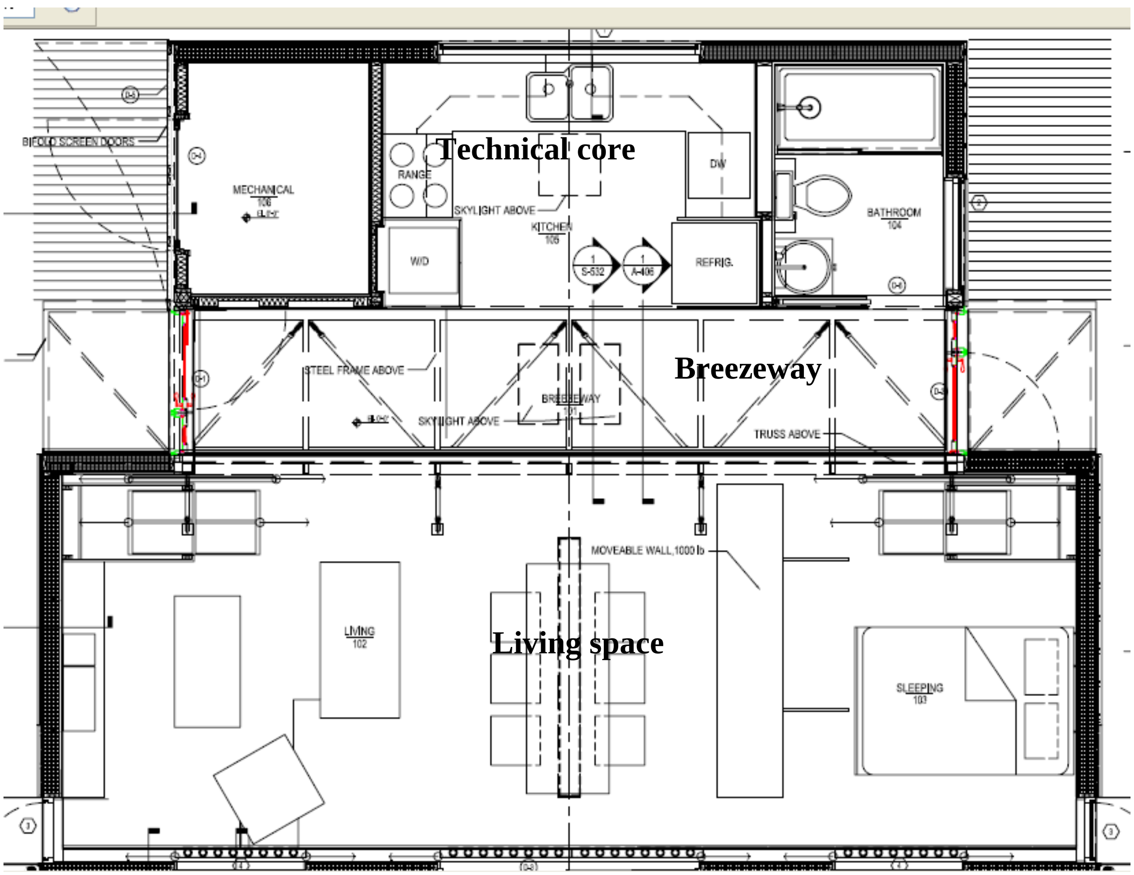


Figure 4-1 Floor plan of the solar house

The main PV system or the AC system had photovoltaic panels mounted to the roof of the house to supply the primary lighting along with other electrical and HVAC loads within the house. This system consisted of 30 panels which were part of the main array and 15 as part of an adjustable array. The total rated power was 8kW, inclusive of the main and the adjustable array. The energy produced by these panels was first converted to AC by an inverter and supplied directly to power the most of the loads in the house. The excess was stored in lead acid batteries for future use.

The secondary PV system was the DC LED lighting system. This system supplied only the DC –based LED lights. One of the ideas of implementing this system within the solar house was to test its design and construction feasibility. The next few sections cover the lighting design goals (primary lighting and secondary), along with providing detailed design features of the secondary PV system.

4.3 Lighting design intent

The main lighting design goal with lighting for the Penn State solar house was to complement the architectural features within the house with a design that is aesthetically pleasing and energy efficient. Primary lighting powered by the AC system was task-oriented and supplied lighting within the living space, the bedroom, kitchen, bathroom and the mechanical room. Described below are brief design details on the primary lighting and an in-depth design description of the secondary lighting system.

4.3.1 Primary lighting concept

The design goal with the primary lighting for the house was to meet target lighting levels as specified by the IESNA to perform specific tasks within these spaces. Providing quality daylight and electric lighting within each space was important. The lighting control system was also a critical part of the design aspect for primary lighting. The idea was to provide flexible controls integrated with the electric lighting within the space. Some of the main light sources used for primary lighting were energy efficient fluorescent lamps; and halogen was used for aesthetics.

An indirect lighting scheme was used for the living space lighting, to create a relaxed atmosphere and bring about a homely feel. Decorative 20W bi-pin halogen pendants were used within the dining area mainly for aesthetics, color rendering, and for their dimming capabilities. A 9W LED desk lamp was specified with individual controls. Low wattage fluorescent light fixtures were used for energy efficiency. A radio frequency based wireless dimming system was specified for flexible controls. A Master control switch was also provided within the living space along with over-ride light switches. Overall, primary lighting provided the main lighting within the space, meeting most of the IES specified target lighting levels. More information on daylighting and electric lighting (primary) is available in Appendix A.

4.3.2 Secondary lighting concept

This section focuses on a secondary PV DC lighting system, which was in place to supply part of the LED lighting within the house. The intent behind the design of this system was to assess the implementation of a stand-alone DC LED lighting system. Some of the potential advantages of having an independent system are that the system does not have to rely on the utility grid for back-up and can be a simple option for design and installation, as it is directly supplied by the PV panels. By assessing the feasibility of design and construction of such a system, parameters that would be considered in the analysis would be the cost and efficiency of the system.

Areas of the house that were supplied by this system, along with their initial design load estimates are given below:

- Clerestory (100W)
- Site and Landscape lighting (100W)
- Kiosk lights (20W)
- Mechanical room spotlighting application (30W)

<u>Total: 250Watts</u>

4.4 LED lighting design description

The lighting goal of this system was to light the spaces for aesthetics and to provide secondary lighting within the space to strike a balance between task oriented lighting and architectural lighting. Clerestories within the house were north-facing, and there were 10 of them. 8 of the clerestories had translucent glazing panels filled with nanogel to illuminate the clerestory section within the breezeway. Nanogel is an air-like material which consists of 95% air-like material and only 5% solid (Cabot Corporation, 2008). Apart from having excellent thermal properties, it also lets in diffuse daylight and offers sound reduction. Linear LED light fixtures were sandwiched within these panels (between inner and outer nanogel filled clerestory panels) to illuminate the clerestory section during night for aesthetic purposes. The breezeway would hence glow of different colors during the night. Design schematic of the lighting concept is shown below:

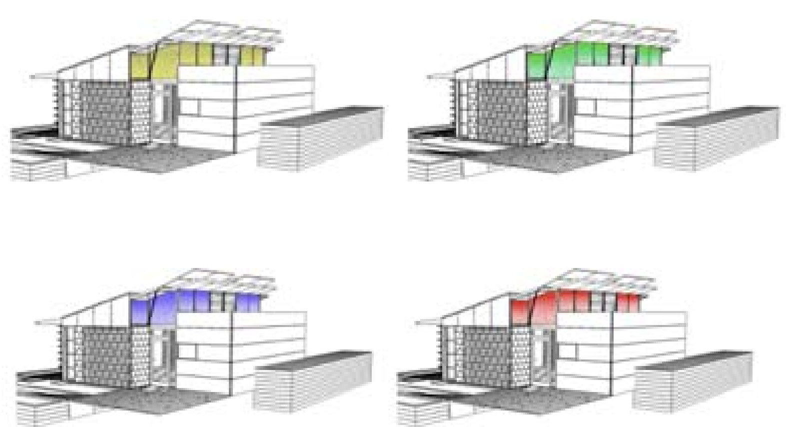


Figure 4-2 Schematic design concept to indicate lights within clerestory

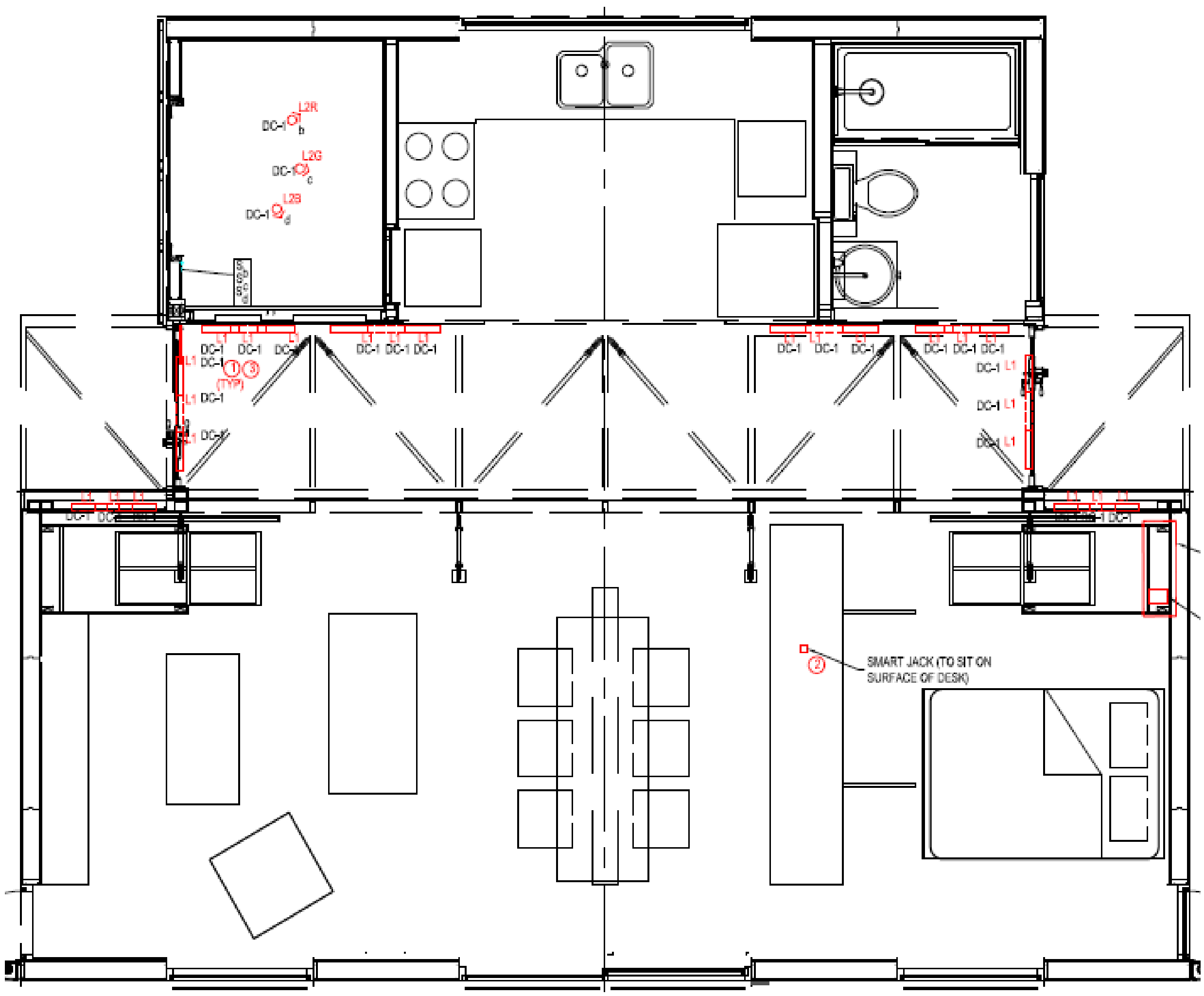


Figure 4-3 DC LED Lighting plan layout

Each clerestory panel has 3 LED lights; rated at $3W_{max}$ white and 2.4W for any color combination of RGB at 24VDC each. In total, 24 LED lights were specified for the entire clerestory. A power data module (PDM) was also specified which controls upto a maximum of 12 LED linear LED lights in a string. Another functionality of this module was to also control the input power to the light fixtures along with enabling different color settings when required. This power module was specified according to the manufacturer's requirements and was rated at 24VDC.

Part of the site lighting was also LED based. The lighting on the ramps at the east and west side of the house, along with the landscape lighting, was part of the design concept for this system. Linear LED fixtures, 2.5 W each at 24VDC, were specified to highlight the ramps, along with lighting other parts of the site.

4.5 Secondary PV system design

The physical parameters and the electrical characteristics of a PV panel chosen depend a lot on the site, the climate, the orientation with respect to the sun and load requirements amongst other factors. A PV panel is then chosen, to be integrated within the building to supply the typical lighting, electrical, and mechanical loads in a building. In this case, the loads for this system were only lighting; in specific, only light-emitting diodes or LED's. PV panels for this system were sized based on the initial design load estimate of 250 Watts. Solar slates (PV panels) were specified to be located vertically on the east and west walls of the house.

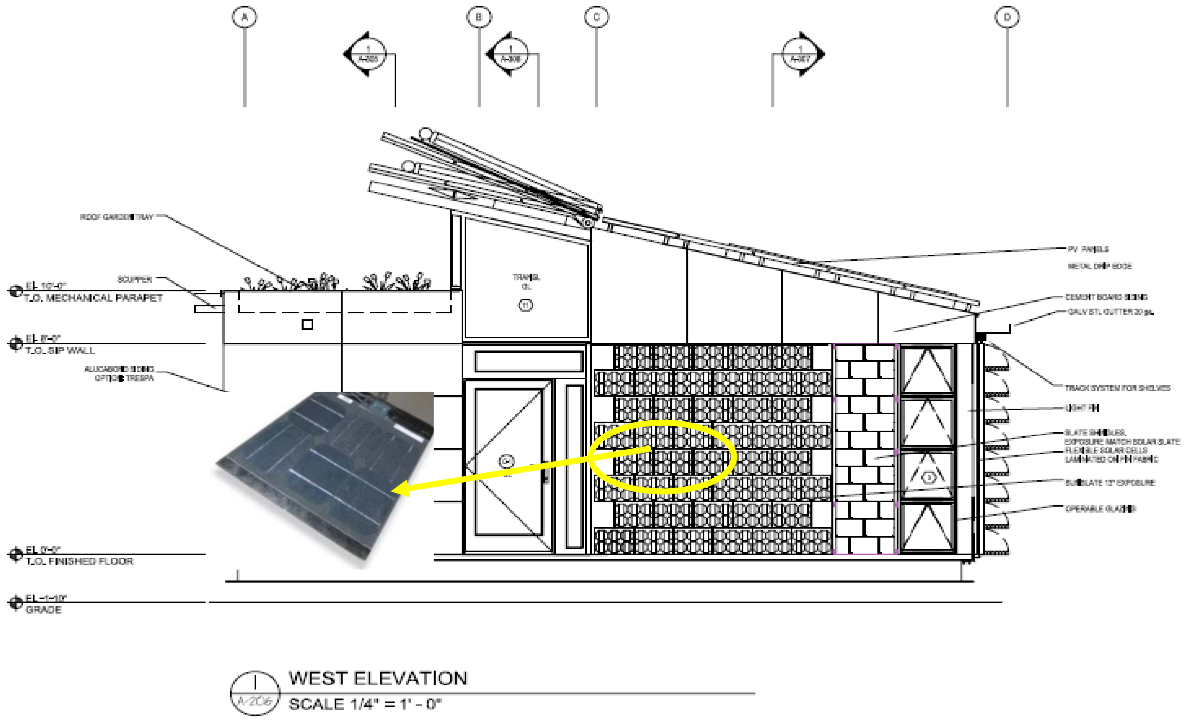


Figure 4-4: Solar slates mounted vertically on the west wall of the Solar house

Solar panels are typically located either on the roof or on the south façade of a building or could also be mounted independently next to a building to ensure maximum sun exposure. In this case, since panels for the AC system were located on the roof, and the south façade of the house was designed to maximize passive solar heating/cooling, the east and west walls were chosen to locate the solar panels. In a typical PV design, the load requirements determine the size of the PV arrays. In this case, after obtaining a very basic understanding of the demand load, PV panels were sized to fit the walls. More than 80% of the walls were to be clad with photovoltaic panels arranged in a staggered fashion to complement the architectural features of the slate walls. This meant the east wall gets more exposure during the early day, while the west gets sun exposure later in the day. The Panel layout arrangement is shown in Figure 4-4.

(A) Electrical characteristics

The following steps were undertaken to determine a common working voltage/open circuit voltage for the panels.

1. The PV panels were laid out as shown in Figure 4-4 on each wall.
2. Each wall had a total of 48 panels, hence there were two arrays (one on the east and one on the west)
3. The 48 panels were divided into 4 strings, with 12 panels on each string. The 12 panels on each string which were in series, with the 4 strings connected in parallel.
4. The open circuit voltage for each panel was taken into account, and an overall V_{oc} (open circuit voltage) was determined based on series and parallel configuration of these panels. It is important to note that during the panel design stage, prospective charge controllers should also be assessed to make sure the open circuit voltage of each array is less than maximum rated charge controller rating.

   V_{oc} of each panel: 3.70; for each string: 3.70 x 12 = 44.4 volts.

   V_{oc} for each array: 44.4 volts (since 4 strings are in parallel). This is the same for east and west wall.

5. V_{max} (Voltage at maximum PowerPoint): 2.98 per panel; For each string: 35.76 volts; and each array: 35.76 volts.

6. I_{sc} (Short-circuit current): 5.14 A per panel, per string: 5.14 A, and per array: 20.56 A for each array.
7. I_{max} (Current at maximum PowerPoint): 4.78 A per panel, and 19.12 per string, and each array.
8. P_{max} (Power at maximum powerpoint): 14.23 per panel

(B) Application of National electric code factors for code compliance (NEC 2005; NFPA 7.0)

For the above open circuit voltage and short circuit current, NEC factors have to be applied for proper sizing of equipment and wiring. NEC 2005 section 690 was applied for code compliance. Since the short circuit current (I_{sc}) is the most important parameter for equipment sizing and wiring; a factor of 1.25% has to be applied while selecting the charge controllers, along with another factor of 1.25% for over current protection device sizing. These are applicable for AC systems along with DC systems 12V, 24V, and 48V DC as well. Hence for further calculations, the short circuit current would be 32.125 Amps.

(C) Physical characteristics

Each solar slate was 15 ¾ inches wide by 12.83 inches tall. Each slate consisted of 6 monocrystalline silicon photovoltaic cells with the exposed area per sun slate being 1.29 sq-ft. The idea was to balance the slates within the array visually, along with obtaining an open circuit voltage that would be compatible with the charge controllers that were to be used.

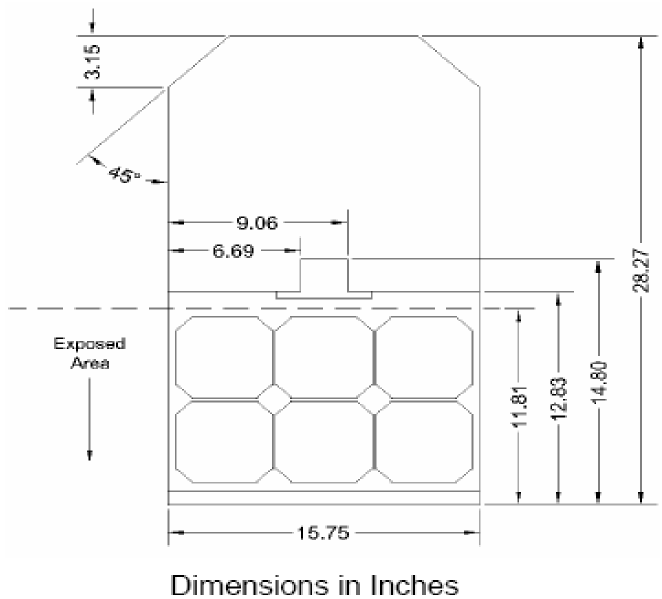


Figure 4-5: Physical dimensions of each solar slate

(D) PV Array output

Since the panel selected had a rating of 14.26 Watts at maximum PowerPoint, the array rating is as follows:

- 48 panels on each wall at 14.26 P_{max} per panel, hence each array is 683 Watts, or the PV system was rated at approximately 1.36kW.

A quick test to check the available output from the PV arrays was done in' PV Design Pro-S' for the entire year. Detailed output simulations from the software for the east and west walls are shown in Chapter 6, the analysis section. As said previously, for the sizing of the PV array for the DC system, a number of panels were selected to fit in with the architectural design of the house. Since, the LED lighting loads to be supplied by this system were secondary, the demand was not critical. Also, since the lighting loads with this system design were LED's, they have a minimal power requirement. In any case, a 1.36kW PV array was considered to be sufficient to supply secondary LED lighting within the house.

4.6 Load Calculations

Detailed load calculations were carried out to estimate the demand load for further calculations. This is shown in table 4-1. Based on these load calculations, related PV and electrical equipment sizing was also determined as detailed in the next sections.

Table 4 -1: Lighting load design estimates

Lighting component	Space	Quantity	W per fixture	Tot W (Con)	Control Intent	Opr power	Avg (hrs)	Tot (Whrs)
Linear LED 12" fixture	Clerestory	24	3	72	Integrated controls via computer	2.4	6	432
LED spotlights	Spotlights in mech room	3	8.4	25.2	Light switches	25.2	6	151.2
Linear 12" LED light fixture	Site - Ramps	20	3.5	70	Switched via timers	70	6	420
LED spotlights (uplighters)	Site - Trees	5	3.5	17.5	Light switches	17.5	6	105
LED linear 12" fixtures	Site - Kiosk	4	5	20		20	6	120
PDM (power data module) controls (For lights in clerestory)	Clerestory	3	1	3	N/A	3	6	18
Light switches /controls/Timers/Misc loads				5	N/A	5	6	30
Totals	**Connected load W:**		**212.7**		**Operational W**	**157.1**		
	Connected load A:		**8.86A**			**Total Whrs per day**		**1276**
						Total Ahrs per day		**53.16**

4.7 Balance of system components

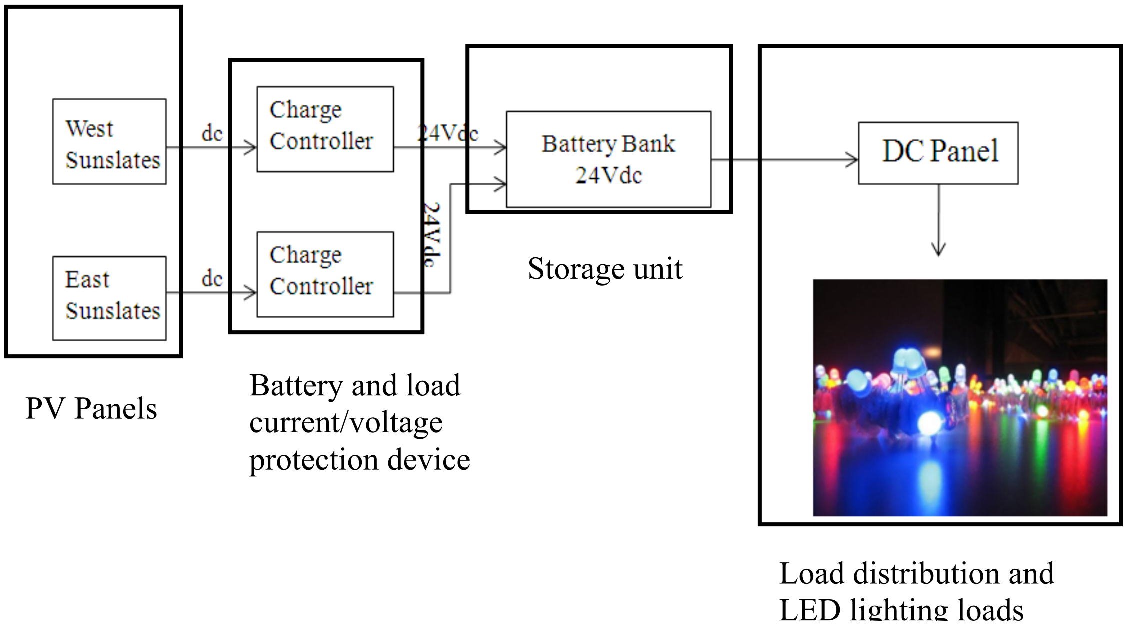


Figure 4-6: A block diagram of the DC LED lighting system

Figure 4-6 shows a basic block diagram of the DC system. Essential parts of this stand-alone Photovoltaic DC system were PV panels; voltage and current controllers /regulators, electrical and/or lighting loads, distribution panel and other components for code compliance such as disconnect switches, and ground fault protection devices.

The system voltage was chosen to be 24V as it is the most commonly used voltage rating for a low voltage PV system. Also, since most of the lighting loads chosen were rated at 24VDC, an identical voltage was chosen so that a voltage regulator could be avoided. A voltage regulator helps regulate a common voltage within the system when loads that have multiple voltages are used. Solar slates, as shown in Figure 4-4 wrapped the east and the west façade of the house. They produced DC power, which was then captured through various PV and electrical equipment to feed to a low voltage distribution panelboard. Charge controllers were used to regulate the current and voltage flow to the batteries to help during charging and discharging. Battery storage was designed for back-up of the power, plus to allow for storage of excess power.

4.7.1 Charge Controllers

A charge controller usually prevents the battery from getting overcharged, and would have the capability of disconnecting the PV module from the battery bank, when the bank is fully charged. It could also be a part of the inverter in a grid-connected system AC system. However, the importance of the controller is higher in a stand-alone system like this DC lighting system, especially when the charging and the discharging of the battery are dependent on the controller. Hence, providing for charge control is one of the most important aspects in a PV system design, as it is critical to the performance of the battery (SEI 2004).

