Solar-Powered Community Lamppost

Final Report

Team 11: Community Lamppost

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Engr339/340 Senior Design Project
Calvin College

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Executive Summary

Team Independent has designed and produced a prototype of a solar-powered lamppost for use in rural communities in third-world countries where there has been a rapid growth in the number of mobile phone users but still a lack in the availability of conventional (off-the-grid) electricity. The lamppost performs two main functions: it provides lighting at night and charging for mobile devices through USB ports. The project is part of a competition among Christian colleges, sponsored by HCJB Global – a global missions organization. At the end of the first semester, we had designed the overall architecture of the system and had made decisions on all the major components. We have now produced a set of comprehensive blueprints and schematics, as well as produced a scaled-down working prototype. Our system works as follows: The power generated from the 50-Watt polycrystalline solar panel is stored in two separate AGM batteries, one that provides power for the LED bulb, and one that provides power to the USB outlets. The charging of the batteries is regulated by two charging controllers, while the discharging process is regulated by a power distribution controller and several DC/DC converters, which provide the correct voltage to the USB outlets, LED light, and microcontroller. Additionally, two USB charging controllers regulate the USB charging. The team designed and populated a PCB, which houses the majority of the electrical components of the system. A user interface allows the user to force the light on or off, to choose the number of hours for the light to remain on at night, and to receive feedback via an LCD on the status of the system. The solar panel will be mounted on a 21-foot schedule-40 galvanized steel pole that will be sunk 3 feet into the ground, supported by a concrete base. Attached to the pole are lockable units that house mobile devices while they charge and will protect the batteries and electrical components from rain and theft. The completed prototype is able to fully charge in 7 hours, and has reserve power for up to two days (running the light for 10 hours a night, and charging two phones for 10 hours a day). It is operable in temperatures from 0° to 130° F, and is also able to sustain wind speeds of up to 60 mph. The system is estimated to run about 3 to 4 years before the batteries would have to be replaced. The total cost for the prototype is just under $1000, and that cost will see a greater decrease if production is in larger quantities.
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1 Introduction
The goal of this project was to design and build a solar-powered lamppost that provides light at night and USB charging capabilities for mobile devices during the day. The design consists of a 50-Watt solar panel that charges two AGM batteries, using a solar charging controller. The 8-Watt LED bulb is powered off one of the batteries, and the USB charging ports are powered of the other. When being charged, the mobile devices would be housed in a polycarbonate box with vents to enable airflow. The completed prototype is able to fully charge in 7 hours, and has reserve power for up to two days (running the light for 10 hours a night, and charging two phones for 10 hours a day). It is operable in temperatures from 0° to 130° F, and is also able to sustain wind speeds of up to 60 mph. The system is estimated to run about 3 to 4 years before the batteries would have to be replaced. The total cost for the prototype is just under $1000, and that cost will see a greater decrease if production is in larger quantities.

This chapter introduces the project, including a description of the course, bios of the team members, and an overview of the rest of the report.

1.1 Course
Senior engineering students at Calvin College undertake a two-semester design course sequence. Students from all four engineering concentrations offered at Calvin – Electrical/Computer, Mechanical, Civil/Environmental, and Chemical – form teams of three to five students and take on a year-long project. The design project brings together engineering knowledge and skills the students have acquired throughout their study at Calvin. The project incorporates many additional skills, including project management and financial management, which help the students prepare for careers in engineering. Although many students choose projects primarily to demonstrate engineering competence and may not solve actual problems, this project is based on a real problem, and we have designed it for a real customer, HCJB Global.

1.2 Team Members

Wisdom Aiyelabowo
Wisdom Aiyelabowo is a senior with a mechanical engineering concentration from Nigeria. Over the last two summers, Wisdom has taken an engineering class in Germany and interned at Lacks Enterprises in Grand Rapids, where he still works. Wisdom plans to get a year or two of engineering experience in industry before pursuing a Masters in Engineering Management in graduate school.

Adam Card
Adam Card is a senior with a mechanical engineering concentration from Cadillac, MI. Adam grew up the son of an Army officer and intends to follow in that career path upon his graduation as part of a Combat Engineer Unit. He has completed Basic Training, Advanced Individual Training, Air Assault School, and the Leadership Development and Assessment Course over the past two summers. Adam has a strong interest in metallurgy and electrical furnace systems, and he builds knives from scrap in his spare time.
Katie McKay

Katie McKay grew up in Lisle, Illinois and came to Calvin College in 2008, where she studied Physics and Mathematics before switching to the Electrical and Computer concentration of Engineering. She will also graduate from Calvin with a major in German and minors in Physics and Mathematics. Katie has studied in Germany twice while at Calvin and would love to work there in the future. She has worked for four years as a peer tutor at Calvin, tutoring chemistry, physics, math, and engineering.

Yoofi Otabil

Yoofi Otabil is a native of Ghana, studying Electrical & Computer Engineering at Calvin College. His interest in the telecommunications field led him to participate in a summer internship program with Twisthink LLC (Holland, MI), where he had the opportunity to work with GPS technology. He hopes to further his training by enrolling in a graduate program (MA and subsequently PhD) in telecommunications. At Calvin, he works with Student Academic Services as a tutor for chemistry, physics, mathematics, and engineering courses. He also has a passion to see the principles of God's kingdom being lived out and actively seeks opportunities where he can serve.

1.3 Overview of the Report

The remainder of this report consists of nine chapters. Chapter 2 defines the problem our design intends to solve. It describes the need that prompted this project, gives an introduction of the customer, HCJB Global, and describes our reasons for choosing this project. Chapter 3 deals with the project management, including the division of work among the team members and the team’s schedule. Chapter 4 gives an overview of the entire system. It includes physical and electrical requirements, as well as a description of the system architecture. Chapter 5 goes into detail on every electrical component of the system, describing the requirements, the alternatives, and the decision of which alternative is best, as well as the implementation and testing of components. Chapter 6 does the same for the mechanical components of the system. Chapter 7 presents the economic aspects of the project. It discusses the finances for both the production of the product by HCJB and the use of the product by the proprietor. Chapter 8 provides assembly instructions for the system. Chapter 9 draws conclusions on the project. Chapter 10 contains the sources we have used in our research, and Chapter 11 acknowledges all of the people who have helped to make this project a success.
2 Problem Definition

This chapter provides information about the need that prompted this project, the customer, and the reason we chose this project.

2.1 Need

Rural communities in Africa, South America, and other parts of the world have limited access to conventional power. Portable generator carts, the common alternative, are expensive to acquire and operate (some charge as much as $40 per kilowatt hour). However, the lack of accessible power has not prevented the increase of mobile phone users. In Ghana, for example, about 70% of the population is active mobile phone users, whereas just about 20% of its population has direct access to electricity. In many of these communities, sunshine is an abundant local resource. With the exception of northern and southern parts of Africa, much of the continent experiences about 8 - 10 sunlight hours per day, which makes it a good location for harvesting solar energy. The map shown below in Figure 1 shows the average number of sunshine hours in Africa and the rest of the world.

![Figure 1: Average yearly total number of hours of sunshine](http://mediawiki.middlebury.edu/wiki/OpenSourceLearning/Solar_Power#cite_note-15)
2.2 Customer
HCJB Global\textsuperscript{2} is a non-denominational, non-profit, evangelical missionary organization that reaches out to people all over the world through both media and healthcare. HCJB Global promotes healthcare by overseeing hospitals and healthcare facilities around the world, as well as developing medical and clean water missions in rural communities and providing emergency medical treatment after natural disasters. HCJB Global’s media ministry includes radio broadcasts and installation of radio stations used to communicate with people beyond the reach of traditional missionaries. HCJB is looking to add solar-powered community lampposts to its outreach. It has proposed a design competition among Christian colleges to develop this solar-powered community lamppost with portable device charging capabilities. This lamppost will not only provide a service that is needed, but it will also require a proprietor, and it can be the basis for a small business in the community. HCJB is exploring the possibility of installing these lampposts next to wells that they have already installed in rural communities around the world.

2.3 Project Choice
The team chose this project primarily because of the opportunity to work with renewable energy sources. We recognize that renewable energy has the potential to provide an efficient and sustainable solution to global energy needs. We are also very much interested in being stewards of God’s world, and renewable energy is one way we can contribute to that. The team is also interested in caring for others. We believe that if we are in a position to improve the quality of life of others, we should. As a result of this project, we are able to help HCJB by providing labor at a much lower cost, and we are also able to help rural communities in Africa and South America.

\textsuperscript{2} http://www.hcjb.org/
3 Project Management

This chapter describes the structure of the team and the duties of each team member. It also describes the work breakdown schedule for the entire project.

3.1 Team Management

The team consists of two mechanical and two electrical engineering students. Wisdom Aiyelabowo is responsible for researching and deciding on the batteries and the solar panel. He is also involved with analyzing the thermodynamics of the system – ensuring that all components are within operating temperature requirements. He is in charge of system CAD drawings and manufacturing of certain system components including the solar mount and lamp holding mechanism. Wisdom also ensures that the team is on schedule with all meetings and deadlines. Adam Card is in charge of research on lighting source options. Because of his interest in metallurgy, he is also involved with the structural analysis of the mechanical components of the lamppost. His metallurgy background proved invaluable in the manufacturing of majority of the system components: charging box, component attachment accessories and structure base. Adam makes sure that the weekly status reports are sent out to Professor VanderLeest. Katie McKay is in charge of drawing up an operational and production budget. She is also in charge of the power distribution control, user interface, and voltage regulation of the system. Katie also takes notes during all team meetings and ensures that assignments are turned in on time. Yoofi Otabil is in charge of research on the charging controller, USB charging of mobile devices, the ambient light sensor, and on the microcontroller that enables the user configure the system. Yoofi spearheaded the design and assembly of the Printed Circuit Board and the system electrical schematic. He is also responsible for updating the team’s project website (http://www.calvin.edu/academic/engineering/2012-13-team11/index.html) and posters.

The team meets weekly to work on the project and ensure that all goals are being met as required. We report to the team advisor, Professor Steven VanderLeest of the Calvin College Engineering Department, and our industrial liaison, Scott McConnell of HCJB. They give weekly feedback on reports of the team’s projects, as well as suggestions that the team could look into.

3.2 Schedule

In order to ensure that the team works at a healthy pace over the course of the year, we developed a work breakdown schedule. A link to the work breakdown schedule can be found here (http://www.calvin.edu/academic/engineering/2012-13-team11/docs/WBS.pod). Table 1 is a summary of the work breakdown schedule that highlights the tasks that have been completed and current progress of the project.
Table 1: A Work Breakdown Schedule

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<tr>
<th>PROJECT MILESTONES</th>
<th>DURATION (hr)</th>
<th>ACTUAL DURATION (hr)</th>
<th>COMPLETION (%)</th>
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<td>Define system components</td>
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<tr>
<td>Consult</td>
<td>4 + 2(weekly)</td>
<td>4 + 2(weekly)</td>
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<tr>
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<tr>
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<td>100</td>
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<tr>
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</tr>
<tr>
<td><strong>CUMULATIVE HOURS</strong></td>
<td><strong>700</strong></td>
<td><strong>900</strong></td>
<td><strong>100</strong></td>
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The team spent less time than anticipated on developing an economic management plan because HCJB bears majority of the responsibility of developing a financial strategy for the product.

One of the primary goals for the team in the first semester was to make decisions on all major system components and order the parts by the end of the semester. At the end of the semester, the team had chosen and ordered the solar panel, batteries, charging controller, switched-mode power supplies, LCD screen, USB outlet ports, LED light bulb, and some acrylic for use in the physical structure. At the end of the second semester, we had met our goal for the entire year is of producing a full set of electrical circuit schematics, a detailed description of the mechanical structure, and a fully working scaled-down prototype of the lamppost. We chose to scale down the prototype to increase the mobility of the unit and to ensure that the project falls within its financial budget.

3.3 Team Scheduling Procedures

The team had a couple of problems with communication and scheduling, so we came up with a set of criteria to ensure no future problems. These procedures are given below:

3.3.1 Meetings
1. 24 hours before a meeting, if you haven’t received a reminder email, send a reminder email to every team member.
2. When you receive a reminder email, reply all to acknowledge.
3. If someone does not acknowledge by 8:00 the next morning, the person who sent the email calls or texts the person.
4. If possible, the team will meet 20 minutes early for every meeting. If a team member cannot make it 20 minutes early, he/she should make sure the other team members are aware.
3.3.2 Due dates
1. For normal assignments, send an email 1 week ahead of time to acknowledge assignment and split up work.
2. 24 hours ahead of due date, email to confirm that it is almost finished.

3.3.3 Replying to emails
1. First person to read email emails the group to communicate about the contents of the email.
2. Everyone else reply immediately with information or reasons why you need to wait to get information.
3. Wisdom should send reply within 48 hours.

3.3.4 Status Report
1. Adam sends a reminder email Sunday night.
2. If the rest of the team receives no email by midnight, the first person to realize this will send an email to the team.
4 System Architecture

This chapter explores the system as a whole (both the mechanical and electrical components). It begins by presenting the objectives of the project and the requirements for each part of the system that were provided by HCJB Global, and then it describes the architecture of the entire system.

4.1 Objectives

These are our objectives for this project:

1. Design a solar-powered lamppost with charging ports for electronic devices to be used in remote locations.
2. Provide security for devices while they are charging.
3. Manage power so that there is enough energy to power light at night.
4. Include a user interface so the proprietor can control the light and be informed about the status of the system.

4.2 Requirements/Specifications

4.2.1 Customer Priority Rubric.

Table 2 shows the priority rubric provided by HCJB Global to indicate to our team the relative importance of different aspects of the project.

<table>
<thead>
<tr>
<th>Factor</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reliability/ruggedness</td>
<td>20%</td>
</tr>
<tr>
<td>Meets or exceeds project specifications</td>
<td>25%</td>
</tr>
<tr>
<td>Operating time to 50% light output without sunlight</td>
<td>10%</td>
</tr>
<tr>
<td>Ease of manufacture</td>
<td>15%</td>
</tr>
<tr>
<td>Cost</td>
<td>20%</td>
</tr>
<tr>
<td>Light output</td>
<td>10%</td>
</tr>
</tbody>
</table>

4.2.2 Physical Requirements

HCJB Global also provided the following requirements for the mechanical infrastructure.

