# Photovoltaic Decorative System

## Final Report



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## INTRODUCTION

Solar-powered lights for home decorative purposes are commonly available but generally underpowered and are not reliable as a consistent source of light for safety and/or security. Rather than include a solar panel on each individual light as many manufacturers have done, we will design a system with a centralized solar array providing the power. The system will automatically activate at night and run for a preset amount of time. The system will only include decorative lights. Our motivation is to create a robust, environmentally friendly, aesthetically appealing, lighting system that will not sacrifice functionality and performance in achieving these goals.

## EXECUTIVE SUMMARY

We received the assignment to design a solar powered lighting system that includes both outdoor decorative landscaping lights and a security light. After initial testing we found it was not feasible to include a security light with the power input we would be receiving from our solar array. We understand that the performance of the lights cannot be sacrificed to achieve their self-sustainability. In order to achieve these goals we have included our engineering analysis of this problem. This report contains our initial findings, analysis, concept generation and selection, as well as our final design and validation.

Our objective is to design and manufacture a lighting system that performs as well as if it ran connected to the grid, but instead runs completely on solar power. There are other customer requirements such as illumination power, aesthetics, and overall performance that we were able to quantitatively describe using engineering characteristics that will be applied to our design process. After initial calculations, based on product specifications, we found that LED bulbs are the best for energy conservation and provides a reliable light source. Once the battery is fully charged the system should run for approximately eleven days without any recharging based on preliminary design power consumption. The systems components have been characterized and we have determined that we will need four solar panels to sufficiently power low-voltage outdoor lights. With the knowledge of our power supply, we successfully generated a final design that reflects the best interests of the consumer.

Concepts were generated attempting to merge the best interests of the consumer as well as the engineer. Encouraging innovation and creativity, we developed different system layouts and weighed the various advantages and disadvantages. From among these concepts came our alpha design through comparing those advantages and disadvantages from each against known benchmarked systems and our engineering specifications. Through the use of Pugh charts, we were able to systematically select the design that has the fewest disadvantages while maintaining the level of performance and reliability we require as our final design.

Currently, our final design involves the use of the four provided solar panels powering a battery through a charge controller. The battery is connected to a photocell and timer to determine when all of the landscape lights will be on or off. Power limitations require us to use low-voltage LED lights for the all landscaping lights. The area lights will be connected to two different switches so they may be turned off if there is insufficient power. This measure was taken to ensure that the path lights would always be powered.

## PROBLEM DESCRIPTION

For this project we are challenged to design a robust solar-powered decorative lighting system. Currently solar-powered landscaping lights are widely available but generally underpowered & ineffective, especially during the winter season and in our northern climate. Instead of placing the solar panel directly on the lights we will have a centrally located larger solar panel to power the entire system. The power source for the lights will be able to sustain the decorative lights through different times of the year and different weather conditions. Also, because we expect residential installation, the lighting system will be designed into the landscaping for greater aesthetical appeal. Our goal is to design a solar-powered lighting system that will have similar or better illuminative capability than current commercial lighting systems, both solar- and grid-powered.

## CUSTOMER REQUIREMENTS AND ENGINEERING SPECIFICATIONS

*Customer Requirements*

Consumers interested in purchasing decorative solar lighting wish to find a lighting system that is usable for security purposes and are not underpowered. By contacting the primary market consumer, four key requirements were determined for the product.

- *Illuminates Desired Areas Well*: Illumination from the lights dependent primarily on the reasonable intensity of light and desired amount of illuminated ground area.
- *Aesthetically Pleasing*: Design, size and placement of solar panels and lights look appealing, including amount of ground it lit up by lights
- *Long Service Life*: Lights do not need to be replaced often. Battery, solar panels, and system hook-up survive a long life with little to no service.
- *Only Solar as Power Source*: Provided an environmentally safe power with no byproducts to power decorative light system.

The rest of the requirements were then established from existing decorative lighting systems in which the primary market uses and expects from the product.

- *Compact for Storage*: Size and weight of product reasonable size for storage purposes.
- *Easy to Clean*: Size and weight do little to interfere with cleaning of product.
- *Low Cost*: Entire lighting system is a reasonable cost for the good quality demand.
- *Entire System is Weatherproof*: Battery and electrical components are properly protected. Overall system unaffected by various weather conditions.
- *Easy to Use*: Little to no human interaction to active when system is in place.
- *Recyclable/Reusable*: Battery is rechargeable and does not need replacing.
- *Automated Light Activation*: Decorative lights automatically activate at certain darkness level outside.
- *Motion Light Activation for Security Light*: Security light automatically activates when motion in detected a certain distance away.

- *Security from Being Stolen*: Solar panels secure to the ground and unable to be removed with ease.
- *Resistance to Normal Wear and Tear*: System sturdy to withstand everyday wear and tear over a long period of time.
- *Freedom to Change Location*: Lights can be replaced in the yard and on the house to customer needs.
- *Not Visually Obtrusive*: Entire system does not take up large amount of space.
- *At Least 2 Positions Available for Season Change*: Solar panels can be placed in other areas due to change in seasons.
- *Sturdy Stand for Solar Panel*: Solar panels are expensive, so a sturdy stand to protect them from facture in necessary.
- *Environmentally and Physically Safe*: Housing of battery will protect environment and people from harm in case of battery leaking. Light intensity not so bright I could potentially blind a passerby or a driver.
- *Easy to Assemble*: After purchase, the system will be reasonably simple to assemble and set-up.

*Engineering Specifications*

Engineering specifications are a means to quantitatively approach the customer requirements and implement them in designing the product. After completing the QFD, shown in Figure A9, chart, a ranking of the engineering characteristics that have the largest impact on the system to satisfy primary customer requirements was determined. In the QFD chart, a comparison of values for each of the engineering specifications between the current market models, the project plan model and what values have currently been achieved for the desired model. In some cases, there is no value for the current market model since they only have very small solar panels on the roof of the fixture and torque and power required to move the cells are not applicable. For all other cases of undetermined values (n/a) is due to the need for further testing when materials arrive for assembly or information is not provided from manufacturer. In accordance with customer requirements, the top four most influential characteristics are as follows:

- *Power Consumption*: Amount of energy in Watts used to power decorative and security light and to power photo-sensor and timer to activate lighting system.
- *Maximum Energy Storage Collection*: Maximum amount of energy in Watts that can be stored in the battery to supply power to light system so it may run even on a day or more with no sunlight. The battery used will be a UB12400 Universal Battery from Creative Energy.
- *Efficiency of Solar Collector*: Only when the sun is at a proper angle will the panels absorb a sufficient amount of energy. Solar array absorbs as much solar energy as possible with limited placement and size. Our solar array consists of four 04-1086 ThinFilm Series solar panels from Silicon Solar.
- *Intensity of Emitted Light*: Measured as the amount of Lumens per square foot. Light intensity depends on the type and the quantity of lights used in each light housing.

The remaining characteristics define the remaining customer requirements in a quantitative interpretation to the product.

- *Torque Required to Turn Panels*: Amount of $^{lb}/_{ft}$ of torque needed to turn panels once every week or so to adjust to changing angle of sunlight with the changing seasons.
- *Power Required to Turn Panels*: The power, in Watts, required providing the torque to turn panels.
- *Length*: The total length, in inches, of the solar panels and the light fixture.
- *Width*: The total width, in inches, of the solar panels and the light fixture.
- *Height*: The total height, in inches, of the solar panels and the light fixture.
- *Weight*: The total weight, in pounds, of the solar panels and light fixture.
- *Sunlight Angle on Solar Panel*: Proper angle, in degrees, of sunlight shining on solar panel to optimize solar radiation collection.
- *Sensitivity of Motion Detector*: Minimum distance customer wishes the security light to detect motion.
- *Length of One-time Operation of Security Light:* The length of time the security lights remain on (using power). This will be determined and adjusted considering power limitations.
- *Sensitivity of Night Activation Sensor*: The time decorative lights activate in respect to the darkness setting outside at nighttime.
- *Duration of Path Lighting:* The path lights are set to turn off at 1:00 AM every night regardless of the time of year.
- *Strength of Casing Material*: Overall strength of material so that it will not fracture or fatigue due to normal wear and tear.
- *Area of Illuminated Ground*: Total area in $ft^2$ in which the decorative and security lights illuminate on ground/house.

## SYSTEM BENCHMARKING ANALYSIS

Shown in Figures A1 – A8 are eight different popular products and their specifications that we used to compare with one another as well as against potential design aspects of our final product.

As for solar-powered landscaping lights we found that the majority of the products were stand-alone with each lamp housing its own top-mounted solar panel, inverter, and battery. They utilize a stake-mounting method and require absolutely no wiring. We were also able to find some products that had a separate solar panel that could be mounted away from the lamps and had wires running from lamp to lamp. Of the products we chose to take a closer look at, all of them used a single LED as its light source. Materials ranged from different kinds of metals to plastics and varied in color. The most common maximum illumination time was found to be between eight and twelve hours.

Part of the problem with the performance of these current products stem from three main areas: the solar panel, the battery, and the light source. First, because the small solar panel is mounted on top of each lamp it always faces directly up. This limits how much direct sunlight the panels actually get, making it especially difficult to receive a full charge even under ideal conditions, not to mention when there is a lack of sunlight to the panels. Second, the battery might not be sufficient to save enough power to run the light for a few days without fully recharging. With a larger battery that powers the entire system, we might be able to store enough power to run the lights even when ideal weather is not present. Finally, the number of LED's per lamp might be seriously inhibiting the luminous power of the lamps. With a full charge and ideal conditions, one small LED may not provide enough light to illuminate the target area to a desired level. To overcome this problem we have decided to use larger, more powerful LED's or simply use multiple LED's in each lamp instead of just one.

All of the landscaping lights used an automatic light sensor. The photocell would turn them off during the day, as long as it was sunny, and leave them on all night long. In contrast to these products, we would apply a control system that employs a photocell as well as a timer to turn the lights on and off to conserve energy. For example, we could set the photocell to turn the lights on at dusk and have a timer turn them off at a given time, say 1:00 AM. The timer would then turn them back on around 6:00 AM. The lights would then stay on until it was light enough to turn them off using the photocell. Leaving the lights on throughout the night wastes unnecessary energy that could be conserved for when less desirable weather might prevent a full charge on the battery.

There were also similarities and differences amongst the solar powered security lights. Although there were not nearly as many products on the market, there was still a fairly wide range of designs. Some of the similarities consisted of using screws as the mounting method, having a separate solar panel that could be placed in a more ideal location, and using a motion sensor to activate the light. Some of the differences that we looked at were the type of light source, the length of time the light would stay on once activated, and how many times the light could be turned on and off with a fully charged battery. Some lights used halogen lamps with others stuck with LED's. At this time we do not know what type of light source would be the best for our application, but if an LED is to be used we will need a high powered one in order to achieve our desired luminosity. We found that the light should stay on for about a minute once activated. This gives enough time to use the light to approach the door, find keys, scare off potential intruders, etc., while not staying on too long and draining the battery. The existing products contained a battery that would turn the light on between 50 and 150 times with a fully charged battery. We think that it would be better to be able to turn the light on closer to 150 times with a full charge. This will allow the light to turn on after a few days of no sunlight to the panels.

We have looked at different products that are already on the market and chose a few areas to focus on. This benchmarking process has given us some ideas as to what works well in existing products and aspects we could change in order to make our product better than what already exists. One of our main goals is to make a product that runs off of solar power but performs as well or better than conventional kits that are plugged into an outlet.

## ALPHA DESIGN CONCEPT GENERATION

### *Wiring Layouts*

There are many different ways to wire a system like this one. Below are five different options along with a list of the different parts and their function. The first is a very basic layout with the solar panels, charge controller, battery, and photo sensor all connected in series. After the photo sensor there is a split in the system. One part goes through a timer and out to all of the landscaping lights. The other uses a motion sensor to turn the security lights on when needed.

The second, third, and fourth layouts are slight modifications to the first. The second and third utilize an assembly that consists of an inverter and a transformer that can be plugged into the normal power grid just in case there is insufficient sunlight to properly run the system. The second layout shows the plug assembly going in before the photo sensor in order to power the entire system, while the third layout has the plug assembly only able to power the security lights. We chose this as one of our possible designs due to the fact that the security light must be more reliable that the landscaping lights. Even if the path this not lit, the customer would still want the security lights to turn on in case of a possible break in or other emergency. The fifth, and final, design shows the panels being split and the use of two charge controllers and batteries. This allows for the security lights and landscaping lights to be run on a completely separate grid. This design goes back to the previous notion of the importance of the security lights and makes it so the landscaping lights will not be able to drain the power for the more essential security lights.

**Table 1: Parts and Functions of System Layouts**

| **Part** | **Function** |
|---|---|
| Solar Panels | Collect sunlight to power system |
| Charge Controller | Monitor power to battery, cutoff power once battery is fully charged |
| Battery | Store power to run system |
| Photo Sensor | Activate system at night, turn off during daytime |
| Motion Sensor | Activate security lights |
| Timer | Turn on/off landscaping lights |
| Switch | Turn on/off parts of system as necessary |
| Inverter/Transformer | Take 120V AC to 12V DC |
| Plug | Plug into house power grid |
| Landscaping Lights | Light pathways and plants |
| Security Lights | Light front door area |

*System Characteristics*

As a group we worked through several different concepts from the solar panels to the lights. Although the overall systems were not much different from one another, there were small, subtle differences. We considered using two, three, or even all four solar panels to power the system. The concepts also consisted of combinations of the different wiring layouts shown above and various light fixtures including path, directional, and security lights. We used different groupings of the lights in order to accent different parts of the landscaping. Advantages and disadvantages of the different setups are thoroughly discussed below in the concept selection and alpha design sections. In an attempt to not be incredibly repetitive, we will not replicate them here.

## ALPHA DESIGN CONCEPT SELECTION

*Decision Matrix*

In order to determine which solar system design concept to pursue for an alpha design, a Pugh chart decision matrix was implemented to weigh each potential concept's strengths and weaknesses to a standard reference.

*Determination of Proper Bulb Selection for Light System*

On the lighting end of the system there are many options as to how many of each type of light that will be used as well as the different kinds of bulbs that can be used. The kinds of bulbs that were considered consisted of halogen, incandescent, fluorescent, and LED. One advantage of using halogen or incandescent bulbs was the amount of light that was emitted from them; however, the power consumption was too large for our solar panels. LED lights were an alternative lighting source that would not draw too much power, but the brightness became a factor for concern. LED lights have a much longer service life than most other types of bulbs, making them more desirable for this system.

The selection criteria, Table 2, are based on the customer requirements and weighted by importance by speaking directly with the primary market consumer. Each of the selection criteria applied to the designs were compared to the reference of the current market systems. The first Pugh chart, Figure A18, is used to determine the proper light bulbs for the system using halogen bulbs as the market reference. LED bulbs were determined to be the best selection along with the current halogen bulbs.

*Wiring Layout Selection for Light System*

There were many lighting layout concepts that used a different variety of path, directional, and security lights. A disadvantage to having more directional lights shining on the landscaping were that the path would not be lit as well as the customer had requested, but the path lights would give very little light to the plants in front of the house. We thought that a good combination of the two types of lights would give us a good lighting setup. After working through numerous lighting layouts we narrowed this list down to three and made layout drawings that can be found in Figure A13-A17.

The next selection process regards the wiring system layout, Figure A19. These current market systems were determined during the benchmarking process, in which the designs include lights with a solar panel on top of the fixture and lights in which a separate small solar panel is used to power the one light. Concept Layout 2 was determined to be the prime arrangement and will be used for the alpha design.