For this system a charge controller was specified for charge control, and a load controller was specified to ensure load control. Although, one controller would usually suffice in both the charging and the discharging modes of the battery, the particular controller chosen could function only in one mode at one time. The charge controller functioned in the charging mode, while the load controller functioned in the discharging mode. The chosen controller was a Morningstar Tri-Star charge controller. In total, there were three controllers; each array had one charge controller, while there was one load controller.

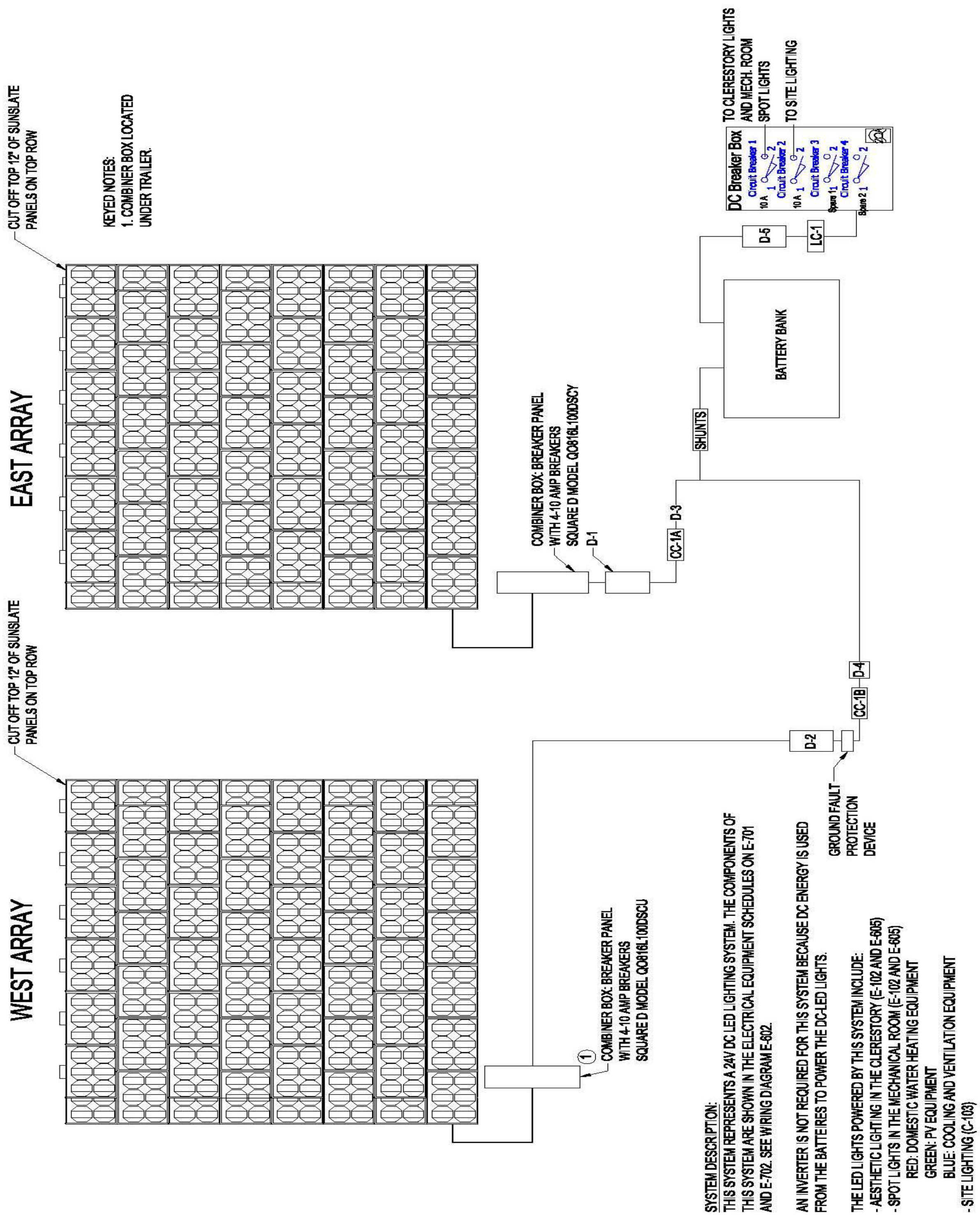


Figure: 4-7: Schematic block diagram of the PV DC LED lighting system

The ratings of the controller are usually selected based on the source side current and the load current. In this case, the source current, or the PV short circuit current after application of the NEC factors, is approximately 32 Amps. A 45A rated charge controller was hence chosen. Since the load is less than 45 A, a 45A rated load controller (for load control) was also chosen.

A schematic block diagram of the PV based DC LED lighting system is shown in Figure 4-7. On each wall, there were 6 slates in each row, with a total of 8 rows. The east and the west array were intended to separately charge their respective charge controllers, and they also could be disconnected independently.

4.7.2 Battery Design

As seen in chapter 2, batteries are an important aspect of a stand-alone photovoltaic system design. They are generally the most expensive part, and the weakest link within a stand-alone PV system, especially when battery replacement is considered (Diaz and Lorenzo 2001; Diaz and Egido 2003). Batteries used within the system must be rechargeable. An analysis was carried out to evaluate the most suitable battery type for the DC LED lighting system. Although, the most common type of batteries utilized within a PV system are the lead acid type, some of the other options commonly available are the Nickel metal hydride batteries, Nickel cadmium and deep cycle.

Lead acid batteries are generally recyclable, have a low cost and are available in many sizes. Although manufacturers generally estimate the typical life of a battery, a number of factors contribute towards the life of the battery system. Factors such as the climate the system is located in, proper sizing of PV panels, and the voltages along with wiring. Proper operational management of charge controllers, battery type, battery maintainence amongst other factors, contribute towards the life of a battery system.

For a typical PV lighting system, a battery's charging cycle is the period when the PV panels are active and energy is being stored within the battery during the daytime, and the discharging cycle is the period when charge is being taken out of the battery for lighting during night-time (National Lighting Product Information Program 2005).

A battery's capacity is usually the amount of energy it can store. It is usually measured in Amp-hours. Battery capacity is hence how much energy from the battery can be withdrawn before it is completely discharged. Deep-cycle batteries or deep-discharge batteries are the most optimal type as they can be repeatedly drained of the energy stored and then recharged. The maximum depth of discharge of a battery is a measure in percentage of the amount of energy that can be removed from a battery without damaging the battery. This percentage is generally 20% for lead-acid batteries.

Another battery type, as mentioned above, is Nickel metal hydride, NimH. Some of the main advantages of using this type are that they have 30-40% higher storage capacity than the nickel cadmium batteries, are easy to store and transport, while also being environmentally friendly. However, some of the main disadvantages of using Nickel metal hydride are that its performance deteriorates after 200-300 cycles if repeatedly deeply recycled and it has a short lifetime. Nickel metal hydride generates a lot of heat during charging and requires slightly longer charge time than nickel cadmium batteries (Mid-State Battery manufacturer, 2007). The battery type chosen for this system was hence a sealed lead acid type. The amount of Ampere-hours (A-hrs) a battery needs to store determines the number of batteries required within the system. These are indicated in the battery sizing calculations.

4.7.3 Battery Bank Calculations

The daily A-hrs estimate of 54 A-hrs can be approximated to 60A-hrs/day for this system to size the battery bank, in order to allow for extra storage capacity when needed. Hence, a battery that is rated at maximum 90-Ahr, which is the closest available rating available from the manufacturer, was chosen to store the energy produced from the PV panels. Also, each battery was rated at 12VDC for the 24V system. Average operating time estimate is 6 hrs a day with the load back-up being for 3 days.

Table 4-2: Battery sizing calculation

Step 1:	Enter daily A-hr requirement	60	A-hrs
Step 2:	Multiply the amp-hr requirement by the number of days	180	
Step 3:	Enter depth-of-discharge of the battery chosen	0.8	
Step 4:	Divide the A-hr storage by the discharge limit	225	
Step 5:	Select the multiplier below that corresponds to the average wintertime ambient temperature your battery bank will experience.		
Step 6:	Multiply the A-hrs by above factor	357.75	battery capacity required
Step 7:	Enter the A-hr rating of the battery chosen	90	
Step 8:	Divide total battery capacity by the A-hr rating of the chosen battery	3.975	batteries in parallel
Step 9:	Divide the total system voltage by battery voltage	2	batteries in series
Step 10:	Total number of batteries required	7.95	

Ambient Temperature Multiplier

80F	26.7C	1
70F	21.2C	1.04
60F	15.6C	1.11
50F	10.0C	1.19
40F	4.4C	1.3
30F	-1.1C	1.4
20F	**-6.7C**	**1.59**

Total number of batteries required: 8

Hence, a total of 8 batteries with 2 in series to give 24VDC, and 4 sets in parallel to give the required A-hrs storage for 3 days were specified.

4.8 System Specifications

In summary, components that were part of the DC lighting system and their specifications are listed below:

1. Solar slates on the east and west façade of the house – Total 96 sun slates

   Make and manufacturer: Q-cell 5” poly Atlantis energy systems

   - Each solar slate:
     - Watts at maximum powerpoint = 14.26 (for maximum sunlight exposure)
     - V_{oc} = 3.7 (Open circuit voltage)
     - Volts at maximum powerpoint = 2.98 V
     - Current at maximum powerpoint = 4.98 Amps
     - Short circuit current = 5.14 Amps
     - Exposed area per slate = 1.29 sq-ft
     - Six polycrystalline cells connected in series
   - 4 strings of 12 slates connected in series, (one array)
   - Slates are oriented vertically
   - V_{oc} (open circuit voltage) per array = 44.6 volts
   - Total rating of the solar slates on the east and west walls = 1.36kW (maximum)

- Short circuit current – per string = 5.14 A, short circuit current per array is 20.56, including 2.56 NEC current factor, it is 32.125 Amps.
- Quantity: 48 slates on each side
- Total Wattage on each façade: 683W

2. Charge controllers and load controller – Charge controller is for charge control, while the load controller is for load control.

    - Make and manufacturer: Tri-Star 60, Morningstar Corp
        - Each controller is rated at 60 Amps.

3. A 20 A DC Breaker panel – To distribute the DC loads in the house.

4. Ground fault protection device (GFP) – for ground fault current protection, as per NEC code for Building integrated PV systems.

5. Fused DC Disconnect Switches –40 Amps rated, for safety and over current protection as per NEC code compliance, for building integrated PV systems.

6. Battery bank – Sealed lead acid batteries

    - Make and manufacturer: Mid-State batteries UB-12900 (Group 27); (Nominal 12 V each)
    - Quantity – 8
    - 2 in series and 4 in parallel
    - Total A-hrs storage for 3 days – 357 approximately

7. Lighting Specification: LED Luminaires

- 1 ft, 3W 24VDC each linear white LED lights (16 total) to light exterior ramps
    - Model and manufacturer: Project linear from LightWild (#LW-LIN-W-3K-12-LFR)
- 1 ft, 3W 24VDC each (at full output white) (24 total) colored LED lights, sandwiched between polycarbonate glazing wall panels which were filled with nanogel.
    - Model and manufacturer: (a) icolorcove QL from Color Kinetics (#101-000051-00); (b) PDM-201 (#118-000062-00)
- Colored LED spotlights 3 number 8.4W each, to highlight equipment in the mechanical room (24VDC rated each).
    - Model and manufacturer: (a) Colorburst (#116-000014-02) from Color Kinetics (b) PDM-101

All of the electrical equipment such as circuit breakers, fuses, breaker panel, disconnect panels was from Square D, other than the ground-fault protection device which was from Xantrex. All of wiring was sized in accordance with the National Electric Code (NEC) 2005. All the overcurrent devices used were fuses and circuit breakers and were all DC rated. For lighting loads, all the LED fixtures were from Color Kinetics, except the site lighting fixtures which were from Light-Wild.

4.9 Wiring Schematic

NEC factors were applied for code compliance during calculations to determine wire sizes, and fuse/circuit breaker sizes. Voltage drop calculations were also performed to determine if the wire sizes selected were adequate for the distances between equipment. Some of the wiring had to be oversized, in case of a huge voltage drop. As the distance between the equipment increases from the source side, (PV panel equipment) the voltage drop also increases and wire sizes have to be upgraded to accommodate this loss, which would otherwise result in power loss. Correction factors, related to the ambient temperature of the PV panels, were applied. Other correction factors including the conduit fill factor, which accounts for the number of wires that can be in a single conduit, were also applied.

A complete calculation indicating all the above details, along with the wire sizes chosen and wire types chosen is shown in table 4-3. Datasheets for all equipment selected are in Appendix B.

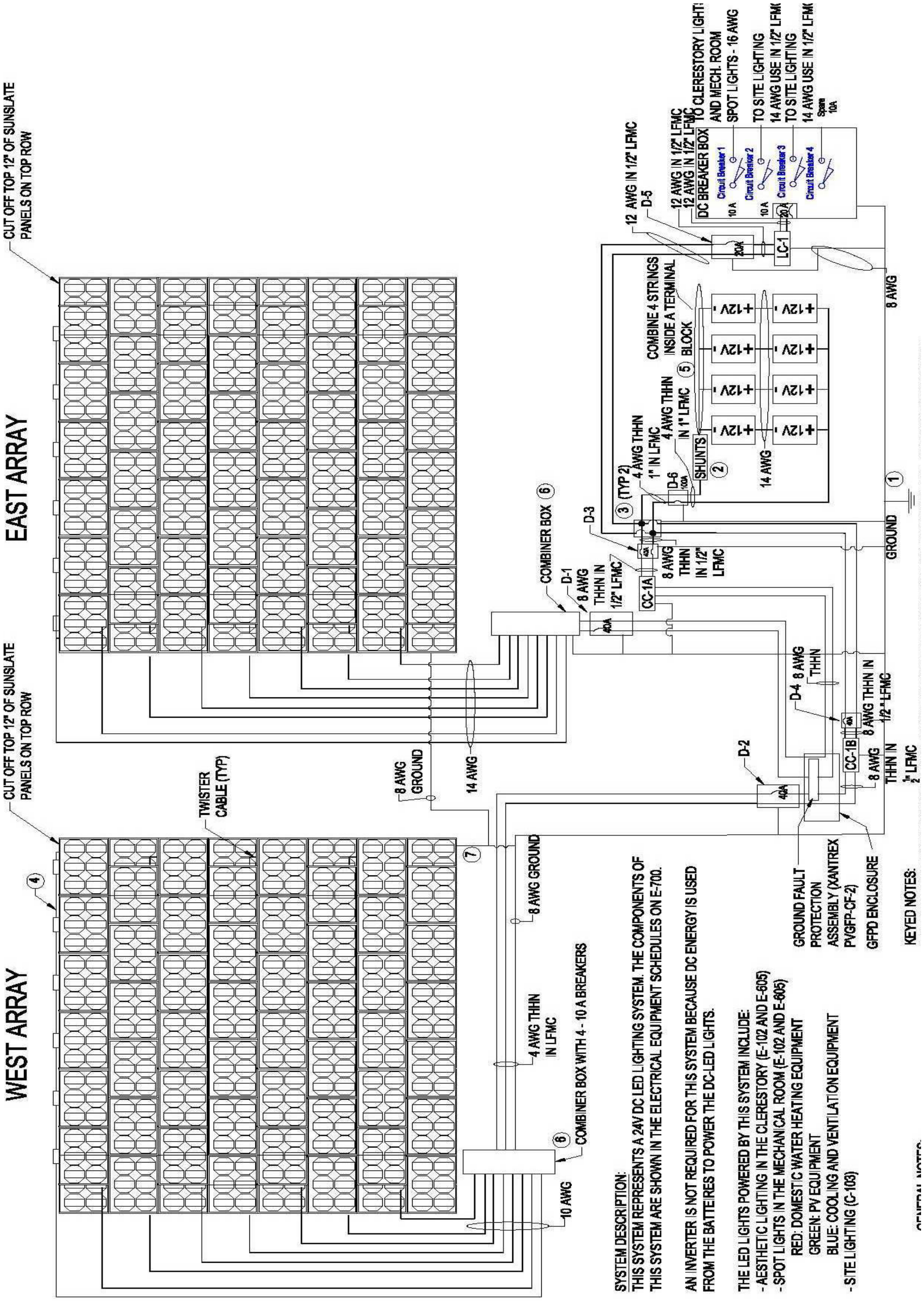


Figure 4-8: Single Line wiring schematic of the DC LED lighting system

Chapter 5

Construction details

5.1 Overview

This chapter covers the construction details of the photovoltaic DC LED lighting system for the Morningstar house. A design summary explaining the intended operation of the system is presented initially. Installation details of the solar slates, the system components; such as the electrical and PV equipment, wiring details along with battery installation details are also presented in this chapter.

5.2 System operation

The DC LED lighting system has a total of 96 solar slates, with 48 on each side of the wall. Each array gets charged separately upon sunlight striking them, which induces a voltage across the panel, and hence creates a path for the current to flow across. As seen previously in the schematic, the positive terminal of each PV string is typically connected to a dedicated fuse, while the negative terminal is connected to a common negative bus. Illustration of this wiring detail is shown in later section 5.3.5 in Figure 5-4.

Current flows across each of the strings, for each array, through the disconnects to the charge controller, to a common point, to charge the batteries. Disconnects are required for compliance with the NEC, for the safe operation of the system. To make the design foolproof, disconnects were placed at every point where there could be a potential safety issue. Wiring from each string of the PV panels was combined within a combiner box located inside the house on either side of the wall. The combiner box contained 10A fuses, which were the over current protection devices for each string, in order to disconnect them separately, if required.

A 20A main switch was provided within each of the combiner boxes, which was the disconnection point for each array. From the combiner box, the next point of connection was again the disconnect switches (which also contained fuses) for each array, before connection to the two charge controllers for each array. The intention in having two charge controllers was to monitor each array separately during “their respective” charging modes.

In other words, since the energy produced by each array was different based on the sun’s angle within the sky for the east and west orientation, separate monitoring of each array via the charge controllers was necessary. From the charge controllers, again, another disconnect switch was placed for each array, before they finally charge the batteries. The two arrays hence charge the battery bank together. From this point on, power was to flow is through the load controller LC1 with a disconnect for disconnecting the power flow when required. The current flow is then to the batteries.

5.2.1 Modes of operation

(A) Battery Charging:

During normal daytime operation, when there is sufficient solar insolation present on the PV panels, the panels get charged and produce DC power. This DC power passes through various equipment (disconnects and charge controllers) as shown in the schematic, before finally powering the lighting loads within the house. The energy produced from the panels is first stored in the battery bank, and does not directly power the loads. Some of the conventional DC systems use the energy produced from the panels to directly power the loads with the excess stored in the battery bank. However, since the loads in this case are lighting, which would not be switched on until the nighttime, the battery bank plays an important role in this system design.

As seen in the schematic in Figure 4-8 in Chapter 4, a total of 8 strings charge the battery bank. In summary, contrary to the DC loads being powered at the same time, the battery is being charged during daytime; during nighttime operation, only the loads are powered, as the battery is in its discharging mode of operation.

(B) Battery Discharging

During the discharging mode, the stored energy is drained from the batteries to power the lighting loads. Depending on the size of the PV panels, and if sufficient energy has been stored within the batteries, all the lighting loads could be powered based on the design load estimates and panel sizing. In any case, if sufficient energy is not available from the batteries, the intention was to power only the lighting loads which were important. An important point to note here is that since the lighting loads that were to be powered by this system were only LED lights and the goal with this lighting design is for aesthetics, the chosen lighting loads were the clerestory lights, and the site lights.

5.3 Construction of the system

Construction of the house was organized into two parts: - in State college and in Washington, DC. The house was also constructed in two parts; the technical core unit and the living space unit. The first half of the year 2007 concentrated on the design details of the system while the second half of the year concentrated on the construction. The table below gives an approximate initial construction schedule for the PV DC LED lighting system. This table was prepared to help with not only work sequencing, but also identifying the priority tasks as well as outstanding tasks.

Table 5-1: Construction schedule of the secondary PV system

PV DC LED system construction timeline		**Period (August 2007-October 2007)**		
	Task	**August**	**September**	**October**
		Number of days		
1	Installation of solar slates (east and west)	1		
2	PV Wiring (per string)	1		
3	PV Wiring termination to combiner boxes			1
4	Installation of PV equipment		1	
5	Electrical wiring between equipment		2	2
6	Battery bank installation			1
7	Installation of light fixtures and wiring			2

5.3.1 DC Equipment Elevation

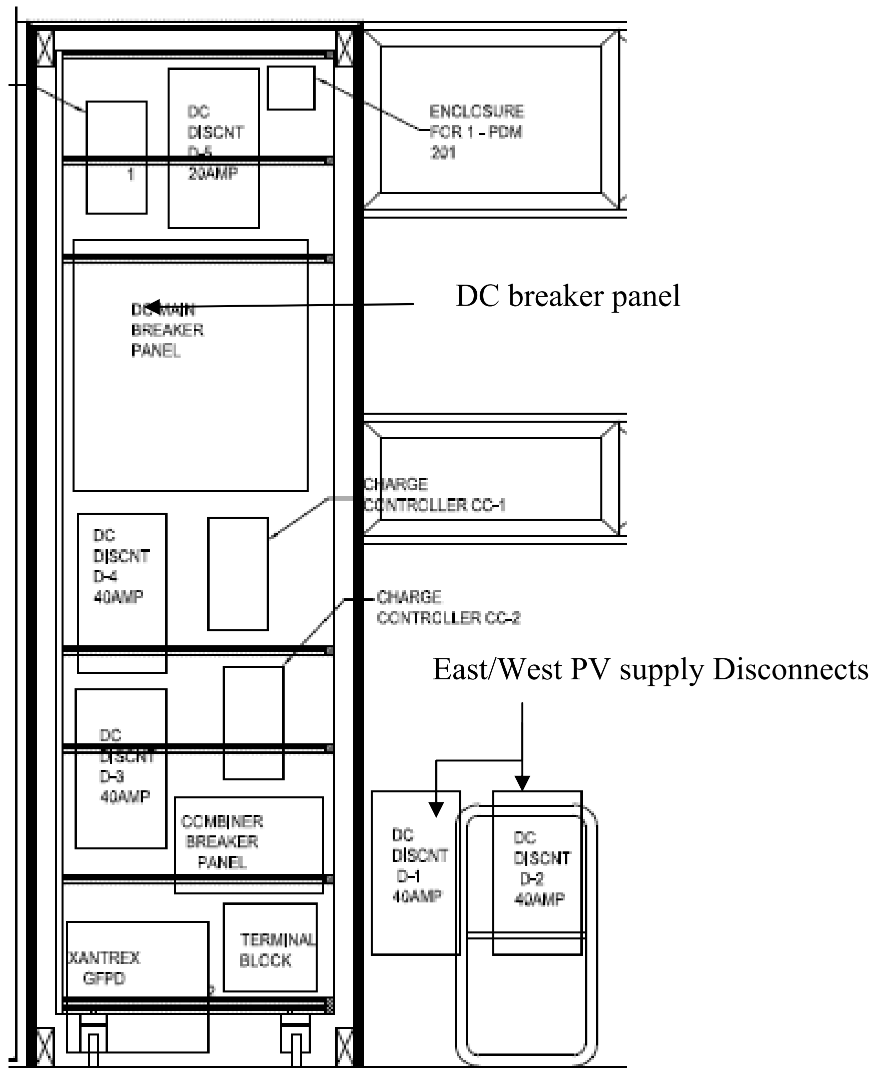


Figure 5-1: DC Equipment elevation on the east interior wall

Equipment elevation above shows the various PV and electrical equipment mounted on the interior east wall. This layout was used to plan and place equipment within the available closet space.

5.3.2 Solar slate installation

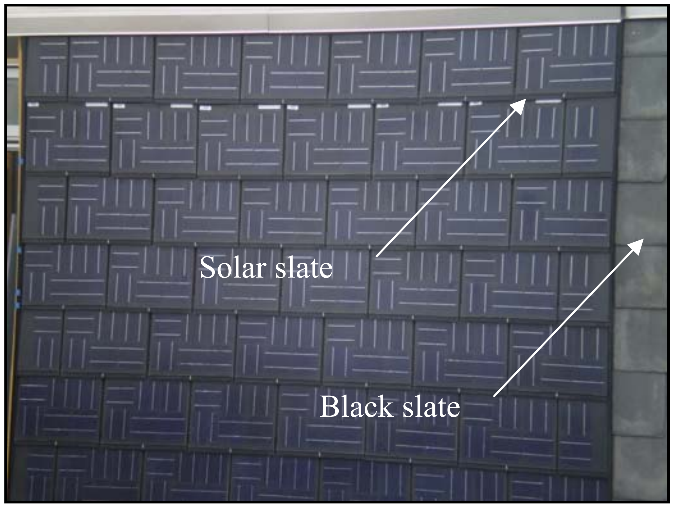


Figure 5-2: Image of the installation of solar slates

Figure 5-2 shows the vertical installation of the solar slates on the house. Vertical and horizontal battens were used to hold up the slates on the walls through hooks. 14AWG wiring was used in between the solar slates before they are tied back to the combiner box located within the house, as mentioned earlier. A Solar slate installation detail indicating the wiring connections between slates is shown in Figure 5-3.

Figure 5-3 (a) Wiring details between slates on walls

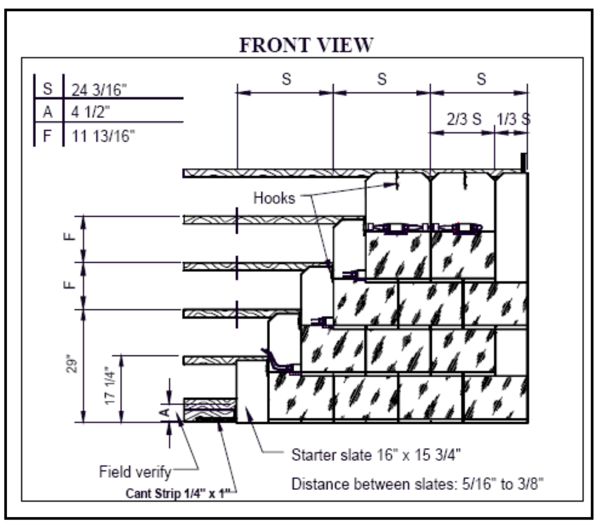


Figure 5-3 (b) A front view section on batten installation and slate

5.3.3 Installation of (BOS) PV Equipment

(A) <u>Charge controller</u>

The balance of the PV system components, such as the charge controllers were installed in accordance with the manufacturer's installation guidelines. As discussed in the previous chapter, the controller, and 'Tri-star' was used for charge and load control.