*Note: To decrease transportation costs, HCJB plans to obtain the steel pole at the location where the lamppost will be installed.*

1. The structure must use a galvanized steel pole 15 to 21 feet long.
2. The pole must be sunk 3 feet into the ground.
3. The pole must have a 1.5-inch nominal diameter.
4. The pole must be Schedule 40.
5. The entire system must be able to withstand temperatures from 0° F to 130° F.
6. The structure must remain intact with wind gusts up to 60 mph and sustained winds of 40 mph.
7. The structure must be reasonably weatherproof.
8. The structure must be durable and require little maintenance over years of life.
4.2.3 Electrical Requirements
HCJB Global provided the following electrical requirements for the system.

1. The system must be able to store enough energy for one day of operation with no sunlight.
2. The system must provide at least 10 hours of light per night.
3. The system must provide two USB charging positions with USB type A ports, running 0.5 Amps at 5 Volts.
4. The system must be able to turn itself on at night.
5. The proprietor must have the ability to program the number of hours the light will be on, 1 to 10 hours with 1-hour resolution.
6. The system must include current limiting and short circuit protection.

4.3 System Design
This project can be divided into three subsystems: the mechanical infrastructure, the electrical system, and the electrical control, as shown in Figure 2. Some components, such as the solar panel, are included in both the mechanical infrastructure and the electrical system, because they have both mechanical and electrical aspects in the system.

- **Figure 2: System Architecture**

4.3.1 Mechanical Infrastructure
The mechanical infrastructure consists of the pole, the solar panel, the LED light source, and the enclosures that contain the batteries, charging ports, and electrical components as shown in Figure 3. The CAD drawing in Figure 4 shows a preliminary design for the mechanical structure of the system.
Figure 3: Mechanical Structure
Figure 4: Preliminary CAD model of lamppost
More details on the mechanical infrastructure are discussed in Chapter 6.

4.3.2 Main Electrical System

The main components of the electrical system are the solar panel, the batteries, the LED light source, and the USB outlets. Other necessary elements include controllers, voltage converters, and short-circuit protection. The electrical control system also includes a low-light sensor, an LCD screen, and control knobs and switches that enable the operator to interact with the system. The controllers and their associated components will be discussed in the next section. The components of the main electrical system are shown in Figure 6. More information on the individual components (the solar panel, batteries, USB outlets, and LED light source) can be found in Chapter 5, respectively.
There were two options for the structure of the electrical system as a whole. Option A was to use a single energy storage device that would provide power to both the USB outlets and the light source. Option B was to have two separate energy storage devices, one for the USB outlets and one for the light source. Option A has the advantage of requiring only one set of energy storage devices, but it requires additional software. The danger with only one energy storage device is that the proprietor may allow too many devices to charge per day, leaving little or no energy to run the light throughout the night. If we chose this system, we would require our microcontroller to measure the remaining charge in the battery and then deny charging capabilities to ensure the light could run all night. Since the voltage across the battery varies with temperature, estimating the remaining charge in the battery would be very complicated. Option B eliminates the need for this battery monitoring by using two separate energy storage systems. The USB charging ports would have access to only one storage device, and the LED bulb would have access to only the other. Table 3 shows the decision matrix for these two options.

**Table 3: Energy System Decision Matrix**

<table>
<thead>
<tr>
<th>Criteria (Score)</th>
<th>Option A</th>
<th>Option B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Components Needed (40)</td>
<td>30</td>
<td>20</td>
</tr>
<tr>
<td>Software Complexity (60)</td>
<td>20</td>
<td>50</td>
</tr>
<tr>
<td>Total</td>
<td>50</td>
<td>70</td>
</tr>
</tbody>
</table>

The decision matrix shows that Option B is preferable to Option A for this system. As a result, we decided to go with two different energy storage devices, one to supply power to the light source and one to supply power to the USB charging ports. Figure 7 shows a block diagram for the flow of energy through the system.
Additionally, the system requires voltage converters between the major components of the electrical system. The batteries can output different voltages than what the USB charging ports and the LED light source require. More information on the voltage converters can be found in Section 5.5. Figure 8 shows a detailed block diagram of the entire electrical system.
4.3.3 Electrical Control

The electrical system contains two major control elements, as well as several supporting control elements. The two major control elements are the charging controllers, which manage the transfer of power from the solar panel to the batteries, and a power distribution controller, which manages the transfer of power from the batteries to the outputs. The functions performed by each controller are shown in Figure 9.

![Diagram of Electrical Control](image)

**Figure 9: Electrical Control**

The charging controller is located between the solar panel and the two batteries. It performs maximum power point tracking, which adjusts the output of the solar panel so that the maximum power is obtained; temperature compensation for the charging; and nighttime protection. It also prevents the batteries from overcharging. More information on the charging controller can be found in Section 5.3.

The distribution control subsystem consists of the distribution controller, as well as the user interface, USB charging controllers, and DC/DC converters, or switched-mode power supplies, which convert the voltage output from the batteries to the voltage required by the USB outlets and the LED light source. The power distribution controller performs four main functions: preventing the batteries from overdischarging, detecting the light level to turn the LED light source on, keeping a timer to turn off the LED bulb after the specified time has elapsed, and interacting with the user interface. More information on the power distribution control can be found in Section 5.7.
5 Electrical Components

This chapter describes each component of the system, including the requirements for the component, the alternatives we looked at, the decision we made, and how we implemented the component in our design.

5.1 Solar Panel

5.1.1 Requirements

The most important requirement for the solar panel is that it must be able to produce at least 350Wh daily. The team decided to go with two battery banks for the system, as discussed previously. In this system, one battery bank provides energy for the USB charging (100Wh) while the other provides energy for the LED lighting (250Wh). The team uses charging controllers to split the output from the solar panel between the batteries based on energy demands for each bank. Furthermore, from the buckling calculation (found in Section 6.1), the solar panel and other components on the pole must not exceed 492 lbs. to prevent failure of the pole. The buckling calculations were done using pole dimensions specified by the customer. With given pole dimensions, the team calculated the maximum allowable force on the pole before it buckles. Further analysis on the structure of the system will be discussed in the system structure subsection (5.1). Additional requirements for the solar panel are as follows: The solar panel must be reasonably robust to withstand harsh weather conditions as well as handling during transportation. Additionally, the solar panels must come with pre-drilled holes to ensure ease of mounting to the frame as well as to lower the assembly cost of the system. If possible, the solar panel should be durable and be designed to charge 12V batteries.

5.1.2 Alternatives

As we learned from our discussion with Michael Walma, the director of engineering from Sound Off Signals, the two main types of solar panels are crystalline and amorphous. Crystalline solar panels have silicon surfaces that are either cut or melted and poured into a mold for surfacing of the panel. On the other hand, though amorphous solar panels also have a silicon surface, they differ on the atomic level. Amorphous solar panels have irregular atomic structures on their silicon surface, while crystalline solar panels have regular atomic arrangements. The advantage of the irregular arrangement on amorphous panels is that the panel is able to absorb more light. Both types of panels could be acquired at output capacities that satisfy the system demand, but other factors were also considered to make the final decision.

First, we considered the price of the solar panel. The team looked for 50W solar panels in the two categories from different vendors. Eventually, we found a vendor selling a crystalline solar panel that would meet system demands at approximately $200. Conversely, the cheapest we could find a 50W amorphous solar panel was $300. The price variation was very evident and made our decision almost automatic. The major contributing factors to the difference in prices are that amorphous solar panels are not demanded much and they are fairly new to the industry. Next, we considered the ease of installing the solar panels. Research showed that amorphous solar panels generally need additional mounting rails for installation. This need increases both the cost and time of installing the solar panel. With the need for additional mounting rails came the need for additional space for installation.

Because stewardship is a design norm we are focusing on, we looked into environmental impacts the solar panels could have. We found out that Cadmium Telluride is used in the production of amorphous solar panels. Cadmium tends to accumulate in plant and animal tissues, and in the long run could be hazardous to their health. Though we are not faced with the threat of this pollution while the solar panel is functioning, the team looked further down the road to when the panel has reached the end of its life and must be disposed of.
With regards to the performance of the solar panels, research showed that crystalline solar panels are more efficient than amorphous solar panels; crystalline solar panels convert 17% to 25% of sunlight to electricity, while their amorphous counterparts convert about 7%. This revelation was a key factor in determining the type of solar panel we choose for the lamppost, since efficiency is very important.

Finally, with regards to durability of the solar panels, research did not bear much fruit in giving specifics about the capabilities of the panels. The crystalline panels are often favored with regards to durability because they have been on the market for a while and have withstood conditions as harsh as space travel. However, the amorphous panel’s durability cannot be overlooked, as its flexibility and possible bulletproof characteristics contribute to its durability.

5.1.3 Decision

Table 4: Decision Matrix for Solar Panel

<table>
<thead>
<tr>
<th>Criteria (score)</th>
<th>Mono crystalline</th>
<th>Amorphous</th>
</tr>
</thead>
<tbody>
<tr>
<td>Price (25)</td>
<td>24</td>
<td>18</td>
</tr>
<tr>
<td>Ease of Installation (20)</td>
<td>18</td>
<td>15</td>
</tr>
<tr>
<td>Required Space (10)</td>
<td>8</td>
<td>6</td>
</tr>
<tr>
<td>General Performance (30)</td>
<td>26</td>
<td>28</td>
</tr>
<tr>
<td>Durability (10)</td>
<td>8</td>
<td>6</td>
</tr>
<tr>
<td>Environmental Concerns (5)</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>Total Score (100)</td>
<td>89</td>
<td>76</td>
</tr>
</tbody>
</table>

From the decision matrix shown in Table 4, it is evident the crystalline solar panel is the most feasible for this system.

The decision of which brand of crystalline solar panel to purchase was a significant decision that necessitated a professional suggestion. The team got in contact with Ameresco, one of the largest independent energy services company in North America. We communicated Garrett Hoffman, from Ameresco solar, for his opinion on a suitable solar panel for our project. Of the numerous brand options we considered, including Sharp, LG Electronics, and Morningstar, he recommended the Value Line Solar (VLS) brand. This was mainly because this solar panel was comparatively cheap and did not have excess properties that were unnecessary for this project. Table 5 contains key properties of the selected solar panel.

Table 5: Selected Solar Panel Specifications

<table>
<thead>
<tr>
<th>Model</th>
<th>VLS-50W</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pm(Wp)</td>
<td>50</td>
</tr>
<tr>
<td>Vmpp(V)</td>
<td>18</td>
</tr>
<tr>
<td>Impp(A)</td>
<td>2.78</td>
</tr>
<tr>
<td>Voc(V)</td>
<td>22.3</td>
</tr>
<tr>
<td>Isc(A)</td>
<td>3.03</td>
</tr>
<tr>
<td>Price</td>
<td>$200</td>
</tr>
</tbody>
</table>
5.1.4 Implementation and Testing

After assembling the entire system, we took it outside and recorded the voltage values as the system charged in the sun. Table 6 shows the battery voltages we recorded at different times.

<table>
<thead>
<tr>
<th>Time</th>
<th>USB Battery Voltage</th>
<th>LED Battery Voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>11:30</td>
<td>11.4</td>
<td>13.1</td>
</tr>
<tr>
<td>11:40</td>
<td>11.3</td>
<td>13.3</td>
</tr>
<tr>
<td>11:45</td>
<td>11.5</td>
<td>13.3</td>
</tr>
<tr>
<td>11:50</td>
<td>11.5</td>
<td>13.3</td>
</tr>
<tr>
<td>11:55</td>
<td>11.4</td>
<td>13.2</td>
</tr>
<tr>
<td>12:00</td>
<td>11.5</td>
<td>13.2</td>
</tr>
<tr>
<td>12:05</td>
<td>11.4</td>
<td>13.1</td>
</tr>
<tr>
<td>12:10</td>
<td>11.3</td>
<td>13.2</td>
</tr>
<tr>
<td>12:15</td>
<td>11.4</td>
<td>13.1</td>
</tr>
<tr>
<td>12:20</td>
<td>11.4</td>
<td>13.1</td>
</tr>
<tr>
<td>13:10</td>
<td>11.4</td>
<td>13.2</td>
</tr>
</tbody>
</table>

As a result of this testing, we discovered that the battery voltages fluctuate quite a bit during the charging process. We can see some increase in battery voltage, although it is not a large increase. We attribute this to several factors: the short time duration of the test, the latitude of Grand Rapids, the cloud cover, and the smaller solar panel.

5.2 Energy Storage

5.2.1 Requirements

According to the requirements provided to us by HCJB, the energy storage component must accommodate a total of 150Wh of energy. The energy storage bank is meant to power both the light source and USB charging ports for 10 hours daily. However, as part of the customer specifications, the system must be capable of providing light for one day without any sunlight. Our team decided to go a step further and make the system also capable of performing USB charging for one day without any sunlight. As a result, our system requires an energy storage capacity of at least 300Wh. The two major outputs of the system are the light and the USB charging. In order to ensure that each output gets sufficient energy from the battery bank, the team decided to have two separate energy storage banks, one for each output. Therefore, we need a 200Wh battery to power the LED light and a 100Wh battery to power the USB charging. This system ensures that the USB charging cannot take more energy than it has been allocated, and the system is guaranteed 10 hours of light in the night for at least one day with no sunlight.

The batteries we considered had to be sealed, to ensure maximum safety during both transportation and use. Also, the batteries had to be able to operate in ambient temperatures as high as 130°F and have about a 12V output voltage. Taking into consideration that the batteries for these systems could get almost fully discharged, the batteries had to be deep-cycle batteries. This means that the batteries can be discharged to 10.5V or lower without adverse effects on the battery lifespan.
5.2.2 Alternatives

a. Lead Acid Batteries

The two main options for lead acid deep cycled batteries are Absorbed Glass Mat (AGM), and Gel. Within these battery types are many specific brands, which will be discussed later. These batteries are available for purchase in 200Wh capacities and are often used with solar systems.

b. Lithium Ion Batteries

With the lithium ion batteries, brand options include “Turnigynano-tech,” “Zippy,” and “Rhino”. Factors considered as important for the decision on which battery to go with include price once again, low self-discharge, low required maintenance, safety, and lifetime.

c. Supercapacitors

Super capacitors are capacitors with very high capacitance that provide energy storage. They are most often used as a secondary or tertiary power source in a system where power availability can fluctuate. This is not the situation we are dealing with. Our energy storage needs are for a primary system that does not have frequent fluctuations. Supercapacitors are very durable but also very expensive. The most inexpensive supercapacitor option we found was a 3000F supercapacitor from Maxwell Technologies (Manufacturer part number: BCAP3000 P270 K05). Even using this supercapacitor, the price for the amount of energy storage we require would be about $5000. Because the supercapacitors are so expensive and their intended applications are not relevant to our project, we quickly ruled them out and decided to go with a more traditional battery for our energy storage.