**Table 2: Abstract of Concept Design Selection Criteria**

| Requirements of Design | Significance to Design |
|---|---|
| Powered only by Solar | Purpose is to power entire system solely on solar radiation |
| Provides Pleasurable Lighting | Entire lighting system illuminates desired areas at a comfortable intensity |
| Illuminates desired areas well | System is designed to illuminate all desired areas effortlessly. |
| Low Cost | Entire system must be reasonably priced to the average homeowner. |
| Amount of Power Supplied to Battery | Each panel produces a certain amount of energy each day to power the battery. Total number of panels to do this can range from 1 to 4. |
| Service Life | Solar cells, battery, wiring, fixtures, and light bulbs do not require replacement. |
| Aesthetically Pleasing | Determined by the number of panels used, number of lights in system to illuminate walkway, and light fixture appearance. |
| Efficient Solar Panels | Solar panel efficiency determined by amount of solar radiation power that enters the panel to the power that exits and enters the battery. |
| Low Power Lighting | Light bulbs used in each fixture require a low amount of power to operate. |
| System activates during continuous worse case days | Light system will still activate due to enough solar collection transferred into the battery to power system during a series of "bad" solar collection days. |
| Easy to use | Once the system is in place, no additional effort is required to operate. |
| Robustness | System must be weatherproof and have a strong enough material for fixtures and housings to be able to withstand wear and tear. |
| Feasibility | The system be powered with specific concept design and use only light bulbs with low voltage and low power. |
| Easy to install/deconstruct | The system can be taken down with ease taking into account all wiring and number of panels used. |
| System Activation Control | Feature to allow user to interface with entire system to activate or deactivate based on personal preference. |

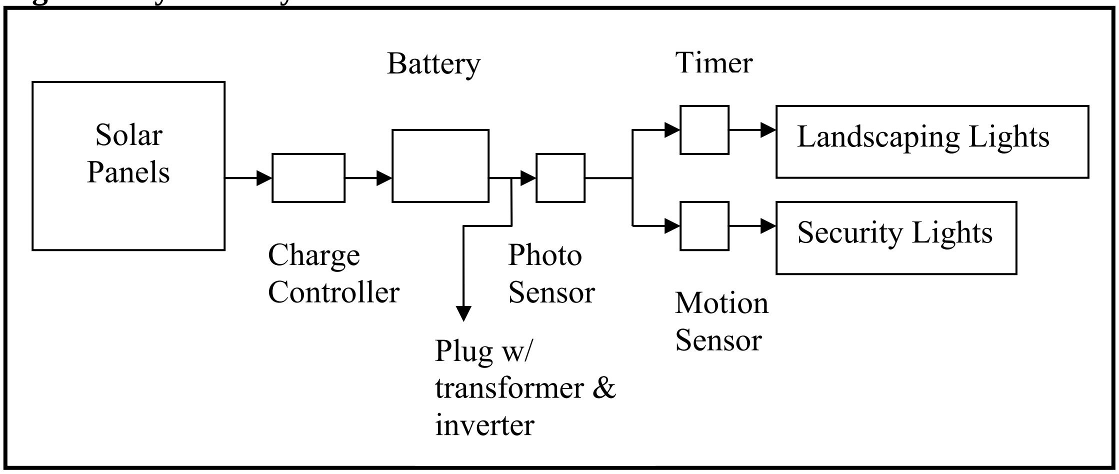
**ALPHA DESIGN**

At first our plan was to use only two of the solar panels. After initial testing we found that it would not be feasible to run the entire system strictly on solar power if only two panels were to be used. We concluded that all four panels would be necessary to power the system without compromising functionality. We also decided to use System Layout #2, shown in Figure 1, in case there was insufficient sunlight and the system would be plugged into the grid for additional power with a switch making it easy for the customer to apply this option. This compromises our goal to use only solar power, but it guarantees functionality and performance.

Even with the use of all four panels we still had less power than we had originally hoped due to lack of sunlight in the winter months and low panel efficiencies. This pointed us in the direction of LED bulbs as opposed to incandescent or halogen bulbs for the landscaping lights. We decided to use halogen bulbs in the security lights, but use low wattage bulbs, approximately five Watts per bulb, instead of the standard 20 to 50 Watt bulbs. As an alternative to using only path lights we chose to insert two directional lights in order to accent some of the plants in the flowerbeds. This helped give us a more unique and attractive look. In the end we chose to use two security lights, two directional lights and six path lights in a layout that would best light the area while being gentle and subtle to the customer but still serve its purpose well. A final layout can be seen below and the functional decomposition of the alpha design is show in Figure A22.

One of the main advantages of our alpha design is that the power used by the lights does not exceed the average power intake of the solar panels. This allows us to run the system effectively as long as there is not an extremely low amount of sunlight. If this extreme is encountered we plan to wire in a plug set up with an inverter and transformer that can be plugged in/switched on to pull power from the grid as a contingency plan. The inverter and transformer take the 120V AC that comes out of a standard outlet and feeds 12V DC to the lighting system. The disadvantage here is that when plugged in, the system does not run on purely solar power. The use of only solar power was high on our design requirements list and is very important; however, the ability to plug in the system assures functionality and performance. The use of LED's in the path lights and directional lights gives us the ability to use more lights due to the low power rating of the LED's. A possible downfall of using LED's as opposed to halogen bulbs is the brightness of the lights. Halogen bulbs emit much more light than LED's. Our solution to this problem is to order replacement LED bulbs with multiple LED's in each bulb. This will help with the brightness issue. The use of low wattage halogen bulbs for the security lights pulls more power from the system than we had hoped at first, but they will produce enough light to serve their purpose without being too bright. Finally, using the setup we have chosen will cut down on cost. Only one charge controller, battery, and photo sensor must be used as seen in System Layout #2. The inverter and transformer add cost but this option will make the system much more reliable.

**Figure 1: System Layout #2**




## INITIAL MANUFACTURING PLAN

A box for the panels to sit in and be mounted to the deck railing must be manufactured in house. The bottom and sides of the box will be made from wood that resembles the texture and look of the deck railing. It will also be painted to match the railing in order to achieve maximum aesthetics. The box will be covered with Plexiglas in order to protect the panels for weather and any other airborne objects. The Plexiglas, however, must not block any light with a wavelength between 350 nanometers and 900 nanometers. This is the usable range of light that the panels absorb. It will be secured to the railing using L brackets. The wiring will then run down the posts and will be painted to match so they may blend in as well as possible. The wood will be cut using a table saw and/or a band saw. The Plexiglas covering could be cut using the laser cutter as long as it is not too large. Everything will be fastened together using galvanized deck screws for weatherproofing and strength. The most critical surfaces are the ones that determine the interior dimensions of the box. It must be able to hold the solar panels completely inside of the box, while not being too large. A box that is too large would simply be a waste of material and resources.

## PROBLEM ANALYSIS

*Placement of LED in Light Housing*

As determined from the concept selection of LED lights from Design Review 2, one issue that has come up is determining a way to fit the Superbright LED lights in the desired light housings. The current models of the light housings that are preferred by the customer have mini-can halogen fixture. Therefore upon construction of the individual lights, the current mini-can halogen fixture will need replacement. A fixture to accommodate the Superbright LED lights was ordered from Autolumination through their website. When manufacturing for the light housing begins, the original halogen fixtures will be stripped and the LED fixture will have to be wired and soldered in place. Therefore, the lighting system will be running on 0.56 Watt LED bulbs rather than 20 Watt halogen bulbs, allowing the system to fully operate under worst case conditions.

*Construction of Lighting System*

After completion of the lighting fixtures, solar cell mounts, and battery housing the implementation of the system on the customer's house will prove challenging. With the rapidly changing weather, snow and permafrost is quickly becoming an issue. Several hundred feet of wiring must be placed in the ground and the lights and panels must be mounted properly without the hindrance of heavy snow or frozen ground. To prevent this issue the fabrication phase of the system must be completed by the last week of November and installation on the house before December 2, 2006. Furthermore, a date that suits both the design engineers and the customer must be determined for the house system setup.

*Solar Cell Damage*

A potential future problem is the possibility of the solar cells being damaged therefore resulting in either expensive replacement of the cell or inadequate power for the lighting system. An outer layer of glass currently protects the cells. A number of objects (such as hail, stones, or falling braches) could render them unusable if the come in contact with enough force. If one panel breaks the system will lose approximately 25% of its daily power storage. Furthermore, there is the risk of further damage to the remaining panels. We have contacted United Solar regarding a protective covering that could be placed over the cells without inhibiting solar radiation collection. To determine how much resistance protection is required, additional impact testing will need to be made. United Solar suggested an acrylic clear plastic material sheet. In order for the protection covering to not inhibit the solar radiation, the sheet must be optically transparent from 350-900nm wavelengths.

*Solar Power Output Data-Log*

As stated before in the solar cell location section, on-site testing was conducted to begin determining the optimal position and angle to allow maximum solar absorption into the cells. However, with the current equipment only instantaneous results could be determined at each angle and position. In order to further prove our hypothesis of panel location and validate our radiation collection model, a continuous analysis of the solar cells must be conducted. On the scope meter provided to our team, an experiment of attaching a panel on the side of the deck and performing a *data-log* of a continuous solar power output of the panels. Furthermore, this data-logging will be done at various cell angles and during varying weather conditions allowing for all possible circumstances. This will allow the creation of a solar radiation power model to validate our system in order to design according to minimum power available during worst case conditions.

*Sunlight Obstruction to Panels*

With the placement of the solar cells being attached to the side of the deck, a new problem arises which will only worsen as time goes on. The panels will be place approximately 25 ft away from a forest being the house. Currently the trees prove to be a nuisance to the design but do not fully inhibit the collection process. Furthermore, over a course of a few years the trees will become a greater threat to the process making it increasingly difficult to capture sunlight. No action can be taken to stop this issue unless a new location for the panels is determined to prove more practical. The concept selection proved the attachment of the panels to the deck was the best situation. However, the lighting system is being designed for operation during worst case conditions, in December with minimum sunlight as possible through the year. Therefore even during the summer when the back trees are their fullest, they will not hinder the power collection enough to stop operation.

## PARAMETER ANALYSIS

*Modeling*

The modeling of our system is broken down into two main sections. The system input is the solar panels and the power going into the battery and the system output includes the power leaving the battery and all of the lights. There are some details that we are aware of but are not specifically assigning values to in our model. These include the losses of power due to the wiring and charging/discharging of the battery. We know that these will cause some power some power losses and there is a safety factor of 1.4 in the system to account for these losses. Unfortunately our system is limited in power by our panels, and our customer wants all ten of the landscaping lights in the system. What we have done is design our system for the worst-case scenario, the least sunlight, which occurs in the month of December according to the Renewable Resource Data Center as seen in Figure 2 below. Since it is the worst case we should be getting more power the rest of the year. In fact, in June the system should receive almost 4 times as much power as in December. We have also designed into the system two switches to shut off up to seven of the ten lights. This way if we get worse than our worst case scenario and the losses are significant, part of the system can be isolated and shut-off to keep the important part, the path lights lit.

*System Input*

We calculated that we will have an average 48.5 W/day of power in December. To determine this value, we used Equation 1.

$$P = R\eta An \qquad \text{Eqn. (1)}$$

where $P$ is the total power input by solar panels, $R$ is the solar radiation of 1600 Wh/m$^2$/day, $\eta$ is the average solar panel efficiency of 0.0265, $A$ is the area of one solar panel, which is 0.287 m$^2$, and $n$ is the number of panels for the system. We predicted our wattage output per day per panel in December to be only 12.1W/day. Due to the low wattage per day we decided to use all four solar panels available. This value was calculated using the minimum of the average daily values for solar radiation in December in Detroit, Michigan over a thirty year period with a 60° tilt angle. This value is 1.6 kWh/m$^2$/day as seen in the Figure 2 below. Also used in this calculation was the tested average efficiency of our panels described more in the solar panel testing section.

### Figure 2: Solar Radiation Data for Detroit

Solar Radiation for Flat-Plate Collectors Facing South at a Fixed Tilt (kWh/m²/day), Uncertainty ±9%

| Tilt (°) | | Jan | Feb | Mar | Apr | May | June | July | Aug | Sept | Oct | Nov | Dec | Year |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | Average | 1.6 | 2.5 | 3.4 | 4.6 | 5.6 | 6.2 | 6.1 | 5.3 | 4.1 | 2.8 | 1.7 | 1.3 | 3.8 |
| | Min/Max | 1.3/1.9 | 2.1/3.2 | 3.1/4.0 | 3.6/5.2 | 4.6/6.5 | 5.5/7.3 | 5.7/6.8 | 4.6/6.1 | 3.5/4.7 | 2.2/3.4 | 1.3/2.1 | 1.1/1.5 | 3.6/4.0 |
| Latitude -15 | Average | 2.4 | 3.3 | 4.1 | 5.0 | 5.7 | 6.1 | 6.1 | 5.6 | 4.8 | 3.7 | 2.4 | 1.9 | 4.3 |
| | Min/Max | 1.8/2.9 | 2.7/4.6 | 3.5/5.1 | 3.7/5.8 | 4.6/6.7 | 5.4/7.2 | 5.6/6.8 | 4.8/6.6 | 3.9/5.6 | 2.6/4.7 | 1.5/3.3 | 1.4/2.5 | 4.0/4.5 |
| Latitude | Average | 2.7 | 3.6 | 4.2 | 4.9 | 5.4 | 5.6 | 5.6 | 5.4 | 4.8 | 3.9 | 2.6 | 2.1 | 4.2 |
| | Min/Max | 1.9/3.3 | 2.8/5.1 | 3.6/5.3 | 3.6/5.7 | 4.3/6.2 | 4.9/6.6 | 5.2/6.3 | 4.5/6.3 | 3.9/5.7 | 2.7/5.1 | 1.6/3.7 | 1.5/2.8 | 4.0/4.5 |
| Latitude +15 | Average | 2.8 | 3.7 | 4.1 | 4.5 | 4.8 | 4.9 | 4.9 | 4.9 | 4.6 | 3.9 | 2.6 | 2.2 | 4.0 |
| | Min/Max | 2.0/3.5 | 2.8/5.4 | 3.5/5.2 | 3.3/5.3 | 3.8/5.5 | 4.3/5.7 | 4.6/5.5 | 4.1/5.8 | 3.7/5.5 | 2.6/5.1 | 1.5/3.8 | 1.6/3.0 | 3.7/4.2 |
| 90 | Average | 2.6 | 3.3 | 3.2 | 3.0 | 2.8 | 2.7 | 2.8 | 3.1 | 3.3 | 3.2 | 2.3 | 2.0 | 2.9 |
| | Min/Max | 1.8/3.4 | 2.5/5.0 | 2.7/4.1 | 2.2/3.6 | 2.3/3.1 | 2.5/3.0 | 2.6/3.0 | 2.6/3.6 | 2.6/4.0 | 2.1/4.2 | 1.3/3.5 | 1.4/2.9 | 2.7/3.1 |

*Solar Panel Testing*

To discover the characteristic parameters of the solar panels, appropriate testing had to be implemented. The panels were taken to the facilities of a local solar cell producer, United Solar Systems. Investigation began by applying direct sunlight of $1000W/m^2$ to each panel, as shown in the test setup in Figure A23, and observing behavior of output voltage and current from the panel. Furthermore, each panel was tested using the parallel connector and a series connector to verify the initial results. It was concluded that the solar panels each provided a maximum output of 6-8Watts of power under optimal conditions. This is much lower than the solar cells' specifications of 14Watts during overcast conditions from the distributor. Probably the most important characteristic of the cells is the efficiency, from the three panels tested there was an average efficiency of 2.65% based on the ratio of power output to power input to the cell. Again, this is extremely low compared to the cells from United Solar with an efficiency of 8.5% and some higher efficiency panels on the market that get between 14% and 22%.

*Power from Panels*

Using all four panels in the worst-case scenario we predicted that we will be able to get 48.5 Wh/day from the solar panels. Therefore, we designed the system to this wattage. This wattage can be seen in Figure 3 below along with the output from panels with higher efficiencies and along with the output we should receive in June, the month with the most solar radiation. Note that in June we should have almost four times the power that we have in December. Also shown in the table below are the power predictions for a one axis tracking system. The increases in power in December are minimal and would not be enough difference to power the motor required for a tracking system.

### Figure 3: Anticipated Power Output

Southern Facing Panels with Optimum Fixed Tilt Angle

| | | December-minimum | | 1600 W/m^2/day | | June-average | | 6200 W/m^2/day | |
|---|---|---|---|---|---|---|---|---|---|
| | | Number of Panels | | | | | | | |
| | Efficiency | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 |
| Given Panels (W/day) | 0.0265 | 12.1 | 24.3 | 36.4 | 48.5 | 47.0 | 94.0 | 141.0 | 188.0 |
| Uni-solar Panels (W/day) | 0.065 | 29.7 | 59.5 | 89.2 | 119.0 | 115.3 | 230.5 | 345.8 | 461.0 |
| High efficiency Panels (W/day) | 0.148 | 67.7 | 135.4 | 203.2 | 270.9 | 262.4 | 524.9 | 787.3 | 1049.7 |
| Area per panel (m^2) | 0.286 | | | | | | | | |

One Axis Tracking with North South Axis

| | | December-minimum | | 1700 W/m^2/day | | June-average | | 8000 W/m^2/day | |
|---|---|---|---|---|---|---|---|---|---|
| | | Number of Panels | | | | | | | |
| | Efficiency | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 |
| Given Panels (W/day) | 0.0265 | 12.9 | 25.8 | 38.7 | 51.5 | 60.6 | 121.3 | 181.9 | 242.5 |
| Uni-solar Panels (W/day) | 0.065 | 31.6 | 63.2 | 94.8 | 126.4 | 148.7 | 297.4 | 446.2 | 594.9 |
| High efficiency Panels (W/day) | 0.148 | 72.0 | 143.9 | 215.9 | 287.8 | 338.6 | 677.2 | 1015.9 | 1354.5 |

*System Output*

The lighting system will include ten landscaping lights. Three will be bollard path lights and seven tiered lights. We calculated that the lights will use 33.6 W/night if they are on for six hours per night. This was calculated using Equation 2

$$P = npt \qquad \text{Eqn.(2)}$$

where $P$ is the total power required for the lights, $n$ is the number of lights which is 10, $p$ is the power for each light of 0.56 Watts, and $t$ is the time the lights are on which is six hours. When we divide the power input by the power output, this results in a safety factor of 1.44. The safety factor will be needed to overcome losses from the wiring and from charging/discharging the battery.