The controller had dip switches which had to be set to specify if the controller was to operate as a charge controller or as a load controller. The dip switches could also be set to specify the battery voltage and the system voltage amongst other parameters. A meter was also attached to the controller to read off the charging rate and discharge rate of the batteries, when the system was functional.

(B) Combiner boxes

As discussed in the previous chapter, and within the section explaining system operation, a combiner box was required for each array, to connect each of the 4 strings to one common point. This combiner box was a basic panel which consisted of tie in points for the strings, with a 10A circuit breaker for each string. This allowed disconnection of each string when required. A main 20A circuit breaker was allowed within each of the combiner boxes.

5.3.4 Installation of electrical equipment

Additional electrical equipment installed with this system included the DC Panel board, the ground fault protection device (for the solar slates), terminal blocks for interconnections between equipment and miscellaneous wiring. The DC panelboard was

24VDC and was sized in accordance with the Penn State building regulations and the NEC.

5.3.5 Installation of the battery bank

The battery bank consisted of 8 batteries in total (2 in series, and 4 of these sets in parallel). They were sealed lead acid batteries, and were installed in an enclosure, with 4 batteries in the top enclosure, and 4 in the bottom.

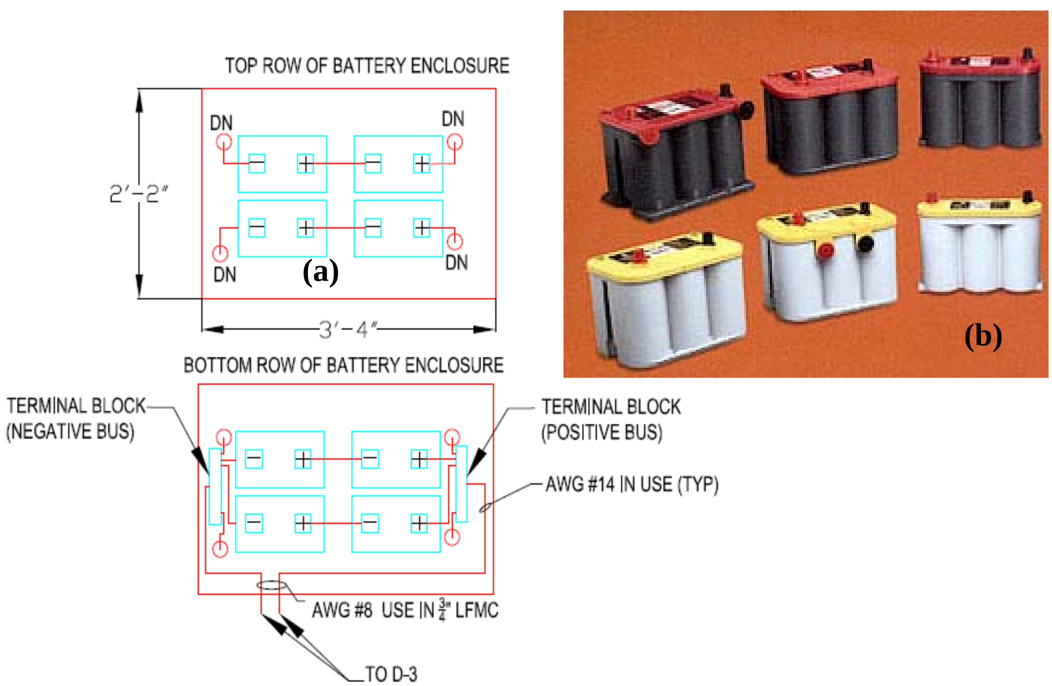


Figure 5-4: (a) 24VDC Battery wiring detail (b) Photograph of batteries

Wiring for battery interconnection was 14AWG, while the main wiring back to the rest of the electrical equipment was an 8AWG wire in 1-inch flexible metallic conduit. The positive terminal from the battery was connected to a positive bus, while the negative terminal was connected to a negative bus. Battery bank interconnection, wiring and enclosure details are shown in Figure 5-4.

5.4 LED lighting

Lighting fixtures were selected for installation along the ramps, across the site (to light a tree, landscape, kiosk display and for the clerestory lighting along with mechanical room spotlighting. LED fixtures chosen were mostly linear and low wattage. A warm white fixture with a color temperature of 2700K, and a lightly frosted lens was chosen for ramp lighting. This fixture consisted of 3 LEDs per inch of the fixture, and the total fixture power consumption was approximately 3.5Watts.

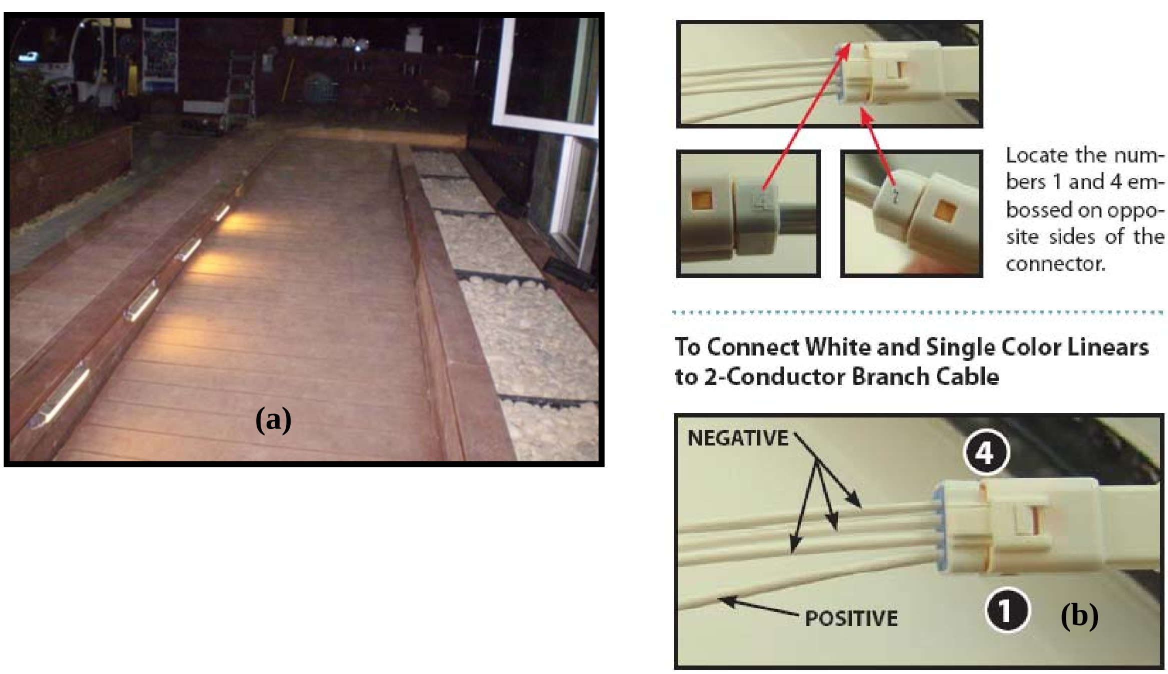


Figure 5-5: (a) Ramp lighting installation photograph (b) Connection details

Figure 5-5 (a) indicates the installation details for ramp lighting, while the wiring and connection details between the fixtures is indicated in (b). Figure 5-6 indicates the lighting installation details for the clerestory lights and spotlights. Figure 5-7 indicates the wiring schematic plan of these fixtures. For these light fixtures, a power supply called the PDM (power data module) was required as a connection point between wiring from the panelboard and the lights. This module was rated at 24VDC, and was the point where dimming of the LED fixtures could occur. During the actual installation of these fixtures, some problems with the current to this module were encountered, which are detailed in chapter 6. Figure 5-8 shows a basic 3D rendering of the solar house.

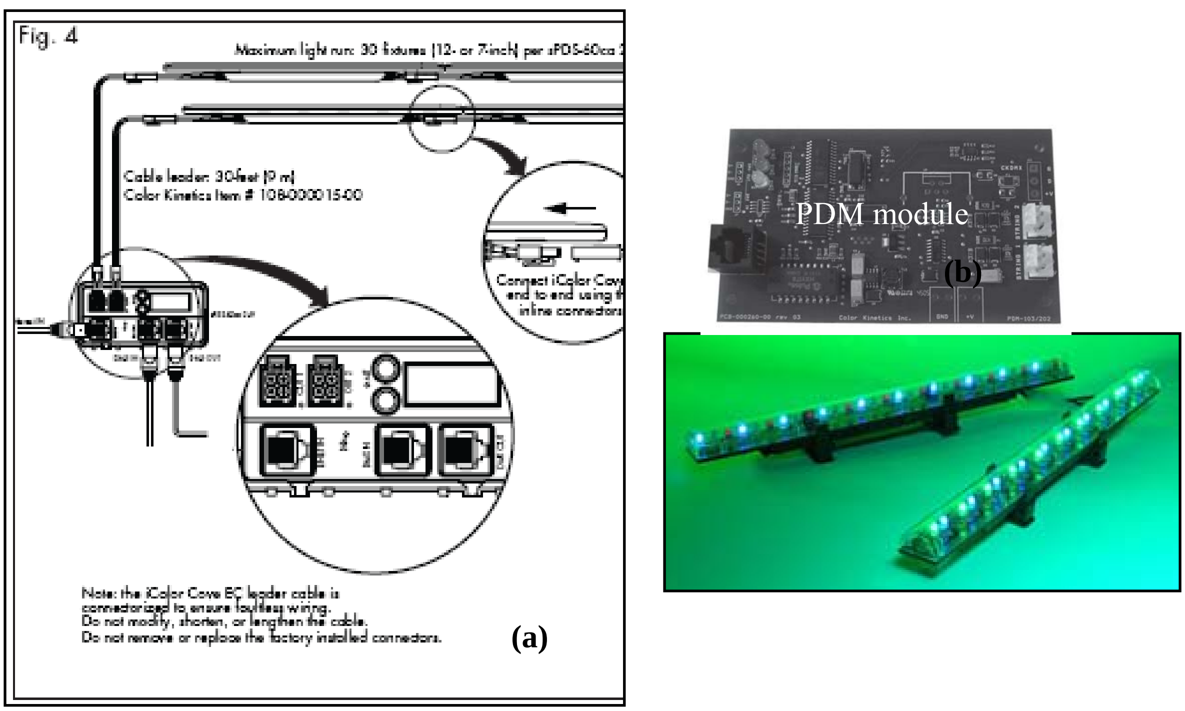


Figure 5-6: (a) LED light fixture details (clerestory light) (b) PDM module (c) Linear LED light fixture for clerestory

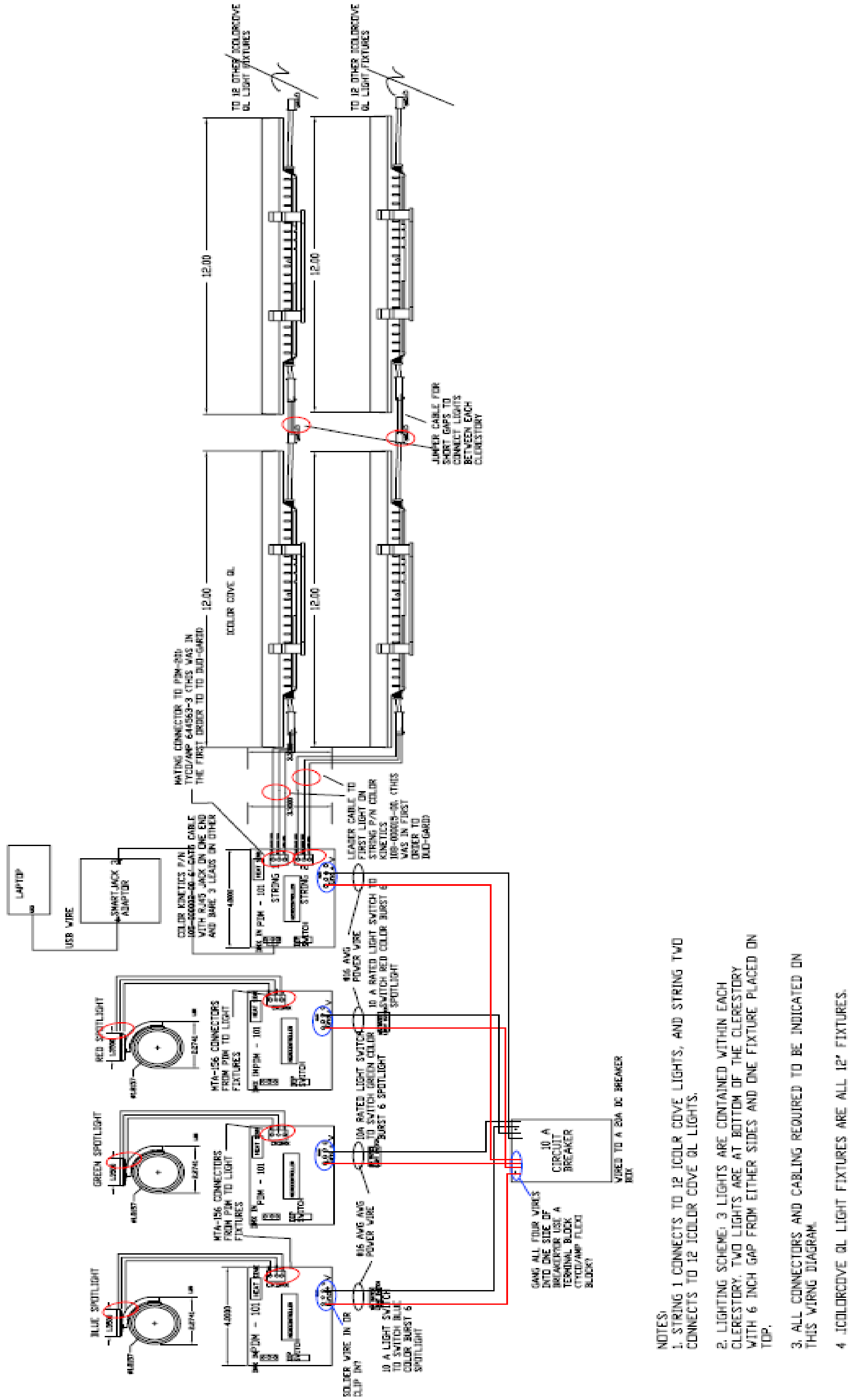


Figure 5-7: Wiring installation schematic for LED lights (clerestory and spotlights)

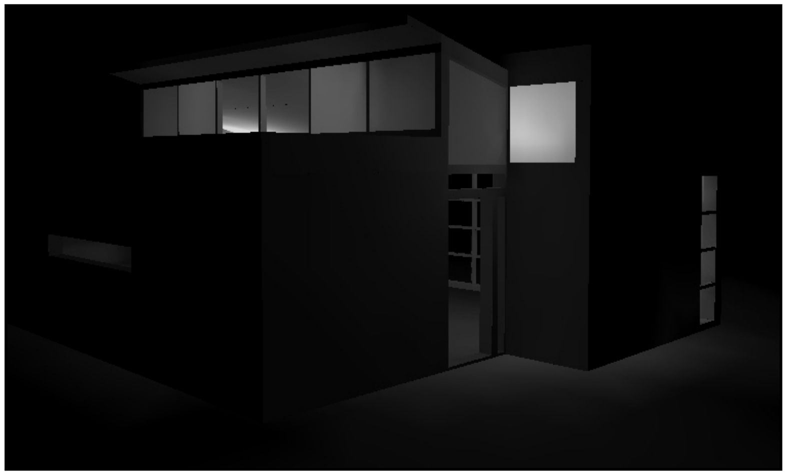


Figure 5-8: 3D lighting rendering of the solar house (Source; Penn State Solar Decathlon lighting team, 2007)

5.5 Disconnects and code compliance

Disconnects were placed at each point in the system design where there could be a potential safety issue. In compliance with the National Electric Code (NEC) and for safety, disconnects were placed at the output from the two arrays, output from the two charge controllers, at the battery bank, and before the main distribution DC panel. The location of these disconnects also had to be coordinated with the architecture, taking into account some of the space constraints within the house. Placement of the disconnects within the house can see be seen within the design schematic in Figure 4-8 in chapter 4, while information on the code compliance issues during installation are detailed in chapter 6.Figure 5-9 shows an image while installation some of the equipment was still under construction.

Figure 5-9: In-progress installation photograph of the system equipment

5.6 Procurement

Most the equipment used for this system was either donated by the manufacturers or obtained at a discounted rate. Equipment was procured taking into account the lead times for delivery so that no delays can occur during installation. PV panels were procured first, followed by the batteries, light fixtures and associated PV/electrical equipment and wiring.

Section 5.7 shows some of the actual installation images. Chapter 6 covers an in-depth analysis of the design and construction of this system in terms of capital costs, and addresses the overall efficiency of this system.

5.7 Installation images

Figure 5-10 (a) Living Room primary lighting

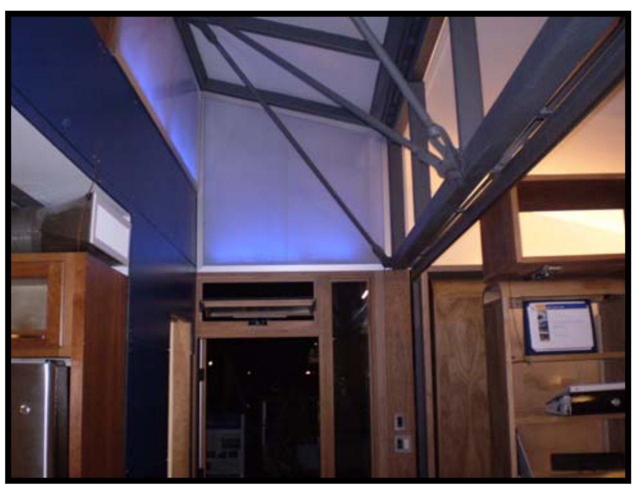


Figure 5-10 (b): Clerestory lighting photograph

Chapter 6

Results and Analysis

6.1 Overview

This chapter covers an in-depth analysis of a stand-alone photovoltaic DC LED lighting system. As part of this analysis, the following aspects of the system have been studied and discussed in this chapter.

1. PV array output simulations (east, west and combined PV output)
2. Design and construction process challenges
3. Cost, payback and efficiency analysis – Design tool

The first section of this chapter will cover PV east and west array output simulation results, along with a comparison of the total output from the PV arrays against the demand of the LED lighting loads as presented in Chapter 4.

The second section of this chapter focuses on the design and construction evaluation of this system by discussing challenges encountered in both these areas. Improvements with the design schematic are presented in this section.

The third section of this chapter covers the costs and efficiency of this system. In other words, this analysis presents a tool which could be used at a schematic design level to analyze the costs and efficiency of a stand-alone PV DC system. Although this tool lists all the costs associated with the design of the DC LED lighting system for the Solar

Decathlon house, such an analysis could also be carried out for other small scale stand-alone DC systems. Revised cost information for the DC system with suggested design improvements from section 2 is also presented. A comparison is made with an AC system for two cases using a similar design concept. A simple payback is calculated for a DC LED lighting system design with the best PV configuration against a conventional lighting system design.

6. 2 PV output simulation study

6. 2.1 Summary

A PV simulation study was carried out to test the solar irradiation on the vertically mounted east and west PV panels throughout the year. The kWhr output from these panels was then compared against the load demand. Software used to carry out this analysis was – 'PV Design Pro-S' for stand-alone systems. A PV array type had to be created using the PV module wizard with its electrical and physical characteristics as specified in the datasheet. To obtain information on the performance of these panels, it was necessary to select these panels along with an appropriate climate file. Battery bank and wiring information was also entered into this software to analyze the charging and discharging of the bank against the load demand. A step-by-step procedure for obtaining results from this analysis is covered in the next few sections.

Simulations

Climate data selection - Step 1

The first step to the analysis was to select a climate file from the database. The climate file selected was "Pennsylvania –Williamsport". Any other climate file could be chosen from the 50 cities listed within the software database. Monthly solar radiation charts or daily radiation charts could be obtained along with hourly climate charts as well. Figure 6-1 shows the monthly climate data and Figure 6-2 shows the monthly radiation data for Williamsport (Note, shading effects could also be applied, if any).

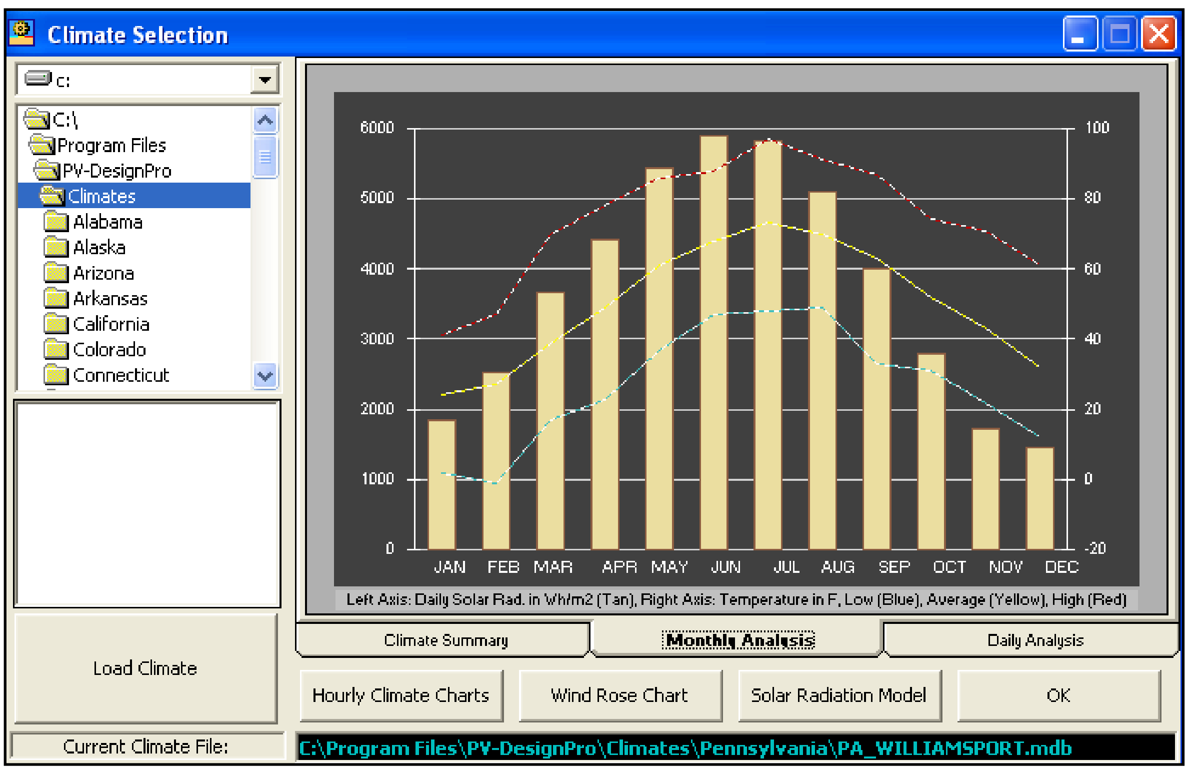


Figure 6-1: Climate summary data for Williamsport

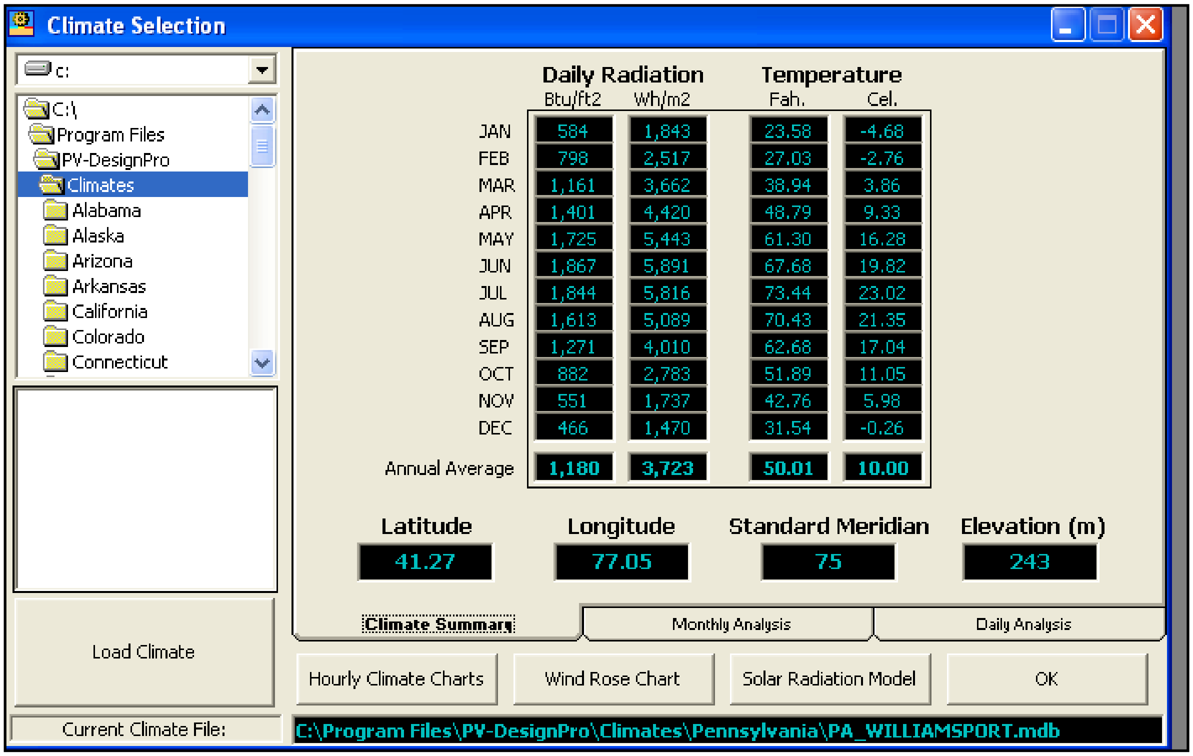


Figure 6-2: Climate summary data for Williamsport indicating radiation data

PV Array configuration – Step 2

The PV module was selected and added to the database. As seen in chapter 4, there are 12 panels in series and 4 in parallel per array. Since, this system had vertically mounted panels and no PV tracking in place; this was entered for the tracking method as shown in Figures 6-3 and 6-4. The slope was fixed, while the azimuth was also fixed, the value for the east array was -90 and west was 90 deg (i.e vertical mount). Each of these arrays had to be separately analyzed within the software. Since, there were no wind turbines in place for this system, zero wind turbines were selected.