Taking price into consideration, the lithium ion batteries are the most expensive of the three battery options and the gelled lead acid battery is the least costly. To power the system with solely a Li-pol battery, it would cost $250. With an AGM battery, it will cost $90 and $65 with a gel lead acid battery.

An unwanted characteristic of batteries is the tendency to self-discharge. Self-discharging refers to the rate at which a charged battery loses charge if it is left to sit in an ideal situation. Therefore, it is a measure of how well a battery can hold its charge over a period of time. Li-pol batteries generally lose 8% in the first month, while lead acid batteries lose 3% in the first month. At the same time, we desire batteries that are able to charge quickly. Li-Pol batteries generally charge faster than lead acid batteries (up to 15C), whereas lead acid batteries take comparatively longer to charge.

With regards to safety, the chosen battery should be leak-free and not release hydrogen gas that could cause an explosion. AGM and Lithium ion batteries do not have the problem of releasing hydrogen gas, but when over-charged, gel lead acid batteries release hydrogen gas. Leaking is not an issue with any batteries we looked at, which guarantees no chemical hazards. The final characteristic we looked at was battery lifetime. Lifetime refers to how long the batteries last on average when operated in deep cycling. Gel batteries generally last 2-5 years, AGM batteries 4-8 years, and lithium ion batteries approximately 3-4 years.

5.2.3 Decision

<table>
<thead>
<tr>
<th>Criteria (score)</th>
<th>Lithium ion</th>
<th>AGM</th>
<th>Gel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Price (15)</td>
<td>10</td>
<td>12</td>
<td>14</td>
</tr>
<tr>
<td>Low Self Discharge (10)</td>
<td>6</td>
<td>9</td>
<td>8</td>
</tr>
<tr>
<td>Fast charging (10)</td>
<td>9</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>Safety (30)</td>
<td>25</td>
<td>28</td>
<td>20</td>
</tr>
</tbody>
</table>

Table 7: Battery Decision Matrix
The decision matrix shown in Table 7 indicates the sealed AGM battery as the ideal energy storage option for our proposed system. This type of battery has a long life span as a result of its low self-discharge rate and ability to discharge deeply. Furthermore, this battery is guaranteed to never leak or discharge hydrogen gas.

At first, the team was wary of the idea of using two separate batteries because of the issue of the weight on the pole, but the team decided to consider the option of using lithium ion batteries, which are very light. The big issue was higher costs that came with using lithium ion batteries to completely power the system. The lithium ion batteries required to power the entire system would cost approximately $250 and weigh 6.8 lbs., while the two lead-acid batteries required to power the entire system would cost approximately $90 and weigh 18.6 lbs. Clearly, both the weight difference and the price difference between the two options are substantial. After putting much thought into it, the team decided to come to a compromise between cost and weight. We decided to use lithium ion batteries to power the USB charging and an AGM battery to power the LED light. This brings the total cost of the batteries to $125 and total weight to 14lbs.

Table 8 and

Table 9 show the specifications for the selected batteries:

<table>
<thead>
<tr>
<th>Battery type</th>
<th>AGM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max Voltage (V)</td>
<td>12</td>
</tr>
<tr>
<td>Min Voltage (V)</td>
<td>10.5</td>
</tr>
<tr>
<td>Current (A)</td>
<td>1.7</td>
</tr>
<tr>
<td>Operating Discharging Temp (°C)</td>
<td>-40 - 60</td>
</tr>
<tr>
<td>Length (in)</td>
<td>7.12</td>
</tr>
<tr>
<td>Width (in)</td>
<td>3</td>
</tr>
<tr>
<td>Height (in)</td>
<td>6.59</td>
</tr>
</tbody>
</table>
Table 9: Lithium Polymer Battery Specifications

<table>
<thead>
<tr>
<th>Battery Type</th>
<th>Li-Pol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. Voltage (V)</td>
<td>11.1</td>
</tr>
<tr>
<td>Min. Voltage (9V)</td>
<td>9</td>
</tr>
<tr>
<td>Current (A)</td>
<td>0.22</td>
</tr>
<tr>
<td>Operating Temperature (°C)</td>
<td>60 (max)</td>
</tr>
<tr>
<td>Current (A)</td>
<td>4.1</td>
</tr>
<tr>
<td>Length (mm)</td>
<td>106</td>
</tr>
<tr>
<td>Width (mm)</td>
<td>24</td>
</tr>
<tr>
<td>Height (mm)</td>
<td>35</td>
</tr>
</tbody>
</table>

For the AGM battery, we selected the Power Sonic model because we can purchase them at an affordable price for operating temperatures up to 60°C (140°F). For the Lithium ion battery, the Turnigynano-tech batteries come in packs that maintain the battery temperature at 60°C maximum. Furthermore, of the various options, this model offered the fastest charging and discharging time.

In the second semester, we decided to switch the Lithium polymer batteries to another AGM battery. The reason for this is that Lithium batteries require balance charging, meaning that each cell must be charged to the same voltage. If one cell reaches a higher voltage than the others, this can cause a danger of explosion. Implementing balance charging would significantly complicate our system and reduce its efficiency. Additionally, since one of the design norms we focused on was caring, we decided that the danger of explosion was too great to put the proprietor and users of our system in danger. Therefore, we decided to switch the Lithium polymer battery array to a second AGM battery. The battery we chose has the same specifications as the first AGM battery we chose to power the LED light, but it has 10.5A-h rather than 18A-h. The battery can be found here: [http://www.atbatt.com/product/8357/sla/power-sonic/12v-10-5ah/battery#tabs](http://www.atbatt.com/product/8357/sla/power-sonic/12v-10-5ah/battery#tabs).

5.3 Charging Controller

The charging controller is basically a voltage and current regulator to keep the batteries from overcharging. This project requires a solar charge controller because, although the nominal voltage of the panel is 12V, it is likely to output about 17V, since most panels are designed to ensure that the panel will still be able to output a voltage high enough to charge the battery even when the sun is low in the sky or there are hazy conditions, cloud cover, or high temperatures.
To successfully charge two independent batteries, the system requires either two charging controllers or a single charging controller that is able to charge two batteries simultaneously. The decision process for using one or two controllers will be discussed in Section 5.3.2. The connection between the controller and the battery is shown below in Figure 10:

Figure 10: Charge Controller Connections

5.3.1 Requirements
The requirements for the charging controller are described below:

a. Temperature Compensation

Although rechargeable batteries can operate in a wide temperature range, performance varies at extreme low or high temperatures. For our applications, we are most concerned about the charging of the battery at high temperatures. Adding temperature compensation is able to prolong battery life to up to 15 percent. Since the voltage threshold drops as temperature increases, the charging of the battery must be adjusted so as to compensate for the drop.

Table 10 shows the recommended voltage limits when recharging and maintaining a stationary lead acid battery on float charge.

Table 10: Voltage Limits for Recharging a Lead Acid Battery

<table>
<thead>
<tr>
<th>Battery Status</th>
<th>0°C (32°F)</th>
<th>25°C (77°F)</th>
<th>40°C (104°F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage limit on recharge</td>
<td>2.55V/cell</td>
<td>2.45V/cell</td>
<td>2.35V/cell</td>
</tr>
</tbody>
</table>

Float voltage at full charge | 2.35V/cell or lower | 2.30V/cell or lower | 2.25V/cell or lower

To show the trend in efficiency, a chart showing the efficiency of a comparable battery (NiCd) is shown below in Figure 11.

![Figure 11: NiCd charge acceptance as a function of temperature](http://solarpowerplanetearth.com/solarchargecontrollers.html)

It is evident from Figure 11 that the charge acceptance is reduced at high temperatures. To compensate for this reduction, the charge controller shall have a built-in temperature sensor to detect outside temperatures and adjust charging accordingly.

b. Maximum Power Point Tracking

Maximum Power Point Tracking (MPPT) is a technique that maximizes the output from a solar panel to optimize the charging of a battery. Because the solar panel receives varying amounts of sunlight throughout the day, the charge controller controls the current and voltage output to ensure the maximum power to charge the battery. Figure 12 shows how a maximum power point is read on an IV curve.
c. Night-Time Protection

The controller must periodically check for nighttime conditions (dark or cloudy weather) and be able to compensate for such conditions (when output from the solar array is minimal) by preventing reverse current leakage. We want this function because reverse leakage current causes a slight discharge from the battery. If the charging controller is able to do this, an external blocking diode will not be required.

5.3.2 Alternatives

The team narrowed down the alternatives based on the manufacturer. We realized that Morningstar had the most accessible information about their controllers, so we focused our efforts on deciding between the different charging controllers they have in production. The second criterion we used to narrow down our selection was the price of the controller. With our budget, we are willing to spend up to $150 for a controller that is able to charge two independent batteries simultaneously or up to $50 for a single controller designed to control one battery (thus requiring two such units for our application).

---

http://solarpowerplanetearth.com/solarchargecontrollers.html
a. Morningstar SunKeeper-6

This controller has a small form factor and is most suited for small solar power applications like this project.

Full description and datasheet can be found at the link below:

b. Morningstar SunSaver-10

This controller has the ability to manage loads as well as the charging of batteries.

Full description and datasheet can be found at the link below:

c. Morningstar SunSaver Duo

This controller is able to charge two separate and isolated batteries at the same time, based on user selectable priorities.

Full description and datasheet can be found at the link below:

d. Morningstar SunGuard

This has the same circuit as the SunSaver but with less expensive packaging to provide an economical controller for small PV systems.

Full description and datasheet can be found at the link below:

As an optional requirement, the controller shall be able to provide some feedback to the proprietor on the status of the battery and the solar panel.

5.3.3 Decision

The decision of whether to utilize two charging controllers or a single controller that is able to charge two batteries simultaneously was based primarily on the price of the two alternatives. Among the alternatives from Morningstar, we concluded that it would be a more economically sound decision to go with two charging controllers. The decision matrix in Table 11 shows our decision-making process.

<table>
<thead>
<tr>
<th>Controller/Requirements</th>
<th>Temp. Compensation</th>
<th>MPPT</th>
<th>Night Protection</th>
<th>Feedback</th>
<th>Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>SunKeeper</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>$45</td>
</tr>
<tr>
<td>SunSaver</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>$39</td>
</tr>
<tr>
<td>SunSaver Duo</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>$134</td>
</tr>
<tr>
<td>SunGuard</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>$27</td>
</tr>
</tbody>
</table>
5.4 Lighting

5.4.1 Requirements
a. The light sources must consume around 5 Watts of power.
b. Light output must be omni-directional but shall be directed below the horizon.
c. Light source must be able to operate indefinitely in an environment of up to 130 degrees Fahrenheit.

5.4.2 Alternative Technologies

5.4.2.1 Incandescent
The traditional source of lamppost lighting, incandescent light-sources are less energy-efficient than other sources (by producing 95% of their light as infrared), but remain cheap and readily available.

5.4.2.1 Fluorescent
Fluorescent lighting is a more expensive but more energy-efficient alternative to incandescent light bulbs. Fluorescent light bulbs have greater lifetimes than incandescent bulbs but are also more sensitive to temperature change, emitting visibly less light in colder environments. Fluorescent light bulbs also contain mercury, a toxic metal, and thus must be handled and disposed of with care.

5.4.2.1 LED
Light emitting diodes, or LEDs, are more expensive than both incandescent and fluorescent options. However, their useful lifetimes are also significantly greater than both. In addition, LEDs are far more efficient than fluorescent lighting, as well as extremely impact resistant.

5.4.3 Criteria/Decision

5.4.3.1 Type of Lighting
The team created a decision matrix to help analyze the alternatives available for lighting, which is shown in Table 12. Our criteria were based upon the project specifications, constraints, and priorities set forth by the customer (toughness was one variable the customer stressed, but did not constrain). We chose LED lighting as the best light source.

<table>
<thead>
<tr>
<th>Decision Matrix</th>
<th>Price</th>
<th>Durability</th>
<th>Power Efficiency</th>
<th>Lifetime</th>
<th>Heat Produced</th>
<th>Environmental Concerns</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Significance</td>
<td>7</td>
<td>8</td>
<td>9</td>
<td>6</td>
<td>5</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Incandescent</td>
<td>10</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>7</td>
<td>151</td>
</tr>
<tr>
<td>Fluorescent</td>
<td>6</td>
<td>3</td>
<td>7</td>
<td>3</td>
<td>5</td>
<td>2</td>
<td>180</td>
</tr>
<tr>
<td>LED</td>
<td>1</td>
<td>9</td>
<td>8</td>
<td>10</td>
<td>6</td>
<td>8</td>
<td>273</td>
</tr>
</tbody>
</table>

5.4.3.2 Specific Products
We conducted studies on the light output of conventional lighting systems. Streetlights have an output of anywhere from 10000 to 50000 lumens but also consume 80-500 watts of power. However, this is for industrial areas and beyond the scope of this project. For a smaller area (20 x 20 meters) in a residential neighborhood, lighting recommendations are approximately 600 lumens.
5.4.3.3 Criteria and Alternatives

HCJB only requires that the light source consume around 5 Watts of power. The additional design guidelines chosen by the team are outlined below:

- The light shall consume around 5 Watts of power.
- The brightness of the light shall be at least 330 lumens.
- The light shall operate between 10 and 12V DC.
- The light shall be able to passively dissipate heat.

To fulfill these guidelines, we considered the following alternatives, shown in Table 13.

<table>
<thead>
<tr>
<th>LED Bulbs</th>
<th>Power Consumption (W)</th>
<th>Voltage (V)</th>
<th>Brightness (Lumens)</th>
<th>Heat sink present</th>
</tr>
</thead>
<tbody>
<tr>
<td>Option A</td>
<td>6</td>
<td>12</td>
<td>540</td>
<td>No</td>
</tr>
<tr>
<td>Option B</td>
<td>5</td>
<td>12</td>
<td>450</td>
<td>No</td>
</tr>
<tr>
<td>Option C</td>
<td>8</td>
<td>12</td>
<td>600</td>
<td>Yes</td>
</tr>
</tbody>
</table>

5.4.3.4 Decision

The determinant design characteristic that differentiates the alternatives is their ability to passively dissipate heat. All the options score adequately on fulfilling our design objectives. As a result, Option C was selected to provide lighting for the lamp post.

5.5 Voltage Regulation

5.5.1 Requirements

Since both batteries can operate at different voltages than the voltages required for their loads, the system requires voltage regulation between each battery and its output. Both AGM batteries operate at a voltage between 10.5V and about 14V. The LED light source operates at 12V, and the USB charging outlets require 5V. For optimum performance of the LED light source, a voltage regulator must be put between the battery output and the LED input to boost the voltage when it drops below 12V and to reduce the voltage when it exceeds 12V. Additionally, the system requires a voltage regulator between the second AGM battery and the USB charging outlets to drop the voltage down to 5V.