*Light Bulbs*

LED bulbs are the only way we will be able to overcome our low power supply problem. We have found LED replacement bulbs, for common landscaping light fixtures, that use only 0.56W of power but replace a 11W Incandescent bulb that comes installed in the lights. Each of these bulbs contains 8 'super-bright' LEDs. The LEDs are positioned all around the bulb housing to neglect some of the direction lighting effects of LEDs. Once we installed the bulbs into the fixtures we saw the LEDs created unsightly spots on the housing glass of the light. To defuse the lights and eliminate the spots the bulb created, we installed a small mirror in the top of the fixture to act as a reflector. Then we aimed all 8 of the individual LEDs at the mirror and it defused the lights and eliminated the spots. Halogen bulbs are generally found in landscaping lights, and use between 7W and 20W of power. If we use a very common 13 W per light bulb, and the same number of lights and duration, the halogen lights will use 780 W per day. This far exceeds our power limit from the solar panels; therefore this eliminates halogen bulbs as a possibility for our lights. The same problem arises with incandescent bulbs, and while fluorescents are more efficient, the only bulbs we found under 4W were LEDs.

*Battery Efficiency and Life Expectancy*

The battery life for our system was calculated to be 11 days. This was based on the total system output, the size of our battery, and the battery efficiency. We tested our given battery and found it has 78% efficiency. That is, it will use up 78% of its power before the lights start to dim. We tested the battery by having our 12V, 40Amp-hour battery fully charged. Then we attached three 50W, 12V light bulbs to it and made observations every half hour; these recordings are displayed in Figure A24. It took 2.5 hours before the lights started to dim, so it delivered 375Wh of power before the lights started to dim and the battery is rated for 480Wh of power at 12V. That comes out to 78% efficiency. Our current 40Amp-hour battery should be sufficient for our system. Based on the fact that the lighting system should run off of 33.6 W per day and our goal is for the system to be able to run off the battery for a seven-day period with no added power. Using the 78% efficiency we get 375 Wh of power from the battery, which is more than the 235, Wh (33.6W*7days) needed for the lights to run seven days. The system should actually be able to run for eleven days without any added power.

*Failure Safety*

There are only minor safety issues associated with our solar panel lighting system. The two areas of safety concern are electrical shock and failure of solar panel box mechanism. There are always safety issues when electricity is involved, however our system uses only low voltage electricity which makes the effect of an electric shock minimal. Our system utilizes conduit to house the wire, when it runs from the panels to the battery, and after the battery the wire will be buried underground. The other possible safety issues occur if solar panels boxes are used inappropriately. When the boxes are in the zero degree position they are level with the deck rail, and provided a convenient spot to set down a drink or light object. However if they were used to support the weight of a person they would fail, resulting in a fall of about 8 feet. We figured the point of failure would be the holes which house the bolts that connect the box to the arms. Through stress analysis of these holes we found that the structure will fail when a load of 40.8 lbs is applied to the top of the solar panel box. Therefore with a safety factor of 2, the load on the solar panel box should not exceed 20 lbs. If these boxes were going to be produced for public use they should contain a label; do not sit, do not exceed 20 lb load. The boxes will also be sanded around the edges and painted to ensure that there are no sharp surfaces.

*Design for Manufacturability/Assembly*

The final design was chosen in part for its ease of manufacturability. Consisting mostly of common, low-cost materials, the system is cost-effective in its assembly. Also, the design of the panel box and mounts is fairly simple with regular geometric shapes. In addition to the mounts is the decorative lighting. They were purchased, though slightly modified. The bulbs were replaced directly in the lights with the same connection, and a fixture was attached inside the remaining lights to adapt from one type of connection to the T5 wedge connection on the LED bulbs. Also, three-inch circular mirrors were attached to the top of each light-housing to facilitate reflection, increasing the intensity of the lights. Granted, the design is yet a prototype and future revisions may promote modifications, but we do not anticipate many manufacturing difficulties.

The panel box consists of a series of 1x2's pieced together with L-brackets and small screws; four pieces creating the sides and two smaller pieces used to create an open back with braces to support the panel. A Plexiglas sheet was placed over the box to cover the panel for protection from environmental and human caused impacts.

The system was designed for a specific location, though it may be easily modified and applied to almost any other site, residential or commercial. The panel boxes and latching system are easily mounted to any deck railing or even the side of a house. The lighting fixtures are also very easily installed at almost any location, making this system very common in a wide variety of applications. There are, however, some aspects of this system that are modular to each individual installation. First, the lighting layout would need to be reworked for each site. The work associated with this portion is minimal and is almost solely based on the customer's desires. The system layout could also be changed, making this system more simplistic or complicated, based on the clients needs.

## FINAL DESIGN CONCEPT SELECTION

*Solar Cell Adjustable Mount Mechanism*

In order for the system to be properly optimized the solar radiation collection, the solar cell panel mounts must have a mechanism to adjust the cell angle to collect the maximum radiation during the winter and summer months. A minimum of two angles is required to achieve the necessary seasonal adjustments for the system. It was determined that required angles of 0º during the summer and 60º from the horizontal, during the winter, will optimize collection during those seasons. Multiple mechanisms were considered and evaluated against the reference of a stationary panel mount. The selection criteria, shown in Table 3, are based on the customer requirements and weighted by importance by speaking directly with the primary market consumer. Through the decision matrix, in Figure A21, three possible mechanisms were considered and weighed. The lock-bar mechanism was the most beneficial and feasible concept. It allows for the minimum of two angles during the season changes, and is extremely low in cost compared to the other hinge mechanisms. In addition, it is easy to replace (components found in any hardware store not special ordered) and is robust to meet our system needs. However, it only adjusts to two angles while it is 3 or more that is desirable for the system, so that it could be more effective in each season according to the solar predictive model. The lock bar system will also require more time to install or deconstruct due to its slight complexity. Due to the project constraints of budget and lack of time the most feasible concept is the lock bar mechanism. Ignoring the constraints and designing for the ideal situation, the *VARILOC* hinge would provide multiple angles, robustness, and ease of use with no drawbacks.

**Table 3: Abstract of Concept Design Selection Criteria**

| Requirements of Design | Significance to Design |
|---|---|
| Low Cost | Must be reasonably priced for the average homeowner. |
| Adjustable Angles | Must be able to adjust solar cell angle. |
| Easy to Use | Mechanism is able to be used by one person with little effort. |
| Maintainability | Able to clean and maintain easily. |
| Weather Resistance | Will not be effected by various weather conditions. |
| Easy to Install / Deconstruct | Mechanism system easy to install and deconstruct. |
| Not Visually Obtrusive | Mechanism will not impair aesthetics of the entire system. |
| Robustness | System will not buckle under heavy loads. |
| Adjust to Three or more Angles | Mechanism can adjust solar cell to desired seasonal angles. |
| Ease to Replace | Easy to purchase and reinstall. |

*Protective Plexiglas Removal*

A protective covering made of Plexiglas will be added to the mount system to shield the glass solar cells from any risk of damage due to weather conditions or any other outside sources. The covering must be removable for cleaning purposes. Since the mount system is will not be sealed, condensation on the inner Plexiglas covering could potentially hinder the collection of solar power on the panels. Therefore a removal system will be necessary that follow a specific set of selection criteria as shown in Table 4. Through the decision matrix, in Figure A29, three possible removal concepts were considered and weighed. The slide motion with stops made from Aluminum L-shape trim was the most feasible design for its purpose and for the panel mount. As shown in Figure A30, the user uses a slide motion under the Al trim until it reaches the stop position. The user must pull the Plexiglas towards himself/herself, this concept along with the bottom and sides Al trim stops, keeps the Plexiglas in place until user removal. This concept is low in cost, allows the covering to be easily completely removed from the mount for cleaning, and will not hinder the robustness for the panel mount. However, the Al L-shape trim stops are not astatically pleasing to the eye and the Plexiglas is not held completely firmly to the mount. In an ideal situation, an adjustment to the mount for higher siding would permit the use of slits into the mount for the Plexiglas to slip into, without potentially causing damage to the mount itself. The chosen concept is the best choice with the time, budget and mount design constraints.

**Table 4: Abstract of Concept Design Selection Criteria**

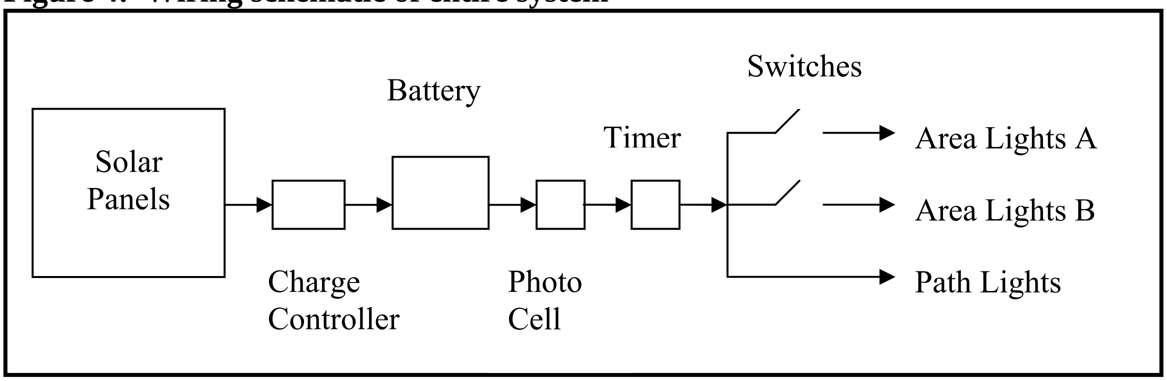
| Requirements of Design | Significance to Design |
|---|---|
| Plexiglas has a Removable Concept from Panel Mount | Unlike the reference, the Plexiglas can be removed with little effort. |
| Plexiglas can be Completely Detached from Mount | The Plexiglas can be entirely removed from the panel mount. |
| Concept will not Cause Damage to Panel Mount | Any adjustments or additions to accommodate the Plexiglas with not hinder the structural integrity of the mounts. |
| Plexiglas held Firmly in Place until Removal | Plexiglas can remain in place until user removes it and not any other outside source. |
| Visually Appealing | Concept is aesthetically appealing to everyone. |
| Ease of Removal | Removal Concept requires little to no effort on the user. |
| Plexiglas Interchangeable with All Mounts | All Plexiglas' can be used with any solar panel mount. |

## FINAL DESIGN DESCRIPTION

Our final design utilizes many of our initial ideas while combining a few new specifications. A functional decomposition of the final design is shown in Figure A25. We have decided on a finalized wiring set up that is similar to our alpha design. A schematic of this design can be seen below in Figure 4. As before the power is absorbed by the four solar panels that will all be mounted next to each other at an angle that will yield the best results in bad solar conditions. This angle will be adjustable for maximum performance of the system at different times of the year. From the solar panels the power will flow through the charge controller and into the battery. The purpose of the charge controller is to regulate the power that enters the battery and to keep the battery from over-charging or over-draining. If the incoming voltage is exceeding what the battery can handle it will reduce it. Also, if the battery is fully charged it will stop the power from even reaching the battery. Between the battery and the actual lighting fixtures there will be a photocell and a timer. The photocell will cause the lights to be off when it is light out and it will connect the circuit to turn the lights on at night. The photocell is triggered when the ambient light drops below one foot-candle and will shut the lights off when the ambient light exceeds one and a half foot-candles. Once the photocell is triggered by lack of light the timer will start. The timer is adjustable from twenty-four seconds all the way up to twenty-four hours.

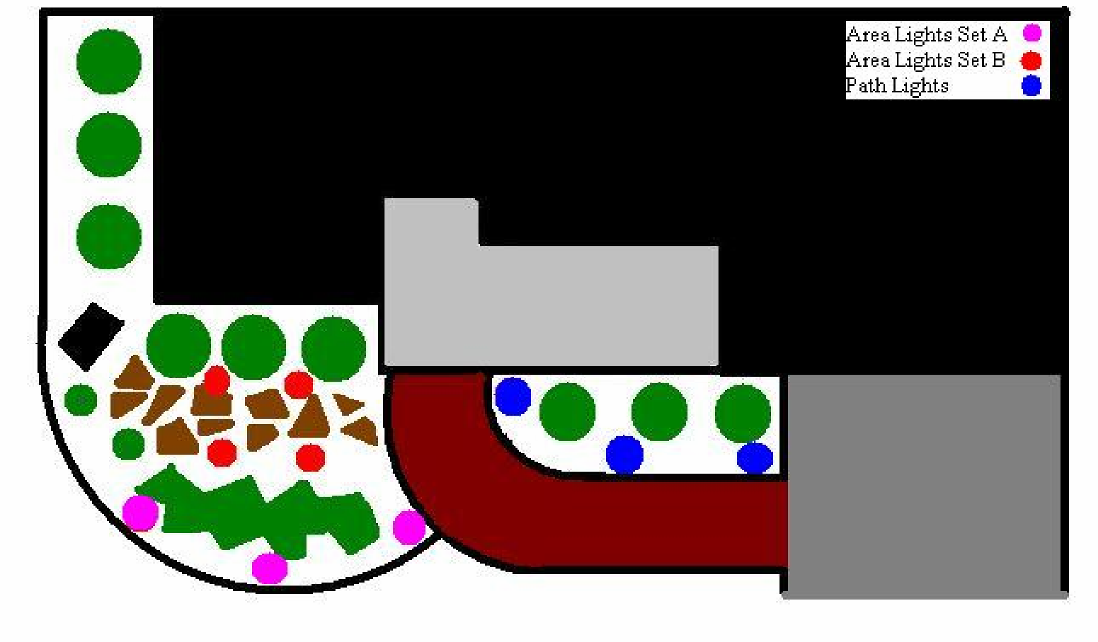
After the lights have been on for a given amount of time, which will be pre-programmed into the timer, the lights will simply shut off. As the sun rises the next morning the photocell will recognize the light and cut power to the system which will cause the lights to turn off and the timer to reset for the next night. For the lights to be on both the photocell and the timer must be active. As long as either of these two components is not allowing power to flow through them, the lights will remain off. From the timer the power flows to the light fixtures. We have chosen to incorporate switches on some of the lights. These can be used in the case of insufficient sunlight to power the entire system. We have divided the tiered area lights into two groups. Each of the two groups will have a switch that will allow them to be temporarily shut off by the consumer at any time. The switches are completely independent of one another as can be seen in the schematic. The path lights do not have a switch due to the fact that they are more for safety when approaching the front door whereas the area lights are more for aesthetics.

**Figure 4: Wiring schematic of entire system**



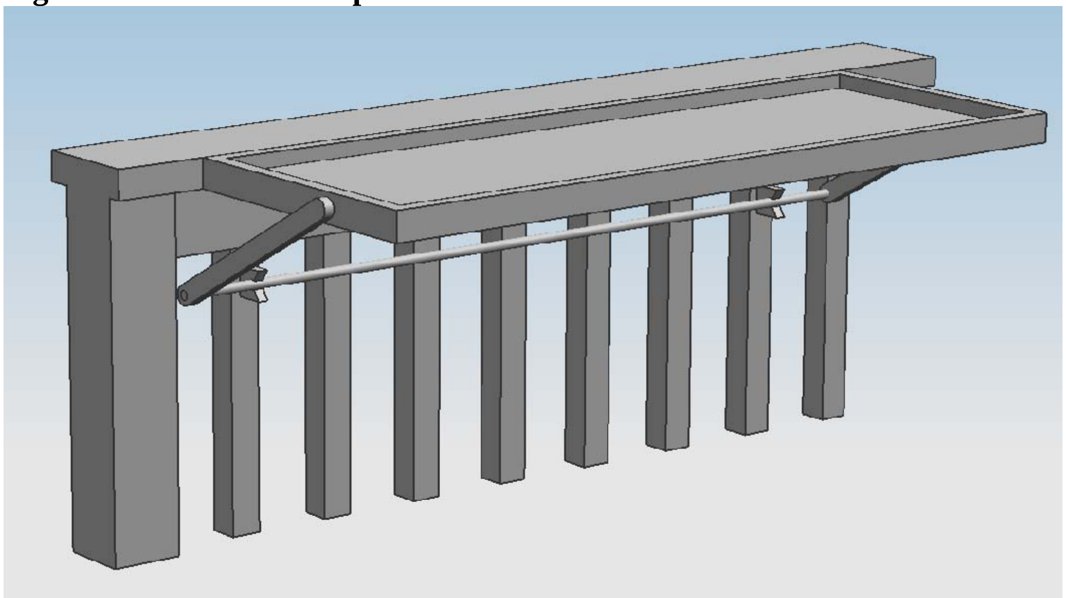

We have chosen a system layout that will be desirable for space and material optimization. The panels will be mounted on the outside of the deck railing with a specially designed bracketed box. There will be two support arms that hold a support rod hanging from each box. The support rod will lock into two latches; which are connected to the deck railing at different positions in order to make the solar array angle adjustable. The photocell will be mounted next to the panels for easy access and accurate readings. The battery, charge controller, and timer will be located in a weatherproof case underneath the deck. The case will be partially buried in order to be aesthetically pleasing while still accessible. The power will be taken from the panels and eventually out to the lights using a 12 gauge, two conductors direct burial cable that is made of special UV and weather resistant material, making installation much easier. After much deliberation, we have selected a final layout for the lighting fixtures shown in Figure 5 below. Each component, from the solar panels to the lights, is depicted where it will be installed.