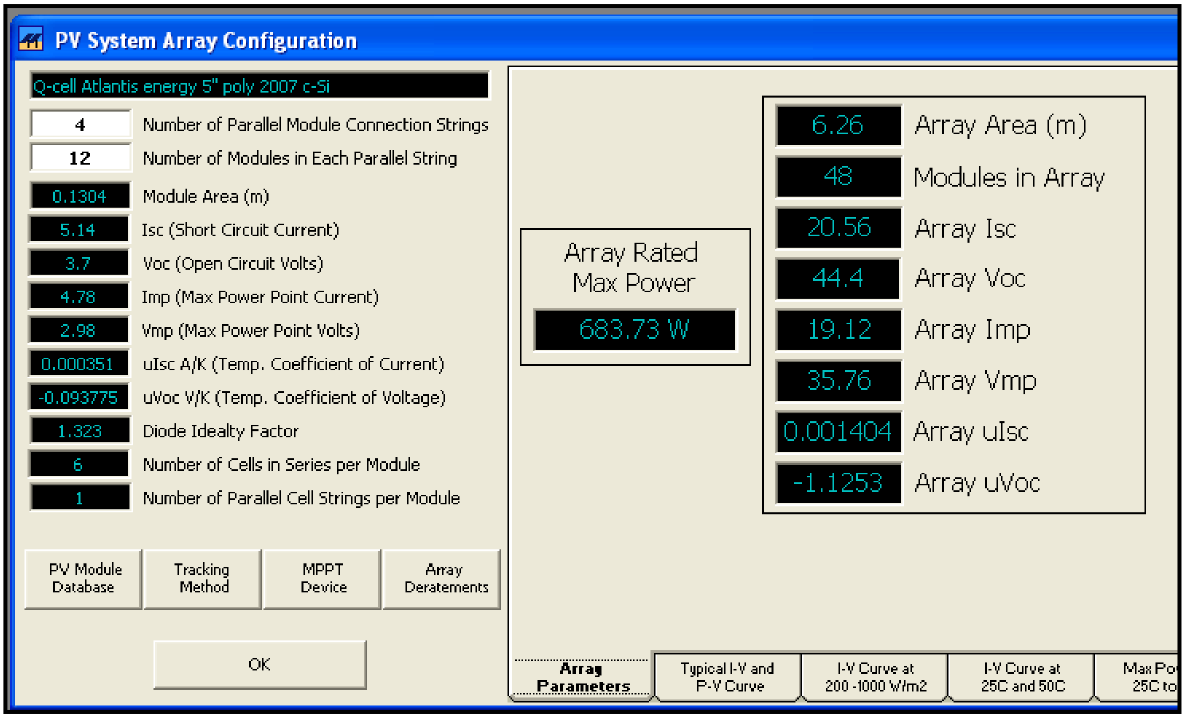


Figure 6-3: PV array configuration

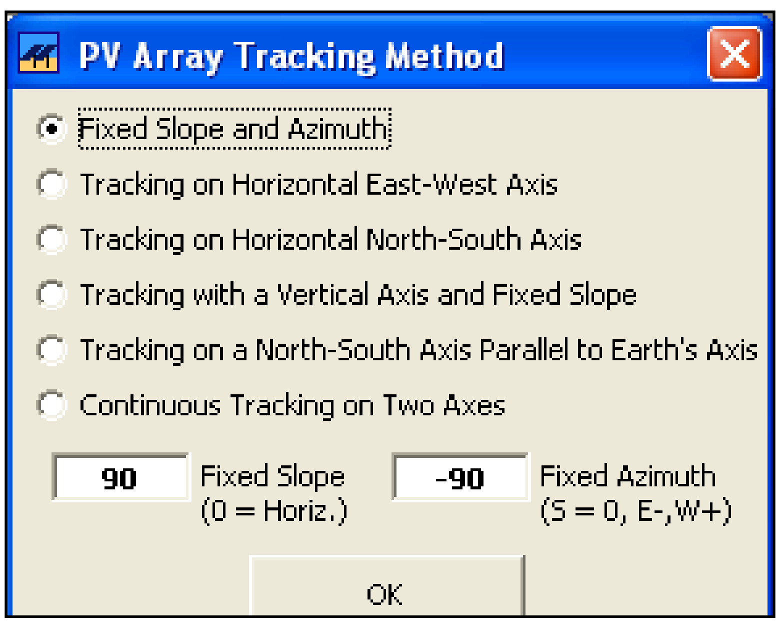


Figure 6-4: East PV Array tracking method

Load input - Step -3

Weekday and weekend loads could be entered under the load input within the software. Since the loads are lighting only, they would be operational only during the evening and nighttime. Winter and summer solstices were considered for setting an operational time within the software. This is indicated in table 6-1. Average operational time (worst case scenario) was 6 hours during the winter months. Weekend load values were all set to zero, assuming the facility is operational only during weekdays. Weekend loads are usually required, if this building was a residential house. A screenshot of this load inputs is shown in Figure 6-5.

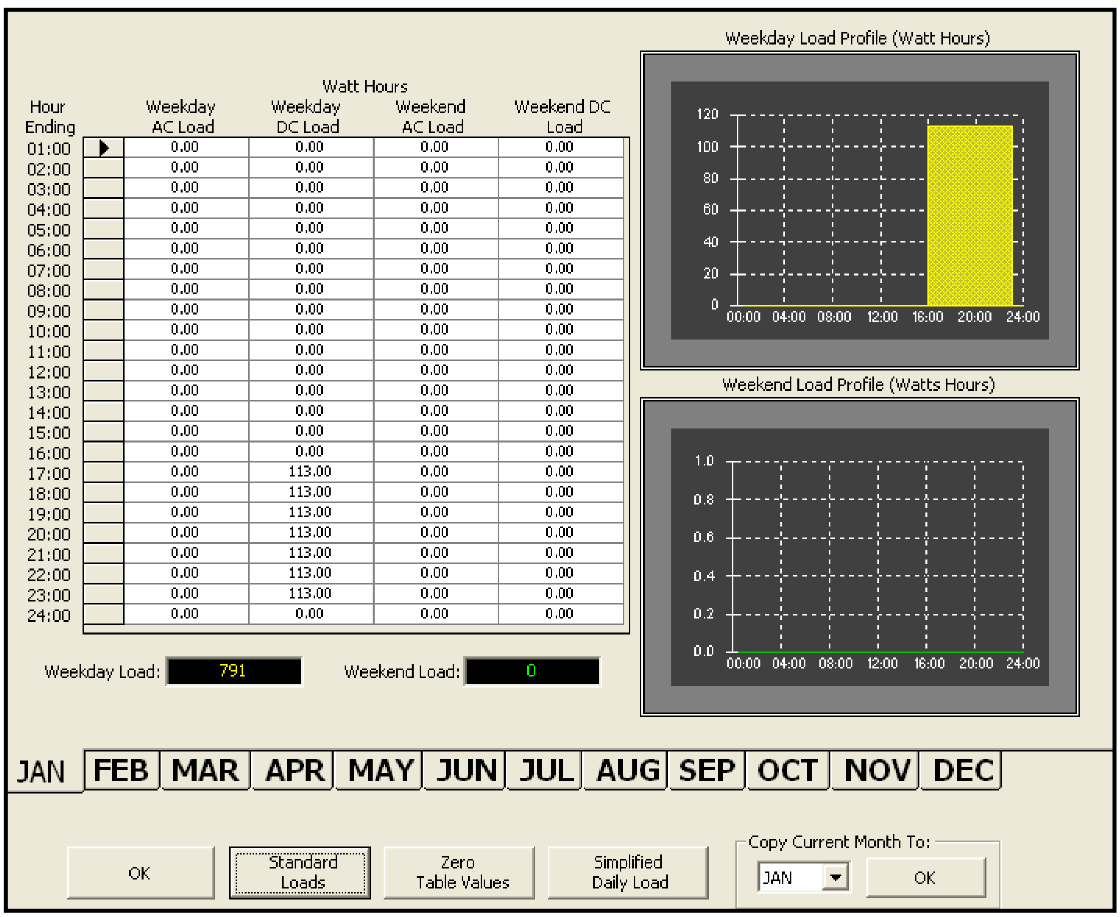
Since each array has to be analyzed separately within the software, to accommodate for this the load demand was halved, assuming each array charges the battery to supply half the load. In reality however, the east and west array charge the battery bank together.

Table 6-1: Average monthly operational time for lighting loads

Month	Operational time (pm)	Operational hours
Jan/Nov	5-11	6
Feb/Oct	5-11	6
Mar/Sept	6-11	5
Aug/Apr	7-11	4
Jul/May	9-11	2
Jun	9-11	2
Dec	5-11	6

PV System battery bank and wiring Step – 4

Battery bank information, such as the total number of batteries, battery configuration along with other details such as the voltage per battery cell, total battery voltage, current information, along with Ampere-hours was also entered. Wire size could also be selected for the approximate distance between the PV array modules and the battery bank. A wire size of 4AWG was selected as indicated in chapter 4. An inverter could be selected if required; however, since the system is DC rated, no inverter is selected.



Hour Ending	Weekday AC Load	Weekday DC Load	Weekend AC Load	Weekend DC Load
01:00	0.00	0.00	0.00	0.00
02:00	0.00	0.00	0.00	0.00
03:00	0.00	0.00	0.00	0.00
04:00	0.00	0.00	0.00	0.00
05:00	0.00	0.00	0.00	0.00
06:00	0.00	0.00	0.00	0.00
07:00	0.00	0.00	0.00	0.00
08:00	0.00	0.00	0.00	0.00
09:00	0.00	0.00	0.00	0.00
10:00	0.00	0.00	0.00	0.00
11:00	0.00	0.00	0.00	0.00
12:00	0.00	0.00	0.00	0.00
13:00	0.00	0.00	0.00	0.00
14:00	0.00	0.00	0.00	0.00
15:00	0.00	0.00	0.00	0.00
16:00	0.00	0.00	0.00	0.00
17:00	0.00	113.00	0.00	0.00
18:00	0.00	113.00	0.00	0.00
19:00	0.00	113.00	0.00	0.00
20:00	0.00	113.00	0.00	0.00
21:00	0.00	113.00	0.00	0.00
22:00	0.00	113.00	0.00	0.00
23:00	0.00	113.00	0.00	0.00
24:00	0.00	0.00	0.00	0.00

Figure 6-5: PV system electrical load

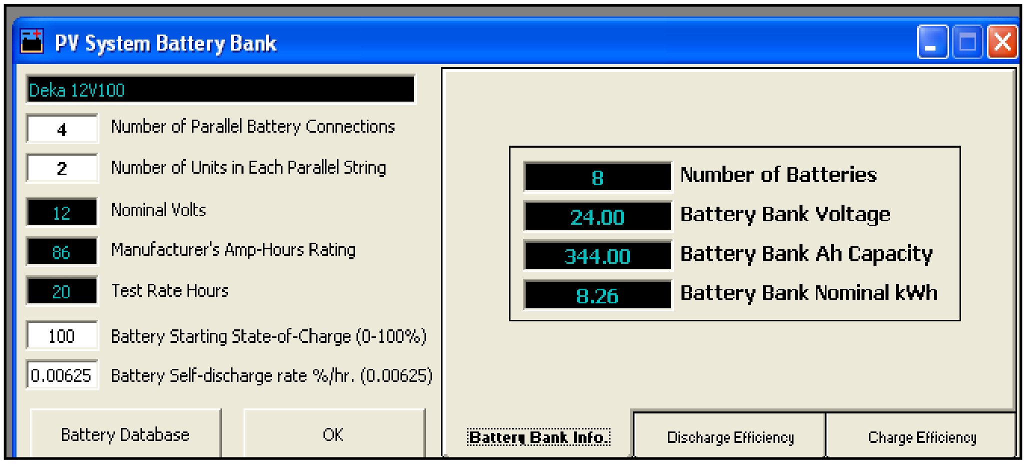


Figure 6-6: PV system battery bank details

6.2.2 Results

Detailed values on solar irradiation on the PV panels including the system performance charts, solar array details, battery charging and discharging details could be obtained through calculations. Figure 6-6 shows the system battery bank details, figure 6-7 shows the battery state of charge per month, and figure 6-8 summarizes the performance of the east array.

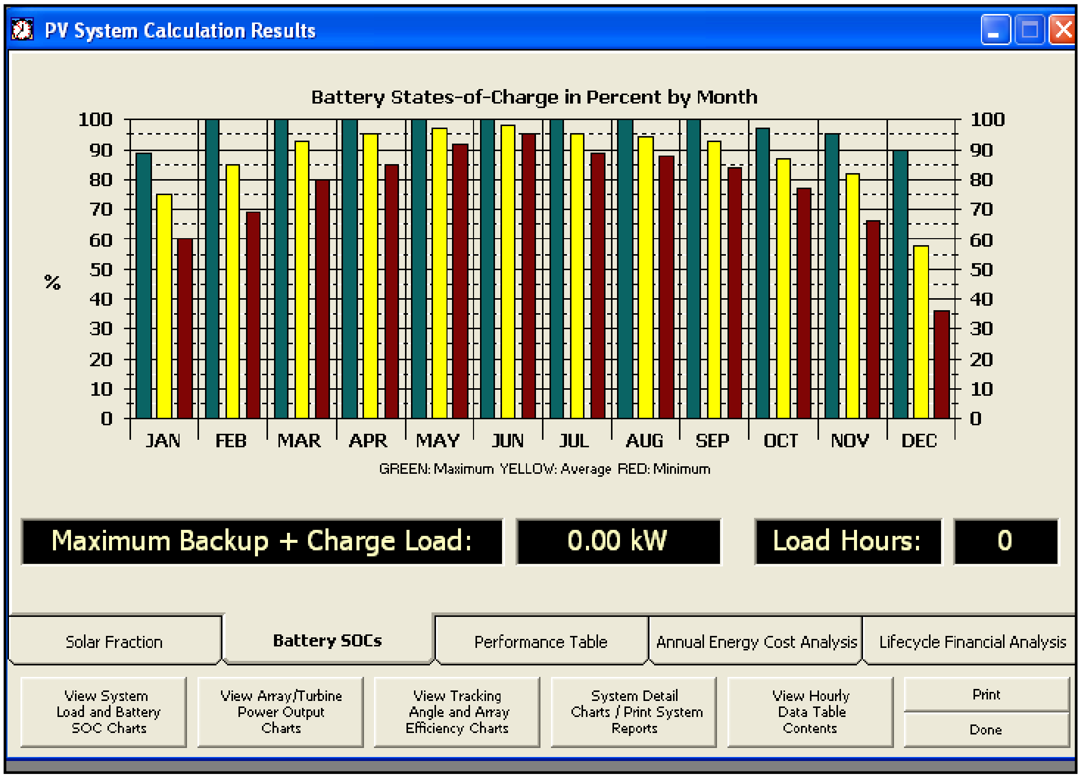


Figure 6-7: Battery state of charge (SOC) in percentage per month

PV System Performance Table

Month	Load Wh	Backup Wh	Charging Wh	PV+Wind Wh	Solar Fraction	Max SOC	Ave SOC	Min SOC	Sellable Wh
JAN	16,611.00	0.00	0.00	16,611.00	100.00%	88.68	75.30	59.68	0.00
FEB	15,820.00	0.00	0.00	15,820.00	100.00%	99.63	85.48	68.95	0.00
MAR	14,238.00	0.00	0.00	14,238.00	100.00%	99.99	92.91	80.02	1,153.47
APR	12,430.00	0.00	0.00	12,430.00	100.00%	99.99	94.87	85.29	3,168.76
MAY	9,492.00	0.00	0.00	9,492.00	100.00%	99.99	97.31	92.38	7,283.47
JUN	7,119.00	0.00	0.00	7,119.00	100.00%	99.99	98.03	94.54	5,148.13
JUL	9,944.00	0.00	0.00	9,944.00	100.00%	99.99	95.30	88.66	2,894.19
AUG	11,865.00	0.00	0.00	11,865.00	100.00%	99.99	94.42	88.18	134.78
SEP	14,238.00	0.00	0.00	14,238.00	100.00%	99.97	93.44	84.37	0.00
OCT	18,193.00	0.00	0.00	18,193.00	100.00%	97.04	87.22	77.33	0.00
NOV	13,447.00	0.00	0.00	13,447.00	100.00%	94.88	81.55	65.76	0.00
DEC	16,611.00	0.00	0.00	16,611.00	100.00%	90.30	58.47	35.92	0.00
YEAR	160,008.00	0.00	0.00	160,008.00	100.00%	99.99	87.86	35.92	19,782.80

Solar Fraction | Battery SOCs | Performance Table | Annual Energy Cost Analysis | Lifecycle Financial Analysis

Figure 6-8: PV east array system performance

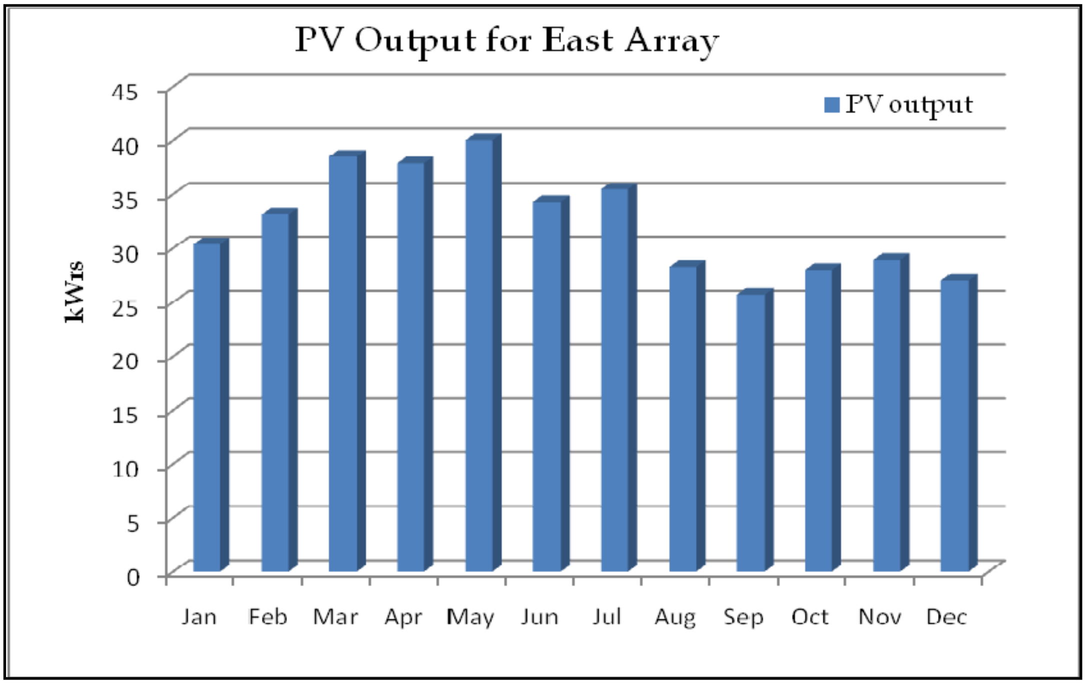


Figure 6-9: East array PV output

Results showing the solar radiation, array efficiency, Array Whrs, sellable Whrs, battery efficiency, and such other information were obtained for every hour in every month for the whole year. This data was then imported to excel for further analysis. Monthly Whrs for the east array was computed from daily data, and summarized in the form of a graph as shown in Figure 6-9. The maximum array output (Whrs) is for May, while the lowest output is for September. Overall for the east array, no month produced less than 25KWhr on average.

West Array simulation

For the west array, all the same parameters were used for the simulation, except that within the tracking method; fixed, and +90 were used for the west vertically mounted array. Again, just as with the east array, data on monthly radiation totals, daily performance charts, battery charging and discharging totals could also be obtained.

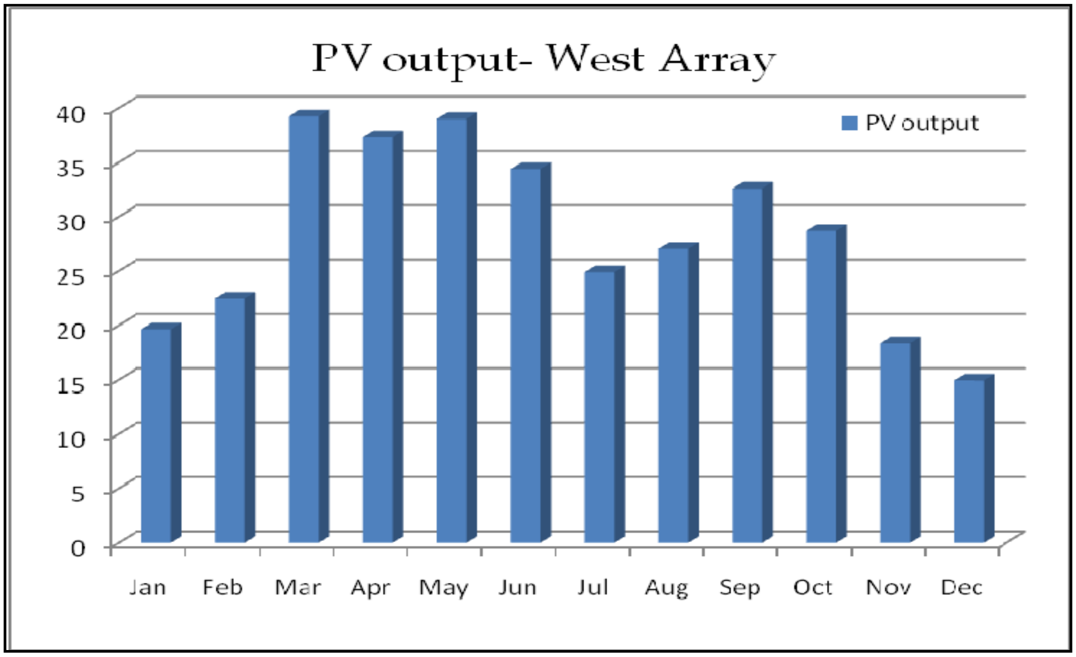


Figure 6-10: West array PV output

As seen in Figure 6-10, there was a slight variation in the output from the west array during July and August months (Note- during the analysis, it was observed that results produced by the software for the month of July, on 14th, time between 4pm-8pm seemed to be off the mark and really high. Although, some variances could be expected for the west array especially during sunset times, values should still be within reasonable ranges, below the maximum that could be produced by the panel and less than the solar radiation available at that time of the day. These values were hence changed to match a previous value from another day).

For the west array, the maximum output in Whrs was obtained from March through to June. Another point worth noting is that the values for July are much lower than the September and October. Although this is an unexpected result, approximation of data could also have an impact of the graphed data.

6.2.3 Array Output Summary

Table 6-2: Total array output against load demand

Months	**Total monthly array kWhrs**	**Monthly operational hrs**	**Total monthly kWhrs (load)**
Jan	50.00	132	27.98
Feb	55.59	120	25.44
Mar	77.69	115	24.38
Apr	75.15	88	18.65
May	79.00	46	9.75
Jun	68.66	44	9.32
Jul	60.34	46	9.75
Aug	55.34	92	19.50
Sept	58.29	110	23.32
Oct	56.68	138	29.25
Nov	47.24	132	27.98
Dec	41.91	138	29.25

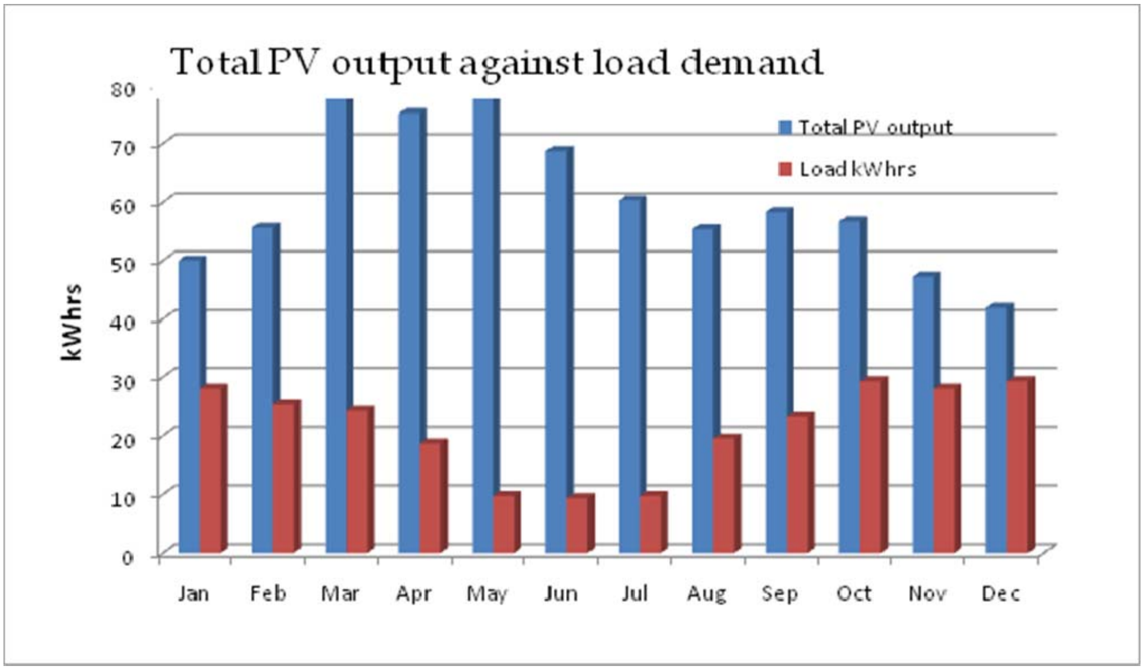


Figure 6-11: Total PV Output against load demand (in KWhrs)

Table 6-2 indicates the total monthly Watt-hours produced by the east and west array combined, monthly operational hours and the monthly load demand. Figure 6-11 indicates the total PV output against the load demand on a monthly basis. For obtaining the total output data graph, results of the east array output and west array output were combined in excel and then graphed. For obtaining the monthly load demand, average operational hours per month were taken, excluding weekends. This was then plotted against the array outputs.