Note that the microcontroller also requires a 5V source, so we decided to power the microcontroller from the USB battery using an additional 12V to 5V DC/DC converter. We did this because the light takes priority over the USB charging.

5.5.2 Alternatives

There are two main types of voltage regulators available: the linear regulator and the switching regulator or switched-mode power supply (SMPS). A linear regulator simply uses a reverse-biased transistor or Zener diode to cut off the voltage at the desired level. Linear regulators are quite simple to implement; a simple linear regulator circuit diagram is shown in Figure 13. A linear regulator can only decrease a voltage; it cannot increase a voltage, so the source voltage must always be higher than the load voltage. Additionally, linear regulators do not increase the current as they decrease the voltage; as a result, they lose a large amount of power that is dissipated to heat. A linear regulator typically has an efficiency of about 30% to 40%.
A switched-mode power supply has more complex circuitry than a linear regulator does. It uses combinations of energy storage elements (inductors and capacitors) and switching elements (transistors) to manipulate the input current and voltage to the desired output current and voltage. Because the voltage across an inductor is proportional to the derivative of the current, the output voltage can be greater than the input voltage of a switched-mode power supply, unlike a linear regulator. Additionally, the switched-mode power supply is much more efficient than the linear regulator. A typical efficiency for a switched-mode power supply is about 75% to 80%.

5.5.3 Decision

Table 14 shows a decision matrix for the voltage regulation.

<table>
<thead>
<tr>
<th>Criteria (score)</th>
<th>Linear Regulator</th>
<th>SMPS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Price (10)</td>
<td>8</td>
<td>5</td>
</tr>
<tr>
<td>Efficiency (30)</td>
<td>5</td>
<td>25</td>
</tr>
<tr>
<td>Heat (30)</td>
<td>5</td>
<td>25</td>
</tr>
<tr>
<td>Complexity (10)</td>
<td>8</td>
<td>5</td>
</tr>
<tr>
<td>Able to increase voltage(20)</td>
<td>0</td>
<td>20</td>
</tr>
<tr>
<td>Total Score (100)</td>
<td>26</td>
<td>80</td>
</tr>
</tbody>
</table>

Both efficiency and heat loss are very important in this project. Efficiency is very important for two reasons. First, stewardship is one of the design norms the team is focusing on, and a more efficient system does not waste as much power. Secondly, less power loss means that the solar panel does not need to provide as much energy, so it does not need to be as large. A smaller solar panel is desirable for two reasons: it is less costly, and it will be affected less by wind, which will increase the physical strength of the system. Heat loss is important to consider, because the system is designed for a hot climate, and temperature is a major concern. Furthermore, it is preferable, although not necessary, that the voltage regulator be able to increase the voltage. This is not necessary for the regulator going to the USB charging ports, since the battery voltage will always be higher than the USB voltage of 5V. However, the AGM battery voltage may drop as low as 10.5V, which is lower than the 12V used by the LED light source. Clearly, the switched-mode power supply is superior to the linear regulator in the most important aspects, so we chose the switched-mode power supply to supply power to both the LED light array and the USB charging ports.

\[http://upload.wikimedia.org/wikipedia/commons/9/92/Zener_reg.gif\]
5.5.4 Implementation

There are two grounding alternatives for a DC/DC converter. One option is to connect the input ground to the output ground or the $-V_{in}$ to the $-V_{out}$. The second option is to leave the output isolated from the input and not connect $-V_{in}$ to the $-V_{out}$. If our circuit contained a non-isolated DC/DC converter, we would risk creating a ground loop, which could be harmful to our system. Therefore, we decided only to use DC/DC converters that are isolated.

For our prototype, we initially chose the following two DC/DC converters, which fit our criteria:

1. To supply power to USB charging stations: Mean Well NSD05-12S5
2. To supply power to LED light source: Mean Well SCW08A-12

Both components are RoHS compliant, which supports our focus on stewardship as a design norm. Also, both components contain short circuit protection, which was a requirement given by HCJB Global. There are many more switched-mode power supplies available that we did not consider for our prototype because they were surface-mounted. We wanted to use components for our prototype that we are able to assemble ourselves as much as possible.

We purchased one of each DC/DC converter at the end of the first semester, because we anticipated using one converter for both USB outlets. We later decided that it would be a better idea to isolate the USB outlets from each other so that a problem with one outlet could not affect the other. Additionally, we needed to supply 5V to the microcontroller, so we needed to purchase two additional 12V-to-5V DC/DC converters. Unfortunately, the Mean Well NSD05-12S5 was not available at that point, so we went back and did more research on similar DC/DC converters. We chose the Mean Well SCW08A-5 (Datasheet: http://www.meanwell.com/search/scw08/SCW08-spec.pdf). This component is also RoHS compliant and contains short circuit protection. Table 15 shows the DC/DC converters we used.

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Part Number</th>
<th>Input Voltage</th>
<th>Output Voltage</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean Well</td>
<td>SCW08A-5</td>
<td>9-18V</td>
<td>5V</td>
<td>75%</td>
</tr>
<tr>
<td>Mean Well</td>
<td>NSD05-12S5</td>
<td>9.2-36V</td>
<td>5V</td>
<td>76%</td>
</tr>
<tr>
<td>Mean Well</td>
<td>SCW08A-12</td>
<td>9-18V</td>
<td>12V</td>
<td>80%</td>
</tr>
</tbody>
</table>
5.6 Power Distribution Controller

5.6.1 Requirements

a. Low light sensing and control of LED light source

The most important function of the distribution controller is to turn on and off the LED light. It must detect the ambient light level and turn on the LED light when the light level drops below a certain threshold, which we will specify. The controller must then turn off the LED light after a certain amount of time, specified by the proprietor. The light does not need to stay on all night, so the proprietor shall be able to tell the light to turn off at a certain time when the light is not needed anymore, even if the proprietor is not there at the time. The controller shall also include manual overrides to turn the light on and off. For example, the light may turn on during the day because of a storm, and the proprietor shall be able to turn the light back off when it becomes bright again.

b. Prevent over-discharging of batteries

The second important function of the distribution controller is to prevent the batteries from discharging below the recommended level. For optimum use of AGM batteries, they should not be discharged below a recommended level. If the batteries are discharged below those levels, they will degrade and lose their ability to be fully charged. The AGM battery has a maximum voltage of 12V, and it should not be discharged below 10.5V. The distribution controller must be able to keep track of the voltage across the batteries and stop the discharging if their voltage drops below the specified level.

5.6.2 Alternatives

Because the team already has experience with the Arduino development kits, and the Arduino has a support library that is largely accessible, the decision to go with an Arduino was automatic. However, the decision between the different models took some comparison between the features offered and the features we needed. The decision matrix between the Arduino models is shown below in Table 16.

<table>
<thead>
<tr>
<th>Arduino Model</th>
<th>Microcontroller</th>
<th>Input Voltage Limits</th>
<th>Digital I/O Pins</th>
<th>Analog Input Pins</th>
<th>Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arduino Uno</td>
<td>ATmega328P</td>
<td>6 – 20V</td>
<td>14 (6 PWM)</td>
<td>6</td>
<td>$26.4</td>
</tr>
<tr>
<td>Arduino Due</td>
<td>AT91SAM3X8E</td>
<td>6 – 20V</td>
<td>54 (12 PWM)</td>
<td>12</td>
<td>$45.73</td>
</tr>
<tr>
<td>Arduino Mega 2560</td>
<td>ATmega2560</td>
<td>6 – 20V</td>
<td>54 (12 PWM)</td>
<td>16</td>
<td>$50.57</td>
</tr>
</tbody>
</table>

For the functions performed by the Arduino, an input voltage of about 12V, 12 digital output pins, and 4 analog input pins are required. Since all three models meet the design requirements, the selection of an Arduino controller was based primarily on the price point.

5.6.3 Decision

The team decided to go with the Arduino Uno because it met the design requirements and offered the lowest price point. In order to increase manufacturability of the system and to decrease overall cost, the team decided to implement a standalone Arduino (the ATmega328P without the development kit) and
attach it to a PCB that was designed in-house. A summary of the specifications of ATmega328P in our systems is shown below in Table 17. A detailed specification for the Arduino Uno can be found at: http://arduino.cc/en/Main/ArduinoBoardUno.

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Digital I/O Pins</td>
<td>14 (of which 6 provide PWM output)</td>
</tr>
<tr>
<td>Analog Input Pins</td>
<td>6</td>
</tr>
<tr>
<td>Operating Voltage</td>
<td>5 V</td>
</tr>
<tr>
<td>DC Current per I/O Pin</td>
<td>40 mA</td>
</tr>
<tr>
<td>Clock Speed</td>
<td>16 MHz</td>
</tr>
<tr>
<td>Flash Memory</td>
<td>32 KB</td>
</tr>
<tr>
<td>SRAM</td>
<td>2 KB</td>
</tr>
<tr>
<td>EEPROM</td>
<td>1 KB</td>
</tr>
</tbody>
</table>

5.6.4 Implementation

In order to achieve the functions we required from the ATmega328P, it was implemented as shown in Figure 14 below:
In order to operate the ATmega328P, the following supporting hardware was needed:

*Power*

To turn on the microcontroller, a 5V source (output from the 12V to 5V DCDC converter) was connected to pins 7 and 8. The input voltage was smoothed using a 100uF and a 0.1uF capacitor.

*Reset*

To reset the microcontroller, a button was connected to pin 1. When pushed, the button connects that pin to ground, which enables the reset function.

*Clock Function*

To enable the clock function, a 16MHz crystal was connected to the pins 9 and 10. The crystal was then connected to two 22pF capacitors that were connected to ground.

### 5.7 Power Distribution Control

This chapter describes the automatic functions of the power distribution control. Chapter 5.8 describes the user interface functions of the power distribution control.

#### 5.7.1 Requirements

The necessary functions of the power distribution controller are as follows:

1. Turn on/off USB charging capabilities.
   a. USB charging shall be activated when the voltage across the designated battery is greater than 10.5V.
   b. USB charging shall be deactivated when the voltage across the designated battery is less than 10.5V.

2. Turn on/off LED light.
   a. The light shall be turned off when the voltage across the designated battery is less than 10.5V.
   b. The light shall be turned off when the control switch is in the Force Off position.
   c. Unless the voltage across the battery is less than 10.5V, the light shall be turned on when the control switch is in the Force On position.
   d. When the switch is in the Auto position, unless the voltage across the battery is less than 10.5V, the light shall be turned on when the light level drops below the designated threshold.
   e. When the light has been turned on automatically, it shall remain on for the designated time period unless Force Off has been activated or the ambient light level rises above the designated threshold.

3. Detect the number of hours the user desires the light to be on for.

4. Display information to the user.
   a. Voltage level of each battery.
   b. Status of each battery (below or above acceptable voltage level).
   c. Number of hours set in auto light sequence.
   d. Number of hours remaining in auto light sequence (if applicable).

We decided to include FORCE ON and FORCE OFF options for the light operation, as well as automatic turning off of the light in bright conditions, although they were not required by HCJB, for the following reasons: The user may want the ability to turn the light on or off for various reasons, including for testing.
purposes. One possible scenario could be if the user wants to turn off the light at night earlier than he had anticipated. Additionally, we added the feature that once the light has automatically turned on, it will automatically turn off again if the ambient light level rises above the designated threshold. One situation when this would be useful is if the light is turned on because of dark weather during the middle of the day caused by a thunderstorm. If the weather clears up and is bright again, there is no need for the light to remain on, but it will if the specified time has not yet elapsed. In a situation like this, the user may want the light to turn off automatically. As a result, we chose to add FORCE ON and FORCE OFF options to the system, as well as automatic turning off in bright conditions for the optimum user experience. This decision supports the design norm of integrity.

5.7.2 Implementation and Testing
The source code used for the power distribution control, as well as the full schematic of the system, can be found as downloads from the team website.

5.7.2.1 Photoresistor
The system uses a photoresistor to detect the ambient light level. When the light level drops below a certain level, the controller turns on the LED light source.

The low light sensing works as follows: The photoresistor is connected to the power supply and a pull-down resistor, as shown in Figure 15. An analog input of the controller measures the voltage across the pull-down resistor and uses that value to determine the light level. The controller uses hysteresis to prevent the light from flickering when the ambient light level is on the threshold of when the light turns on.

![Figure 15: Photoresistor Setup](http://learn.adafruit.com/photocells/using-a-photocell)

We tested the resistance of the photoresistor in different light levels to determine the appropriate threshold for turning on the light at night. Table 18 shows the resistances we measured at different times and locations.

---

Table 18: Photoresistor Resistance

<table>
<thead>
<tr>
<th>Time, Place</th>
<th>Resistance (kΩ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>in EB at station</td>
<td>2.5</td>
</tr>
<tr>
<td>outside EB at dusk (8:35pm)</td>
<td>3</td>
</tr>
<tr>
<td>dusk, shade of EB (8:35pm)</td>
<td>7.5</td>
</tr>
<tr>
<td>sunset, 8:41PM</td>
<td>4.5</td>
</tr>
</tbody>
</table>

Using a voltage divider, as shown below, and a photoresistor resistance of 4.5 kΩ, we came up with a threshold voltage of 3.4V.

\[
V_{\text{input}} = \frac{10kΩ}{10kΩ + R_{\text{photo}}} \cdot 5V
\]

We found that even staying in one position with a seemingly constant ambient light level, the resistance of the photoresistor fluctuated by up to approximately 0.5 kΩ. Since we did not want the light to flicker when the light level was near the threshold, we added a hysteresis algorithm to the control code. The hysteresis works as follows:

- If the measured voltage is greater than the threshold + gap, turn light on.
- If the measured voltage is below the threshold – gap, turn light off.
- If the measured voltage is between the threshold + gap and the threshold – gap, leave the light in its previous state.

Using the voltage divider shown above, we calculated hysteresis ranges for the photoresistor resistance using different voltage gap values. We decided to use 0.2V, since that gave us a resistance gap of about 0.5 kΩ. Table 19 shows the values we calculated.