**Figure 5: System layout from solar panels to lights.**




Due to the nature of our project, most of the components of our final design are purchased. There will be some re-fabrication of the path lights so that we can install our replacement low wattage LED bulbs. A full bill of materials with quantities and total cost can be found in the Appendix as Figure A27. Once these items are acquired we will need to connect them with the wire and install them in the yard.

**Figure 6: Plans for solar panel mount**



## FINAL MANUFACTURING PLAN

The one main part of our system that will be fabricated in house is the mount for the panels. Each panel will be set in its own panel box. Each box will be made of wood fastened with deck screws. They will be fastened to the outside of the deck railing with two hinges. This will provide enough strength to the panel and box in place. Two support arms with a support rod will be locked into two latches mounted to the railing in order to make the box angle adjustable for optimum performance. A CAD model of this mount is shown below. The panels are 36.5 inches long. The inside of the mount will accommodate for this space requirement and give about a quarter inch spacing all the way around the panel. There will also be a removable, protective cover over the panels made of Plexiglas. The Plexiglas to be used must not obstruct light of wavelengths from 350 nanometers to 900 nanometers so it will not block any usable light. All of the materials are made of weatherproof material including the hinges, latches, and fasteners. The wood will be painted to match the deck to achieve excellent aesthetics. The most critical surfaces are the ones that determine the interior dimensions of the box. It must be able to hold the solar panel completely inside of the box, while not being too large. A box that is too large would simply be a waste of material and resources.

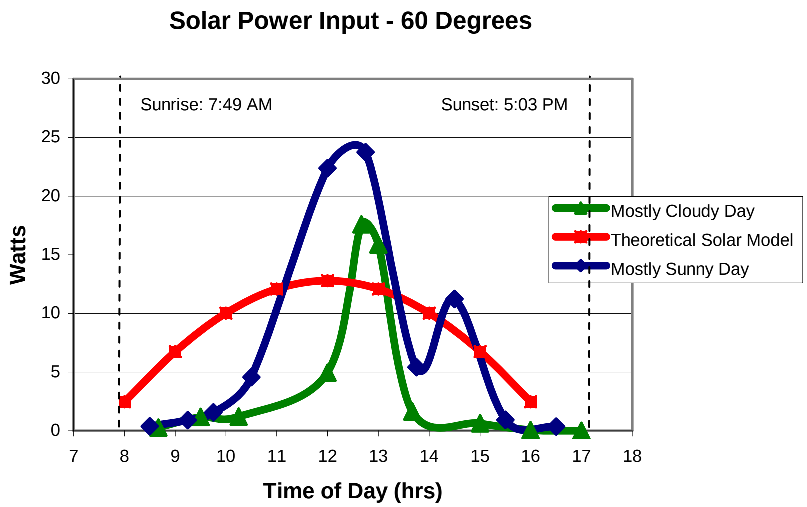
## VALIDATION TESTING AND ANALYSIS

The goal of our testing was to verify that our initial system analyses were correct and that the system once installed will perform properly. In order to achieve this goal we needed to perform validation testing for our power input, power output, and system losses.

### *Power Input*

The testing of the power input made us confident that we would receive a least our predicted average daily power of 48.5 Wh/day. We performed the testing over two complete days. The first day was overcast and mostly cloudy; there was an average cloud cover of 71%. On this day the panels output an estimated 43.4 Wh with the panels at the 60° position. The second day was mostly sunny with an average cloud cover of 45%, and on that day the panels output an estimated 71.4 Wh. This is well above our predicted average. Therefore we are confident that the average output from the panels will be able to exceed the 33.6 Wh/day that are required to power the ten lights for six hours a night. Graph X.X below shows the power output of the panels by hour for the two days along with the predicted theoretical output of the panels. The theoretical power data is based upon an equation with the following variables; the latitude, solar declination angle, time of day, and tilt angle of the panel. The equation for the theoretical panel outputs are in Appendix B.

**Figure 7: Experimental vs. Theoretical Solar Input**




As seen in the graph the experimental data really peaks at 12 pm and 1 pm and is higher than the theoretical model. During December this is the time of day when we will receive the bulk of our solar insolation. This is different from the theoretical data which has a steady increasing and then decreasing curve. This is what we expected to see because in the winter the sun is the closest to the earth, giving the highest peak value, but the sun is only in direct contract for a couple hours, explaining the sharp peak. We believe that the experimental data will follow the theoretical model curve more closely in the summer months. The theoretical model is supposed to be for the entire year but more closely follow the trend of the summer months.

The optimum angle for our system was found to be at the 60° position. The theoretical optimum angle for December in Ann Arbor was 63°, but we rounded that to 60° for convenience of testing. We also tested the panels at a flat 0°, which will be an optimum angle during the summer months. Table 5 below shows that our experimental data matches up to our theoretical prediction that 60° is better than 0°. Due to lack of time to test and the lack of a data logging system, we were unable to test other angles.

**Table 5: Optimum Angle Table**

| Panel Tilt Angle | Mostly Sunny Day | Mostly Cloudy Day |
|---|---|---|
| 60° | 71.4 Whr | 43.4 Whr |
| 0° | 45.8 Whr | 24.0 Whr |

*Power Output*

We attempted to test the system output efficiency by first completely discharging the battery so we would have a reference value for power in the battery. Then we charged the battery with the solar panels for an entire day and estimated that 71.4 W got charged into the battery. Then we attached six LED lights to the battery and they lasted longer than expected, however the lights started to dim before the expected time. The total power used by the lights was 54 W; however they were still lit when we ended the testing. It took over 64 hours to use up the 54W. This was due to the lights using significantly less power when running at lower voltage. The dimming of the lights was due to the lower voltage the battery was putting out after it had been connected to the light for a period of time. We believe that this was caused from the battery being near total discharge. As we discovered in our battery testing the lights start to dim when the battery is below 8.8 Amp-hrs. The charge we put into the battery from the one day of solar power from the panels was less than this amount.

The main problem with this discharging testing process is that we needed a reference value to charge from and discharge to. Trying to completely discharge the batteries brought about the problem of the lights dimming. Therefore in further testing we suggest that a voltage reference value is chosen with a set amount of lights attached. The reference voltage should be under 12 V but above 7 V where the lights appear dim. This should overcome the problem of having a reference value and the lights not dimming. We were unable to do this ourselves because of a lack of time.

Therefore we believe that the charging/discharging of the battery is efficient, and advise that the battery be charged by an external source before it is implemented into the system to avoid these dimming effects.

*Battery Testing*

We tested our given battery and found it has 78% efficiency. That is, it will use up 78% of its power before the lights start to dim. We do not want the lights to dim sacrificing performance; therefore we need to keep a minimum of 8.8 Amp-hrs in the battery at all times. We tested the battery by having our 12V, 40Amp-hour battery fully charged. Then we attached three 50W, 12V light bulbs to it and made observations every half hour; these recordings are displayed in Figure A24. It took 2.5 hours before the lights started to dim, so that is 375Wh of power and the battery is rated for 480Wh of power at 12V. That comes out to 78% efficiency. Our current 40Amp-hour battery should be sufficient for our system. Based on the fact that the lighting system should run off of 33.6 W per day and our goal is for the system to be able to run off the battery for a seven-day period with no added power. Using the 78% efficiency we get 375 Wh of power from the battery, which is more than the 235, Wh (33.6W*7days) needed for the lights to run seven days. The system should actually be able to run for eleven days without any added power.

*Wiring Losses*

We found that the loss of power due to the wiring in our system will only be 4.4% loss in efficiency. We calculated this by finding the resistance of a 100 ft. section of the lighting wire we will be using we the system is installed to be 1.2 Ω. Then we interpolated that value to our actual length of wire we will be using which is approximately 130 ft., and got the resistance of the entire wire to be 1.5 Ω. Then we divided the predicted voltage loss by the battery voltage to come up with the efficiency loss.

## IMPROVEMENTS TO SOLAR MODEL

The current solar predictive model takes into account latitude, solar declination angle, panel tilt angle, and the hour angle. This current model does not take into account cloud cover or weather. If we had more time and data logging ability we believe that we could add a corrective factor in the model to adjust for weather conditions. For example we were only able to test for 2 full days, but we found a 65% increase in daily power with a decrease of 26% average cloud cover. So there are very strong trends with cloud cover and power. However this corrective factor will have to be an average and will not be extremely accurate for instantaneous power, because a cloud cover percent can be low and the sun can temporarily be behind a cloud and alter the data. Over an entire day the cloud cover and power should average out.

Another improvement to the solar model is its inaccuracy in the winter. During the winter months the power really peaks for only around two hours a day and during those two hours the experimental power was higher than the model predicted power. This result is expected, because the sun is closer to the earth during the winter but the direct sunlight is only received for a short period of time. The current solar model is more accurate in the summer because it has a steady increase and decrease of power throughout the day, but the peak power is lower. This is what we expect to see with the experimental data in the summer. Figure 7, above in the validation section, shows the steady curve of the predictive model and the sharper peak and higher value of the experimental power in the winter.

## INFORMATION SOURCES

*AWARE@Home*

Professor Skerlos provided for us the report that provided the specifications of the battery and solar panels. This report gave us the exact specifications of the supplied materials and detailed information as to where we could locate more about them. Also, the report included specific information as to how the panels were characterized, which provided us another means to accomplish the task.

*United Solar*

United Solar is a company that produces solar cells in Auburn Hills, Michigan. Close-by, it often works closely with the University of Michigan Solar Car Team and we were introduced to them through a fellow classmate. They kindly assisted us and characterized our solar panels. We were able to make full use of their facilities, which provided us with conclusive evidence of the inefficiency of our solar panels.

*Vista Professional Outdoor Lighting*

This landscaping catalog provided us with the necessary information about outdoor lights. The wide range of different lights included in this catalog allowed us to draw conclusions about the different kinds of lighting systems we could install outside of Professor Skerlos' home.

*Lacking Information*

As a team, we still must find a way to fabricate the housing as well as understand how to install the system in a landscaping context. Currently, we are contacting landscaping companies as well as machine shop technicians here at the university.

*Budget*

As expected, the budget of our project will breach the $400.00 limit set by the course instructors in the beginning of the year. However, due to the nature of the project, Professor Skerlos will be providing the funds for most of the parts. As noted previously, a Bill of Materials may be found in Appendix A as Figure A27.

## ENVIRONMENTAL IMPACT

A customer utilizing solar panels instead of energy from the grid to power our designed landscape lighting system will save approximately 19 $^{\text{lbs CO2}}/_{\text{Year}}$ from Michigan power plants. Environmental impact for power production from Michigan coal power plants was determined to be 1.54 $^{\text{lbs CO2}}/_{\text{kW-hr}}$. This is based on the fact that Michigan generates 70% of its power from coal power plants and 30% from Nuclear power plants. Therefore this alternate power not only saves $CO_2$ from escaping into the environment but also prevents toxic waste created from being created. Furthermore, our light design with the use of the selected low power LED bulbs combined with reflectors to replace traditional Halogen bulbs will prevent an additional 443 $^{\text{lbs CO2}}/_{\text{Year}}$ if they were to be wired to the house power grid.

The landscape lighting system requires 122.6 $^{\text{kW}}/_{\text{yr}}$ and our amorphous solar panels have an embedded production energy of 116 $^{\text{kW-hr}}/_{\text{m\^{}2}}$. Therefore embedded energy payback necessary for the solar panels will be approximately 10.8 years. However, the life of a solar panel is usually 20-40 years; therefore the system will have a reduction on environmental impact in the long term. The energy payback could be significantly sooner if the solar panels were used to their full potential. However we designed our system to perform properly in December, so in June when the solar radiation is almost four times as much, we will still only be using the same amount as in December. This potential could be utilized if “summer lights” were added to the system or the energy was used to power something else.

Photovoltaic power is generated directly from the sun. Unlike other renewable energy sources such as wind or water power systems, photovoltaic power methods contain no moving parts and require practically no maintenance.

## DESIGN CRITIQUE AND MODIFICATIONS

*Power Prediction Model*

In order to track and predict the power input to the system from the sun via the panels, a model created from weather, sunlight, cloud-cover, and time-of-day data taken at multiple tilt angles is necessary. Ideally, with an accurate model, the user of the system would be able to predict approximate power input levels throughout the year. However, due to time constraints and planning, we were only able to validate our system – unable to create a proper model. A successful design of experiments would record the power input from the solar panels over a given time period, varying one of the parameters through each trial. A longer testing time period would be the most beneficial, with a month of data being nearly ideal. A multi-meter connected to a computer is suitable to record the instantaneous power levels at various times. The model would be most significantly affected by the sun's path over a year, and loosely based on weather and cloud-cover. Due to the chaotic nature of weather, creating an accurate model strongly based on weather and cloud-cover is impossible. Ideally, data from this experiment in conjunction with sun path data should be used to approximate power input levels over the course of a year. Ultimately, a rigorous experiment such as this produces confident power data, allowing us to design our system for greater efficiency by finding optimum tilt angles for the photovoltaic panels.

*Safety Factor*

Our system was designed with a safety factor of 1.45 on the available power to the amount required to supply the lights due to product goals and power limitations. Of course, our system was not designed with the industry standard safety factor of two and that is a necessary improvement for increased robustness and greater reliability.

*Reflectors*

A future modification of this system should include reflectors surrounding the solar panels to aid in energy collection. This was not directly researched and therefore not implemented in our final design, though it is widely accepted that reflectors would increase collection levels to the panels. Reflective tape lining to the inside of the panel boxes will increase power input to the system. The panel boxes need slanted edges onto which the reflective tape adheres, reflecting as much sunlight as possible to the panels without being obtrusive and maintaining a low profile. The significance of the reflectors on the power input would have to be theoretically and experimentally examined to complete a cost/benefit analysis.

In addition to the reflectors affecting the power input, reflectors added to the decorative light housing was also considered. Currently, our design accounts for mirrors on the top of the housing to redirect the light coming from the directional LEDs pointing upwards. Adding to that effect would be another mirror located on the bottom of the housing to ensure that most of the light emitted from the LEDs would escape only through the sides of the housing, increasing the intensity of the lighting system. The significance of this addition is measured using a light intensity meter. Also, approval from the customer is necessary as the added intensity may not be in line with the intended purpose of the system.

## CONCLUSIONS

Our task is to design and build a robust solar-powered decorative lighting system without sacrificing functionality and aesthetics using centrally located solar panels. Our final design involves the use of the four provided solar panels for us to power a 40 Amp-hr battery through a charge controller. To the battery are connected seven tiered area lights, and three path lights. Between the battery and lights will be a photocell and timer that will control the power source to the lights. Power limitations require us to use low-voltage LED lights for the path lights.

Instead of having the option to pull power from the grid we have added switches that allow us to turn off three, four, or up to seven of the lights in order to conserve energy for the path lights. Through testing we validated the power input of the solar panels was sufficient to power the lighting system. We are confident in the efficiency of the charging and discharging of the battery, although more testing should be completed. The power losses due to the wiring of the lights are only 4.5%, which we will be able to overcome with our safety factor of 1.4. A customer utilizing solar panels instead of energy from the grid to power our designed landscape lighting system will save approximately 19 $^{lbs\ CO2}/_{Year}$ from Michigan power plants. The use of low power LED bulbs combined with reflectors to replace traditional Halogen bulbs will prevent an additional 443 $^{lbs\ CO2}/_{Year.}$ The solar panels have embedded production energy of 116 $^{kW\text{-}hr}/_{m\hat{}2}$, therefore it will take approximately 10.8 years to payback that power. However, the life of a solar panel is usually 20-40 years; therefore the system will have a reduction on environmental impact in the long term.