As explained previously, the intention for this system operation was to combine the output from the arrays to charge the battery bank and hence supply the lighting loads, though they are monitored separately through different charge controllers. As seen in the graph, the summer months have the lowest load demand, while the winter months have the highest. As with the PV array, more power is obtained from the panels during the summer months; while during the winter months the panels do not produce as much power. Though, the power produced by the panels meets the lighting demand for this system, excess power is produced which is stored in batteries for future use. However, if the panels produce more than what the batteries can store, the charge controller automatically disconnects the array so that the batteries are not overcharged, as overcharging of the batteries could result in damage and ultimately reduce the life of the batteries.

For an evaluation of this DC system, firstly the design and construction challenges with this system for the Solar Decathlon house are presented in section 6.3. This system is then compared to a PV AC lighting system design under two cases by assuming certain parameters. For the first design case, the size of the PV array is reduced to match the load demand (1276 Watt-hours per day). For the second design case, the load demand is increased to match the PV array size (1.36kW). For this design case, fluorescent light sources are added along with a few LED sources. For the above cases, their costs and efficacy would be presented.

In summary, by studying the existing PV DC LED lighting system against an AC PV lighting system for two cases, (changing the load and PV array size) would help understand the relation between the load demand and the PV array in terms of costs and efficiency. Section 6.4 covers the cost, efficacy analysis and a payback analysis.

6. 3 System design and construction analysis

6.3.1 Discussion

Designing PV systems can be a complicated task for an engineer, especially without much experience and with limited resources available that focus on the integration of PV systems with the rest of the electrical/mechanical system design. Stand-alone systems pose further complications, especially since there is no grid back-up, and for this reason, batteries need to be highly efficient. One solution might be to slightly oversize the PV panels as seen in the previous section, to cope with the cloudy days and other inefficiencies within the overall system. However, PV panels are expensive and adding more panels demands more surface area, which is not feasible in all situations. Also the question then comes, where does the excess energy get stored? Although, the battery bank should be sized sufficiently to accommodate the variation in solar radiation and array output, this again is not possible in all situations.

This section of the chapter covers a detailed analysis of the design and construction details as presented in chapters 4 and 5. As part of this analysis, this section highlights the challenges encountered during the system design process, and during construction. Within these challenges, also noted are the limitations with stand-alone systems and DC systems, in general, along with code implications with the design.

1. <u>PV Systems are not yet common</u>

PV system applications are relatively new, especially BIPV applications. Hence, there are a lot of unknowns that still exist with the application of these systems.

Energy from the sun is unreliable as the sun's angle varies according to the latitude of the location during the course of the day. This makes placement of PV panels, or even estimating the exact energy produced by a PV panel during any given time of the year more complicated. Although, there are software currently available that compute the estimated solar radiation striking a PV panel, it is still not possible to accurately determine the exact energy produced by a PV panel through only computations. As seen in section 1, most of the information presented on array output is approximate. In any case, these systems pose challenges to an engineer due to the variability of energy available.

2. PV panels are expensive

The cost of PV panels is not yet affordable by the average population. Industry analysts predict, as the cell efficiency goes up, the prices might come down, and this might enhance the use of PV panels for all applications. However, one has to keep in mind the basic concept of "supply demand" as commercializing the use of these systems to a greater extent through better marketing strategies, and by increasing PV system applications, could ultimately increase the production of these panels, hence lowering the costs to meet the demand.

3. Code implications on PV systems

Code related issues and standards with PV systems could be better developed. At present, although the NEC covers some information on code implications relating to PV systems, some of this information is left for interpretation by the engineer. It is also important to make the code clear with PV systems for DC voltages although it is not common type for power distribution in buildings. This is partly because, since PV systems produce DC power, there is a potential scope for small scale standalone DC systems to be developed.

One of the major challenges during the course of design and construction of the solar house for Penn State was understanding the NEC code requirements for stand-alone systems. The code required disconnects to be placed at certain points for easy disconnection of supply. However, this was interpreted that disconnects were required at points where there could be a potential safety hazard due to the flow of power, and hence disconnects were placed at locations as indicated in the schematic in Chapter 4. Hence, clarity of code requirements for beginners is very important to ensure engineers are designing to appropriate safety standards.

4. **LED technology is relatively new to the market**

LED's are relatively new within the lighting industry when compared to most commonly available other light sources - fluorescent, metal halide, or incandescent. As discussed earlier in Chapter 2, anything related to the LED lighting technology that was prevalent even a few years ago, may not be the best solution to a lighting design problem today. The challenge lies in keeping up with the pace of this technology, and understanding LEDs thoroughly in order to apply them in applications best suited to their needs. Also, as the lighting industry speculates the potential development of high-efficient white LED's in the near future, the efficiency of an entire LED fixture is not yet comparable with an equivalent wattage compact fluorescent fixture.

In regard to the challenges encountered with the design of this system, selection of fixtures that could operate on DC voltages was tough, as manufacturers tend to sell their products for operation with AC systems. Again, since LED fixtures are not very common, procurement suited to the needs of a DC system was a difficult task.

5. LED fixtures are expensive

LED light fixtures are an expensive option when compared to other light sources such as fluorescent. Only when the lighting industry is revolutionized with the application of LEDs, and better efficient LED light fixtures are specified in most applications, will the prices go down.

6. 24VDC rated LED light fixtures are not common

LED fixtures usually operate on low voltages, and are commonly available as 12V fixtures. Though fixtures rated at 24VDC are available, they are quite rare. With the PV system being rated at 24VDC, the idea was to keep all the loads at the same voltage to avoid a voltage regulator. Finding DC rated 24VDC LED fixtures was a challenge.

7. Challenges with DC power

Challenges exist with using DC power for commercial applications; especially with power distribution in buildings. DC wiring cannot be run for large distances, without significant voltage drop, and hence power loss. For this 24VDC system design, slightly thicker copper wires had to be used, i.e. wires had to be upsized to adjust for any wiring losses. Voltage drop and wires that had to be upsized were presented in detail in Chapter 4.

Since DC voltages are not very common for power reticulation in buildings, a lot of contractors are still unfamiliar with the codes, standards and basic principles of DC power. When PV panels are involved, the system design gets more complicated with limited working knowledge of DC systems by engineers and contractors. For the Morningstar house, it proved to be a challenge to obtain guidance and advice on DC wiring methods.

8. Stand-alone systems and batteries

A PV based DC LED lighting system will always be a stand-alone system, as it cannot be grid-tied. Hence, as mentioned previously, batteries are then an integral part of the system. The typical lifetime of batteries is said to be 1 to 5 years, although they could also last as long as 10 years in many circumstances depending on the manufacturer. However, in any case, incorporating batteries within the system design means space issues and safety issues to be dealt with as batteries are potentially hazardous if not installed properly (European Photovoltaic Industry Association 1996). Also, batteries add extra costs to the system.

9. Construction challenges

(a) Power supply for LED fixtures – AC or DC?

Most of the power supplies for an LED luminaire today come with a transformer, to convert the low voltage produced across the LED, to line voltage across the luminaire. These power supplies can be either built into the fixture, or be externally mounted. This easy conversion of voltages, through a power supply, which is most of the times a compact device, indicates the rapid development of these tiny sources, not limiting them to just low voltage applications.

On one hand, though this might be an advancement of this technology, rarely are LED luminaires made to be used with a PV system and tailored to be part of a DC system. However, due to the rarity of the use of LED luminaires with PV systems on DC voltages, manufacturers generally do not sell their luminaires without an existing power supply. This again adds to the cost of extra equipment which might not be used, hence producing a redundancy of equipment on site. Another point to be considered here is that if an intermediate power supply (dc driver) is not used within the DC system design, this could result in variable current across the device, hence not being operational at certain times if the current being supplied is higher than the rating of the LED fixture. Since LED fixtures are highly tolerant to variable current, a dc driver and a voltage regulator should be in place to avoid complications.

The original design intent of the PV DC LED lighting system was to supply LED lights within the north facing clerestories, spotlighting applications within the mechanical room, site lighting including the landscape, and ramp lighting for the house as seen in Chapters 4 and 5. However, due to construction delays, time constraints and manufacturer related issues during the course of construction of the solar house in Washington DC, only the ramp lights were finally powered by this system. The LED lights within the clerestory were finally powered by the AC lighting system due to manufacturer related challenges associated with the DC power supply (PDM module) encountered during installation. . A power data module (intermediate power supply) is usually required to control the current flow to the LED light fixtures The Power data module could not handle its rate current during operation under DC voltages.

Also, as discussed earlier, the absence of a common dc driver for all the lighting loads, along with the current variations within the PDM module as described above, caused problems with the system operation, especially with the clerestory lights and the mechanical room spotlights. Summarizing, only when LED light fixtures are produced for compatibility with DC systems, will some of these driver related problems be avoided.

(b) *Placement of disconnects*

Code implications with the DC system design have been discussed briefly above. With the placement of disconnects at almost every point in the system design (see design schematic in Chapter 4), the intent during construction was to make it "fail-safe" while also following the code requirements. This however added to the costs of extra equipment that had to be purchased to supply a total DC load of less than 1kW. While this also created a contradiction to the original idea of reducing the equipment in a DC system, overall it added extra costs, time, and labor along with design and construction changes in the field.

For this system design, disconnects were used at the point of entry of main conductors within the building as required by the NEC code. Also, according to code, these main (PV) disconnects have to be visible without any object obstructing the access to them for maintainence and/or emergency shut-off in any residence or building that incorporates PV systems. As discussed in detail in chapter 4, since the incorporation of this system (DC system) was after the design decisions had been made for the main AC system, and the majority of the architecture of the building decided, these main disconnects were placed inside the house. Although this was undesirable, this occurred due to certain space constraints while also taking into account the code requirements of visibility of disconnects.

Overall, it is critical for an engineer to take into account all the existing code requirements associated with PV systems, whether DC or AC systems. As said earlier, though parts of the section 690 in the NEC might be unclear, proper interpretation of these codes along with guidance from an expert will result in better design decisions and would ultimately reduce problems during construction.

6.3.2 Summary

Although, it would seem that a DC photovoltaic system which is stand-alone and has a minimal load requirement would be easy to design and construct, this is usually not the case. Challenges are encountered when an innovative approach to a design problem is implemented without much experience. Issues related to costs, maintainence and code complications rise with extra equipment, and other uncertainties within the process.

In summary, to eliminate some of the above challenges, the objective of the engineering system design would be to integrate the electrical distribution system with the PV system efficiently, along with choosing energy efficient loads, which would ultimately produce a sustainable engineering design solution. The objective for the lighting part of the design is to strike a balance between energy efficiency and quality of lighting within the space.

6. 4 Costs and efficiency Analysis

6.4.1 Overview

Section 3 of this chapter covers a detailed cost assessment of the PV DC LED lighting system. Costs of the PV panels and the costs for the balance of system components have been summarized in a spreadsheet indicated in Table 6-3 attached. All the costs included within this table are the original costs of the items, and equipment without applying any discounted prices as obtained by the manufacturer. The main objective of a cost analysis was to firstly, to understand the costs associated with a DC LED lighting system, and secondly compare these costs with a stand-alone AC system design.

The cost analysis of this system design was performed in four main parts.

1. The actual costs of the DC LED lighting system was determined

2. Costs were estimated for a stand-alone AC system by assuming certain parameters, for two case scenarios presented later.

3. Simple payback is calculated for an improved DC LED lighting system design (with the best configurations) against a conventional grid lighting system.

6.4.2 Cost analysis

CASE -1 (Original costs of the DC system)

For the first part of this cost analysis, costs of PV panels, PV equipment, associated electrical equipment, wring related costs, and costs for lighting for the actual DC system were analyzed in a spreadsheet format to study the individual costs. Results of this are attached in Table 6-3 (a). A pie chart as shown in Figure 6-12 was plotted to indicate the cost percentages by different components within the system design.

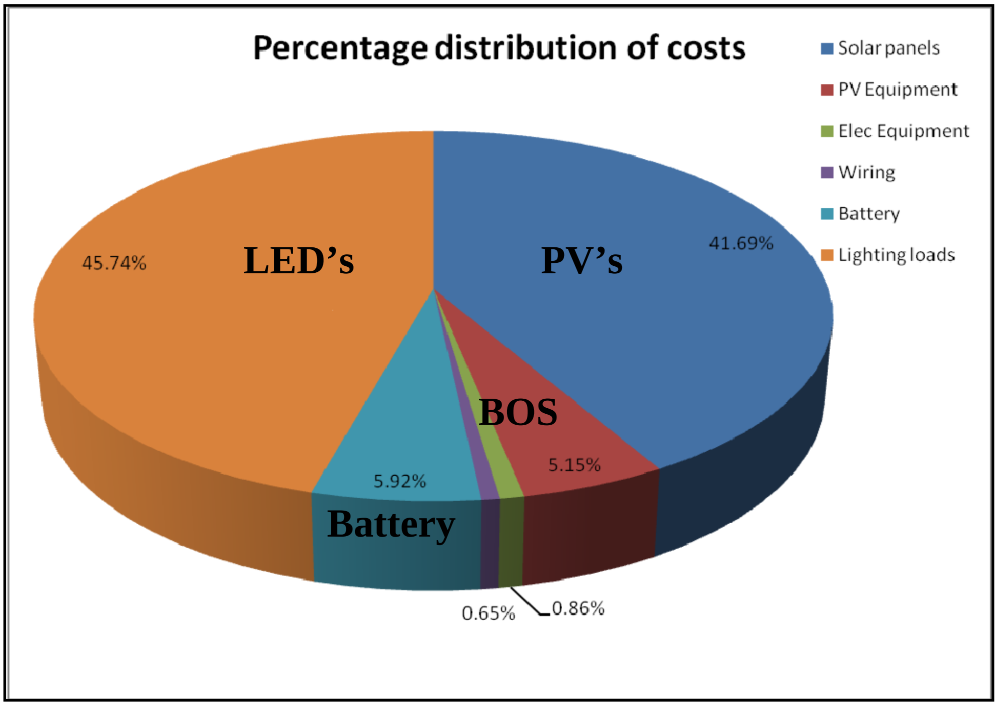


Figure 6-12 Percentage distribution of costs for DC system

As seen in the graph, the maximum cost share is by the lighting loads, while next is by the solar panels. As discussed earlier, in section covering the challenges with a DC system, LED light fixtures and solar panels are the most expensive within the system design. From research and current industry trends, it can be said that though the cost of LED fixtures are high today, the percentage of cost reduction in LED's is faster than the reduction in costs of PV panels.

AC lighting system Cost Analysis Scenarios

To determine the costs of an AC lighting system, the following two case scenarios were used:

- The DC load demand was kept the same (1276Whrs as seen in Chapter 4), while the size of the PV array was determined, and an overall cost of the system was estimated. The lighting loads were kept to be the same LED light fixtures from the DC system design.

- The PV array size was kept the same (1.36kW arrays) while extra loads were added. As seen earlier in section 6.1, excess power was available which could be potentially used to supply more loads. In this case, lighting loads could mixed – LED's, and fluorescent fixtures.

The main purpose of having two scenarios for estimating the costs of an AC system design was to determine the cost-effective system and efficient design solution with an AC lighting system against a DC lighting system with LED's. As seen in the first part of this analysis, excess power was produced by the PV system, and this could potentially supply more loads. Hence, by changing the two most important parameters within a PV system – load demand and array size, a cost-effective result could be predicted. These cases presented in the cost and efficacy analysis help understand how the costs and efficiency of PV panels and lighting loads can impact the overall performance of a PV LED lighting system.

Table 6-4: Costs and Efficacy analysis

Analysis	Cases	Costs and efficacy
Original PV DC LED lighting system for the Solar Decathlon house	Part -1(CASE -1)	Actual DC system costs
Comparitive parameters to study the original system design by varying the PV panels first and then the load demand	AC LED lighting system (CASE - 2)	PV panels reduced to meet demand with some spare capacity (36 panels) LED lighting loads the same (1276Whrs) Inverter required
	AC lighting system (CASE - 3)	PV panels kept the same (1.36kW) Increased lighting demand (1700Whrs per day) Added CFL and LFL sources with LED's (inverter required)

CASE 2

<u>Lighting load demand is the same (light sources are LED's), PV array size is reduced (panel type the same, array size reduced, orientation changed)</u>

Some of the assumptions for a typical AC stand-alone lighting system in order to calculate the costs estimate are as follows;

- Load demand is 1276Whrs or 38kWhr per month

- Loads are LED light sources

- Lowest sun hours per day in State college Pennsylvania: 2.79 (Advanced Energy Group, 2008)

- Average sun hours per day in State college Pennsylvania: 3.91

- Sizing the PV array for the worse case; 1276/2.79 = 457 Watts appx need to be met

- PV array orientation and number of panels: South (30 deg), and 36 panels with 3 in parallel, and 12 in series.

- PV panel type : Atlantis energy systems (same as original), 14.26 watts each at maximum power point

Assuming only one array facing south at 30 degree orientation while also making some provision for efficiency losses and for some excess storage during winter and cloudy days, the PV array could be sized to be rated to ***512Watts.***. The same PV panel is used for this case, except that the orientation is now south and tilt is 30 degree with continuous tracking. This is a very basic assumption for this analysis without taking into account the actual daily Watt-hour production by the panels.

For estimating the size of an inverter, wattage rating of the PV array was multiplied by 1.25 to accommodate for losses, and protection. Hence, size of the inverter was estimated to be 640Watts.

For cost estimate of this system, the same solar panels which were used for the DC system were used; hence the price per panel was the same. For estimating the price of the inverter, $1 for every watt was estimated. Hence the price estimate of the inverter was $640. Changes in associated wiring and electrical equipment are taken within this cost analysis. Costs associated with the power supply/external transformer for LED fixtures were also added to this cost analysis. Table 6-3 (b) attached summarizes costs for this case.

CASE 3

Load demand and light sources are changed (fluorescent and LED's), PV array (size, orientation) is the same

For this scenario, the PV array size was kept the same as the DC system, i.e 1.36kW for two arrays with the same panel type. To calculate the cost estimate for this scenario, extra mixed lighting loads were added to the system.

Compact fluorescent and linear fluorescent fixtures were added to increase the load demand, and to meet the excess power produced by the panels. Components within the system that changed were hence, the lighting loads, and equipment related to powering these loads. As a rough load estimate, 1700Whrs (fluorescent and LED light fixtures) was assumed to be the load demand on a daily basis.

In terms of getting a cost estimate for these lighting loads, assumptions below were made: (Cost estimates were then calculated for this scenario, and reflected in Table 6-6).

- Total Watt-hours: 1700 appx

- Compact fluorescent light fixtures: 5 fixtures at 20W each; Cost: $80 each

- Linear fluorescent fixtures: 2 fixtures with 2 lamps each at 32W. (2x32W); Cost: $140 each

- LED light fixtures: (Site fixtures): 3.5W each, 8 fixtures, Cost: $220 each with a power supply included.

Table 6-3 (c) summarizes the costs for case 3.

6.4.3Discussion

Costs for the original DC system (case 1) were then compared with the AC system design cost estimate (cases 2 and 3) for the above scenarios. The cost analysis is shown in spreadsheet attached while the results are summarized in Table 6-5.

Table 6-5: Summary of results from Cost analysis

SYSTEM TYPE	COSTS ($)
ORIGINAL DC SYSTEM (CASE1)	$25,586.37
PV AC LED LIGHTING SYSTEM (CASE 2)	$19,463.32
PV AC LIGHTING SYSTEM (CASE 3)	$17,317.22
COST DIFFERENCE (original DC system – PV AC LED lighting system)	$6123.05
COST DIFFERENCE (original DC system – PV AC lighting system (fluorescent and LED fixtures)	$8269.15

6.5 Simple payback Analysis

Improved PV DC LED lighting system design:

For determining the cost effectiveness of a PV DC LED lighting system, improvements to Case 1 (original PV DC LED lighting system) have been made. Changing the panel orientation to south, and type while meeting the load demand (1276 Watt-hours per day) would result in a more efficient overall system design. Parameters as shown in Table 6-6 have been assumed for a best configuration of a PV DC LED lighting system.

LED fixtures chosen for the Solar Decathlon house were expensive (Color Kinetics and Lightwild) with their cost being around $15/ (lumens/watt). However, assuming the cost of LED's around $8 / (lumen/ watt) for cheaper fixtures would be more reasonable considering the progress of LED's within the lighting industry. Hence assuming the average cost of LED fixtures to be approximately $150 seems more logical for this analysis. PV panels chosen for the original system were also expensive (Atlantis Energy systems). Hence, as a substitute BP Solar panels, with a wattage rating of 125 Watts each under standard test conditions have been chosen to form an array rated at 512 Watts which should be sufficient to meet the load demand. Since, the orientation is south; this should improve the overall performance of the system. Load in Kilowatt hours per day is hence 1.276kWhrs, 38kWhrs per month, and around 459 kWhrs per year. Assuming $5 per watt for the new panels also seems reasonable for this 0.5kW system with more efficient panels and cost at market rate, compared to $9 per watt original PV system (1.36kW at $10,800).

Table 6-6: Improved PV DC LED lighting system with best PV array configuration

Design load demand	1276 Watt-hours
PV panels	4 panels (2 in parallel, 2 in series) 124 watts rating per panel
PV orientation	South at 30 deg
Type of PV panels	BP Solar
Total PV array size	512 Watts
Cost of PV's (assume $5 per watt for average panels)	512 watts x $5 = $2560
Cost of Balance of system components	$1000
Cost of batteries	$1500
Cost of LED light fixtures (cost estimate for average LED fixtures)	$4500
Labor	$2000
Cost of maintainence (after 25 years for PV's and battery replacement every 15 years)	$1000
US Federal incentive	$2000
Cost of entire system (after incentive, without tax credits for state)	$9560

For calculating the payback of a PV DC LED lighting system against a conventional non-PV LED lighting system, the following parameters have been assumed for the conventional non-PV lighting system design.

Table: 6-7: Conventional non-PV grid LED lighting assumptions

Design load demand	1276 Watt-hours
KWhrs per month	38kWhrs
PV panels	- None -
First cost of residential electric system estimate (breaker panel + LED light fixtures+ Misc wiring and labor)	$4500
Cost of electricity (average)	$0.17/kWhr
Cost of electricity per month (first year):	$6.46
Cost of system cost (First year, incl electricity costs for one year)	$4578
Electricity rate of rise (per year)	4%

Payback Analysis:

For a basic payback analysis, without any inflation, the payback period would be the total cost of the PV system divided by the savings per year in electricity costs. The total cost for electricity yearly is approximately $100, which would be met 100% by the new improved south facing PV DC LED lighting system design.

Considering the increase in fuel costs and electricity rates, it is likely that the cost of electricity would also go up every year. A conservative number of 4% increase has been estimated for this. Table 6-8, attached spreadsheet shows a simple payback analysis of the stand-alone PV DC LED lighting system. As seen in the table, the simple payback is **33 years** before any costs for the PV system are recovered.

It is to be noted that, typically PV panels have a warranty of 25 years before their efficiency goes down with discoloration of the protective glass over the PV cells. PV panels do not wear out, but however, their efficiency reduces depending on the panel make and manufacturer. Hence, it can be said that theoretically, the payback of this PV DC LED lighting system is **33 years**, without taking into account any efficiency losses and maintenance charges over time and under test ideal conditions (Seacoast Consulting Engineering, 2007). In a typical stand-alone PV system, though the panels themselves require cleaning, batteries require maintainence and replacement every 12-15 years depending on the manufacturer's warranty.

From the cost analysis it can be said that first costs for PV DC LED lighting are high owing to the expensive PV panels and LED light fixtures. It can also be said the costs in any stand-alone PV system are high for the panels and loads. Improvement in the efficiency of these panels and LED fixtures in the near future would reduce their capital costs along with their increased use. Overall, though the payback for the PV DC system is **33 years**, it could be worth the investment considering that such a system is good for the environment and can make a difference in energy costs in the future. Such a decision for investment upfront is however the choice of the home owner.

6.6 Efficacy of a PV lighting system

Efficacy of a stand-alone PV lighting system is "expressed as the lumens per watt of the solar energy arriving at the PV panels" (Zhou and Narendran 2005). To determine this overall efficacy of the lighting system, individual efficiencies of components have been taken into account.

Efficiency ratings can be obtained from manufacturer's recommendations for that particular equipment or can be estimated based on typical efficiency losses for certain equipment. According to the document "NLPIP Lighting Answers: Photovoltaic Lighting", by the NLPIP in conjunction with the LRC, the total efficiency of a photovoltaic lighting system is generally associated with the efficacy of the light sources, and efficiencies of other equipment down to the wiring back to the loads (National Lighting Product Information Program 2005).