Table 19: Hysteresis Values

<table>
<thead>
<tr>
<th>Gap (V)</th>
<th>Low (kΩ)</th>
<th>Mid (kΩ)</th>
<th>High (kΩ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>4.3</td>
<td>4.5</td>
<td>5.2</td>
</tr>
<tr>
<td><strong>0.2</strong></td>
<td><strong>3.9</strong></td>
<td><strong>4.5</strong></td>
<td><strong>5.6</strong></td>
</tr>
<tr>
<td>0.3</td>
<td>3.5</td>
<td>4.5</td>
<td>6.1</td>
</tr>
</tbody>
</table>
5.7.2.2 Battery Voltage Monitoring

The distribution controller must monitor the voltage across each battery so that neither battery is discharged below the minimum recommended level. The controller can only detect voltages between 0 and 5V, but the batteries operate around 12V. Therefore, we decided to use a voltage divider to decrease the voltage proportionally to a value that our controller can detect. Figure 16 shows the voltage dividers we used.

![Figure 16: Voltage Dividers to Measure Battery Voltages](image)

Similarly to the way it detects the voltage across the pull-down resistor to determine the ambient light level, the Arduino distribution controller also monitors the voltage across each set of batteries. It continually checks the voltage across the battery against the minimum allowed voltage, and if the battery voltage drops below that minimum allowed voltage, the power distribution controller disconnects the battery so that it cannot discharge any more until it has recharged. The distribution controller then monitors the battery voltage level and reconnects it when the voltage rises again to an acceptable level. This function works successfully. Using a laboratory voltage source, we simulated different battery voltages and observed the voltage reported by the microcontroller. When we raised or lowered the simulated battery voltage, the observed voltage also rose or fell accordingly. There was a voltage difference of about 0.2V between the simulated and observed values for both batteries, and we conjecture that this difference could be due to tolerance in resistor values. However, the observed voltages were lower than the simulated voltages, so this difference will not cause damage to the batteries. This 0.2V difference was confirmed when we connected the actual batteries to the system.

5.8 User Interface

The user interface consists of both input and output, through which the user can interact with the system.

5.8.1 Requirements

The requirements for the user interface are as follows:
1. The user shall be able to input a number of hours (1 to 10, with 1 hour resolution) to indicate the amount of time the light shall stay on at nighttime.
2. The user shall be able to force the light on or off, regardless of the light level or time of day.
3. The system shall display information to the user, including the voltage level of each battery, the mode of the light (force on, force off, or auto), and at night the number of hours the light will remain on.

The first requirement was provided by HCJB and the other requirements were added by the team to enhance the system.

5.8.2 Alternatives and Decisions
One decision the team made regarding the user interface was whether to use a control switch or a second control knob to determine the mode of the light. We decided to use a control switch that would click into position rather than a knob that would be more imprecise, for a better user experience.

5.8.3 Implementation and Testing
The user interface consists of the following elements: an LCD screen, a potentiometer to determine the number of hours the light will stay on, a three-way switch to determine the mode of the light (force on, force off, or auto), and a push-button to activate the LCD. The implementation of each element is described below.

5.8.3.1 LCD Screen
The team purchased this LCD screen, which is compatible with the Arduino Uno. The microcontroller is programmed to activate the LCD when the push-button is pushed, and it will remain on for one minute after the button is pushed. The rest of the time the LCD display will be off. This allows for conservation of power. When the LCD is on, it displays (for 10 seconds each) the voltage across the batteries, the status of the LED and USB subsystems (force on, force off, and auto mode). To enable the microcontroller to write to the LCD screen, it was connected to the LCD with the scheme depicted below in Table 20:

<table>
<thead>
<tr>
<th>LCD Pin</th>
<th>Pin Connection</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (VSS)</td>
<td>GND</td>
<td>Display power ground</td>
</tr>
<tr>
<td>2 (VDD)</td>
<td>+5V</td>
<td>Display power +5V</td>
</tr>
<tr>
<td>3 (CONTRAST)</td>
<td>10K Potentiometer</td>
<td>Contrast Adjustment</td>
</tr>
<tr>
<td>4 (RS)</td>
<td>Pin 16</td>
<td>Register Select</td>
</tr>
<tr>
<td>5 (RW)</td>
<td>GND</td>
<td>Data Write Selector</td>
</tr>
<tr>
<td>6 (ENABLE)</td>
<td>Pin 14</td>
<td>Enable Strobe</td>
</tr>
<tr>
<td>7</td>
<td>No Connection</td>
<td>Data Bus 0</td>
</tr>
<tr>
<td>8</td>
<td>No Connection</td>
<td>Data Bus 1</td>
</tr>
<tr>
<td>9</td>
<td>No Connection</td>
<td>Data Bus 2</td>
</tr>
<tr>
<td>Pin</td>
<td>Connection</td>
<td>Data Bus</td>
</tr>
<tr>
<td>-----</td>
<td>-------------------</td>
<td>----------</td>
</tr>
<tr>
<td>10</td>
<td>No Connection</td>
<td>3</td>
</tr>
<tr>
<td>11</td>
<td>Pin 12</td>
<td>4</td>
</tr>
<tr>
<td>12</td>
<td>Pin 11</td>
<td>5</td>
</tr>
<tr>
<td>13</td>
<td>Pin 6</td>
<td>6</td>
</tr>
<tr>
<td>14</td>
<td>Pin 5</td>
<td>7</td>
</tr>
<tr>
<td>15</td>
<td>Pin 13</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>Collector of transistor</td>
<td></td>
</tr>
</tbody>
</table>

5.8.3.1 Light On-Time Control Knob

The user interface includes a knob for the proprietor to use to program how long the light shall stay on each night. The proprietor can set the on time for any time from one to ten hours, with one hour resolution. We decided to use a potentiometer as this control knob. We used the potentiometer as a voltage divider, so that the voltage input to the controller specifies the position of the knob and thus the number of operational hours desired by the user. Figure 17 shows the operation of this potentiometer. Note that pin 2 connects to an analog input of the controller.

![Figure 17: User Input Potentiometer](image)

5.8.3.2 User Control Switch

There are three basic modes of operation for the light: FORCE ON, FORCE OFF, and AUTO. In the FORCE ON mode, the light is turned on regardless of the ambient light level (unless the battery voltage is below the acceptable threshold, in which case the light is off regardless of the mode). In the FORCE OFF mode, the light is turned off regardless of the ambient light level, and in the AUTO mode, the light turns on or off depending on the ambient light level as measured by the photosensor. We used a three-position switch with connections as shown in Figure 18. We came up with a resistor configuration (shown in Figure 19) that only uses one analog input of the controller.
When the switch is in the high position, the top two pins are connected, and the microcontroller sees a voltage of 2.5V. When the switch is in the middle position, none of the pins are connected, and the microcontroller sees a voltage of 0V, and when the switch is in the low position, the bottom two pins are connected, and the microcontroller sees a voltage of 5V. Table 21 shows the correspondence among the switch position, pin connections, input voltage, and system function.

Table 21: Control Switch
5.8.3.3 LCD Wake-up Button

To conserve energy in the system, the LCD screen should not be on continuously; it should only be on when the user wishes to see information about the system. To do this, the team decided to implement a wake-up button to activate the LCD screen. Once the wake-up button has been pushed, the LCD turns on and remains on for one minute; then it will turn off until the wake-up button is pushed again. Figure 20 shows the implementation of this wake-up button.

![Figure 20: LCD Wake-up Button](image-url)
5.9 USB Charging

5.9.1 Requirements

The system should be able to charge mobile devices through USB outlets. It should have two USB outlets that would be able to charge two mobile phones simultaneously. As stated by the customer, the outlets should be a standard USB 2.0 type A outlet, and should be able to provide at 500mA at 5V. The outlets should allow charging of mobile devices for a time period that can be specified by the proprietor.

The decision to be made concerning USB charging was concerning the type of charging port controller to use. In order to enable charging of various kinds of mobile devices, the charging unit should be able to detect what handshakes are being sent by the connected device, and then apply the appropriate electrical signatures on the USB connectors’ data lines to enable charging.

In accordance with the USB Battery Charging 1.2 compliance plan specification, the USB dedicated charging port should be able to support the following charging schemes:

- Divider DCP, required to apply 2.7V and 2.0V on the D+ and D- lines respectively or 2.0V and 2.7V on the D+ and D- lines respectively
- BC 1.2 DCP, required to short the D+ line to the D- line
- 1.2V on both D+ and D- lines

5.9.2 Alternatives

The team decided on two approaches to take to accomplish this function. There was the option to manually hard wire the different charging schemes using voltage dividers, and the option to obtain a USB dedicated charging port controller that was able to detect the appropriate scheme and correctly implement it. The decision matrix for these options are shown below:

<table>
<thead>
<tr>
<th></th>
<th>Hardwired (Manual)</th>
<th>Microcontroller (Automatic)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ease of Implementation (10)</td>
<td>6</td>
<td>9</td>
</tr>
<tr>
<td>Price (5)</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>Accuracy (5)</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>Total</td>
<td>13</td>
<td>16</td>
</tr>
</tbody>
</table>
5.10 Short-Circuit Protection

One of the system requirements is that it must include short-circuit protection. Our system utilizes short-circuit protection in several different locations in order to protect the system from excessive current.

5.10.1 Fuses between batteries and DC/DC converters

Our design includes two 8-Amp fuses, one at the output of each battery so that it cannot send a current higher than 8 Amps to the DC/DC converters. For our prototype, we used traditional fuses (found here: http://www.digikey.com/product-detail/en/0217008.HXP/F2396-ND/777112) that need to be replaced if they are tripped. Obviously, this is not a prudent solution for the final design. We do not want the proprietor to need to change a fuse. It is possible that a fuse would not be easily available, and we do not want the system to shut down for this reason. We only chose to use a traditional in-line fuse because of time constraints.

For our final design, we chose a resettable fuse. A resettable fuse does not need to be replaced if it is tripped. Rather, the resettable fuse will begin conducting again once the high current situation is resolved. A resettable fuse works as follows: When a high current occurs, the resettable fuse heats up quickly, and the high temperature causes the impedance of the resettable fuse to rapidly increase by several orders of magnitude, effectively breaking the circuit. Once the high current diminishes, the impedance of the resettable fuse returns to its original value, and the circuit is complete again.

5.10.2 Short-Circuit Protection in DC/DC Converters

Additionally, all four DC/DC converters incorporate short-circuit protection. Table 23 shows the short-circuit protection included with each DC/DC converter.

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Part Number</th>
<th>Short-Circuit Protection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean Well</td>
<td>SCW08A-5</td>
<td>Hiccup mode, recovers automatically after fault condition is removed</td>
</tr>
<tr>
<td>Mean Well</td>
<td>NSD05-12S5</td>
<td>Recovers automatically after fault condition is removed</td>
</tr>
<tr>
<td>Mean Well</td>
<td>SCW08A-12</td>
<td>Hiccup mode, recovers automatically after fault condition is removed</td>
</tr>
</tbody>
</table>
5.1 Printed Circuit Board

The team decided to design and order a printed circuit board (PCB) to connect most of the electrical components of the system. We decided to design the PCB using EAGLE. We had considered three different PCB design software, EAGLE, PCB Artist, and PCB Express. Table 24 shows the decision matrix we used to choose which to use. We wanted to use a tool that included design rule checking, a feature of the program that checks our design against a set of criteria for a sound design.

<table>
<thead>
<tr>
<th>PCB design software</th>
<th>Design Rule Checking</th>
<th>Ease of Use (10)</th>
<th>Quality of support forums (10)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PCB Express</td>
<td>No</td>
<td>7</td>
<td>5</td>
</tr>
<tr>
<td>PCB Artist</td>
<td>Yes</td>
<td>8</td>
<td>5</td>
</tr>
<tr>
<td>EAGLE</td>
<td>Yes</td>
<td>9</td>
<td>10</td>
</tr>
</tbody>
</table>

EAGLE has many libraries containing both symbols and footprints for parts, but it does not include all of the parts that we are including on our PCB, so we had to design some of them ourselves. The board has two layers and is 3” by 5.2”. The bottom layer consists also of a poured ground. The EAGLE schematic files are located on the team’s website.

The CAD drawing of the completed printed circuit board is shown below with red traces representing the top copper layer, grey traces representing the bottom copper layer, dark blue lines showing the component outlines, green showing the solder pads, and the silkscreen layer represented by light blue text.
Figure 21: Printed Circuit Board CAD Drawing
6 Physical Components

6.1 Lamp Pole

6.1.1 Requirements

6.1.1.1 Customer Supplied Constraints

1. The lamppost must be built out of 1.5” Schedule 40 galvanized steel pipe. This material is readily available on site in fifteen to twenty-one foot lengths, saving shipping expenses. Table 25 shows specifications for typical steel poles on the market.

<table>
<thead>
<tr>
<th>Diameter (Inches)</th>
<th>Wall Thickness (in)</th>
<th>Weight per Foot, (Lbs)</th>
<th>Properties of Sections</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal</td>
<td>Inside</td>
<td>Outside</td>
<td>Pipe</td>
</tr>
<tr>
<td>1/8</td>
<td>.269</td>
<td>.068</td>
<td>.24</td>
</tr>
<tr>
<td>1/4</td>
<td>.364</td>
<td>.088</td>
<td>.42</td>
</tr>
<tr>
<td>3/8</td>
<td>.493</td>
<td>.091</td>
<td>.57</td>
</tr>
<tr>
<td>1/2</td>
<td>.622</td>
<td>.109</td>
<td>.85</td>
</tr>
<tr>
<td>5/8</td>
<td>.824</td>
<td>.113</td>
<td>1.13</td>
</tr>
<tr>
<td>1</td>
<td>1.049</td>
<td>.133</td>
<td>1.68</td>
</tr>
<tr>
<td>1 1/4</td>
<td>1.380</td>
<td>.140</td>
<td>2.27</td>
</tr>
<tr>
<td>1 1/2</td>
<td>1.610</td>
<td>.145</td>
<td>2.72</td>
</tr>
</tbody>
</table>

Actual dimensions for 1.5” Schedule 40 pipe are a 1.610” inside diameter, 1.900” outside diameter, and a 0.145” wall thickness, as can be seen from the table above. It is important not to confuse the nominal dimensions with these, as each will provide very different results during strength calculations.

2. The post will be sunk three feet into the ground, and for the purposes of this project may be considered fixed at the point it enters the earth (we will later conduct soil and ground composition analysis in order to determine suitable anchorage and to double-check assumptions).

3. The lamppost structure must be able to survive in constant wind speeds of 40mph and gusts of 60mph.

4. The light fixture must be a minimum of ten feet above the ground, but not more than eighteen. The maximum length of available piping and the necessary length that to be sunk into the ground will determine the maximum height.

5. The lamppost will be in an open area with clear sky above (no trees or buildings will shade the solar panel to any significant effect).