## RECOMMENDATIONS

After completing this project we have some recommendations to others who might desire to further this report or do one like it. One idea is to add the percentage cloud cover to existing theoretical solar insolation models. Cloud cover has a large impact on how much sunlight is absorbed by the solar array; however, cloud cover is not included in the solar models we have studied. As seen in our testing and product validation graphs the percentage of cloud cover has a strong correlation to the amount of power absorbed by panels. Another addition to the solar model is making it more adaptable to winter sun patterns. We chose to attach mirrors in the top of the tiered area lights in order to reflect the light back down to the ground. The bottom and the top of the interior of the light is painted a flat black color and has a rough surface. This is incredibly bad for the reflection of light. We believe it would be beneficial to produce landscaping lights with reflectors in both the top and the bottom of the housing for greater illumination. Finally we recommend the use of Polycrystalline or Crystalline Silicon solar panels instead of amorphous panels. They have much higher efficiencies reaching up to 22 percent. This project was limited by the power input factor. If more efficient panels were used instead our three percent efficient panels we might have been able to incorporate more lights or even kept the security light option open.

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## BIOS

### Andrew Cook

My name is Andrew Cook. I grew up in Brighton, Michigan only about 20 miles north of Ann Arbor. My interest in mechanical engineering stems from always being interested in mechanical systems, how they work, how to fix them. I graduate form U of M after this semester and I am currently looking for a full time job for after I graduate.

In September 2004, I moved to France with my girlfriend and lived in a city called Montpellier for six months. She was teaching English in a high school there and I went along with her. During this time we got to do a lot of traveling around Europe, including Italy and Spain.

For the last two summers I have had my own landscaping and sprinkler system business. It has been a great experience for me, and I have really enjoyed it. There are a lot of really rewarding things about having your own business, but there are also many frustrating and challenging parts.

I have also been in the University of Michigan Boxing the entire time I have been at the University. Last year I finally started fighting in competitions. We fought against other colleges and I have done fairly well but won only one out of three of my matches.

### Josh Fagan

My name is Josh Fagan. I was born in Grand Rapids, Michigan and moved to Grand Haven at a young age. Grand Haven is located on the West side of the Michigan directly on Lake Michigan. I have always been interested in how things work, from disassembling my remote control cars as a child to designing of mechanical systems now.

I have a brother, 10, and a sister, 12, back home. My dad works for a distribution company in the Red Bull division, and my mom works at an insurance agency. I am very close to my family and I frequently see them, especially during the summer.

This past summer I worked for a company called Carter Manufacturing where "Bearings Are Our Business." I had the opportunity to design many standard as well as custom bearings for many different applications. The highlight of the job was doing the final design revisions on a top secret bearing for the government that would be used in hummers for the Army.

I am also the match coordinator for the University of Michigan Rugby Football Club and have been playing here for nearly three years. We have a great program that is constantly improving and we remain one of the best teams in the state.

### Peter Kolleth

My name is Peter Kolleth. My hometown, Shelby Twp., is only about an hour away from Ann Arbor. I originally was in Computer Science Engineering; however I soon found that was not for me. When I was trying to find something I was interested in, I took ME250 and immediately knew what I wanted to pursue. I enjoy the design and manufacturing aspects of ME, exactly what this class will test. I am also getting a concentration in Manufacturing Systems for ME. Over the summer I worked at Faurecia Automotive in the Seating Division as a Testing Engineer Intern and hopefully will be returning as a full time engineer after I graduate in December.

This past summer I proposed to my girlfriend of 5 years and have gotten many wedding plans out of the way already but plenty more to do. The date will be August 5, 2007. Although I worked full time at Faurecia Automotive, I also still work part-time at the largest movie theatre in Michigan which I have been apart of the last 6 years and have reached a managerial position. The most extreme thing I have ever done has been going skydiving from 15,000ft and I have done that twice.

**John Shin**

I was born in Seoul, South Korea and immigrated with my family to the United States at the age of two. I was raised in the suburbs of Philadelphia where my family currently resides. I have one sibling, and older sister with whom I fought yet love for many years. My parents own a dry cleaning business at which they have faithfully been working for over thirteen years.

My interest in mechanical engineering started at a young age during a phase when I broke all my toys to see the insides. This, my interest in seeing how things “work”, and my love and passion for cars and driving has prompted me to seek a future in mechanical engineering. I will graduate from the University of Michigan in May 2007 after which I will be looking to enter the work force, hopefully somewhere interesting in the automotive industry.

Recently my summers have been spent going to Peru for a missionary trip as well as researching here at the university for PLM Alliance. My area of research was mostly on data AAmining and text analysis for engineering documents.

Currently I am heavily involved at the church I attend as a ministry leader.

## APPENDIX A

*Figure A1: Solar Light by Columbus*

| | | |
|---|---|---|
| 1 | Height (in) | 8.25 |
| 2 | Length (in) | 4.75 |
| 3 | Width (in) | 4.75 |
| 4 | Material | Metal |
| 5 | Finish | Black |
| 6 | Color of Light | Amber |
| 7 | Illumination Time (hrs) | 8--10 |
| 8 | Type of Bulb | LED |
| 9 | Number of Bulbs per Light | 1 |
| 10 | Price | $89.99 |
| 11 | Number of Lights | 6 |
| 12 | Mounting Method | Stake |
| 13 | Cord | None |
| 14 | Location of Solar Panel | Top of light |
| 15 | On/Off Type | Automatic Sensor |

*Figure A2: Three Tier Solar Light*

| | | |
|---|---|---|
| 1 | Height (in) | 14 |
| 2 | Length (in) | 5.25 |
| 3 | Width (in) | 5.25 |
| 4 | Material | Brass |
| 5 | Finish | Brass |
| 6 | Color of Light | White |
| 7 | Illumination Time (hrs) | 8--12 |
| 8 | Type of Bulb | LED |
| 9 | Number of Bulbs per Light | 1 |
| 10 | Price | $39.99 |
| 11 | Number of Lights | 1 |
| 12 | Mounting Method | Stake |
| 13 | Cord | None |
| 14 | Location of Solar Panel | Top of light |
| 15 | On/Off Type | Automatic Sensor |

*Figure A3: Shaded Solar Light by Raleigh*

| | | |
|---|---|---|
| 1 | Height (in) | 15.75 |
| 2 | Length (in) | 8.5 |
| 3 | Width (in) | 8.5 |
| 4 | Material | Metal |
| 5 | Finish | Copper |
| 6 | Color of Light | White |
| 7 | Illumination Time (hrs) | 8--10 |
| 8 | Type of Bulb | LED |
| 9 | Number of Bulbs per Light | 1 |
| 10 | Price | $34.99/$65.99$125.99/$165.99 |
| 11 | Number of Lights | 1/2/4/6 |
| 12 | Mounting Method | Stake |
| 13 | Cord | None |
| 14 | Location of Solar Panel | Top of light |
| 15 | On/Off Type | Automatic Sensor |

*Figure A4: Solar Tulip Light by Intermatic*

| | | |
|---|---|---|
| 1 | Height (in) | - |
| 2 | Length (in) | - |
| 3 | Width (in) | - |
| 4 | Material | Plastic |
| 5 | Finish | Black |
| 6 | Color of Light | White |
| 7 | Illumination Time (hrs) | - |
| 8 | Type of Bulb | LED |
| 9 | Number of Bulbs per Light | - |
| 10 | Price | $49.99 |
| 11 | Number of Lights | 4 |
| 12 | Mounting Method | Stake |
| 13 | Cord | 20 feet |
| 14 | Location of Solar Panel | Separate |
| 15 | On/Off Type | Automatic Sensor |

*Figure A5: Pagoda Light Kit*

| | | |
|---|---|---|
| 1 | Height (in) | - |
| 2 | Length (in) | - |
| 3 | Width (in) | - |
| 4 | Material | Aluminum |
| 5 | Finish | Black |
| 6 | Color of Light | White |
| 7 | Illumination Time (hrs) | Indefinitely |
| 8 | Type of Bulb | Incandescent |
| 9 | Number of Bulbs per Light | 1 |
| 10 | Price | $159.99 |
| 11 | Number of Lights | 6 |
| 12 | Mounting Method | Stake |
| 13 | Cord | 100 feet w/ 3 feet lead wire |
| 14 | Location of Solar Panel | Plugged into outlet |
| 15 | On/Off Type | Automatic Sensor |

*Figure A6: Solar Security Light*

| | | |
|---|---|---|
| 1 | Height (in) | 7.75 |
| 2 | Length (in) | 8 |
| 3 | Width (in) | 10 |
| 4 | Material | Plastic |
| 5 | Finish | Black |
| 6 | Color of Light | White |
| 7 | Number of Illumination Times | 50 |
| 8 | Illumination Time (sec) | 20 |
| 9 | Type of Bulb | Halogen |
| 10 | Number of Bulbs per Light | 1 |
| 11 | Price | $83.99 |
| 12 | Mounting Method | Screws |
| 13 | Cord | Yes |
| 14 | Location of Solar Panel | Separate |
| 15 | On/Off Type | Motion Sensor |

*Figure A7: Security Spot Light*

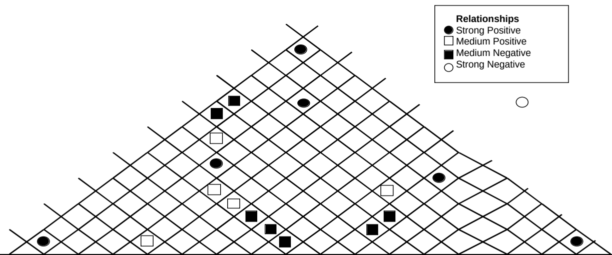
| | | |
|---|---|---|
| 1 | Height (in) | 8.5 |
| 2 | Length (in) | 5 |
| 3 | Width (in) | 7 |
| 4 | Material | Plastic |
| 5 | Finish | White |
| 6 | Color of Light | White |
| 7 | Number of Illumination Times | 150 |
| 8 | Illumination Time (sec) | 60 |
| 9 | Type of Bulb | Super bright LED |
| 10 | Number of Bulbs per Light | 1 |
| 11 | Price | $149.99 |
| 12 | Mounting Method | Screws |
| 13 | Cord | Yes |
| 14 | Location of Solar Panel | Separate |
| 15 | On/Off Type | Motion Sensor |

*Figure A8: Security Floodlight*

| | | |
|---|---|---|
| 1 | Height (in) | 9 |
| 2 | Length (in) | 8 |
| 3 | Width (in) | 7.75 |
| 4 | Material | Plastic |
| 5 | Finish | White |
| 6 | Color of Light | White |
| 7 | Number of Illumination Times | 150 |
| 8 | Illumination Time (sec) | 60 |
| 9 | Type of Bulb | Halogen |
| 10 | Number of Bulbs per Light | 1 |
| 11 | Price | $149.99 |
| 12 | Mounting Method | Screws |
| 13 | Cord | Yes |
| 14 | Location of Solar Panel | Separate |
| 15 | On/Off Type | Motion Sensor |

*Figure A9: QFD*

| | |
|---|---|
| 1 | Not related |
| 3 | Weakly related |
| 5 | Neutral |
| 7 | Moderately related |
| 9 | Strongly Related |




| Customer Requirements \ Engineering Characteristics | Importance | Maximum Energy Storage Collection | Efficiency of Solar Collector | Intensity of Emitted Light | Torque Required to Turn Panels | Power Required to Turn Panels | Length | Width | Height | Weight | Power Consumption | Sunlight Angle on Solar Panel | Sensitivity of Motion Detector | Sensitivity of Night Activation Sensor | Strength of Casing Material | Area of Illuminated Ground | Length of Time Security Light is Active | Length of Time Battery Last as until Dead before Recharging | TOTAL - QUALITY CHARACTERISTICS |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Compact for storage | 0.1 | 1 | 1 | 1 | 1 | 1 | 9 | 9 | 9 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | **3.9** |
| Easy to clean | 0.4 | 1 | 1 | 1 | 1 | 1 | 5 | 5 | 5 | 5 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | **12.4** |
| Low Cost | 0.7 | 7 | 1 | 7 | 1 | 1 | 5 | 5 | 5 | 5 | 1 | 1 | 1 | 1 | 5 | 1 | 1 | 7 | **32.9** |
| Environmentally and Physically Safe | 0.8 | 1 | 1 | 7 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 5 | **16.8** |
| Aesthetically Pleasing | 0.8 | 1 | 1 | 1 | 1 | 1 | 7 | 7 | 7 | 3 | 1 | 1 | 1 | 1 | 1 | 9 | 1 | 1 | **34.4** |
| Easy to use | 0.8 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | **12** |
| Long Service Life | 0.9 | 9 | 9 | 5 | 1 | 7 | 1 | 1 | 1 | 1 | 9 | 1 | 1 | 1 | 7 | 1 | 3 | 7 | **49.5** |
| Recyclable/Reusable | 0.2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 9 | **3** |
| Automated Light Activation/Deactivation | 0.7 | 5 | 3 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 7 | 3 | 1 | 9 | 1 | 1 | 7 | 1 | **25.9** |
| Motion Light Activation/Deactivation for Security Light | 0.7 | 5 | 3 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 7 | 3 | 9 | 1 | 1 | 1 | 7 | 1 | **25.9** |
| Security from being Stolen | 0.7 | 1 | 1 | 5 | 1 | 1 | 3 | 3 | 3 | 9 | 1 | 1 | 1 | 1 | 1 | 1 | 3 | 1 | **23.1** |
| Freedom to Change Location | 0.4 | 1 | 1 | 1 | 1 | 1 | 7 | 7 | 7 | 9 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | **16.4** |
| Not Visually Obtrusive | 0.5 | 1 | 1 | 1 | 1 | 1 | 9 | 9 | 9 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | **19.5** |
| At Least 2 Positions Available for Season Change | 0.4 | 1 | 1 | 1 | 7 | 5 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | **10** |
| Sturdy Stand for Solar Panel | 0.6 | 1 | 1 | 1 | 1 | 1 | 7 | 7 | 7 | 7 | 1 | 1 | 1 | 1 | 9 | 1 | 1 | 1 | **28.2** |
| Only Solar as Power Source | 1.0 | 9 | 9 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 7 | 7 | 1 | 1 | 1 | 1 | 3 | 5 | **43** |
| Entire system is Weatherproof | 1.0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | **15** |
| Easy to Assemble | 0.4 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | **6** |
| Resistance to Normal Wear and Tear | 0.6 | 1 | 1 | 1 | 9 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 9 | 1 | 1 | 1 | **18.6** |
| Illuminates Desired Areas Well | 1.0 | 1 | 7 | 9 | 1 | 1 | 1 | 1 | 1 | 1 | 7 | 7 | 5 | 5 | 1 | 9 | 7 | 5 | **57** |
| **Units** | | **W** | **%** | **Lm** | **lb*ft** | **W** | **in** | **in** | **in** | **lb** | **W** | **deg** | **ft** | **Lm** | **lb/ft^2** | **ft^2** | **sec** | **days** | |
| **Now** | | 24 | 2.56 | n/a | n/a | n/a | 50.00 | 23.25 | 5.75 | 7.50 | n/a | 0-60 | 20 | n/a | n/a | 3 | 60 | 9 | |
| **Competitor** | | n/a | n/a | 120 | - | - | 14.00 | 5.25 | 5.25 | 1.50 | 112 | n/a | 20 | n/a | n/a | 3 | 60 | 9 | |
| **Target (Plan)** | | 24 | 5 | 120 | 5 | 2 | 45 | 22 | 5.5 | 7.5 | 48.5 | 0-60 | 25 | 10 | 50K | 3 | 60 | 8 | |
| **Total** | | 37.7 | 36.7 | 36.1 | 19.9 | 19.7 | 34.1 | 34.1 | 34.1 | 31.1 | 40.3 | 27.5 | 22.3 | 22.3 | 30.5 | 27.1 | 32.3 | 35.1 | |
| **Rating (%)** | | 8.3% | 8.1% | 8.0% | 4.4% | 4.3% | 7.5% | 7.5% | 7.5% | 6.9% | 8.9% | 6.1% | 4.9% | 4.9% | 6.7% | 6.0% | 7.1% | 7.7% | |
| **Ranked Importance** | | **2** | **3** | **3** | **16** | **17** | **6** | **6** | **6** | **10** | **1** | **12** | **14** | **14** | **11** | **13** | **9** | **5** | |

| Customer Requirements | RANK | Importance | Now | Competitor | Plan | Ratio of Improvement | Sales Point | Absolute Wt. | Demanded Wt. |
|---|---|---|---|---|---|---|---|---|---|
| Compact for storage | **19** | **-0.28** | 3 | 4 | 3 | 1.00 | 1.0 | **-0.3** | **-0** |
| Easy to clean | **15** | **0.83** | 2 | 3 | 3 | 1.50 | 1.0 | **1.3** | **0.015** |
| Low Cost | **5** | **3.61** | 2 | 5 | 4 | 2.00 | 1.5 | **10.8** | **0.131** |
| Environmentally and Physically Safe | **12** | **1.67** | 3 | 3 | 5 | 1.67 | 1.2 | **3.3** | **0.04** |
| Aesthetically Pleasing | **4** | **3.89** | 3 | 3 | 5 | 1.67 | 1.5 | **9.7** | **0.118** |
| Easy to use | **16** | **0.56** | 3 | 3 | 4 | 1.33 | 1.5 | **1.1** | **0.013** |
| Long Service Life | **2** | **4.44** | 3 | 3 | 5 | 1.67 | 1.5 | **11.1** | **0.134** |
| Recyclable/Reusable | **20** | **-0.56** | 3 | 2 | 3 | 1.00 | 1.0 | **-0.6** | **-0.01** |
| Automated Light Activation/Deactivation | **7** | **3.06** | 4 | 4 | 4 | 1.00 | 1.5 | **4.6** | **0.055** |
| Motion Light Activation/Deactivation for Security Light | **7** | **3.06** | 4 | 4 | 4 | 1.00 | 1.5 | **4.6** | **0.055** |
| Security from being Stolen | **9** | **2.50** | 3 | 1 | 4 | 1.33 | 1.5 | **5.0** | **0.061** |
| Freedom to Change Location | **13** | **1.39** | 2 | 4 | 3 | 1.50 | 1.0 | **2.1** | **0.025** |
| Not Visually Obtrusive | **10** | **2.22** | 2 | 5 | 3 | 1.50 | 1.2 | **4.0** | **0.048** |
| At Least 2 Positions Available for Season Change | **17** | **0.28** | 2 | 1 | 3 | 1.50 | 1.0 | **0.4** | **0.005** |
| Sturdy Stand for Solar Panel | **6** | **3.33** | 3 | 2 | 4 | 1.33 | 1.2 | **5.3** | **0.065** |
| Only Solar as Power Source | **3** | **4.17** | 5 | 5 | 5 | 1.00 | 1.5 | **6.3** | **0.076** |
| Entire system is Weatherproof | **14** | **1.11** | 3 | 4 | 4 | 1.33 | 1.0 | **1.5** | **0.018** |
| Easy to Assemble | **18** | **0.00** | 1 | 3 | 3 | 3.00 | 1.2 | **0.0** | **0** |
| Resistance to Normal Wear and Tear | **11** | **1.94** | 2 | 3 | 3 | 1.50 | 1.2 | **3.5** | **0.042** |
| Illuminates Desired Areas Well | **1** | **4.72** | 4 | 3 | 5 | 1.25 | 1.5 | **8.9** | **0.107** |
| | | | | | | | **Total** | 68.78 | 0.833 |