Zhou and Narendran summarized, in their paper, "Photovoltaic powered lighting emitting diode systems" in 2005, the basic formula in calculating the efficacy of a stand-alone PV lighting system as follows:

$$E = \text{Ø} / P \qquad (6\text{-}1)$$

Where, Ø = light output from a PV panel system (in lumens)

P = Input solar power (in watts)

$$Ø = P * \eta_{pv} * \eta_{bat} * \eta_{ele} * \eta_{lum} \qquad (6\text{-}2)$$

η_{pv} = Efficiency of a PV panel

η_{bat} = Efficiency of the batteries in the system

η_{ele} = Efficiencies of electrical equipment and PV equipment in the system (expressed as a percentage)

η_{lum} = Efficiency of the luminaire (expressed in lumens/watt)

Using the methodology stated by Zhou and Narendran to estimate the overall system efficacy, efficiencies of LED light fixtures have been used for the DC lighting system, while efficiencies of various light sources have been used for the AC lighting system.

For a system with only one light source, be it LED's, CFL, LFL, or halogen, η_{src} is the efficiency of that light source, and η_{lum} is the efficiency of the luminaire comprising of the light source. For LED's, the later might differ hugely against the former number, since the efficiency of the LED luminaire might vary vastly against the actual LED.

Calculations for estimating the efficiency of the DC system as well as the AC system are listed below.

DC System – Case-1

1. *Firstly, the efficiency of the PV panels is determined:*

Efficiency of the PV Panel is determined by taking into account the peak sun intensity, and the total module area along with the PV output rating (Makofske 2004).

- Assume peak intensity of the sun (maximum) is 1000 W/m^2
- Maximum Watts from the PV panel is: 14.26 (See datasheet in Appendix B)
- Module area: 0.13 m^2
- Actual module efficiency: $P_{actual\ peak}/P_{maximum\ peak}$

Hence, assuming 100% efficiency at maximum output P = I x A = 1000 x 0.13 = 130

Efficiency of the panel: 14.26/130 = 10.9% efficient (Note: This is the efficiency of the panel to indicate how much solar energy arriving at the panel is converted to electricity. This number might vary with temperature and other conditions).

2. *Typical efficiencies of batteries within a PV system* are nearly 80% (HMSO, 2002)
3. *Efficiencies of PV and electrical equipment:*

- Chapter 4, table 4-3 presented detailed calculations on the voltage drop, wire sizes and power losses present within the system associated with wiring. Hence, the overall power loss within the system is approximately 71.23Watts, or 5.94% losses of the total rated kW of the system. Hence the efficiency of all wiring is 94%.

4. Efficiency of charge controllers

- According to the manufacturer's efficiency ratings, the charge controller, TriStar-45 has a series resistance of ~10.7mohm when the MOSFETS (commonly used field effect transistor in digital and analog circuits) are cool. When the MOSFETs junction temperature reaches 80C, the resistance increases by a factor of 1.5. Since, the charge current from each array at 80C junction temperature is 32A, the power loss would be determined as follows:

  Power loss: $32^{\wedge 2}$*R = 1024 * 0.00533 * 1.5 = 8.1 Watts which is less than 1% loss from the charge controllers. Hence, efficiency of the charge controller is taken to be 99%.

5. Efficacy of the luminaires

- LED spotlights (Colorburst) : 11.9 lumens/watt
- Icolorcove QL (Clerestory lights): 14.4 lumens/watt
- Project linears (Lightwild): 16.54 lumens/watt

  For an overall efficiency of the LED luminaires, an average lumens/watt of all the three light fixtures was taken: 14.28 lumens/ watt

(Input solar power (P) in this case is: 1200 Watts (1.36kW) or PV array rating)

Ø = 1360 x 10.9% x 80% x (94% x 99%) x 14.28 (lumens/watts)

E = Ø/P

Therefore, E = 1.158 lumens/watt

Case-2 AC lighting system (LED's only)

A quick calculation of the efficacy of the AC lighting system using only LEDs, which also had fewer PV panels, yields the following:

(Note: The input solar power is 512 Watts (0.5kW), which is the PV array size)

Ø = 512 x 10.9% x 80% x 94% x 99% x 85% x 14.28 (lumens/watts)

E = Ø/P

Therefore, E = 0.984lumens/watt

AC System with mixed light sources (Case-3)

For calculating the efficacy of the stand-alone AC lighting system Case-2 with mixed light sources (compact fluorescent, linear fluorescent and LED's); the following has been assumed:

- Efficiency of the PV panel: 10.9%
- Efficiency of batteries: 80%
- Average efficiency of electrical equipment: 94% (since most the equipment is the same as the Case-1 DC system design)
- Efficiency of an inverter: Assume 85%

For determining the efficiency of an AC lighting system, Case-2 presented in the previous section has been considered. To obtain the system efficiency of a PV lighting system with mixed light sources, an average lumens/watt has been taken.

- Average efficacy of fluorescent light fixtures is: 65 lumens/watt
- Efficacy of LED fixtures is:16.54 lumens/watt (one type of LED fixture)
- Efficiency of electrical/PV related equipment: 94%

(Note: The input solar power is 1360 Watts (1.36kW))

Since, $Ø = P * \eta_{pv} * \eta_{bat} * \eta_{ele} * \eta_{lum}$

$Ø = 1360 \times 10.9\% \times 80\% \times (94\% \times 99\% \times 85\%) \times 65$ (lumens/watts)

$E = Ø/P$

Therefore, E = 4.48lumens/watt

6.7 Performance Summary

Comparing the efficacy calculations for all the three cases as presented above, the best performance in terms of efficacy from all the three cases has been obtained from the scenario where the AC lighting system had mixed light sources (fluorescent and LED's). In this case, the efficacy, "expressed as the lumens/watt of the solar energy that arrives at the PV panels" is 4.48 lumens /watt. One thing to be noted is that the PV panels selected for the original design, which have been kept constant throughout the design scenarios, have an efficiency rating of only approximately 11%. Although the efficiency of commercially available PV panels is typically around 15%, a more efficient solar panel could be substituted for the existing one.

Case-2 AC system that had only LED fixtures had a much lower efficacy, accounting to the inverter efficiency for this system. Case -3 AC system also had an inverter, but had a better efficacy overall, owing to the mixed light sources selected. Case 1, the DC LED lighting system had an efficacy of 1.15 lumens /watt.

6.8 Summary

To test the PV DC LED lighting system, firstly the output from the PV panels for the original system design was tested. Secondly, a cost analysis for the DC LED lighting system was carried out and compared against an AC lighting system for two cases; an AC LED lighting system and second, an AC lighting system with fluorescent and LED fixtures.

From the results, it can be seen that the original design of the DC LED lighting system was the most expensive option, considering that expensive LED fixtures and panels were chosen for the Solar Decathlon house. The most affordable option based on capital costs, would the PV AC lighting system with mixed light sources. The cost of the AC LED lighting system, case 1 was approximately $19k, mainly due to the reduced number of panels required with orientation being south. From the efficacy analysis, the

PV AC lighting system with mixed light sources seemed more efficient. Overall, as a result of the payback assessment of the improved PV DC LED lighting system with the best configuration, it can be said that such a system will a good choice in the near future. Summarizing the results from this analysis, the following solutions if implemented would make an impact towards the improvement of such a system.

Solutions for a better future system design

1. One potential solution for a PV DC system design would be to increase the load and add other DC rated loads such as DC rated appliances and motors along with LED fixtures.

2. As seen in the analysis, clearly a good orientation makes a difference in reducing the quantity of panels required to produce power. South orientation is the best suited for a PV system. Having a tilt further improves the power generation capacity.

3. Efficient and affordable lighting loads are very important for the performance of a PV DC lighting system.

4. Some of the disconnects that were specified within the original system design could be eliminated, while still retaining the main disconnects for the PV panels. Also, combining the charge controllers, having only one array that faces south at an optimum orientation angle could certainly have an impact on the overall performance of the system.

5. Development of LED light fixtures to ensure proper operation with DC voltages when coupled with photovoltaics is another potential solution for the future. Future research on LED's should also be focused not only on improving the efficiency of LED's, but to also make them efficient for operation with DC voltages so that they can be applied in BIPV applications successfully.

6. For the system design for the Solar Decathlon house, different components of the DC system had to be purchased separately and then combined together as a traditional installation. This resulted in problems associated with the intermediate power supply for LED fixtures, expensive panels, expensive light fixtures, and code issues.

An integrated design approach, where the system could be purchased as an integrated product with PV's (similar to the streetlight example in Chapter 2) would help market the PV DC LED lighting application more efficiently and would reduce some of the above challenges faced with a traditional design scheme. Such an approach where the system could be purchased by a home owner as a product would help reduce costs, eliminate code issues after purchase, would decrease labor costs, and would also help increase the system efficiency.

In summary, considering that LED's have a great potential when used with photovoltaics, an integrated approach is essential. Creating a market for such systems through implementation of such systems would bring down costs and improve efficiency.

Chapter 7

Conclusions

7.1 Conclusions Summary

This thesis presented the design and construction of a photovoltaic DC LED lighting system for the Penn State Solar Decathlon house. The main goal of this research was to study the effectiveness of this stand-alone system by mainly assessing the system design and construction process. As seen in the literature review, photovoltaic lighting system applications are not very common and can be an expensive option when compared to conventional lighting systems. Using energy efficient light sources, along with reducing the overall energy demand (W/m^2) of lighting within an installation can produce an effective system design. The prediction by researchers is, although fluorescent light sources are established to be the energy efficient light source today, LED's present a new opportunity in further limiting the energy demand due to their low energy consumption.

Existing installations on PV LED lighting systems are very rare and on a small scale. Review of the available literature on PV lighting systems suggests that knowledge on using LED's as light sources with PV systems, costs, long term performance and analysis on payback of such systems is very limited. As seen in the literature review, LED lighting technology is rapidly evolving. In the current market, light output from

LED light fixtures is not yet comparable with fluorescent light fixtures, for the same wattage though is getting close. However, if comparable light fixtures are available, costs of such fixtures are very high and not affordable in PV lighting installations where payback is important. Using LED's with photovoltaics, however presents a new possibility in the use of this technology within sustainable lighting design. Considering the demand for research on LED's and their applications is higher now than ever, utilizing them in a photovoltaic lighting system tests the possibility of a new kind of sustainable lighting solution. The prospect of such an application calls researchers to study the current photovoltaic market and LED lighting systems.

This research attempted to study such a system through its design and development. Furthermore, this research also tested the possibility of photovoltaics and LED lighting on DC voltages, which is a common point in both the technologies. As part of the test method, an AC lighting system was used to provide a comparative analysis against the DC photovoltaic LED lighting system.

As presented in the results section in Chapter 6, the main parameters used for the evaluation of the DC LED lighting system were; the performance of the PV arrays, ease of design and construction of this system, system efficacies, a detailed cost analysis and a simple payback assessment. For an effective evaluation, this system was compared to a fabricated AC lighting system under two case scenarios, one where the system would have mixed light sources with no changes to the PV array, while the other case where the system would have only LED light sources, with a smaller array and south orientation.

As seen in the PV output simulation results, the combined output of the original PV DC LED lighting system array (east and west) was sufficient to power the load, while excess power was available during the summer months. It could also be said that the vertical orientation of the east and/or west arrays is a possibility when *load demand is very little and not critical*. When comparing the costs of the DC system against the AC system under the two scenarios stated previously, the case with the stand-alone AC system having mixed light sources with an increased load demand proved to be a more affordable option considering only first costs. Making improvements to the original PV DC LED lighting system design and comparing it against a conventional grid non-PV LED lighting system for payback, indicated that the payback was **33 years**. Comparing the improved PV system against a conventional lighting system with fluorescent fixtures only could yield a longer payback time as the first costs for fluorescent fixtures is less compared to LED's.

Photovoltaic system applications using DC power are not very common considering the losses during transmission of DC power over long distances. Though grid-connected systems are more likely to be used in urban areas, stand-alone systems present a possibility within rural areas. With regards to lighting systems coupled with photovoltaics, today there are more options available in selecting light sources there were a decade ago. Results from this research suggests, the LED lighting market is growing rapidly; though not yet at a rate competitive enough against fluorescent light sources when used with photovoltaics today. Factors such as affordability, efficiency and development of better standards are critical for the success of PV LED lighting systems in the future.

7.2 Research contributions

This thesis aimed to bridge the existing gaps in PV lighting applications while presenting an evaluation of a DC LED lighting system. From the review of the existing literature, it can be said that the research available on PV lighting systems is very limited. Current research on LED's focuses on the development of high brightness and efficient white LED's but rarely on the effectiveness of the application of LED light fixtures in general and special lighting applications with photovoltaics. This research identifies the possible development of this technology by highlighting its potential use with photovoltaics. Some of the research contributions are;

1. Identifying the challenges with the development of a photovoltaic DC lighting system application
2. Identifying the challenges with the design and construction of a stand-alone photovoltaic LED lighting system
3. Presenting a cost-analysis of the DC LED lighting system along with the potential for payback
4. Presenting an evaluation of the efficacy of a DC LED lighting system

Through this research, a new outlook towards PV lighting system applications is presented. Evaluations presented within this research could be used in understanding PV lighting systems better for future applications.

7.3 Research limitations

Some of the research limitations have been identified as follows;

1. *Limited results due to the challenges during design and construction process of the DC system*

   During the design and construction of the system, certain challenges were encountered, which resulted in the limited operation of this system. Hence, most of the results presented in the analysis are based on the design schematic and design development phase and not based on actual performance data.

2. *AC lighting system assumptions*

   There have been certain assumptions made while evaluating the AC system design against the existing DC system design which could lead to limited research results. The DC system has been built as a full-scale residential lighting application. However, for evaluating the AC system, certain design parameters have been assumed for the case scenarios presented. Actual full-scale construction of the two cases of the AC system would lead to a more comprehensive analysis.

3. *DC lighting systems are limited*

This research focused on a DC lighting system design which is not common in commercial or residential scale photovoltaic system applications. Limited knowledge is available on DC systems which can further complicate the implementation of such systems.

4. *Costs and efficiency of the LED light fixtures selected*

Including the efficiency and costs of the light fixtures within the cost, payback and efficacy analysis is important for a detailed study of the PV system. Light fixtures selected for the original system design may not necessarily be the most inexpensive fixtures and fixtures were chosen based solely on the application. It could also be possible that more efficient and more cost-effective fixtures are available for the intended lighting application or will be available in the future.

7.4 Future Research

Some of the research areas that require further efforts and have scope for future development have been identified. Evaluation of the operational performance of the systems could be one aspect where further analysis could be done. Obtaining results from measured data on full-scale built systems, AC and DC could yield detailed and more practical results for system efficiency. Studying stand-alone systems that have mixed DC loads (lighting, appliances etc) could be another aspect where research could be focused. Stand-alone photovoltaic systems present a new scope to sustainable design where grid-connection is not a possibility, or is not a cost-effective option.

Further research on LED lighting system applications with photovoltaics on grid-connected systems could be performed as another aspect to this analysis. Photovoltaic lighting systems do present a new perspective to sustainable lighting design. While LED light sources may not be comparable with fluorescent light sources today in terms of ***cost or performance,*** they have a huge potential for future success in energy efficient lighting design when applied effectively in PV systems.

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Appendix A

Penn State Solar Decathlon house

Figure: A-1 A photograph of the Penn State solar house in Washington DC

Solar Decathlon is an international competition held every two years, (the first one was in 2005) in Washington DC. Universities from all over the world participate in this competition to design, and build a completely solar powered house. The house would then be on display for the public and for judging based on ten contests set by the Department of Energy (DOE). Full information on the Penn State's solar decathlon entry, and detailed information on the engineering systems in the house, or the architecture of the house, is available on www.solar.psu.edu. The house will be on display for public tours and educational research on the Penn State campus in 2008.

Penn State's Solar house Design Concept

The main components of the solar house included the technical core, the living space and the breezeway. The technical core included the mechanical room which contained all the mechanical equipment in the house, a kitchen, and a bathroom. This core, also called the "brain of the house" is designed utilizing skilled labor to be a prefabricated unit which could be shipped to any location in the world. The living space is designed to be the "heart of the house." This unit is designed utilizing locally available sustainable materials with unskilled labor giving an opportunity for local people to learn and understand the process. The component that connects the living space with the technical core is the breezeway, which helps the flow of air through the house also allowing daylight to enter the house.

The roof consists of an 8kW array (a fixed and an adjustable array) to supply most of the electrical, HVAC and lighting loads in the house. This system consisted of lead-acid batteries for a back-up. Some of the features in the house include; an energy dashboard, which predicts the energy consumption of HVAC system, appliances, and lighting in the house. This dashboard would help an occupant monitor his/her energy use and hence would help them to plan their day ahead and also be more conservative of their energy needs. In terms of materials used, Morningstar Pennsylvania utilized local materials such as the Pennsylvanian black slate, which is 60 years old, and is reclaimed from a building in York, Pennsylvania. Most of the wood in the house is sustainably harvested and is made up of cherry, white oak and elm.

Another very interesting feature in the house is the movable wall which separates the living space from the bedroom. A milk bottle wall on the south façade forms adds to the layer of thermal mass and is part of the passive solar system for the southern façade of the house. The south façade also had exterior sliding panels which could act as a shading device if required. Figure A.2 shows the exterior sliding panels which add to the aesthetics of the space, along with being a shading element.

Figure A-2 Photograph to show the exterior sliding panels of the house

Lighting Strategy and concept

"Let there be light and color in every other home – Penn State's Lighting Design team"

Solar houses and issues pertaining to green design are increasingly becoming popular as we are now able to define the term "sustainable design" better than we could a decade ago. Integrating energy efficient luminaires into the architecture with ease of controls is very important for the overall flexibility of the space.

LIGHTING DESIGN GOALS:

Morningstar's lighting concept is to focus on three main goals:

1. Energy efficiency
2. Aesthetics and
3. Ease of lighting controls

DESIGN STRATEGY:

Penn State's lighting strategy was to achieve its goals by splitting the lighting concept into two main design systems: – Photovoltaic based AC system supplied primary lighting for the house which is more functional and provides ambient lighting, while secondary lighting included LED lighting for exterior/accent lighting applications.

Maximize Daylighting: High levels of both daytime habitiation and passive daylighting combine to increase the value of the daylighting strategies while saving energy and improving living quality. Appropriately placed skylights in a North-south axis provide adequate ambient lighting in the living space, the Breezeway and kitchen also allowing for proper integration with electric lighting when required. North facing clerestories provide for good levels of daylighting and ventilation. These clerestories have aerogel filled translucent panels which helps diffuse the light better. Linear LED lights supplied by the DC system are sandwiched between these panels to provide for accent lighting during evening.

Explore LED Lighting and DC Power through a Dedicated DC LED lighting system: Solar panels typically produce DC power. Utilizing this DC power produced by the panels to supply exterior/accent LED lighting in the house is an innovative design concept which will thereby reduce losses in the system due to an inverter. Also utilizing LED's, which can operate on DC input power decreases the total connected load on this system due their low power consumption. This system also avoids the need for an intermediate power supply which would otherwise be required typically when designing a system using LED's. Implementing this synergistic energy system will serve to assess the DC power needs of the home.

Implement Advanced Lighting Controls: Energy use reduction is addressed by incorporating dimmers on the lighting control systems to create "scenes" of minimal but appropriate lighting levels for specific activities or time of day to create a mood for lighting in that space. Using an advanced system like the Radio RA controls, not only reduces the associated wiring during installation, but also provides for flexible controls using a Master Controls panel. This system utilizes radio frequency waves to provide wireless communication between systems in the house. This system could be customized easily by adding additional components if required, such as a car visor which helps the occupant turn on/off their lights from their car, a cordless tabletop controls, or even have an interface with a telephone.

Develop Weather-Based Lighting Controls to obtain occupant feedback: Solar energy production is intimately related to weather. Our lighting design explores how occupants can be alerted to good, average, and poor solar days based on web-based weather data. Our lighting design is linked to the energy dashboard to obtain weather data from accuweather. The LED lights in the clerestory not only provide accent lighting to the house, but do so by also engaging the occupant to understand the weather better by visualizing this change of colors in the lights.

Deploy Diverse and attractive Luminaires: Advancements in luminaires, ballasts, and lamp design create new arrangement opportunities using a diverse set of luminaires to introduce light in innovative ways while improving overall energy efficiency. Our design experiments with a diverse set of the latest energy efficient lamp sources. Light sources such as Compact fluorescent and linear fluorescent with warm color temperatures were utilized throughout where decent amount of ambient lighting was required. Halogen and LED sources were utilized where accent lighting was required. A sleek 9W warm white LED desk lamp is used to provide task lighting on the desk, which is part of the movable wall feature in the house.

Appendix B

Equipment Datasheets

PDFs of datasheets of the following equipment are attached.

1. PV panel
2. Charge controller
3. Batteries
4. LED light fixtures

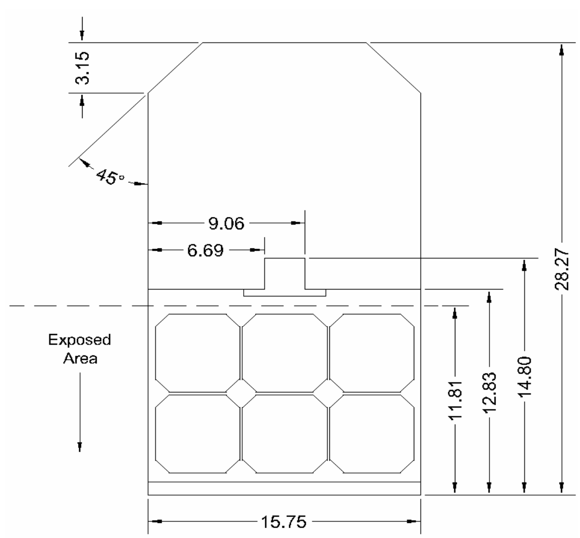
Atlantis Energy Systems, Inc.
Sunslates® Product Information

All Specifications at Standard Test Conditions (STC): 1000W/m^2 Irradiation, 25°C Cell Temp, 1.5 Air Mass
Each Sunslate has six crystalline photovoltaic cells connected in series

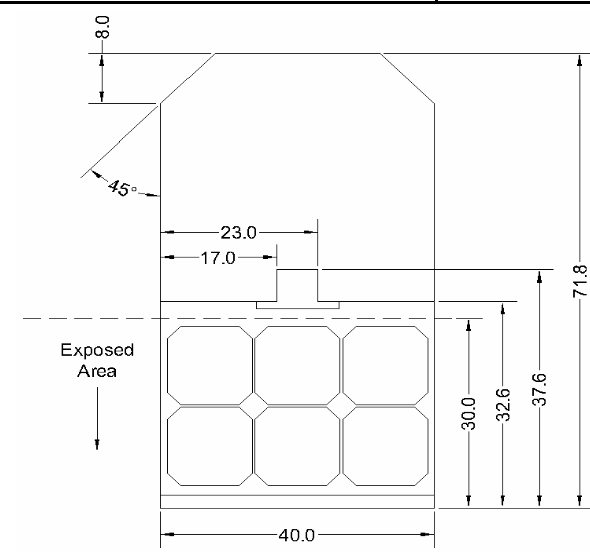
Model	Pmax Watts @ Max Power Point	Vmax Volts @ Max Power Point	Voc Open Circuit Voltage	Imax Amps @ Max Power Point	Isc Short Circuit Amps
Q Cell - 5" Poly	14.26	2.98	3.70	4.78	5.14

NOTE: Voltage, Current and Power Output Numbers are Estimated and Will Be Confirmed by a Qualified Testing Facility

American Units		Metric Units	
Exposed Area Per Sunslate	1.29 ft^2	Exposed Area Per Sunslate	0.120m^2
Used Area Per Sunslate	1.32 ft^2	Used Area Per Sunslate	0.123m^2
Pounds Per Roofers Square (100 ft^2)	750	Kilograms Per m^2	36.6
Slates per Roofers Square (100ft^2)	75.75	Slates per m^2	8.13
Watts per Roofers Square (100ft^2)	1080.1	Watts per m^2	115.9



Dimensions in Inches



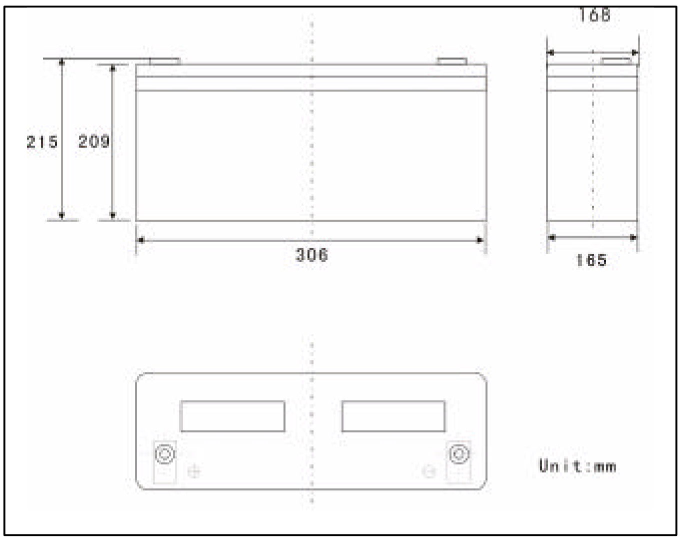
Dimensions in Centimeters

Batteries

UB12900

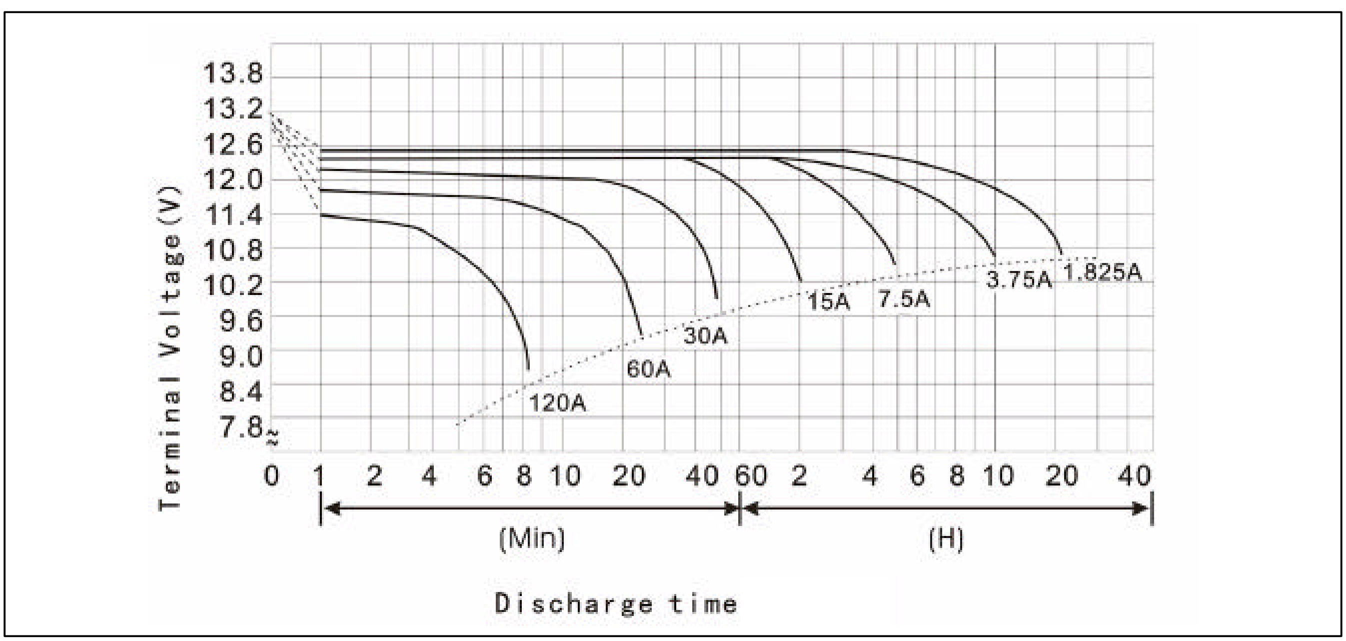
Specifications

Nominal Voltage		12V
Rated Capacity (20 hour rate)		90Ah
Dimensions	Tot. Height (with terminal)	8.46 in (215 mm)
	Height	8.23 in (209 mm)
	Length	12.05 in (306 mm)
	Width	6.49 in (165 mm)
Weight		Approx. 62.61 lbs



Characteristics

Capacity 77ºF (25ºC)		20 hr. rate 20	90Ah
		10 hr. rate 10	83.7Ah
		5 hr. rate 5	76.5Ah
		4 hr. rate 4	75Ah
		1 hr. rate 1	54Ah
Internal resistance. Full charged battery 77ºF (25ºC)			6.7 milliohms
Capacity affected by Temperature (20 hour rate)		104º F (40ºC)	102%
		77ºF (25ºC)	100%
		32ºF (0ºC)	85%
		5ºF (-15ºC)	65%
Self Discharge 77ºF (25ºC)	Capacity after 3 months storage		90%
	Capacity after 6 months storage		80%
	Capacity after 12 months storage		60%
Watts per cell @ 1 hour			36
Run time @ 25A			3 hr. 32 min.
Discharge rate @ 4 hours			18A
Charge (Constant-Voltage)	Cycle	Initial charging current less than 27A. Voltage 14.5~14.9V/12V 77ºF (25ºC)	
	Float	Voltage 13.6~13.8V/12V 77ºF (25ºC)	



MORNINGSTAR corporation

TRISTAR™

THREE-FUNCTION SOLAR CONTROLLER

Morningstar's ***TriStar Controller*** is a three-function controller that provides reliable solar battery charging, load control or diversion regulation. The controller operates in one of these modes at a time and two or more controllers may be used to provide multiple functions.