6.1.1.2 Calculated Constraints

a. The post must be able to carry the load, regardless of where you place the components. The maximum force that may be exerted downward upon the post is 491 lbf (buckling). Therefore it is paramount that upward weight be minimized.

b. Wind places horizontal force upon the pole, which weakens the buckling strength still further. Therefore, it is critical to minimize the wind profile, especially by placing bulky items near the ground.
6.1.2 Alternatives

Due to the large number of individual components, we considered many different design alternatives. The physical structure consists of five main pieces: the securable weatherproof charging compartment, the solar panel, the LED fixture, the sealed battery compartments, the junction boxes, and the pole itself (other minor components are considered subsets of these).

For initial design, most of the options we considered depended upon the position of the battery compartment, of which there was originally only one. The reason for this was consideration of two variables: temperature and theft. The batteries initially being considered did not perform well in hot environments. Additionally, our industrial consultant informed us that theft of batteries is a major issue in the target environment, suggesting a secure design or a location out of reach. Options we considered are as follows:

a. Place the battery box at the top of the pole, just above the LEDs, but under the solar panels. The securable compartment would be at an easier access level, about one yard off the ground.

b. Place the battery box at the base of the pole and the securable compartment directly on top of it.

c. Place the battery box at the base of the pole, but place the securable compartment one yard above it, at an easier access point.

d. Place the battery box underneath the ground. This would make it easier to attain a stable cool temperature (the ground would act as a natural insulator). The downside to this would be the constraint stating that the design must be “reasonably weatherproof”. In order to waterproof the compartment underground, either an airtight container or some interesting technology would be needed. The airtight route is out of the question; batteries cannot be stored in sealed containers due to explosion risk. That would leave the choice of an air periscope or some type of one-way valve.

All of the designs assume a lighting fixture placed near the top of the pole and the solar panel above that. The reasons for this are multiple:

a. First, this design is an assumption [and strong preference] made by the customer and industrial consultant.

b. Regarding the solar panel, placement on the ground would create inefficiency in the form of shadows, both from the light post itself (and attached pieces) and from people walking nearby. The panel would not get the same power production due to these factors, and thus more or larger panels would be necessary, at a greater weight and cost.

c. The solar panel is somewhat fragile, and implementing it at ground level creates an additional risk of walking or dropping something on it by accident, resulting in damage. This contradicts our design norm of trust, as the proprietor should not have to fear accidental damage to the light post.

d. For the light source, the higher it is placed above the ground, the larger a radius it can light. Placing it above the panel would shield the ground from the light, which would be counter-productive, making it difficult to meet our objective while simultaneously hard to abide within the constraint of restricting light below the horizon. However, placing the LED under the panel would shield only the sky from the light, which is desirable. It is also possible that this path for design could result in a greater environmental protection for the light.

6.1.2.1 Structural Attachment

For structural attachment, we struggled to balance the strength of the finished project and ease of manufacturing with product portability and on-site assembly capabilities. Our two major choices were welding or screw fasteners:

a. Welding.
Welding provided a strong, versatile method of attachment. Welds are significantly stronger than screw fasteners and generally make the part stronger than the original pieces. Downsides to welding are expensive manufacturing, bulky parts if pre-fabricated making for difficult shipping, and difficulty in field assembly due to heavy and consumable equipment if built on site.

b. Screw fasteners. Screw fasteners provided our alternative to welding. Whether screws, bolts and nuts, or bolts threaded directly into steel parts, screws make for an easily transported and easily assembled option. Manufacture is relatively cheap compared to welding, and the option of pre-fabrication or on-site assembly made them particularly attractive to our client. Negative aspects of screw fasteners include significant strength reduction at joints and many more individual pieces resulting in time-consuming manufacturing.

6.1.3 Decision

6.1.3.1 The Pole
The actual light pole itself was constrained to a schedule 40 1.5 inch pole. The pole overall length was designed to be twenty-one feet, with three feet underground for a total aboveground height of eighteen feet. This was to provide light distribution to the widest possible ground area, maximizing effect.

6.1.3.2 Structural Attachment
Although we initially intended to weld most of the joints in the structure, we eventually switched to screw fasteners for a variety of reasons. Chief among them were the logistics of shipping and field assembly, which made our industrial consultant and client, HJCB Global, strongly prefer an alternative to welding. The weighted decision arguments can be seen in Table 26: Attachment Decision Matrix

<table>
<thead>
<tr>
<th>Criteria (weight)</th>
<th>Welding</th>
<th>Screw Fasteners</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strength and Toughness (30)</td>
<td>28</td>
<td>14</td>
</tr>
<tr>
<td>Manufacturing Cost (20)</td>
<td>8</td>
<td>17</td>
</tr>
<tr>
<td>Manufacturing Time (10)</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>Ease of Shipping (20)</td>
<td>3</td>
<td>16</td>
</tr>
<tr>
<td>Ease of Field Assembly (20)</td>
<td>5</td>
<td>18</td>
</tr>
<tr>
<td>Total Score (100)</td>
<td>54</td>
<td>70</td>
</tr>
</tbody>
</table>

As screw fasteners were highly preferable to welding, we looked for a method of attaching the components to the pole using some sort of bracket. In an attempt to keep the opposing sides perfectly parallel, we took some angle-iron and designed it to attach on two perpendicular planes with screws attaching directly in line with a pole radius and seen in Figure 22:
Because the commercial battery compartments we had chosen had recessed attachment points spaced wider than the angle-iron bracket faces (which would be difficult, and result in structurally weakening, to shift), we implemented a pair of spacers whose only purpose was to widen the screw attachment points (also seen in Figure 22). Our solar panel attachment consisted of an extension of this design, with angle-iron flanges being used to make the necessary ninety-degree turns.

A finite elements analysis was conducted upon the screw fasteners to ensure safe attachment, and yielded safety factors of 8-10 with the number and placement of screws we settled on using. Taking into account that 12 screws were used on each angle iron attached to the pole and the batteries weighed between 12-15lbs, the screws evenly arranged to distribute the load. In this light, 1lbf will be the load carried by each screw at the points where it is in contact with pole. This load is in the form of shearing along the sides of the screw. To account for uncertainties of how much load each screw is carrying, a 2lbf instead of 1lbf load was put in contact positions on the screw in simulation. Below is an illustration of the FEA result for stress:
As expected, the highest stress is along the side of the screw but safety factors of 10 were achieved depicting that the system design will not fail.

Our client at HCJB stressed to us that the design of a base was unnecessary, as they had already determined to sink any design provided in three feet of concrete, but we needed to provide a safe base for school presentations. After considering several temporary designs, we decided to thread the base of the pole, attach a flange, and screw the flange to a flat steel base.

Although the other elements of the structure will be discussed in further detail in the following chapters, the final CAD constructed design (except the base bracket) can be seen in Figure 24.

![Figure 24: Complete Structural Design](image)

6.1.4 Implementation

In manufacturing, we discovered that our simplistically-intended build was far more complex than we had ever imagined. The difficulty of lining holes in the pipe with holes in the angle-brackets led to the conclusion, after some discussion with the shop supervisor, that the brackets would have to be built simultaneously with the pole. Two options were available to us: clamps or tack welds. As we desired to
complete the entire build without welding we initially went with the clamps. These, however, proved
difficult to position correctly and unreliable during the manufacturing process, so we turned to tack
welding.

After securing the angle-iron pieces for the brackets to the pole, we coded a program into the mill and ran
it through bracket and pole together to ensure matching accuracy. Upon disassembling the brackets from
the pole (with an angle grinder), we punched numbers into the pole and the backs of the identical battery
compartment brackets for perfect matching in future builds. The resulting brackets proved very secure:

Figure 25: Manufactured Angle Bracket

As we moved into threading the base, we realized that the solar panel bracket might well be accomplished
far more easily in a similar fashion. After some research at the local hardware store, we determined to
use pipe joints and create a T at the top of the pole to which the solar panel bars could then be clamped:

Figure 26: Solar Panel Bracket Modification

The additional lure of this design was the ability to clamp the solar panel at different angles, allowing for
optimization of sunlight collection for implementation in different countries, especially those far from the
equator. After test modeling the design in CAD, we built it:
The base also underwent serious change. Upon consideration of our problem, the shop supervisor lent us a ready-made base for testing and presentation purposes, as seen in Figure 28. The designed bracket will still be included when we deliver the prototype to the client.

Figure 27: New Solar Panel Attachment System

6.2 **Enclosure**

6.2.1 **Requirements**

1. There must be a weatherproof, lockable enclosure that is securely attached to the post.
2. The enclosure must contain the two USB-type plug-in outlets and be large enough to accommodate two cell phones while charging.
3. The ambient operating environment will be between 0 and 130 degrees Fahrenheit; all components must be able to operate within these parameters. Higher tolerances may be necessary for components inside closed compartments (the pole, lockbox, or battery compartment).

6.2.2 **Alternatives**

Because the target location is an area in which cell phones are large targets for theft, our client instructed that we should design a tough and securable location in which the cell phones can be left while charging. Our team additionally elected to collocate the PCB in same container as the charging box, where the
attached controls would be readily accessible to the user. This decision, along with consideration of the
delicate electronics seen in some cell phones, caused a hard look at thermodynamics as well.
Furthermore, the team came to the conclusion that it would be beneficial to have the ability to see inside
of the charging container without having to disengage the lock and open the door. This detail might not
be included in the customer constraints, but it was nevertheless in accordance with our design norm of
caring. It is our desire to make the design as user friendly as possible, and small details like placing the
user interface at an accessible level and allowing users to quickly see what is or is not charging are
subsets of this design norm.

6.2.2.1 Steel Plate
The advantage of a plate steel design is primarily strength. Steel is a tough, durable material used in
thrift-defeat systems of all types, including safes. A welded or bent steel construction would be the
strongest of all the options presented, but even a steel compartment built using screw fasteners could be
fortified by applying epoxy to the screw threads before applying or filling the fastener heads with the
same. Downsides to a steel case are bad thermodynamics and the inability to see the charging cell
phones. Steel additionally tends to heat to unsafe touching temperatures in hot environments, such as the
one in which this lamppost will be integrated.

6.2.2.2 Wire Mesh
A wire mesh container, or even a steel case with a mesh window, would allow the user to see the interior
of the charging container. Mesh would also have greatly improved thermodynamics, but on the same
note, would probably not provide much in the way of weather protection. Therefore, some alternative
would most likely have to be used in combination with wire mesh to make it a viable option.

6.2.2.3 Polycarbonate
Polycarbonate provides something of a compromise between steel plate and mesh. Clear, it provides easy
identification of anything inside. This tough, impact resistant material (polycarbonate is the same
material used in safety glasses and bullet-proof glass) is easily machined and is often used as a base-board
for electronics as it does not conduct electricity. Unfortunately, it has the same issues as steel in the
problem of thermodynamics. These issues might be fixed through a combination of mesh with the base
material or with milled venting to allow air flow. Polycarbonate would have to be used in combination
with screw fasteners, as controlled welding is not feasible with plastics; however, the same theft defeat
tactics as suggested for steel plate fasteners could also be applied here.

6.2.3 Decision
Our choice for the charging box material was polycarbonate:

<table>
<thead>
<tr>
<th>Criteria (weight)</th>
<th>Steel Plate</th>
<th>Wire Mesh</th>
<th>Polycarbonate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strength/Theft Toughness (25)</td>
<td>25</td>
<td>10</td>
<td>18</td>
</tr>
<tr>
<td>Thermodynamics (15)</td>
<td>9</td>
<td>14</td>
<td>9</td>
</tr>
<tr>
<td>User Friendlyness (20)</td>
<td>6</td>
<td>11</td>
<td>18</td>
</tr>
<tr>
<td>Ease of Electrical Integration (15)</td>
<td>8</td>
<td>7</td>
<td>13</td>
</tr>
<tr>
<td>Weather Resistance (25)</td>
<td>21</td>
<td>3</td>
<td>21</td>
</tr>
<tr>
<td>Total (100)</td>
<td>69</td>
<td>45</td>
<td>79</td>
</tr>
</tbody>
</table>
There was one exception, however: in order to prevent direct sunlight (and UV radiation) from striking the electrical components to be mounted in the top-most portion of the box, steel plating was to be used for the roof material. Steel was used instead of aluminum for the following reasons:

<table>
<thead>
<tr>
<th>Table 28: Roof Material Decision Matrix</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
<tr>
<td>Weight (20)</td>
</tr>
<tr>
<td>Theft Resistance (80)</td>
</tr>
<tr>
<td>Total (100)</td>
</tr>
</tbody>
</table>

Theft resistance for the aluminum could not be increased by raising plate thickness due to limitations on the sheet metal bending tools available in the machine shop to build the piece. Therefore steel won out as the ideal roof material due to higher strength in a fixed thickness plate.

The reason for placing the PCB and other electronics at the top of the box was actually practicality for us: the electrical engineers needed to be able to access the PCB up to the last minute, after every other part of the physical structure had already been assembled (including the charging box).

The remainder of the box was divided into two shelves for easier storage of smart phones. After some basic market research (see Figure 28), we settled upon dimensions of minimum 3.5” by 6” in order to fit the largest readily available smart phone we found, the Motorola Droid:

![Figure 29: Smart Phone Dimension Comparison](image)

Later in the design process, however, we discovered that the electrical engineers needed more space for their PCB, which turned out to be larger than they had anticipated. In order to accommodate the PCB and still leave room for the USB port locations, which were to be located on the same surface as the PCB, we enlarged the inside box dimensions to 7” by 7” (some extra space was built in case the electrical engineers enlarged their build again). The electronics portion was slightly smaller at 7” by 5.75”, sacrificing some floor room at the front in order to leave room outside the electronics compartment for the potentiometer control knob, LCD backlight button, and three-position switch (as can be seen, the LCD fit flush with the face plate and needed no extra clearance):
Venting was built into the box in order to maintain a survivable temperature for both the cell phones and the PCB. While optimizing air flow through the compartments, our weather proof design was maintained by folding the edges of the steel roof over the vents, leaving a sufficient gap for air flow while protecting the openings from rain:
In order to meet the requirement for a “securable” charging location, we designed a lock point for the door. This consisted of simply taking a piece of 14-gauge steel sheet and designing a hole-punched tab to fit through a matching milled slot in the charging box door. We conducted some basic research on lock shank sizes (by visiting the hardware store) and settled upon a clearance hole for a 3/8” shank, which was the largest size commonly available:

![Figure 32: Locking Point with 3/16” Lock](image)

The full design was modeled in CAD prior to manufacture in order to test strength and thermodynamics:

![Figure 33: Charging Box CAD Design](image)
6.2.4 Implementation

In application, polycarbonate was considerably more complicated to work with than previously anticipated. Because it could not be shaped using sheet metal techniques, we were forced to use screw connectors and drill and tap every hole (We briefly considered building a non-disassemble-able part, but dismissed the idea due to packing issues in the parts shipping). In order to provide a safety factor for human build error, we went from \( \frac{1}{4} \)” up to \( \frac{1}{2} \)” thick plate, which was considerably more expensive at twice the price.