*Figure A10-A12: Layouts 1-3*

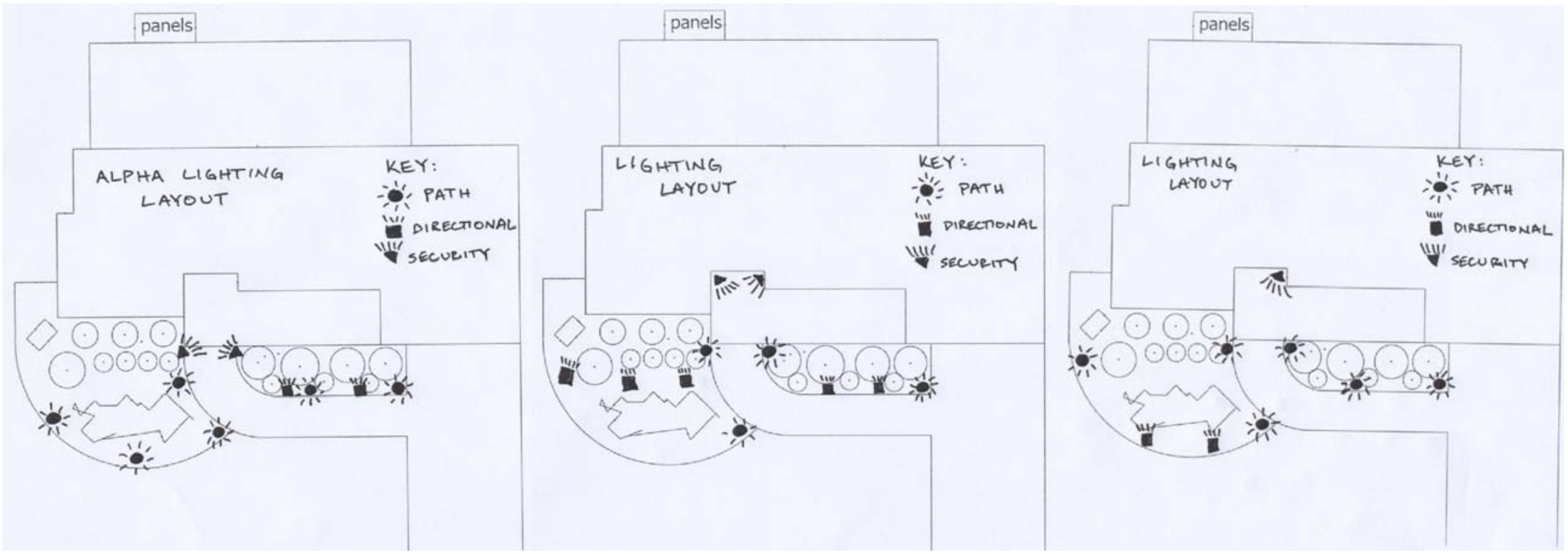
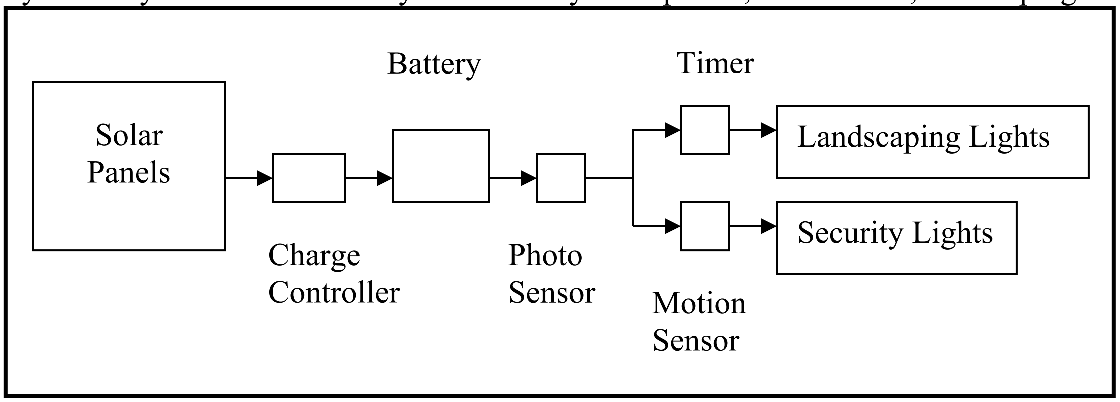
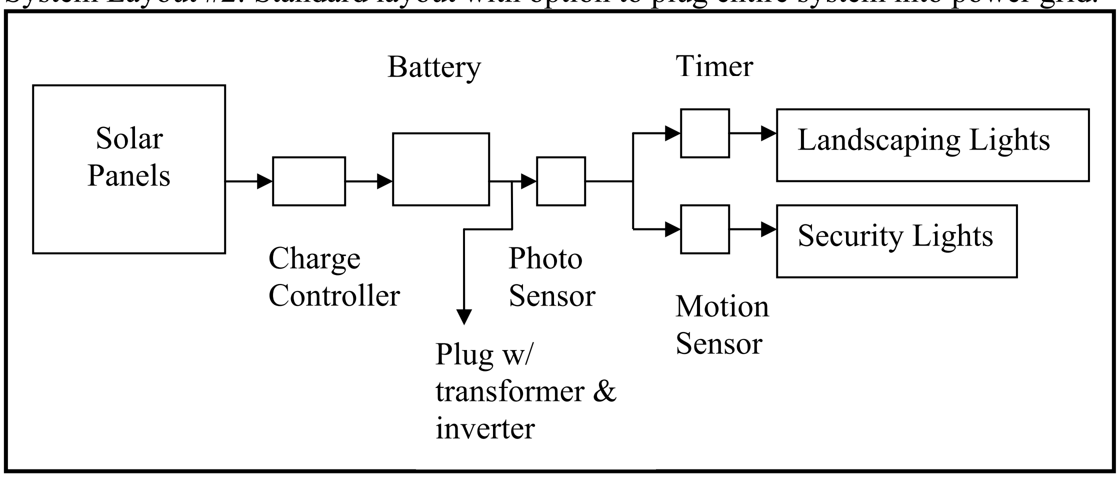


*Figure A13-A17: System Layouts 1-5*

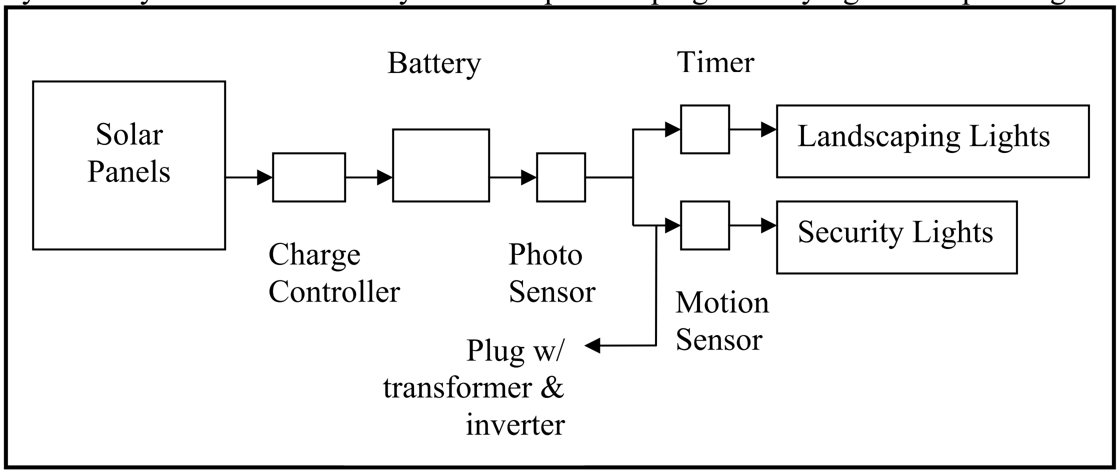
System Layout #1: Standard layout with only solar power, no switches, and no plugs.



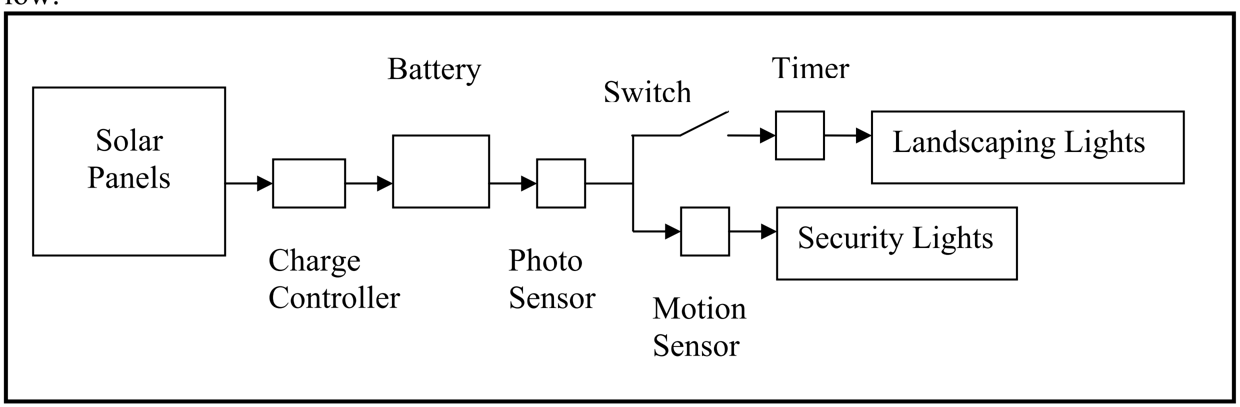

System Layout #2: Standard layout with option to plug entire system into power grid.



System Layout #3: Standard layout with option to plug security lights into power grid.




System Layout #4: Standard layout with switch on landscaping lights giving the ability to run only the security lights when power runs low.



System Layout #5: Running landscaping lights and security lights off of separate panels and batteries, making them individual systems.

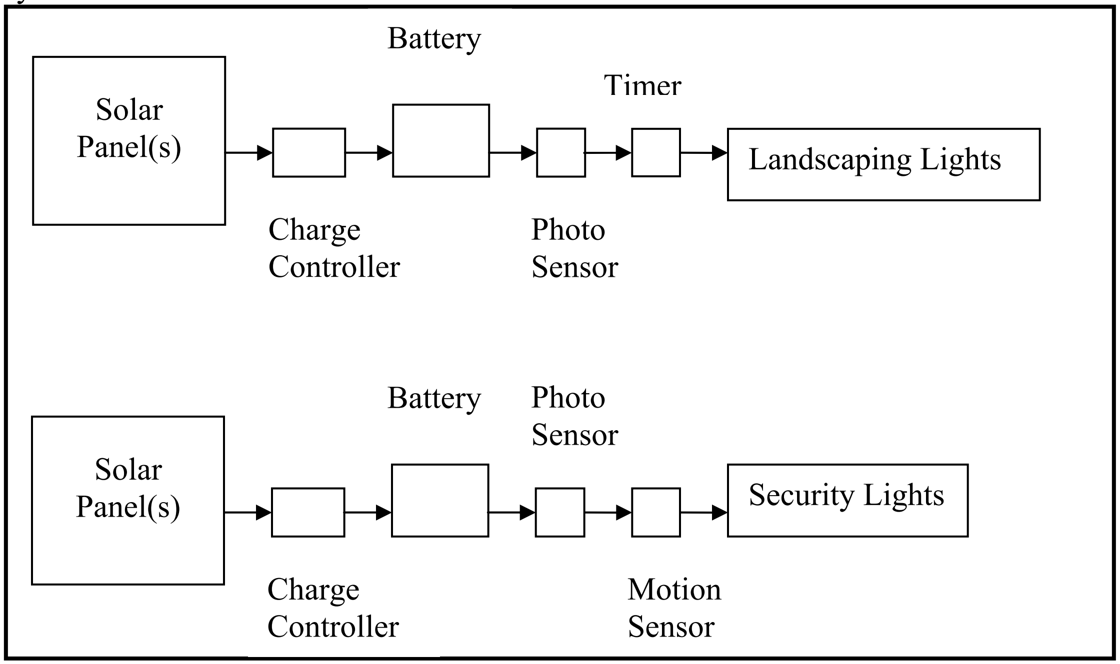


*Figure A18: Pugh Selection – Light Bulbs*

**LIGHT BULB CONCEPT SELECTION**

| | | CONCEPT VARIANTS | | | | |
|---|---|---|---|---|---|---|
| SELECTION CRITERIA | Wt. | LED | HALOGEN | INCONDESCENT | FLOURESCENT | REF |
| Low Power for Operation | 10 | + | 0 | - | 0 | 0 |
| Provides Pleasurable Lighting | 8 | 0 | 0 | 0 | - | 0 |
| Illuminates desired areas well | 10 | 0 | 0 | 0 | 0 | 0 |
| Low Cost | 7 | + | 0 | + | - | 0 |
| Long Service Life | 7 | + | 0 | - | + | 0 |
| PLUSES | | 24 | 0 | 7 | 7 | |
| SAMES | | 18 | 35 | 18 | 20 | |
| MINUSES | | 0 | 0 | 17 | 15 | |
| NET | | 24 | 0 | -10 | -8 | |
| RANK | | 1 | 2 | 4 | 3 | |
| CONTINUE? | | YES | YES | NO | NO | |

*Figure A19: Pugh Selection – Wiring Layout*

**WIRING SYSTEM CONCEPT SELECTION**

| | | CONCEPT VARIANTS | | | | | |
|---|---|---|---|---|---|---|---|
| SELECTION CRITERIA | Wt. | LAYOUT 1 | LAYOUT 2 | LAYOUT 3 | LAYOUT 4 | LAYOUT 5 | REF |
| Powered only by Solar | 10 | + | - | - | + | + | 0 |
| Low Cost | 9 | - | - | - | - | - | 0 |
| Amount of Power Supplied to Battery | 9 | + | + | + | + | - | 0 |
| Service Life | 8 | + | + | + | + | + | 0 |
| Aesthetically Pleasing | 7 | + | + | + | + | - | 0 |
| Efficient Solar Panels | 7 | - | - | - | - | - | 0 |
| System activates during continuous worse case days | 7 | - | + | + | - | - | 0 |
| Easy to use | 6 | 0 | 0 | 0 | + | 0 | 0 |
| Robustness | 6 | + | + | + | + | - | 0 |
| Feasibility | 9 | - | + | - | - | - | 0 |
| Easy to install/deconstruct | 5 | - | - | - | - | - | 0 |
| System Activation Control | 4 | - | + | - | + | - | 0 |
| PLUSES | | 40 | 50 | 37 | 50 | 18 | |
| SAMES | | 6 | 6 | 6 | 0 | 6 | |
| MINUSES | | 41 | 31 | 44 | 37 | 63 | |
| NET | | -1 | 19 | -7 | 13 | -45 | |
| RANK | | 3 | 1 | 4 | 2 | 5 | |
| CONTINUE? | | NO | YES | No | YES | NO | |