The TriStar uses advanced technology and automated production to provide exciting new features at a competitive cost. The optional TriStar meter is the most sophisticated and informative controller meter on the market. The controller is UL listed and is designed for both solar home systems and professional applications.

Key Features and Benefits

Highest Reliability

Large heat sink ❶ and conservative design enables operating at full ratings to 45°C. No need to de-rate.

More Power

Ratings to 60A at 48VDC will handle solar arrays up to 4kW.

Communications Capability

RS-232 ❷ connects to a personal computer for custom settings, data logging and remote monitoring and control.

Fully Adjustable

DIP switch ❸ provides user with a choice of 7 different digital presets and custom settings via RS-232.

Extensive Electronic Protections

Fully protected against reverse polarity, short circuit, overcurrent, high temperature and overvoltage.

Simple Mechanical Interface

Larger power terminals ❹ and conduit knockouts ❺. Extra space for wire turns. Fits on power panels.

Better Battery Charging

Connecting battery sense wires ❻ and optional remote temperature sensor ❼ will improve control accuracy. Constant voltage series PWM algorithm increases battery capacity and life.

More Information

3 LED's ❽ to indicate status, faults and alarms. Optional meter ❾ displays extensive system and controller information, automatic self-test and reset capabilities. Meter connection via RJ-11 phone jack ❿.

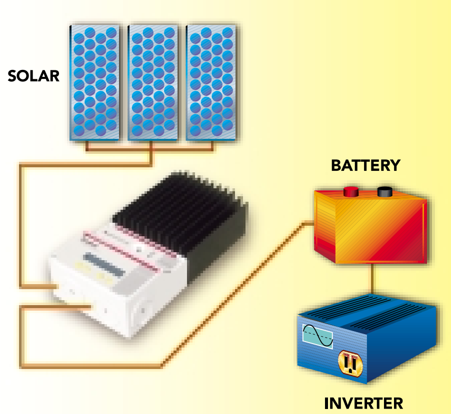
Easy to Reset

Pushbutton ⓫ provides manual reset and stop/start battery equalization or load disconnect.

Low Telecom Noise

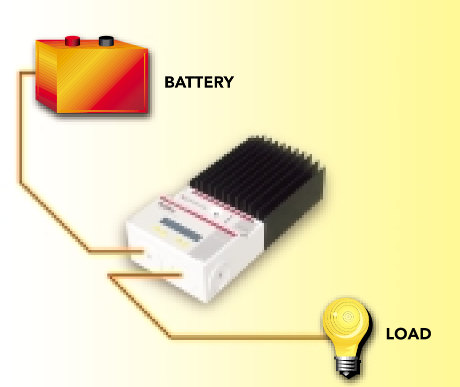
DIP switch setting will change PWM to "On-Off" battery charging.

CHARGE CONTROL



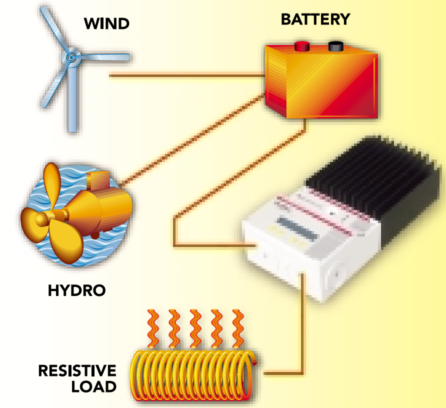
- Constant voltage series PWM design to provide highly efficient battery charging
- 4-stage charging to increase battery capacity and life: bulk charge, PWM regulation, float and equalize
- Parallel for larger solar arrays up to 300 amps or more

LOAD CONTROL



- Starts large loads including motors and pumps with no damage to controller
- Allows inrush current to 300 amps
- Electronic short-circuit and overload protection with automatic reconnect
- LVD is current compensated and has a delay to avoid false disconnects

DIVERSION CONTROL



- May be used for solar, wind or hydroelectric
- To protect against battery overcharge, excess energy is diverted from primary battery to a secondary battery or alternate DC resistive load
- PWM reduces power into diversion load during overcurrent conditions

Electrical Specifications

- Rated solar, load or diversion current:

TriStar-45	45A
TriStar-60	60A

- System Voltage 12-48V
- Accuracy

12/24V:	≤0.1% ±50mV
48V:	≤0.1% ±100mV

- Min. voltage to operate 9V
- Max. solar voltage (Voc) 125V
- Self-consumption:

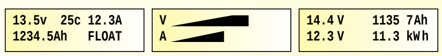
Controller	<20mA
Meter	7.5mA

Electronic Protections

- Reverse polarity protection (any combination)
- Short-circuit protection
- Overcurrent protection
- Lightning and transient surge protection using 4500W transient voltage suppressors
- High temperature protection via automatic current reduction or complete shut down
- Prevents reverse current from battery at night

TriStar Options:

- **TriStar Meter** — 2 x 16 display mounts to controller and provides system and controller information, data logging, bar graphs and choice of 5 languages



- **TriStar Remote Meter** — Includes 30 meters of cable for mounting meter away from the controller
- **Remote Temperature Sensor** — Provides temperature compensated charging by measuring temperature at the battery (10 meter cable)

Environmental Specifications

- Operating ambient temperature:

Controller	–40°C to +45°C
Meter	–40°C to +60°C

- Storage temperature: –55°to +85°C
- Humidity: 100% (non-condensing)
- Tropicalization: Conformal coating on both sides of all printed circuit boards

Mechanical Specifications

• Dimensions:	Height: 26.0cm/10.3 inch Width: 12.7cm/5.0 inch Depth: 7.1cm/2.8 inch
• Weight:	1.6 kg/3.5 lb
• Largest Wire:	$35mm^2$/2 AWG
• Conduit knockouts:	Eccentric 2.5/3.2cm (1.0/1.25 inch)
• Enclosure:	Type 1, indoor rated

Certifications

- CE Compliant
- UL Listed (UL 1741)
- cUL (CSA-C22.2 No.107.1-95)
- Complies with U.S. National Electric Code
- Manufactured in a certified ISO 9001 facility

c UL us LISTED

WARRANTY: ***Five year warranty period. Contact Morningstar or your authorized distributor for complete terms.***

AUTHORIZED MORNINGSTAR DISTRIBUTOR:

MORNINGSTAR corporation

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Washington Crossing, PA 18977 USA
Tel: 215-321-4457 Fax: 215-321-4458
E-mail: info@morningstarcorp.com
Website: www.morningstarcorp.com

PRINTED IN USA 212E-R1-6/03

iCOLOR COVE QL

The iColor® Cove QL fixture is a low-profile LED cove light featuring Chromasic® technology. From large-scale commercial installations to simpler residential applications, iColor Cove QL delivers color-changing illumination and lighting effects to alcoves, task areas, accent areas, and other confined spaces. Employing Chromasic technology, iColor Cove QL has the capability of auto-addressing, which simplifies installation, addressing and programming.

Encased in a vented, molded plastic housing, iColor Cove QL is available in 6" (15cm) and 12" (30cm) lengths with a 100° x 40° beam angle and features in-line power/data connectors that allow a run to turn up to 180°, reducing installation time. The mounting bracket provides 180° aiming rotation.

iColor Cove QL is driven by the Color Kinetics® Chromasic chip, which integrates power, communication, and control. It therefore lowers the overall system cost, making it an affordable alternative for edge and alcove lighting. Each one-foot fixture can be individually controlled or grouped as one address for simplified installation.

Power and data are supplied by sPDS-60ca 24V, a dedicated Color Kinetics power/data supply available for DMX and Ethernet applications, or PDS-60ca 24V for pre-programmed effects. Each power/data supply supports up to 20 12" fixtures or 36 6" fixtures in a single run or divided into two runs. End-to-end is the preferred method of installation. However, jumper cables are available for areas that require spacing.

iCOLOR COVE QL SPECIFICATIONS

COLOR RANGE	64 billion (36 bit) additive RGB color, continuously variable intensity
SOURCE	High brightness LEDs
BEAM ANGLE	100° x 40°
HOUSING	Rigid, vented plastic housing. 12″ L x 1.5″ W x 1.4″ H (30cm) x (6.8cm) x (3.5cm) (with base) 6″ L x 1.5″ W x 1.4″ H (15cm) x (6.8cm) x (3.5cm) (with base)
CONNECTORS	Integral 3-pin male/female connectors
LISTINGS	UL/cUL, CE

COMMUNICATION SPECIFICATIONS

DATA INTERFACE	Color Kinetics Chromasic data interface system
CONTROL	Color Kinetics line of controllers, including Light System Manager, Video System Manager, or other DMX512 (RS485) sources

ELECTRICAL SPECIFICATIONS

POWER REQUIREMENT	24VDC
POWER CONSUMPTION	3W at full output for 12" fixture; 1.7W at full output for 6" fixture
POWER SUPPLY	sPDS-60ca 24V (Item# 109-000021-02) for DMX/Ethernet applications, PDS-60ca 24V (Item# 109-000016-00) for Preprogrammed applications
LEADER CABLE	30-ft (9m) iColor Cove EC Leader Cable (Item# 108-000015-00)
JUMPER CABLE	1-ft (0.3m) iColor Cove EC/QL Jumper Cable (Item# 108-000020-00) 5-ft (1.5m) iColor Cove EC/QL Jumper Cable (Item# 108-000020-01)

ENVIRONMENTAL SPECIFICATIONS

TEMPERATURE RANGE	-4˚F to 122˚F (-20˚C to 50˚C) based on testing of specific product

LED SOURCE LIFE

In traditional lamp sources, lifetime is defined as the point at which 50% of the lamps fail. This is also termed Mean Time Between Failure [MTBF]. LEDs are semiconductor devices and have a much longer MTBF than conventional sources. However, MTBF is not the only consideration in determining useful life. Color Kinetics uses the concept of useful light output for rating source lifetimes. Like traditional sources, LED output degrades over time (lumen depreciation) and this is the metric for SSL lifetime.

LED lumen depreciation is affected by numerous environmental conditions such as ambient temperature, humidity, and ventilation. Lumen depreciation is also affected by means of control, thermal management, current levels, and a host of other electrical design considerations. Color Kinetics systems are expertly engineered to optimize LED life when used under normal operating conditions. Lumen depreciation information is based on LED manufacturers' source life data as well as other third party testing. Low temperatures and controlled effects have a beneficial effect on lumen depreciation. Overall system lifetime could vary substantially based on usage and the environment in which the system is installed.

Temperature and effects will affect lifetime. Color Kinetics rates product lifetime using lumen depreciation to 50% of original light output. When the fixture is running at room temperature using a color wash effect, the lifetime is in the range of 30,000-50,000 hours. This is based on LED manufacturers' test data. For more detailed information on source life, please see www.colorkinetics.com/lifetime.

CHROMACORE® BY COLOR KINETICS

CHROMASIC® BY COLOR KINETICS

OPTIBIN® BY COLOR KINETICS

DRY

c UL US LISTED 78GF

ITEM# 101-000051-00 (12")
101-000051-01 (6")

This product is protected by one or more of the following U.S. Patents and their foreign counterparts: 6,016,038, 6,150,774, 6,292,901, 6,340,868, 6,777,891, 6,788,011, 6,806,659, 6,969,954, and 6,975,079. Other patents pending.

BRO152 Rev 05

Specifications subject to change without notice. Refer to www.colorkinetics.com for the most recent version.

iCOLOR COVE QL 12"

PHOTOMETRIC PERFORMANCE

Photometric data is based on test results from an independent testing lab.

SOURCE SPECIFICATIONS

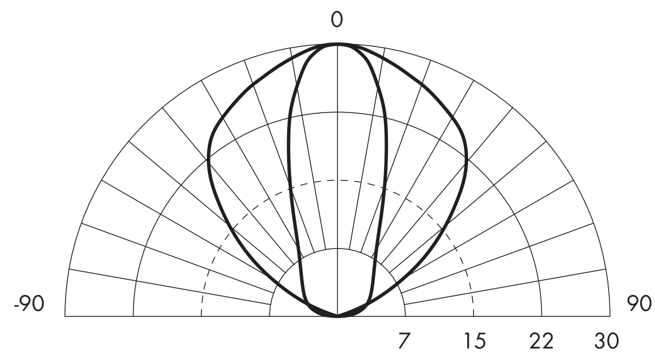
Optics:	PMMA (Acrylic)
Source:	30 LEDs (10 Red, 10 Green, 10 Blue)
Beam Angle:	100° x 40° (at 50% of peak illuminance)
Distribution:	Asymmetric direct illumination
CCT:	Adjustable 1,000–10,000K
CRI:	Not measurable (CIE 13.3-1995)

ILLUMINANCE DISTRIBUTION

0.3 / 2.2	0.4 / 4.3	0.6 / 6.5	0.4 / 4.3	0.2 / 2.2	0.1 / 1.1	3.0′/1.0m
0.3 / 3.2	1.6 / 17.2	2.4 / 25.8	1.7 / 18.3	0.5 / 5.4	0.2 / 2.2	
0.4 / 4.3	2.1 / 22.6	4.6 / 49.5	4.0 / 43.1	1.5 / 16.1	0.3 / 3.2	
0.3 / 3.2	1.5 / 16.1	4.0 / 43.1	4.6 / 49.5	2.1 / 22.6	0.4 / 4.3	0′/0m
0.2 / 2.2	0.5 / 5.4	1.7 / 18.3	2.4 / 25.8	1.3 / 14.0	0.3 / 3.2	
0.1 / 1.1	0.2 / 2.2	0.4 / 4.3	0.6 / 6.5	0.4 / 4.3	0.2 / 2.2	3.0′/1.0m
3.0′/1.0m		0′/0m			3.0′/1.0m	

Units:	Footcandles (top)/Lux (bottom) 10.8 lux = 1 fc
Location:	Center of grid, 1′/0.3m from surface, light at perpendicular to surface
Measured on:	White, reflectance model: 50%

CANDLE POWER DISTRIBUTION



Measured on:	White
Beam center:	30 cd
Thin dashed lined:	Indicates 50% of peak
Multipliers:	0.24 Red, 0.48 Green, 0.28 Blue

ILLUMINANCE

DISTANCE	3′ / 1m	6′ / 2m	9′ / 3m	15′ / 5m
WHITE	3.0 / 32.3	0.8 / 8.6	0.4 / 4.3	0.4 / 4.3
RED	0.8 / 8.1	0.2 / 2.2	0.1 / 1.1	0.1 / 1.1
GREEN	1.4 / 15.5	0.4 / 4.1	0.2 / 2.1	0.2 / 2.1
BLUE	0.8 / 9.0	0.2 / 2.4	0.1 / 1.2	0.1 / 0.2

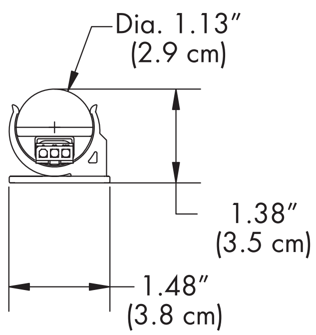
Measured in Footcandles (top)/Lux (bottom) on axis.
Measured on white, reflectance 0

LIGHT OUTPUT

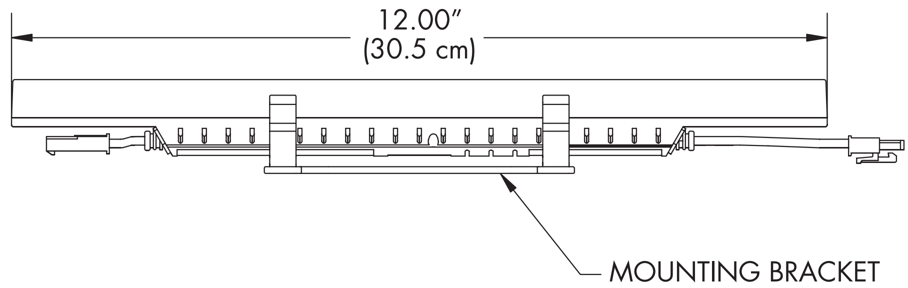
COLOR	TOTAL OUTPUT (LUMENS)	POWER (WATTS)	EFFICACY (lm/W)
WHITE	46	2.9	15.9
RED	11.5	0.7	16.4
GREEN	22.1	1.2	18.4
BLUE	12.9	1.2	10.7

Note: Efficacy figures are for a complete tested fixture not simply a lamp source.

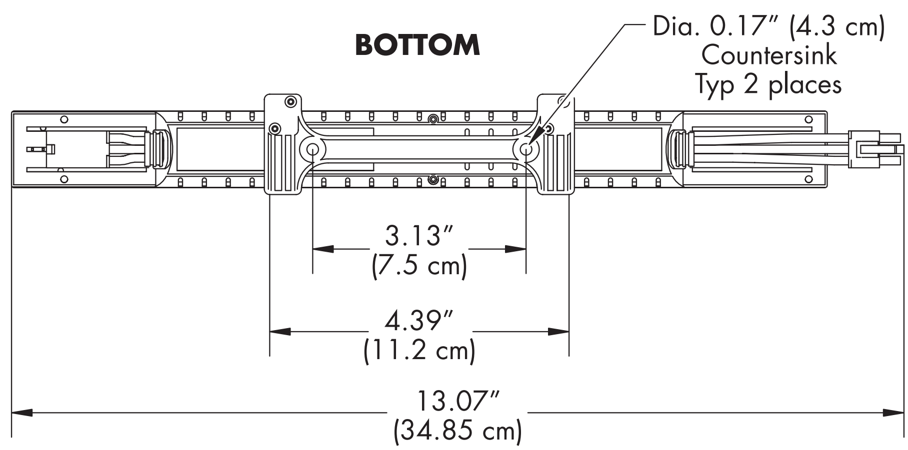
END



SIDE

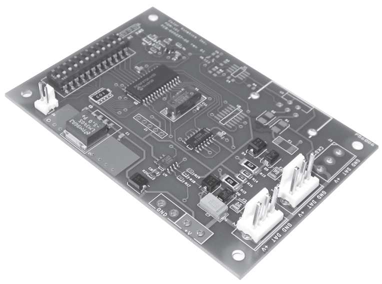


BOTTOM



iColor Cove QL 12" SPECIFICATIONS	
DATA/POWER CONNECTOR	Integral 3-pin male/female connectors
POWER/DATA SUPPLY	sPDS-60ca 24V (Item# 109-000021-02) for DMX/Ethernet applications PDS-60ca 24V (Item# 109-000016-00) for Preprogrammed applications

PDM-201



Color Kinetics® PDM-201 is a Series 200 power/data module. PDM-201 allows product designers to easily integrate the Series 200 digital light engines (DLEs) and lamps with a variety of available power supplies. By supporting 7.5VDC, 12VDC, or 24VDC power input, the PDM-201 supports standard power supplies in a variety of configurations which allows several power and data distribution options. The simple design allows you to combine it with a power supply or integrate it directly into a light fixture. The total number of DLEs that a single PDM-201 can drive is dependent on the wattage of each DLE.

PDM-201 data circuitry conditions data supplied from standard or differential DMX data inputs or from on-board preprogrammed settings to a format compatible with Series 200 DLEs based on Chromasic™ technology. The Chromasic microchip integrated into each Series 200 DLE integrates power, communication, and control to enable the Series 200 system.

PDM-201 offers a choice of controls including Color Kinetics or third-party controllers, or preprogrammed effects. The preprogrammed effects include fixed color, color wash, rainbow wash, and random color. The 12 dipswitches allows selection the effect mode, and then modification of the effect by setting the speed, color, etc.

FEATURES

- Economical
- Compact size
- Ease of installation
- DMX ready
- Choice of preprogrammed light effects
- Support automatic and manual configuration of number of lights per output

PDM-201 SPECIFICATIONS

POWER INPUT	7.5VDC, 12VDC, or 24VDC
POWER OUTPUT	7.5VDC, 12VDC, or 24VDC
AMBIENT OPERATING TEMP	14°F to 122°F (-10°C to 50°C)
CONNECTORS	Output: 3-pin vertical header, Power: solder pads
DATA INPUT INTERFACE	DMX512
DATA OUTPUT INTERFACE	Chromasic

U.S. AND FOREIGN PATENTS AND PATENTS PENDING

PDM-201 ITEM# 118-000062-00

Applications using this technology or product may be covered under one of the following patents:
U.S. Patent Nos. 6,016,038, 6,150,774 and other patents listed at http://colorkinetics.com/patents/.
Other patents pending.

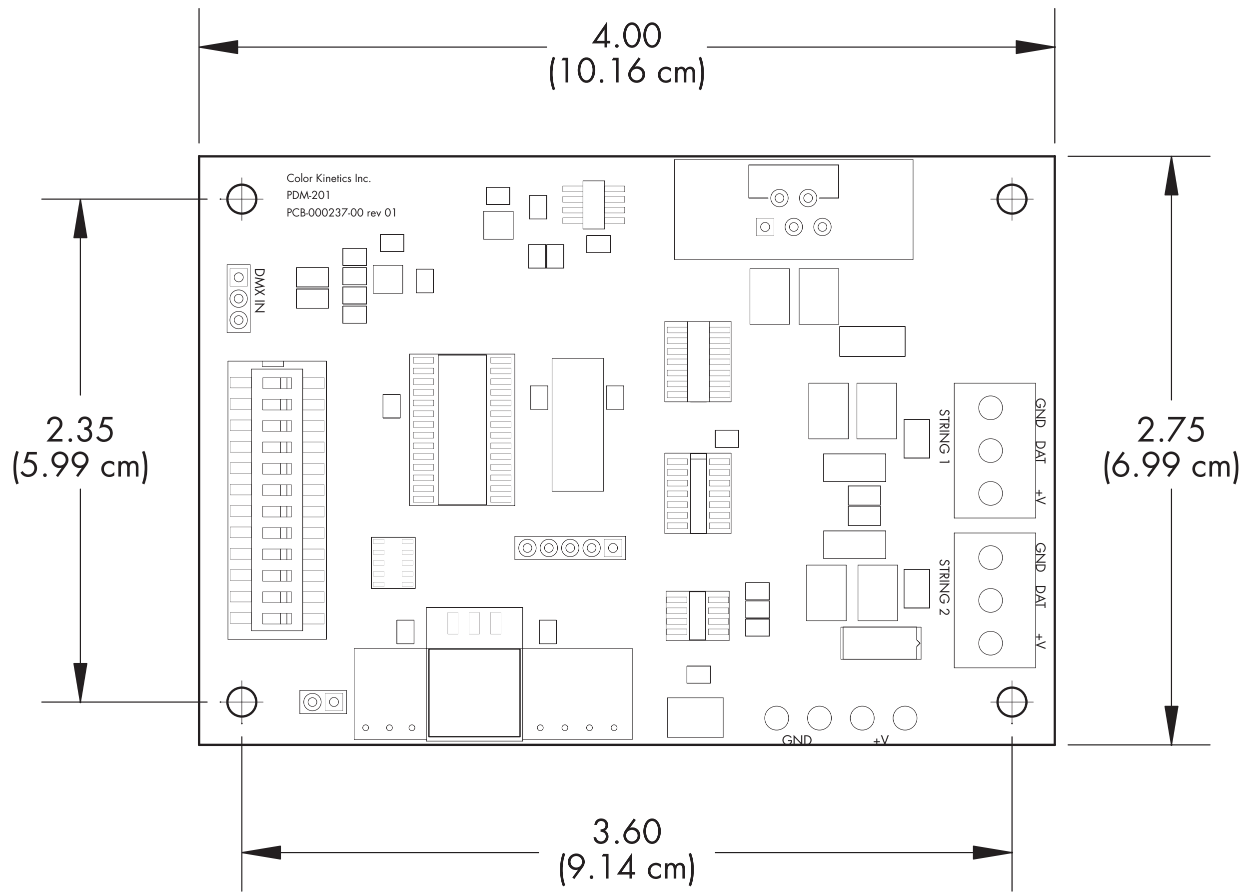
BR0164 Rev 01

Specifications subject to change without notice.