Tolerances had to be extremely tight, up to one sixteenth of an inch, in order for the pieces to come together correctly. As a result, all of the holes, both clearance and tapped, had to be done on a mill using programming to maintain close tolerance. Additionally, the table saw was used repeatedly to shave down the edges of some of the more generous measurements.

After the charging box had been built the electrical engineers discovered that they needed more PCB place. Initially, they planned on added a second layer vertically with the first, but in attempting to do so, it was found that the second layer interfered with the placement of the LCD. Fortunately, extra space had been built into the electrical housing floor place for just this instance, and the second PCB place was implemented behind the first:

![Figure 34: The Added Second PCB on the Electrical Floor Space](image)

As can be noted in the figure above, the final holes for the USB ports did not end up perfectly side-by-side. This was due to horizontal spacing issues. It was desired to move the ports as close to the front as possible for increased user-friendliness, but the location of the PCB (which was constrained to the front due to the fixed potentiometer), left for insufficient space to place both ports forward. Therefore, one port was moved further back about three inches (in order to avoid interfering with the USB attachments fixed to the PCB).

The final build of the charging box can be seen in 34:
6.3 LED Light Support

6.3.1 Requirements
1. The light must be protected enough to survive in an outdoor environment over long periods of time. This requires at minimum a housing to shield the bulb from rain and other precipitation.
2. The housing built must not cause the bulb to exceed its operating temperature capabilities. This is especially significant in the case of a sealed unit.
3. The light fixture must be a minimum of ten feet above the ground, but not more than eighteen.

6.3.2 Alternatives
Finding a light housing on the market to fit the purchased LED bulb and its use in the project proved more difficult than anticipated. To circumvent the issue, the team decided to build a bulb housing in the Calvin College metal shop that would meet the system requirements.

The two materials available in the shop were steel and aluminum. These two are weatherproof and could be shaped/machined to meet desired dimensions and profile. Steel and aluminum are both metal and hence meet strength requirements for the light bulb housing. However, it is important to note that aluminum has a higher strength to weight ratio than steel. Furthermore, aluminum resists corrosion better than steel does. Though, these two options could be suitable the team was leaning more towards using aluminum metal sheet to make the bulb housing.
6.3.1 Decision

Table 29: LED Housing Decision Matrix

<table>
<thead>
<tr>
<th>Criteria (score)</th>
<th>Steel</th>
<th>Aluminum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ductility (15)</td>
<td>10</td>
<td>14</td>
</tr>
<tr>
<td>Strength-to-Weight Ratio (10)</td>
<td>6</td>
<td>9</td>
</tr>
<tr>
<td>Weatherproof (10)</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>Corrosion (30)</td>
<td>22</td>
<td>28</td>
</tr>
<tr>
<td>Total Score (65)</td>
<td>47</td>
<td>60</td>
</tr>
</tbody>
</table>

It is apparent from the above table that aluminum is the preferable material for the design and manufacture of the bulb housing. Ductility was weighed relatively heavily because the material chosen would have to be bent/rolled into a conical shape to house the bulb. Hence, the more ductile the material the easier the bending process will be. Furthermore, corrosion was a huge factor considered because unlike the other steel components in the system, the steel freely available to be used was not substantially coated to fight corrosion. In this light, considering that the bulb housing will be exposed to rain, resistance to corrosion will be necessary to ensure the longevity of the system structure.

6.3.2 Implementation

The LED bulb housing is first design in CAD to meet required dimensions of the bulb. Next, the design is converted into sheet metal in the software which permits the cutting and opening up of the design into a flat pattern. Dimensions on the flat pattern provide the information needed for the cutting and bulb housing profiling on the sheet metal. Once the required profile is cut out of the sheet metal, it has to be bent/rolled into the required conical shape. 1/8” rivets are then used to hold the intact. Finally, the cone is riveted to the housing of the bulb socket.

![Figure 36: Dimensioned Flat Pattern of Light Enclosure](image)
6.4 Battery Compartments

6.4.1 Requirements

1. The ambient operating environment will be between 0 and 130 degrees Fahrenheit; all components must be able to operate within these parameters. Higher tolerances may be necessary for components inside closed compartments (the pole, lockbox, or battery compartment).
2. Must be weatherproof.
3. Must be lockable for security of batteries.
4. Must be mechanically strong enough to sustain weight of the batteries.

6.4.2 Alternatives

The team decided to use AGM batteries for the system. This meant rareness of battery maintenance and maximum safety because the battery never leaks and hardly releases any poisonous gases when functioning. In this light, the battery compartment could be fully enclosed, locked, and positioned at the upper section of the pole since accessibility of the compartment was not a priority. Considering that the deciding factor on the battery compartment was the fact that it was weatherproof, the team decided to find and purchase an industrial grade box. The compartment had to be strong enough to carry the weight of the AGM batteries and if possible, lockable. Fortunately, battery compartments that met the system criteria
were readily available on the market but the team was faced with choosing between two materials. The compartments were available in steel and PVC.

6.4.2.1 Steel
This is no doubt the stronger of the options but it pays the price in weight. Considering that the batteries are located at the upper section of the pole, less weight is desirable to avoid load on the pole that could lead to buckling. Next, steel is conductive and could hence make maintenance of ambient temperature around the AGM battery difficult. Furthermore, steel is relatively susceptible to corrosion when exposed to moisture. With the guarantee that the battery boxes will be exposed to rain, moisture around the battery boxes is inevitable.

On the bright side, the strength of the steel box highlights the compartment as desirable to avoid theft. In addition to the strength, the steel compartment is lockable and completely weather proof. In the long run of the system, the box compartment will be exposed to cycles of hot and cool temperatures. This means the battery compartment is bound to go through cycles of expansion and contraction. Steel as a material has good resistivity to alteration of its properties due to temperature cycles. Finally, the steel box can be easily machined to meet system specifications without destroying it in any way.

6.4.2.2 PVC
Considering the desirability of less weight hanging on the upper section of the pole, the relative lightness of PVC compared to steel cannot be overlooked. Also, the cheapness of the PVC option is a plus when taking the project budget into account. The available PVC battery compartments also come with functional lock systems to ensure security of whatever is kept inside.

The downside to using a PVC battery compartment is the low longevity of the box. PVC as a material does not fare well with cycling of hot and cool temperatures over time. The plastic eventually becomes brittle and easily cracks. With longevity of the system being one of the criteria assessed by HCJB, this was a major flaw the team had to look into.

6.4.3 Decision

<table>
<thead>
<tr>
<th>Criteria (score)</th>
<th>Steel</th>
<th>PVC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strength-to-weight (15)</td>
<td>14</td>
<td>12</td>
</tr>
<tr>
<td>Longevity (30)</td>
<td>28</td>
<td>18</td>
</tr>
<tr>
<td>Weatherproof (15)</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>Corrosion (15)</td>
<td>10</td>
<td>14</td>
</tr>
<tr>
<td>Price (10)</td>
<td>8</td>
<td>9</td>
</tr>
<tr>
<td>Total Score (85)</td>
<td>75</td>
<td>68</td>
</tr>
</tbody>
</table>

It is evident from the above table that the steel box is the better of the two options mainly because it does substantially better than PVC in the longevity category. The team decided to weigh longevity so heavily not only because it was one of the system criteria provided by the customer, but also because it meant minimizing maintenance of this fairly complicated system. On the other hand, price was not weighed heavily mainly because though the PVC compartments are cheaper than the steel, the cost difference was negligible. Corrosion is a factor that could affect the longevity of the steel box but fortunately, with industrial grade outdoor steel boxes, surface coating is applied to fight corrosion. With this, corrosion was not to be greatly feared for both cases. Finally, both materials are strong enough to sustain the weight of
the batteries used in the system but looking into the chemical bonding properties of metals and plastics, steel has stronger bonds than PVC and hence could be considered to be superior in that sense. Furthermore, though the steel was heavier than the PVC, the weight difference between the options had no effect on the structural integrity of the whole system because the difference was relatively small.

6.4.4 Implementation

Once the coated steel battery boxes were acquired some machining had to be done to ensure it suits the systems. Firstly, the box opening through which the batteries are to be inserted was not big enough for easy insertion of the LED battery. This meant the sides of the opening had to be grinded just enough to permit easy movement of battery in and out. Next, wiring had to travel from the battery to the controllers and other electrical components. To achieve this, a ½ inch hole was drilled at the top of the battery boxes to match the holes drilled in the bottom of the junction box. Finally and most important was the venting of the battery boxes. Though the batteries could operate beyond the 130°F, the team decided it will be safest for the batteries to be maintained at ambient temperature. The meant creating airflow passages into the battery compartments. The team successfully milled strips off the bottom of the battery boxes to ensure the weather proof characteristic of the box is maintained.

The batteries were attached inside the compartments by two different means. For the smaller USB battery, aluminum strap was used. For the larger light battery, however, there was insufficient space to implement this build; therefore we designed a sheet metal tab for one side, which locked in place very securely.

![Designed Battery Compartment](image)
6.5 Junction Boxes

6.5.1 Requirements
1. The ambient operating environment will be between 0 and 130 degrees Fahrenheit; all components must be able to operate within these parameters. Higher tolerances may be necessary for components inside closed compartments (the pole, lockbox, or battery compartment).
2. Must be weatherproof.

6.5.2 Alternatives
The job of the junction box is to house wiring from the solar panel, controllers, batteries, and charging box. Clearly, with all this wiring, this component must be weatherproof to avoid electrical hazards. Once again, due to the importance of what this component is housing, the team opted to find an industrial grade weatherproof box instead of building one in house. The material options for the junction box are steel and PVC.

6.5.2.1 Steel
Though strength is not a required property for this system component, the superior strength of steel increases the safety factor of both this component and the system as a whole. Corrosion could however be the downfall of the steel junction box because the junction box would definitely be exposed to rain and other moist weather conditions. The junction box is also bound to experience cycling of hot and cold temperatures. This highlights cycled expansion and contraction of the junction which steel will fare well against. Next, considering that some custom work will have to be done to ensure the junction box suits the system, using a material that can be easily machined like steel is a bonus.

6.5.2.2 PVC
PVC is strong enough for the purpose of housing the wires and more impressive is the fact that it is relatively light compared to steel. Corrosion is not a problem to be battled when PVC is used. Hence, exposure to rain and other moist weather conditions is not a problem. Just like steel, PVC can be machined easily too to meet system requirements.

The downside of PVC that cannot be overlooked is how poorly it performs when exposed to cycling of hot and cold temperatures. It tends to become more brittle and could easily crack.
6.5.3 Decision

Table 31: Junction Box Decision Matrix

<table>
<thead>
<tr>
<th>Criteria (score)</th>
<th>Steel</th>
<th>PVC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strength-to-weight (10)</td>
<td>8</td>
<td>7</td>
</tr>
<tr>
<td>Longevity (30)</td>
<td>28</td>
<td>18</td>
</tr>
<tr>
<td>Weatherproof (15)</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>Corrosion (15)</td>
<td>10</td>
<td>14</td>
</tr>
<tr>
<td>Price (10)</td>
<td>8</td>
<td>9</td>
</tr>
<tr>
<td>Total Score (80)</td>
<td>69</td>
<td>63</td>
</tr>
</tbody>
</table>

As shown above, the steel junction box slightly edges the PVC as the better option. The major factors considered were the longevity and the extent to which the options are weatherproof. Both options being industrial grade and totally weatherproof, hence this factor was of no help in the selection process. Conversely, the longevity of two options proved to be the deciding factor. As discussed earlier, when PVC is exposed to cycles of hot and cold temperatures (sun and nighttime) it eventually becomes brittle and cracks whereas steel remains intact. Corrosion, specifically with steel was not a major issue because the industrial grade steel junction boxes are suitably coated to fight corrosion and permit outdoor use.

6.5.4 Implementation

Machining had to be done to steel junction boxes to ensure compatibility with the system. Firstly, a ½ inch hole had to be drilled at the bottom of the box to allow for movement of wire to and from the batteries. Next, screw holes had to be drilled on top of the box to allow for attachment of the terminal block holding numerous wires. Finally, holes were drilled at the back of the junction box to permit attachment of the junction boxes to the pole using screws.
Figure 41: Designed Junction Box

Figure 42: Actual Junction Boxes
7 Economics

7.1 Business Plan
There are two levels to the business side of our project. One is the production of the system by HCJB, and the other is the micro-business model that HCJB envisions for the use of the lamppost in the place where it is installed.

7.1.1 Production
The team has no say in production methods employed by HCJB but has rather been solely tasked with delivering an optimized design at the end of the project. In this light, the team does not have concrete marketing plans from the customer.

7.1.2 Local Micro-Business
The plan for the implementation of this lamppost in third-world countries involves the establishment of a small business around the lamppost. Once HCJB has set up the system, a local proprietor will take over the running of the lamppost. That proprietor will then have the sole responsibility for running, maintaining, and repairing the lamppost system. The proprietor will be able to charge money for people to charge their mobile devices at the lamppost. He or she may charge whatever rate seems appropriate. The duties of the proprietor will include watching over the system to prevent theft, as well as programming the distribution controller for how long the light shall stay on each night.

7.2 Cost Estimates

7.2.1 Operational Cost Estimate
Table 32 shows our original budget estimate, which gave us a total cost of approximately $800. We received a total budget of $1000, $500 from HCJB and $500 from Calvin, based on our request for funds.
### Table 32: Cost Estimate of Parts

<table>
<thead>
<tr>
<th>Component</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar Panel</td>
<td>$300</td>
</tr>
<tr>
<td>Batteries</td>
<td>$200</td>
</tr>
<tr>
<td>LEDs</td>
<td>$75</td>
</tr>
<tr>
<td>Steel Material</td>
<td>$75</td>
</tr>
<tr>
<td>Microcontroller</td>
<td>$30</td>
</tr>
<tr>
<td>USB cables</td>
<td>$30</td>
</tr>
<tr>
<td>Voltage Converters</td>
<td>$20</td>
</tr>
<tr>
<td>LCD Display</td>
<td>$15</td>
</tr>
<tr>
<td>Other Electronics</td>
<td>$100</td>
</tr>
<tr>
<td>Replacement Parts</td>
<td>$35</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>$780</strong></td>
</tr>
</tbody>
</table>

### 7.2.2 Productions Cost Estimate

Our team estimates that it will cost $1026.66 per unit to produce our product, as shown in Table 33 through Table 35. Table 33 is a cost manifest of electrical components and Table 34 of structural. The total cost of each unit includes manufacturing and shipping costs for the grand total per unit, as seen in Table 35.