*Figure A20: Solar Cell Location Concept Selection Pugh Chart*

***SOLAR CELL LOCATION CONCEPT SELECTION***

| | | **CONCEPT VARIANTS** | | | | |
|---|---|---|---|---|---|---|
| **SELECTION CRITERIA** | **Wt.** | **Above Deck Mounted on Side of House** | **Adjacent to Flower Bed Located on Ground** | **Connected to Side of Deck** | **On Roof of House** | ****REF** |
| Maximum Solar Radiation Collection | 10 | + | - | + | + | 0 |
| Feasibility to Install | 9 | + | + | + | - | 0 |
| Aesthetically Pleasing | 8 | - | 0 | + | + | 0 |
| Maintainability | 6 | 0 | 0 | 0 | - | 0 |
| Low Cost to Construct | 6 | - | + | - | - | 0 |
| No Risk of Injury (Before or After Installation) | 6 | - | 0 | 0 | - | 0 |
| Easy to Install/Deconstruct | 5 | 0 | 0 | 0 | - | 0 |
| Risk of Solar Cell Breakage | 5 | + | - | + | + | 0 |
| PLUSES | | 24 | 17 | 24 | 23 | |
| SAMES | | 11 | 23 | 25 | 0 | |
| MINUSES | | 20 | 15 | 6 | 26 | |
| NET | | 4 | 2 | 18 | -3 | |
| RANK | | 2 | 3 | **1** | 4 | |
| CONTINUE? | | NO | NO | **YES** | NO | |

**Reference = Panels Located Adjacent to Landscape Lights

*Figure A21: Adjustable Mount Mechanism Concept Selection Pugh Chart*

| | | | | | |
|---|---|---|---|---|---|
| | | *ADJUSTABLE MOUNT MECHANISM CONCEPT SELECTION* | | | |
| | | **CONCEPT VARIANTS** | | | |
| **SELECTION CRITERIA** | **Wt.** | ***VARILOC* Hinge [1]** | **Ratcheting Hinge Support [2]** | **Lock Bar Mechanism** | ****REF** |
| Low Cost | 10 | - | - | 0 | 0 |
| Adjustable Angles | 10 | + | + | + | 0 |
| Easy to Use | 9 | + | + | + | 0 |
| Maintainability | 9 | 0 | 0 | 0 | 0 |
| Weather Resistance | 7 | + | - | + | 0 |
| Easy to Install / Deconstruct | 7 | - | - | - | 0 |
| Not Visually Obtrusive | 5 | 0 | 0 | - | 0 |
| Robustness | 5 | + | + | + | 0 |
| Adjust to Three or more Angles | 4 | + | + | - | 0 |
| Ease to Replace | 4 | - | - | + | 0 |
| PLUSES | | 35 | 28 | 35 | |
| SAMES | | 14 | 14 | 19 | |
| MINUSES | | 21 | 28 | 16 | |
| NET | | 14 | 0 | 19 | |
| RANK | | 2 | 3 | **1** | |
| CONTINUE? | | NO | NO | **YES** | |

**REF- Solar Cell Mounts in Stationary Position

[1] http://www.adjustablelockingtech.com/Variloc.htm
[2] http://www.hardwaresource.com/Store_ViewProducts.asp?Cat=797

*Figure A22: Functional Decomposition of Alpha Design*

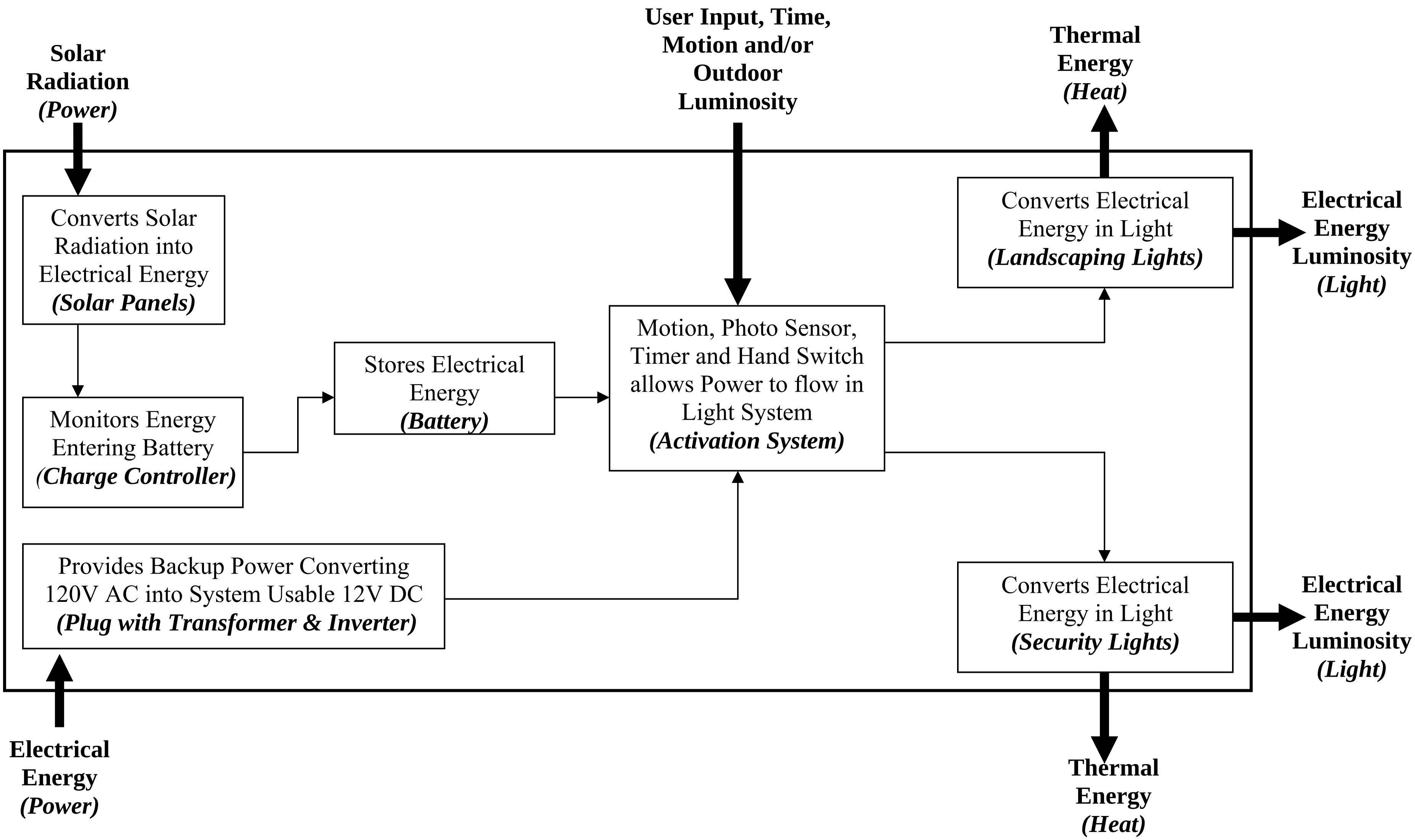


*Figure A23: Solar Panel Test Setup*

*Figure A24: Battery Efficiency Test*

| | | |
|---|---|---|
| Battery Efficiency Test<br>UB12400 - Non-spillable, sealed, lead-acid battery | *Subjective Luminosity Test | Last Modified: 10/8/06<br>By: John Shin |

| Constant Voltage Charge at 20°C | Voltage Regulation | Initial Current |
|---|---|---|
| Standby Use | 13.6 - 13.8V | 6A |
| Cyclic Use | 14.5 - 14.9V | 12A |

| Time (hours) | On/Off | Same/Dimmer | Comments |
|---|---|---|---|
| 0 (6:15PM) | On | - | Initial connection is good and working properly. Lights are very bright. |
| 0.25 | On | Same | - |
| 0.5 | On | Same | - |
| 0.75 | On | Same | - |
| 1 | On | Same | - |
| 1.25 | On | Same | - |
| 1.5 | On | Same | - |
| 1.75 | On | Same | - |
| 2 | On | Same | - |
| 2.25 | On | Same | - |
| 2.5 | On | Dimmer | Lights have dimmed. |
| 2.75 | On | Dimmer | Dimming fast. Dimmer than the 2 60W bulbs in my room. Great reading light. |
| 3 | On | Dimmer | Three lights combine to an OK reading light. |
| 3.25 | On | Dimmer | Less of a difference. Bad reading light. Reasonable flashlight. |
| 3.5 | On | Dimmer | Each light is like a large candle. |
| 3.75 | On | Dimmer | Each light is like a regular candle. |
| 4 | On | Dimmer | Each light is like a small candle. |
| 4.25 | On | Dimmer | Each light is like a nightlight. |
| 4.5 | On | Dimmer | They might as well be off. |
| 4.75 | Off | - | - |

*Figure A25: Functional Decomposition of Final Design*

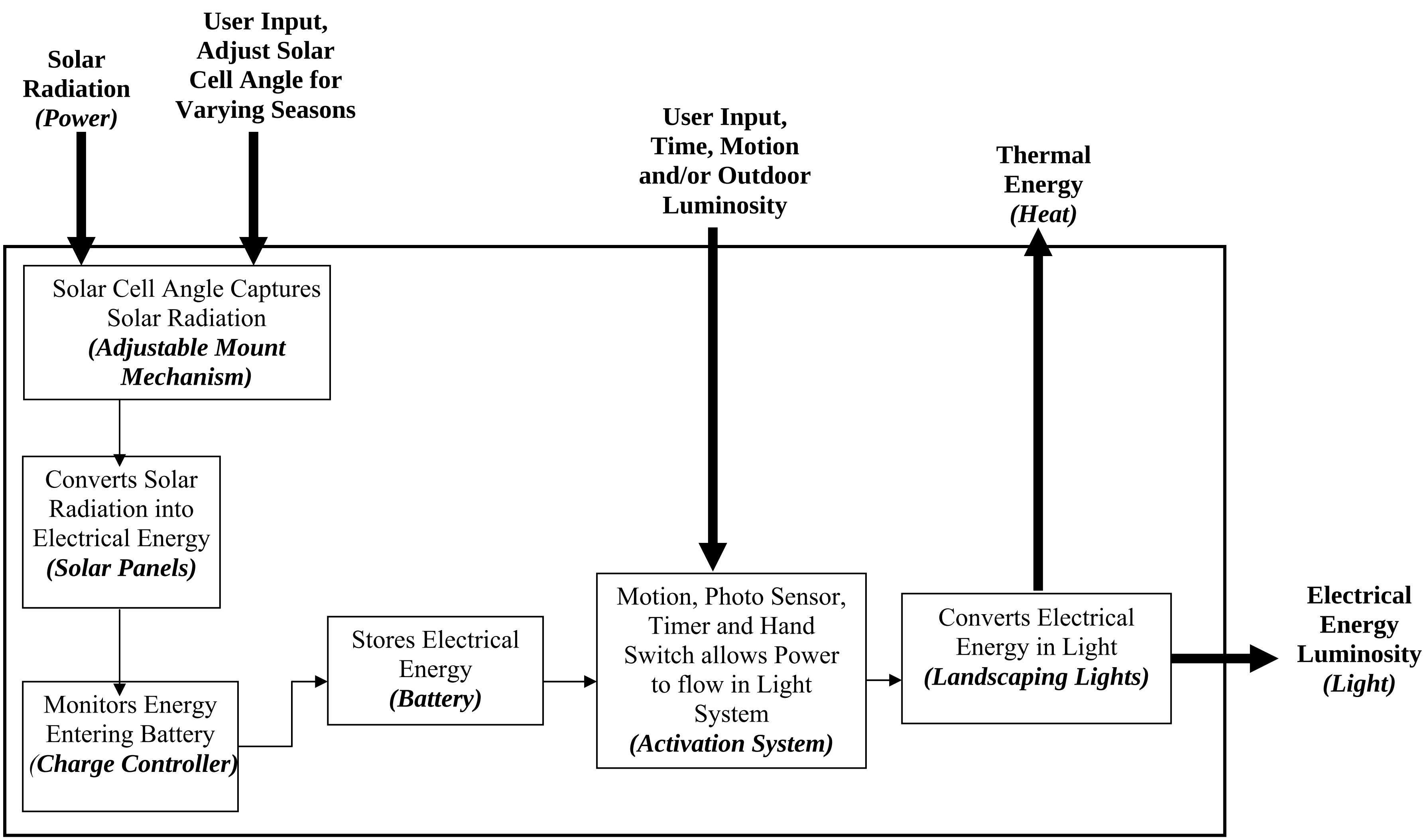


*Figure A26: Plans for solar panel mount.*

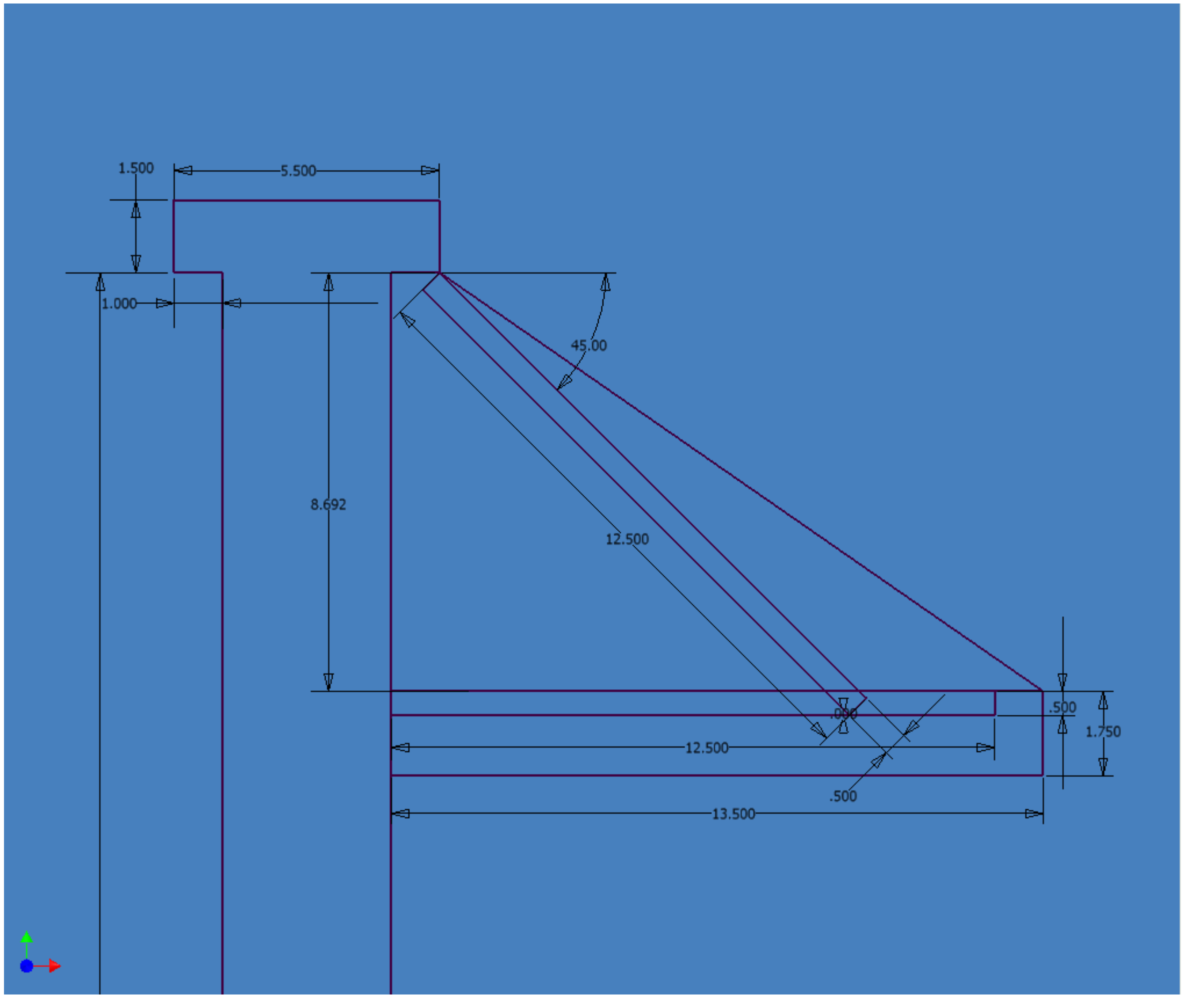


*Figure A27: Bill of Materials*

| Quantity | Part Description | Manufacturer | Part Number | Unit Cost |
|---|---|---|---|---|
| 4 | Solar Panel | Silicon Solar | 20WSEP | $149.00 |
| 1 | Charge Controller | Silicon Solar | CT-XR4A | $29.95 |
| 1 | Universal Battery | Creative Energy Technologies | UB12400 | $79.95 |
| 1 | Photo Sensor | Precision | LCS-612D | $30.20 |
| 1 | Timer | Altronix | 6062 24HR | $22.26 |
| 2 | Switch | Leviton | R41-05611-2IS | $4.90 |
| 7 | Area Light | Malibu | CL191 | $12.85 |
| 3 | Path Light | Vista Professional | 8240 | $100.00 |
| 1 | Battery Box | AD Products Co. | EJ12108 | $63.94 |
| 2 | Wiring | Home Depot | 79407901548 | $15.97 |
| 11 | LED Bulbs | Super Bright LEDs | T8M White | $3.95 |
| 3 | LED Sockets | Autolumination | 60-64 | $2.99 |
| 10 | Wood - 1x2 | Home Depot | 90489071974 | $1.49 |
| 2 | Wood - 2x4 | Home Depot | 98945060081 | $1.88 |
| 1 | Wood - 2x2 | Home Depot | 90489918514 | $1.71 |
| 1 | Liquid Nails | Home Depot | 22078190728 | $2.27 |
| 1 | Cauld Gun | Home Depot | 6920000601097 | $1.96 |
| 8 | Hinge | Home Depot | 33923148658 | $2.58 |
| 16 | Latch | Home Depot | 33923403306 | $4.39 |
| 1 | Screws & Fasteners | Home Depot | Assorted | $39.51 |
| 2 | Aluminium L Frame | Home Depot | N/A | $6.42 |
| 10 | Mirror | Jo-Ann Fabrics | 7325723 | $0.40 |