Color Kinetics Incorporated • 10 Milk Street, Suite 1100 • Boston, MA 02108 • USA
Tel 888 FULL RGB • Tel 617 423 9999 • Fax 617 423 9998 • info@colorkinetics.com • www.colorkinetics.com

PDM-201

PHYSICAL DIMENSIONS



For complete installation instructions and safety precautions, refer to the DLE Integration Guide and wiring diagrams located at www.colorkinetics.com/support.

COLORBURST 6

The ColorBurst® 6 fixture is a Chromacore®-powered product designed to meet the needs of lighting professionals, providing them with a small, sleek solution for spotlighting and wall-washing with rich, saturated colors and color-changing effects.

Projecting a soft-edge beam of light, ColorBurst 6 is a sealed product designed for both indoor and outdoor installations. The fixture is fully enclosed in a stylish and rugged die-cast aluminum housing and meets or exceeds specifications for use in wet locations. Enclosed wiring gives ColorBurst 6 a neat appearance and optimum positioning. The housing is equipped with a three-screw accessory ring to affix spread lenses, louvers, and other attachments and is available in either a black or white finish to match its environment and prevent oxidation. ColorBurst 6 has three 18AWG wire leads and attaches to a standard junction box or an optional mounting base, which has a 60-foot (18.3 m) three-conductor cable. The 350° locking base swivel, with 350˚ locking fixture rotation, offers a versatile range of light positioning.

ColorBurst 6 can be controlled by a Color Kinetics® controller or a third-party controller. Each fixture comes pre-addressed to light number one. With a Color Kinetics controller, simple effects, such as fixed color and color wash, require no additional addressing. Other effects across multiple lights, including Chasing Rainbow or Color Sweep, require further addressing using one of the following Color Kinetics addressing tools: Serialized Addressing Software (SAS) or Zapi. For protection from extreme temperatures, ColorBurst 6 has been designed with a temperature monitoring feature. If operating temperatures rise to an unsafe level, a compensation circuit is triggered and ColorBurst 6 operation is interrupted causing the light to turn dull red. After 30 minutes the light will auto-cycle and return to full intensity.

COLORBURST 6 SPECIFICATIONS

COLOR RANGE	16.7 million (24 bit) additive RGB colors; continuously variable intensity output range
SOURCE	High intensity power light emitting diodes (LEDs)
BEAM ANGLE	12° clear lens, 22° ground lens
HOUSING	Die cast aluminum in black or white
LISTINGS	UL/cUL Listed

COMMUNICATION SPECIFICATIONS

DATA INTERFACE	Color Kinetics data interface system
CONTROL	Color Kinetics full line of controllers or DMX512 (RS485) compatible when using Color Kinetics power/data supply

ELECTRICAL SPECIFICATIONS

POWER REQUIREMENT	24VDC
POWER CONSUMPTION	25W Max. at full intensity (full RGB)
POWER SUPPLY	PDS-150e (ITEM# 109-000008-01) - Maximum of 6 fixtures/supply
	PDS-60 24V (ITEM# 109-000017-00/03) - Maximum of 2 fixtures/supply

ENVIRONMENTAL SPECIFICATIONS

TEMPERATURE RANGE	-40°F to 122°F (-40°C to 50°C) operating temperature
	-4°F to 122°F (-20°C to 50°C) starting temperature
PROTECTION RATING	IP66

LED SOURCE LIFE

In traditional lamp sources, lifetime is defined as the point at which 50% of the lamps fail. This is also termed Mean Time Between Failure [MTBF]. LEDs are semiconductor devices and have a much longer MTBF than conventional sources. However, MTBF is not the only consideration in determining useful life. Color Kinetics uses the concept of useful light output for rating source lifetimes. Like traditional sources, LED output degrades over time (lumen depreciation) and this is the metric for SSL lifetime.

LED lumen depreciation is affected by numerous environmental conditions such as ambient temperature, humidity and ventilation. Lumen depreciation is also affected by means of control, thermal management, current levels, and a host of other electrical design considerations. Color Kinetics systems are expertly engineered to optimize LED life when used under normal operating conditions. Lumen depreciation information is based on LED manufacturers' source life data as well as other third party testing. Low temperatures and controlled effects have a beneficial effect on lumen depreciation. Overall system lifetime could vary substantially based on usage and the environment in which the system is installed.

Temperature and effects will affect lifetime. Color Kinetics rates product lifetime using lumen depreciation to 50% of original light output. When the fixture is running at room temperature using a color wash effect, the lifetime is in the range of 80,000-100,000 hours. This is based on LED manufacturers' test data. High output is defined as any LED device that is 1/2 watt or above. For more detailed information on source life, please see www.colorkinetics.com/lifetime.

OPTIBIN®

There are inherent variations in the fabrication processes of all semiconductor materials. For LEDs, this variance results in differences in the color and intensity of light output as well as electrical characteristics. Due to these differences, LED manufacturers sort production into "bins," but insuring the availability of a single bin is very difficult. To minimize this issue and achieve optimal color consistency in its products, Color Kinetics has developed and uses a proprietary technology called Optibin. Optibin is an advanced production binning optimization process that minimizes the effects of LED variance for the best possible output uniformity in the final product. Color Kinetics Optibin technology gives you the most consistent control of color and intensity from product to product.

CHROMACORE® BY COLOR KINETICS

OPTIBIN® BY COLOR KINETICS

DRY

WET & DAMP

LISTED 78GF

ColorBurst 6 ITEM# 116-000014-00 (White, Frosted)
116-000014-01 (Black, Frosted)
116-000014-02 (White, Clear)
116-000014-03 (Black, Frosted)
ColorBurst Base ITEM# 116-000005-00 (White)
116-000005-01 (Black)

This product is protected by one or more of the following U.S. Patents and their foreign counterparts: 6,016,038, 6,150,774, 6,292,901, 6,340,868, 6,777,891, 6,788,011, 6,806,659, 6,969,954, and 6,975,079. Other patents pending.

BR0100 Rev 08

Specifications subject to change without notice. Refer to www.colorkinetics.com for the most recent version.

COLOR KINETICS INCORPORATED • 10 MILK STREET, SUITE 1100 • BOSTON, MA 02108 • USA
TEL 888 FULL RGB • TEL 617 423 9999 • FAX 617 423 9998 • INFO@COLORKINETICS.COM • WWW.COLORKINETICS.COM

COLORBURST 6 - CLEAR LENS

PHOTOMETRIC PERFORMANCE

Photometric data is based on test results from an independent testing lab.

SOURCE SPECIFICATIONS

Optics:	Clear tempered glass
Source:	18 LEDs (6 Red, 6 Green, 6 Blue)
Beam Angle:	12°
Distribution:	Symmetric direct illumination
CCT:	Adjustable 1,000K-10,000K
CRI:	Not measureable (CIE 13.3-1995)

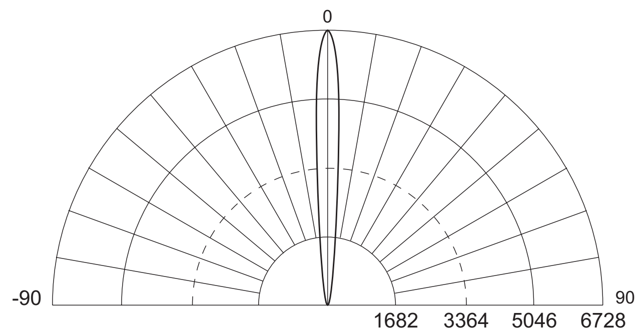
ILLUMINANCE DISTRIBUTION

1.2 / 12.9	4.0 / 43.1	6.6 / 71.0	4.7 / 50.6	1.9 / 20.5	1.0 / 10.8	6.0′/2.0m
1.6 / 17.2	14.4 / 155.0	28.5 / 306.8	19.1 / 205.6	4.6 / 49.5	1.2 / 12.9	5.0′/1.5m
1.6 / 17.2	15.0 / 161.5	39.2 / 421.9	39.0 / 419.8	14.7 / 158.2	1.5 / 16.1	4.0′/1.2m
1.0 / 10.8	4.9 / 52.7	20.1 / 216.4	29.5 / 317.5	14.6 / 157.2	1.4 / 15.1	3.0′/1.0m
0.4 / 4.3	1.4 / 15.1	4.7 / 50.6	6.9 / 74.3	4.0 / 43.1	0.8 / 8.6	2.0′/0.6m
0.3 / 3.2	0.4 / 4.3	0.8 / 8.6	1.2 / 12.9	0.8 / 8.6	0.4 / 4.3	1.0′/0.3m

3.0′/1.0m 0′/0m 3.0′/1.0m

Units:	Footcandles (top)/Lux (bottom) 10.8 lux = 1 fc
Measured on:	All, reflectance model 80/50/20%
Distance from surface:	Bottom center of grid, 3′ (1.0 m) from surface, light at a 45° angle off horizontal

CANDLE POWER DISTRIBUTION



Measured on:	White
Beam center:	6728 cd
Thin dashed line:	Indicates 50% of peak
Multipliers:	0.36 Red, 0.46 Green, 0.18 Blue

ILLUMINANCE

COLOR	3′ / 1m	6′ / 2m	9′ / 3m	15′ / 5m
WHITE	750.0 / 8073.0	187.0 / 2012.9	83.2 / 895.6	29.9 / 321.8
RED	269.3 / 2899.0	67.2 / 722.8	29.9 / 321.6	10.7 / 115.6
GREEN	345.0 / 3713.6	86.0 / 925.9	38.3 / 412.0	13.8 / 148.0
BLUE	134.3 / 1445.1	33.5 / 360.3	14.9 / 160.3	5.4 / 57.6

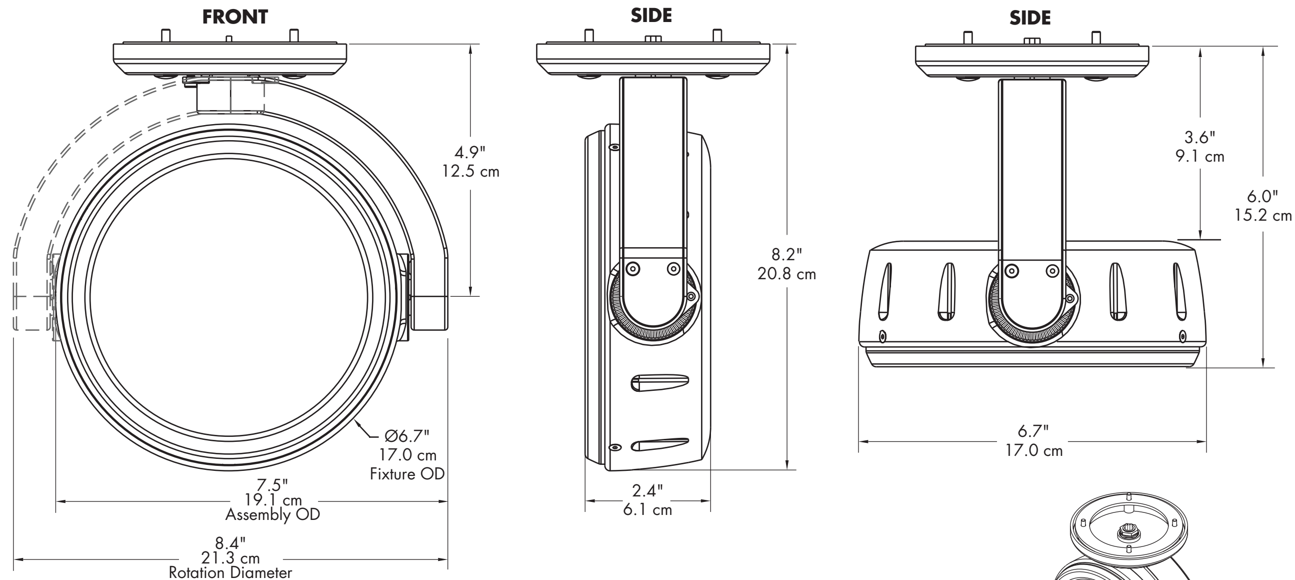
Measured in Footcandles (top)/Lux (bottom) on axis.
Measured on: All, reflectance 0.

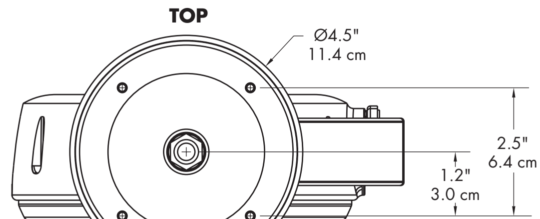
LIGHT OUTPUT

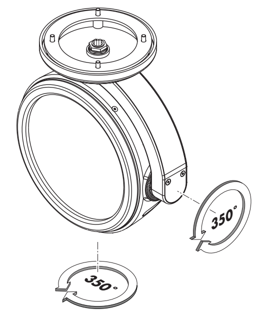
COLOR	TOTAL OUTPUT (lumens)	POWER (Watts)	EFFICACY (Lm/W)
WHITE	295	24.7	11.9
RED	105.9	8.4	12.6
GREEN	135.7	8.4	16.2
BLUE	52.8	8.4	6.3

COLORBURST 6

PHYSICAL DIMENSIONS

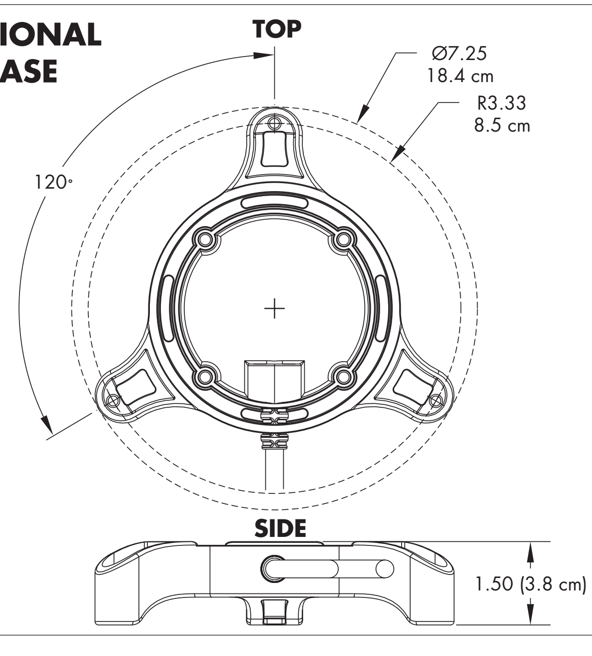






COLORBURST 6 ITEM#116-000014-00/01/0203	
POWER CONNECTION	3-Wire power/data cable
POWER REQUIREMENT	24VDC (25W)
WEIGHT	3.25 lbs (1.48 kg)

OPTIONAL BASE



COLORBURST 6 OPTIONAL BASE ITEM#116-000005-00/01/02	
POWER CONNECTION	60-foot, 3-Wire power/data cable
POWER REQUIREMENT	24VDC (25W)
WEIGHT	4.13 lbs (1.87 kg)

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LIGHTWILD

Project Linear

Site Lighting LED fixture (Ramps)

CHECK THE APPROPRIATE BOXES:

LW-PLIN- ☐G ☐R ☐A ☐B ☐WW ☐CW ☐RGB – ______ – ☐LN ☐LC ☐LLF ☐LFR

LED COLOR	LENGTH in INCHES	LENS
G=Green **R**=Red **A**=Amber **B**=Blue **WW**=Warm White **CW**=Cool White **RGB**=Color Controllable	List as a whole number. See available lengths and limitations below.	**LN**=No Lens **LC**=Clear Lens **LLF**=Lightly Frosted Lens **LFR**=Frosted Lens

LightWild Project Linears are perfect for edge lighting glass and acrylic surfaces and smoothly illuminating under cabinet areas, coves, and display cases.

GENERAL

- **Nominal Colors*:** Warm white*, cool white*, red, blue, green, amber, RGB
- **Source:** 3 LEDs per inch of specified fixture.
- **Lenses:** No lens (60°), Clear lens (60°), Lightly frosted lens (90°), Frosted lens (110°)
- **Connectors:** Self-locking water-tight connectors
- **Mounting:** Brackets for screw mounting to any surface
- **Housing:** Silver aluminum
- **Cable Attachment:** Cables exit ends of fixture on same side
- **Housing Width:** 1 in. (2 ins. with optional mounting feet)
- **Housing Height:** 1.25 in.
- **Housing Length:** *White and Single Color LEDs:* 6 ins, 8 ins, and from 1 ft to 8 ft long in 2-inch increments (12 ins, 14 ins, 16 ins, etc., to maximum of 96 ins.) *RGB LEDs:* From 6 ins. to 8 ft. long in 6-inch increments (6 ins, 12 ins, 18 ins, 24 ins, etc. to maximum of 96 ins.)
- **Listings:** UL Listed (E306264). Suitable for wet locations. Use only with LightWild supplied Class 2 power unit.

ENVIRONMENTAL

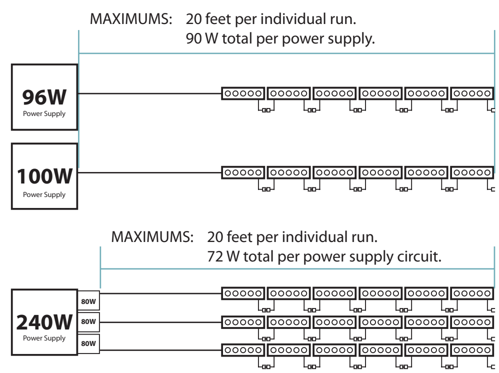
- **Temperature Range:** -10 to 150 F (-25 to 65 C)
- **Moisture Ingress:** Use in dry, damp, or wet locations

CONTROL

- **Options:** LightWild offers turnkey control solutions including basic power on/off control, dimming, pre-programmed controllers for effects, and interfaces to third party DMX controllers.

ELECTRICAL

- **Power Requirement:** 24VDC (Contractor supplies 120/240 VAC to control unit. Control unit includes a transforming power supply that delivers 24VDC to fixture.)
- **Power Consumption:** Approximately 0.3W per inch of specified fixture
- **Life of Bulbs:** 50,000 to 80,000 hours**
- **Runs per Power Supply:**



* LightWild selects from an LED bin with a range of 2700K-3200K with a goal of matching 3000K for its warm white Project Linear products and from an LED bin with a range of 5600K-9000K with a goal of matching 7300K for its cool white Project Linear products.

** As with all light sources, users can expect a depreciation in brightness during the course of this estimated lifetime. A depreciation in brightness can be expedited by a change in environmental conditions and electrical uses.

P: (913) 851-3000 • **F:** (913) 851-3008 • **E:** projects@lightwild.com • **W:** http://www.lightwild.com

Landscape LED lighting fixture

ML6C SERIES

Extérieur Vert

SURFACE REAR MOUNTED PROJECTOR
High Output LED Source
3W / 24V

MINILINI™

IP 66 | 3W | 24V

Projector body

- Suitable for wet locations, IP66 rated
- Compact low profile under 2" diameter
- Lengths available in 1', 2', 3' and 4'
- Consult factory for other lengths
- Grey powder coat (RAL#9006) Standard
- For additional colors consult factory
- 24V DC Remote constant voltage power supply
- UL Listed
- 10 Year Warranty anti-corrosion
- 3 Year Warranty on driver

Lamp / Optics

- Nominal LED spacing: 2"
- Light source: High power 3W Cool White, Amber, Red, Green & Blue LED
- 10° x 40° spot (linear spread), 25° narrow flood & 50° flood optics
- 10° x 40° optics create smooth light distribution for wall grazing effect
- Other optics available, consult factory
- 50,000 hour lamp life @ 70% lumen output

Remote Power Supply

- 120-277V Primary 24VDC Secondary Class I power supply (required) order separately
- 15' max length for remote power supply
- Consult factory for longer lengths

Cover

- UV polycarbonate lens cover
- UV Stabilized (Non yellowing)

Mounting

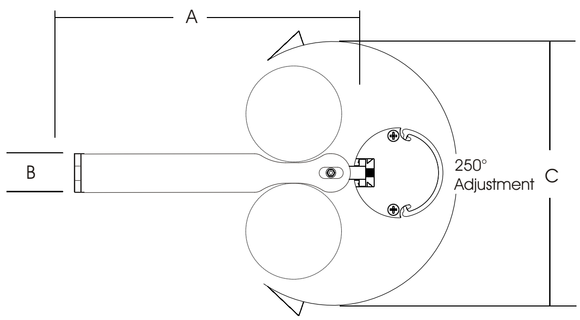
- Can be mounted end to end with zero clearance
- Mounted horizontal or vertical and can be rotated 220° on its axis
- Three mounting bracket lengths

Features

- Available in 1', 2', 3' & 4' lengths
- Adjustable mounting brackets
- High light output LEDs (3W/LED)
- IP 66 rated
- Class 1 fixture continuous runs of 15' plus available (consult factory)

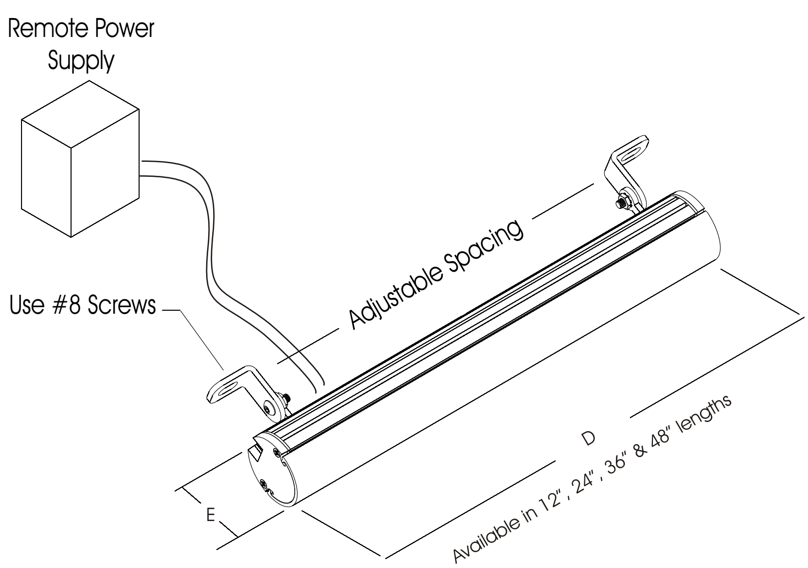
Applications

- Building facade lighting
- Wall washing
- Area Lighting
- Effects Lighting



Dimensions

A Bracket Length Standard	B Bracket Width	C	D Fixture Length	E Fixture Diameter
1"	0.75"	4.5"	12.5"	1.75"
3"	0.75"	4.5"	24.5"	1.75"
5"	0.75"	4.5"	36.5"	1.75"
			48.5"	1.75"



LED technology is changing rapidly. LED's are made in lots and sorted into bins based on wavelength ranges that achieve colors. Products ordered at different times may not have the same color appearance due to variations of up to 10% within lots.

EXTERIEUR VERT a division of TARGETTI NORTH AMERICA
www.exterieurvert.com
1513 E. Saint Gertrude Place Santa Ana, Ca 92705
Tel 714 957-4960
Fax 714 957-4965

Extérieur Vert

MINILINI

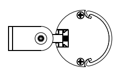
Part # Logic

ML6C	41	2	2	1	10R	3	4
Base Part#	Lamp Type	LED color	LED Spacing	Length	Optics	Wattage	Finish
ML6-Minilini Projector	LED	1 - Cool White 2 - Blue 3 - Amber 4 - Red 5 - Green	2= 2" Spacing	1=1 foot 2=2 foot 3=3 foot 4=4 foot	10R=10° x 40° Spot 25R=25° Narrow Flood 50R=50° Flood	3=3 Watt	Color 4 - Grey (std.) 9 - Custom

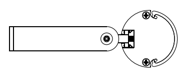
* Other optics available
Consult factory

Required Choices for Mounting Fixture

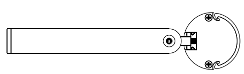
MLBK01



MLBK02



MLBK03



MLBK01, MLBK02 or MLBK03 can be used with any fixture lengths

Part No.	Extension from wall
MLBK01	1" mounting bracket length
MLBK02	3" mounting bracket length
MLBK03	5" mounting bracket length

LED Driver required, consult factory

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