### Table 33: Electrical Component Manifest

<table>
<thead>
<tr>
<th>Electrical Components</th>
<th>Quantity</th>
<th>Price</th>
<th>Total Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>USB Cable</td>
<td>2</td>
<td>$3.33</td>
<td>$6.66</td>
</tr>
<tr>
<td>Photoresistor</td>
<td>1</td>
<td>$1.51</td>
<td>$1.51</td>
</tr>
<tr>
<td>LCD Screen</td>
<td>1</td>
<td>$12.95</td>
<td>$12.95</td>
</tr>
<tr>
<td>Charge Controller</td>
<td>2</td>
<td>$44.85</td>
<td>$89.70</td>
</tr>
<tr>
<td>Temperature Sensor</td>
<td>2</td>
<td>$26.51</td>
<td>$53.02</td>
</tr>
<tr>
<td>AGM Battery to LED</td>
<td>1</td>
<td>$50.39</td>
<td>$50.39</td>
</tr>
<tr>
<td>50 Watt Solar Panel</td>
<td>1</td>
<td>$138.95</td>
<td>$138.95</td>
</tr>
<tr>
<td>LED Light Bulb</td>
<td>1</td>
<td>$32.76</td>
<td>$32.76</td>
</tr>
<tr>
<td>DC/DC Converter</td>
<td>3</td>
<td>$9.57</td>
<td>$28.71</td>
</tr>
<tr>
<td>DC/DC Converter</td>
<td>1</td>
<td>$13.70</td>
<td>$13.70</td>
</tr>
<tr>
<td>USB Charging Controller</td>
<td>2</td>
<td>$2.58</td>
<td>$5.16</td>
</tr>
<tr>
<td>AGM Battery to USB</td>
<td>1</td>
<td>$35.99</td>
<td>$35.99</td>
</tr>
<tr>
<td>Knob</td>
<td>1</td>
<td>$0.50</td>
<td>$0.50</td>
</tr>
<tr>
<td>Button</td>
<td>1</td>
<td>$3.69</td>
<td>$3.69</td>
</tr>
<tr>
<td>Potentiometer</td>
<td>1</td>
<td>$0.99</td>
<td>$0.99</td>
</tr>
</tbody>
</table>
### Table 34: Physical Component Manifest

<table>
<thead>
<tr>
<th>Structural Components</th>
<th>Quantity</th>
<th>Price</th>
<th>Total Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>Schedule 40 pipe, 25'</td>
<td>1</td>
<td>$0.00</td>
<td>$0.00</td>
</tr>
<tr>
<td>1&quot; pipe, 12&quot;</td>
<td>1</td>
<td>$1.25</td>
<td>$1.25</td>
</tr>
<tr>
<td>Light Port w/Junction Case</td>
<td>1</td>
<td>$3.29</td>
<td>$3.29</td>
</tr>
<tr>
<td>Battery Compartments</td>
<td>2</td>
<td>$28.09</td>
<td>$56.17</td>
</tr>
<tr>
<td>Junction Boxes</td>
<td>2</td>
<td>$7.16</td>
<td>$14.32</td>
</tr>
<tr>
<td>Junction Box Face Plate</td>
<td>1</td>
<td>$1.04</td>
<td>$1.04</td>
</tr>
<tr>
<td>Modified Face Plate</td>
<td>1</td>
<td>$3.24</td>
<td>$3.24</td>
</tr>
<tr>
<td>Angle Iron, 3'</td>
<td>1</td>
<td>$3.75</td>
<td>$3.75</td>
</tr>
<tr>
<td>Steel Bar, 35&quot;</td>
<td>1</td>
<td>$4.30</td>
<td>$4.30</td>
</tr>
<tr>
<td>Pipe Cap</td>
<td>2</td>
<td>$3.67</td>
<td>$7.34</td>
</tr>
<tr>
<td>Pipe T-Junction</td>
<td>1</td>
<td>$7.75</td>
<td>$7.75</td>
</tr>
<tr>
<td>Concrete 80lb Mix</td>
<td>5</td>
<td>$3.65</td>
<td>$18.25</td>
</tr>
<tr>
<td>1/2&quot; Polycarbonate, 12&quot; by 36&quot;</td>
<td>1</td>
<td>$63.28</td>
<td>$63.28</td>
</tr>
<tr>
<td>Terminal Port</td>
<td>1</td>
<td>$13.30</td>
<td>$13.30</td>
</tr>
<tr>
<td>Screw Fasteners and Nuts</td>
<td></td>
<td></td>
<td>$20.00</td>
</tr>
<tr>
<td>Other</td>
<td></td>
<td></td>
<td>$10.00</td>
</tr>
<tr>
<td>TOTAL</td>
<td></td>
<td></td>
<td><strong>$227.28</strong></td>
</tr>
</tbody>
</table>

### Table 35: Total Costs for One Unit

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SUBTOTAL</strong></td>
<td><strong>$751.66</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Manufacturing Costs</td>
<td>$200.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shipping</td>
<td>$75.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>GRAND TOTAL</strong></td>
<td><strong>$1,026.66</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
This pricing is representative of the total costs to produce and deliver exactly one lamppost built to the specifications outlined in this report. In practicality, the actual costs per unit, if it were mass produced, would actually be much lower due to bulk purchasing, batch manufacture for cheaper labor costs, and more efficient shipping per unit. However, as we have no numbers on any scale for the possible production of this product, any calculations we made would be mere speculation.

It is also possible that additional fees might be incurred due to customs taxes in the countries HJCB might be flying these lamppost components into. Our consultant, however, did not mention any of these costs of business. As they are experienced in this method of shipping, having used it with previous projects, we will leave this concern to them.

7.2.3 Payback Time

When HCJB Global first outlined the project to us, they quoted a price of $40/kW*hr as the rate for current electricity sales off of gas generators in the location of interest. These high electrical rates were much of the rationale behind building in cell phone charging. HCJB had in mind establishing one of our lamp-posts with a proprietor who could market cell phone charging as a business. With this setup and the assumptions outlined in Table 36 (six hours of cell phone charging on each USB port), we compiled a graph describing the payback period, seen in Figure 43:

<table>
<thead>
<tr>
<th>Table 36: Electrical Usage Assumptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost Electric</td>
</tr>
<tr>
<td>Energy usage</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>

Payback Time if Selling Power at Market Rate ($40/kW-hr)

Figure 43: Business Return on Investment
As seen in the graph, the break-even time is about 2.3 years, after which point the proprietor would begin to produce net positive revenue at a rate of about $450 a year if selling at the market price. It is not assumed that the proprietor must sell at these high profits to maintain this business plan; a lower selling point would encourage higher demand, for which there is room for expansion from the assumption of six hours. The increase in demand would help to balance out the diminishment of pricing.

If all of the electricity costs are taken into consideration, the return on investment is much steeper. Assuming a run time of just five hours per night for the light as seen in Table 37, the ROI for the light alone or both charging and light combined would be something like this:

<table>
<thead>
<tr>
<th>Table 37: Lamppost ROI</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Year</strong></td>
</tr>
<tr>
<td><strong>Upfront Cost</strong></td>
</tr>
<tr>
<td><strong>Yearly Balance</strong></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td><strong>Break-Even Time</strong></td>
</tr>
</tbody>
</table>

As can be seen, the ROI for both together has a break-even time of about 1.0 year; this is the amount of time at which the solar power at the price you could have paid locally has paid for the full cost of the lamppost.
This revenue may be limited, of course, by the cost of replacement components. Although we designed our system very robust, with the intention of decades of survival, two components will need replacement around the four year mark: the AGM batteries. These batteries naturally age due to cycling and must be replaced. The replacement costs for a set of new AGM batteries, one for the charging and one for lighting, may be seen in Table 38:

<table>
<thead>
<tr>
<th></th>
<th>New AGM charging battery</th>
<th>$35.99</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>New AGM lighting battery</td>
<td>$50.39</td>
</tr>
<tr>
<td>Total Cost for Replacements</td>
<td></td>
<td>$86.38</td>
</tr>
</tbody>
</table>

By factoring this periodic maintenance cost, occurring every four years, into the economic tables, we can get a more accurate view of the lamppost ROI:

![Payback Time with Maintenance Factored in](image)

As it turns out, there is almost no effect on the inflow of revenue over a long period of time, the cost of the replacement batteries comprising an almost trivial amount. The lamppost should provide a four or five to one ROI prior to major maintenance barring unforeseen major damage. It ought also to be noted that the periodic cost of the batteries has no effect on the payback time, as the batteries will first need to be replaced well after the break-even point.
8 System Integration

8.1 Attaching the Brackets

Step one is attaching the angle iron brackets (see in Figure 46) to the pole:

There are three brackets to attach: two 10.75” ones for the battery compartments and junction boxes located opposite each other on the pole, and one 12” piece for attachment of the charging box. In order to match each the identical 10.75” brackets to the correct side of the pole, numbers have been punched into both bracket and corresponding location on the pole:

Figure 46: Pole and Brackets

Match the bracket to the correct side of the pole and screw in using the supplied 10-24 ½” screws. Repeat for the opposite bracket and the charging box bracket:

Figure 47: Bracket Identification Numbers
Once the brackets are attached, four spacers need to be added. These spacers look like:

Figure 48: Attaching the Brackets

Take these spacers and attach them to the appropriate points on the two 10.75” brackets with the provided \( \frac{1}{4}” \)-20 countersunk screws (there are only two points at which they fit, both correct):

Figure 49: Battery Compartment Brackets
8.2 The Junction Boxes, Battery Compartments, and Solar Panel

The battery compartments can now be attached directly to the spacers with the ¼”-20 round-head screws; screw them on. There are two of these, one on each side; don’t forget to put the second one on:

The two junction boxes can also be attached using the 10-24 round head screws:
Once finished with the junction boxes, grab the pipe joints: two caps, a t-joint, and two short 8” pieces of threaded pipe. Thread them together as seen to form a cross-brace:

Next, thread the T-joint on the cross-brace to the top of the pole.

Step back from the pole assembly for a bit. Take the solar panel and flip it upside down in front of you. There are side bolt attachments on the underside. You will be using the outermost four. Attach the bars supplied with the panel to each side with the 3/8”-16 bolt and nut also supplied:
The crossbars just attached to the solar panel can be clamped to the pipe cross-brace at any angle desired to obtain the ideal sunlight collection. Determine your desired angle and attach accordingly:

Figure 54: Attaching the Cross-bars to the Solar Panel

Figure 55: Clamping Solar Panel Crossbars to Pipe Cross-Brace
8.3 Wiring the Solar Controller

The wiring diagram for the Solar Controller is shown below.

The battery positive lead should be fused no further than 12 inches (305 mm) from the battery. An 8 A fuse should be connected between the red cable from the charging controller and the battery using an in-line fuse holder.
8.4 The Faceplate
To mount the LCD, take the 2” by 7” faceplate and flush-fit the display into the slot built for it. Four 4-40 screws are provided for attachment. The three position switch and backlight pushbutton are both attached using a 9/16” wrench:

Position the faceplate next to the potentiometer on the green PCB so that the potentiometer rod penetrates the remaining center hole. Attach the knob to the end of the potentiometer rod using the small screw located on the side:

Figure 57: Attaching the Pushbutton and Switch to the Faceplate

Figure 58: Attaching the Potentiometer Knob
The completed faceplate should look like this:

![Completed Faceplate](image)

**Figure 59: Completed Faceplate**

### 8.5 Mounting the PCB
The PCB is mounted to its floorplate prior to assembling the Charging Box. To begin, take the 6.5” by 7” plate and screwing the green PCB with attached faceplate to it as shown using the metric M3-16 screws:

![Attaching the PCB](image)

**Figure 60: Attaching the PCB**

Continue by attaching the yellow PCB behind the green one using the supplied ¼”-20 screws:
Figure 61: Attaching the Secondary PCB

The completed PCB attachment should look like this:

Figure 62: The PCB and LCD attached to the Floor plate
8.6 The Charging Box

Figure 63: Attach Back of Charging Box to Angle Iron

Use 10-24 3/4” screws to attach the back of the phone-charging box to the angle iron screwed onto the pole. A total of 8 screws are required for this job.
Figure 64: Get all Charging Box pieces together

To aid with assembly of this component it is advisable to arrange all pieces in a singular location.

Figure 65: Attach side of Charging Box
Next, one side of the compartment must be attached to corresponding layers. To attach the side to the layers of the box, use 10-24 1” screws. Ensure that the vented section of the box side is set beside the electrical components level. For the faceplate of the user interface level, use 6-32 screws to attach it to the compartment side.

![Figure 66: Attach door lock accessory](image)

Use 10-24 ½” screws to attach the door lock tab to the other side of the charging box.
Now, the other side of the box can be screwed onto the preassembled layers of the charging box. Once again, 10-24 1” screws are required for this job. Also, ensure the vents are located at the electrical components layer. For the faceplate of the user interface level, use 6-32 screws to attach it to the compartment side.
Figure 68: Screw door hinges to door

The door hinges can now be attached to the door. Use 10-24 ½” screws for this task.

Figure 69: Screw door hinges to box

Next, assemble the door to the charging box through the hinges using the same screws (10-24 ½”)
Now the sub assembled components of the phone charging box can be attached to the back of the charging box that was previously attached to the angle iron on the pole. Use 6 10-24 1” screws to attach the three layers of the phone charging box to the back of the box.
Finally, to attach the roof to the phone charging box, 10-24 ½” screws are required. Locate the 6-screw hole, align them with screw hole on the charging box, then insert screws.

8.7 Connecting the Printed Circuit Board
The connections to the PCB are labeled on the board. They should match the picture shown in Figure 72. The cable from the positive battery terminal should be connected to a 1A inline fuse before connecting to the PCB terminal.

The button, LCD, switch, and knob on the front of the PCB should be connected to the faceplate as shown in Error! Reference source not found..
Figure 72: Connecting the LCD and power to the PCB
9 Conclusion

Team Independent has successfully designed, built, and tested a prototype of a solar-powered lamppost with USB charging. The prototype uses a 20 W polycrystalline solar panel, two Morningstar SunKeeper charging controllers, two AGM batteries, an Arduino power distribution controller, four DC/DC converters, and a 7 W LED light bulb as the light source. The team has modeled and tested all of the major components of the system, and the prototype has successfully met all of the requirements of the system.
10 Sources

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