**Total Cost: $1,478.22**

*Figure A28.1: Gantt Chart*

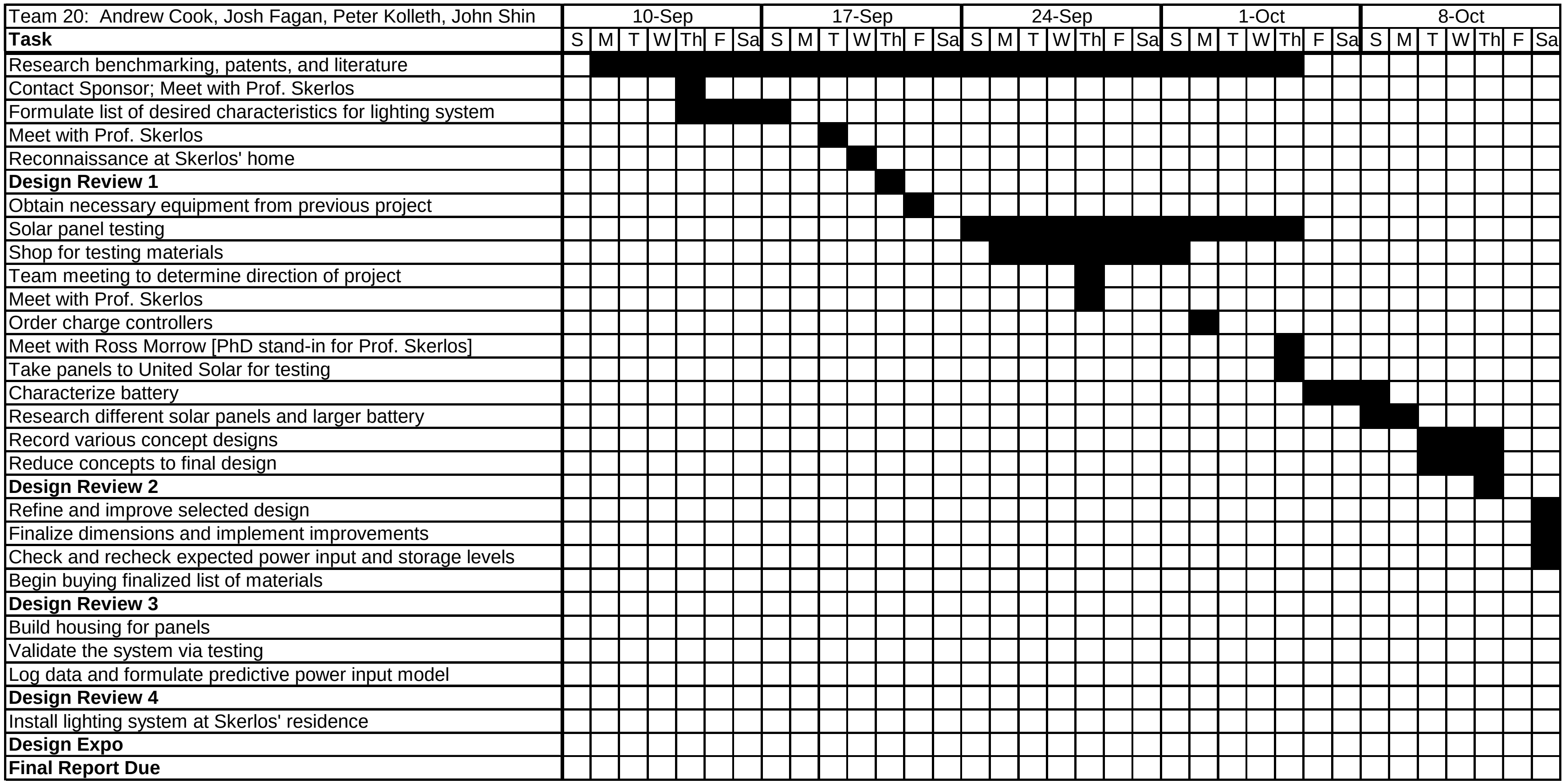


*Figure A28.2: Gantt Chart*

| Team 20: Andrew Cook, Josh Fagan, Peter Kolleth, John Shin | 15-Oct | | | | | | | 22-Oct | | | | | | | 29-Oct | | | | | | | 5-Nov | | | | | | | 12-Nov | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Task** | S | M | T | W | Th | F | Sa | S | M | T | W | Th | F | Sa | S | M | T | W | Th | F | Sa | S | M | T | W | Th | F | Sa | S | M | T | W | Th | F | Sa |
| Research benchmarking, patents, and literature | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Contact Sponsor; Meet with Prof. Skerlos | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Formulate list of desired characteristics for lighting system | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Meet with Prof. Skerlos | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Reconnaissance at Skerlos' home | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **Design Review 1** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Obtain necessary equipment from previous project | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Solar panel testing | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Shop for testing materials | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Team meeting to determine direction of project | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Meet with Prof. Skerlos | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Order charge controllers | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Meet with Ross Morrow [PhD stand-in for Prof. Skerlos] | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Take panels to United Solar for testing | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Characterize battery | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Research different solar panels and larger battery | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Record various concept designs | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Reduce concepts to final design | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **Design Review 2** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Refine and improve selected design | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | | | | | | | |
| Finalize dimensions and implement improvements | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | | | | | | | | | | | | |
| Check and recheck expected power input and storage levels | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | | | | | | | | | | | | | | | |
| Buy finalized list of materials and battery | ■ | ■ | ■ | ■ | ■ | ■ | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **Design Review 3** | | | | | | | | | | | | | | | | | | | | | | | | | | ■ | | | | | | | | | |
| Build housing for panels | | | | | | | | | | | | | | | | | | | | | | | | | | | | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ |
| Validate the system via testing | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | ■ | ■ | ■ | ■ |
| Log data and formulate predictive power input model | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | ■ | ■ | ■ |
| **Design Review 4** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Install lighting system at Skerlos' residence | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **Design Expo** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **Final Report Due** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |

*Figure A28.3: Gantt Chart*

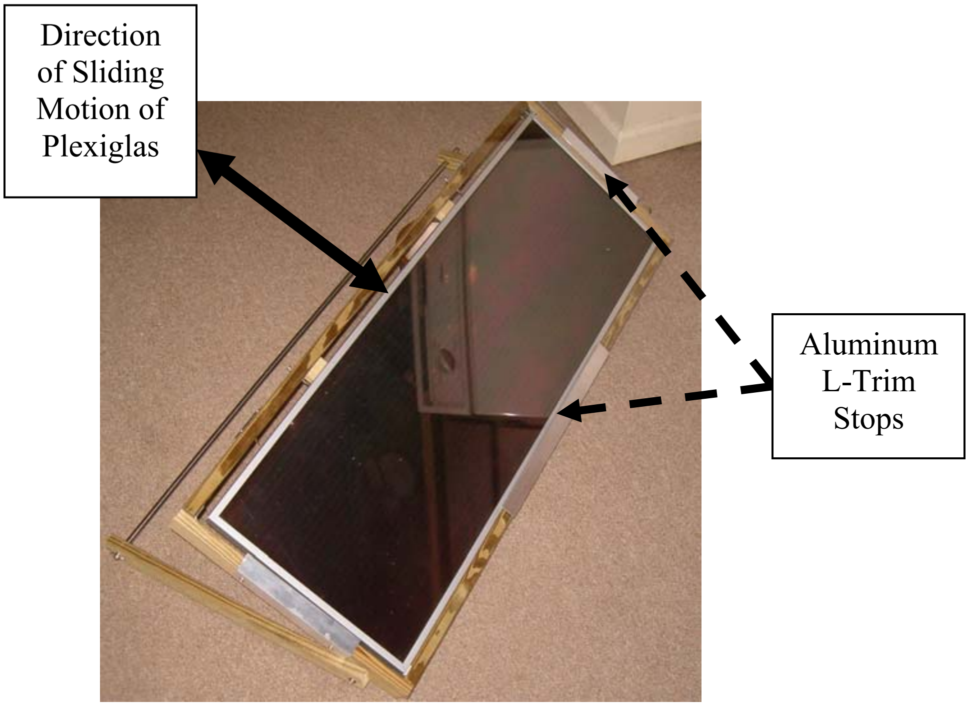
| Team 20:  Andrew Cook, Josh Fagan, Peter Kolleth, John Shin | 19-Nov | | | | | | | 26-Nov | | | | | | | 3-Dec | | | | | | | 10-Dec | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Task** | S | M | T | W | Th | F | Sa | S | M | T | W | Th | F | Sa | S | M | T | W | Th | F | Sa | S | M | T | W | Th | F | Sa |
| Research benchmarking, patents, and literature | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Contact Sponsor; Meet with Prof. Skerlos | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Formulate list of desired characteristics for lighting system | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Meet with Prof. Skerlos | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Reconnaissance at Skerlos' home | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **Design Review 1** | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Obtain necessary equipment from previous project | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Solar panel testing | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Shop for testing materials | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Team meeting to determine direction of project | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Meet with Prof. Skerlos | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Order charge controllers | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Meet with Ross Morrow [PhD stand-in for Prof. Skerlos] | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Take panels to United Solar for testing | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Characterize battery | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Research different solar panels and larger battery | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Record various concept designs | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Reduce concepts to final design | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **Design Review 2** | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Refine and improve selected design | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Finalize dimensions and implement improvements | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Check and recheck expected power input and storage levels | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Buy finalized list of materials and battery | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **Design Review 3** | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Build housing for panels | ■ | ■ | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Validate the system via testing | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | | | | | | | | | | | | | | | | | | | | |
| Log data and formulate predictive power input model | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | | | | | | | | | | | | | | | | | | | | |
| **Design Review 4** | | | ■ | | | | | | | | | | | | | | | | | | | | | | | | | |
| Install lighting system at Skerlos' residence | | | | | | | | ■ | ■ | ■ | | | | | | | | | | | | | | | | | | |
| **Design Expo** | | | | | | | | | | | | | | | | | | | ■ | | | | | | | | | |
| **Final Report Due** | | | | | | | | | | | | | | | | | | | | | | | ■ | | | | | |

*Figure A29: Protective Plexiglas Removal Concept Selection Pugh Chart*

| | | | | | |
|---|---|---|---|---|---|
| | | *PROTECTIVE PLEXIGLAS REMOVAL CONCEPT SELECTION* | | | |
| | | **CONCEPT VARIANTS** | | | |
| **SELECTION CRITERIA** | **Wt.** | **Slide Motion with Aluminum L-Trim Stops** | **Hinge Mechanism** | **Slide Motion into Slits in the Cell Mount** | ****REF** |
| Plexiglas has a Removable Concept from Panel Mount | 10 | + | + | + | 0 |
| Plexiglas can be Completely Detached from Mount | 8 | + | - | + | 0 |
| Concept will not Cause Damage to Panel Mount | 7 | + | + | - | 0 |
| Plexiglas held Firmly in Place until Removal | 7 | - | - | - | 0 |
| Visually Appealing | 6 | - | 0 | 0 | 0 |
| Ease of Removal | 6 | + | 0 | + | 0 |
| Plexiglas Interchangeable with All Mounts | 5 | + | - | + | 0 |
| PLUSES | | 36 | 17 | 29 | |
| SAMES | | 0 | 12 | 6 | |
| MINUSES | | 13 | 20 | 14 | |
| NET | | 23 | -3 | 15 | |
| RANK | | **1** | 3 | 2 | |
| CONTINUE? | | **YES** | NO | NO | |

**REF- Plexiglas connected directly to cell mount

*Figure A30: Protective Plexiglas Removal System*

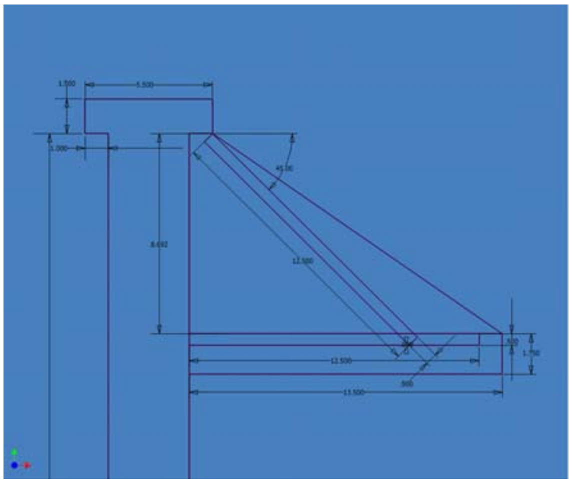


## APPENDIX B: ENGINEERING CHANGES

Due to the nature of our project, photovoltaic power potential and design validation were emphasized over the manufacturing of the panel mounts. Therefore, there were not many significant engineering changes to the design since Design Review 3. However, there were a few notable changes that warrant documentation.

*Photovoltaic Panel Support*

*Was*



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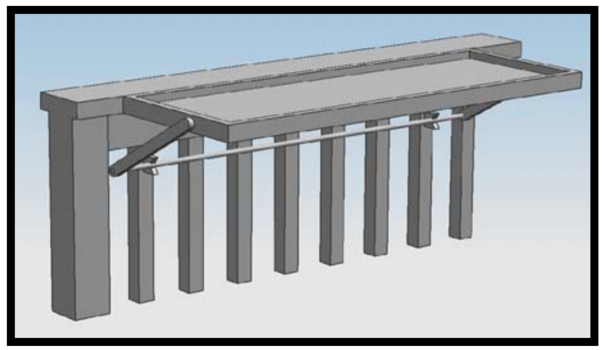

Initially, we did not have a clear idea of how to support the panels on the back of Professor Skerlos' deck, though we had the dimensions of all the components. We knew it had to be a variable-position, hinging mechanism to tilt the panels. We finalized on a bar-and-latch mechanism that would fully support the weight of the panels in three different positions. This change was made because it was a low profile, self-supporting mechanism that would allow the user to tilt the panels to three positions. Andrew Cook and Josh Fagan made the change shortly after Design Review 4, November 21, 2006. Professor Skerlos authorized the change.

Solar Prediction Model and Validation

Originally, a solar prediction model was discussed to be the most accurate method for obtaining experimental data to support the choice of optimum operating angles for the solar panels. Such a model would have been created using data-logging methods in conjunction with variable weather, solar path, and cloud-cover data. Over a period of a week or more, data would be gathered and the model created. However, due to time constraints, a complex solar predication model was difficult to create and removed from the project with permission from Professor Skerlos.

Theoretical operating angles were chosen as the system's optimum angles with little support from our validation process. The validation process was also adjusted, as we were expecting the solar model creation to also stand as our validation. Therefore, a separate validation process was created over the course of two days to capture and record power input to the system at our two operating angles. Cloud-cover and weather changes were noted as the angles were adjusted and power levels recorded. Professor Skerlos authorized this engineering change.

**Theoretical Solar Power Equation**

$P=I*\eta*A$

$$I = S(\sin\Phi\sin\delta + \cos\Phi\cos\delta\cos H)\sin(90 - \Phi + \delta + B)$$

$P$ = power output by the panels
$\eta$ = average efficiency of the panels
$A$ = area of the panels
$I$ = solar insolation received by the panels
$S$ = Solar radiation at surface of earth = 1000W/m^2
$\Phi$ = latitude = 42.27(in Ann Arbor)
$\delta$ = solar declination angle = -22.7 (December 7) = *23.45*sin[(360/365)(284+d)]*
$d$ = day of the year
$B$ = tilt angle of the panels
$H$ = hour angle = *15°*(time-12)*