“Off Grid Solar Powered Street Light”

A Senior Project

presented to

the Faculty of the Electrical Engineering Department

California Polytechnic State University, San Luis Obispo

In Partial Fulfillment

of the Requirements for the Degree

Bachelor of Science

by:

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June, 2013

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Acknowledgements

We would like to express our deepest gratitude for the support from our parents and the faculty of the electrical engineering department. Without our parents as our financial pillars, the knowledge and experience we gained from Cal Poly would not have been possible. We would like to thank our senior project advisor, Dr. Vladimir Prodanov for taking the time to oversee our project and share his experience and insight with us.

We would also like to thank Dr. Taufik for introducing us to the world of power electronics and its benefits for efficiency and power delivery. Without the support and help of our colleagues, this project would not have been possible. The knowledge and exposure to solar powered energy was invaluable.

ABSTRACT

Street lights are fixtures found in every city and serve the important purpose of illuminating the streets and keeping the roads safe for pedestrians and drivers. Current street lights are powered by the grid, power which is paid for by the taxpayers and could have been used to power homes instead. With this project, our goal is to design and implement an electric power system that collects and stores solar energy, and delivers power to an LED smart street light. The resulting system would reduce street light energy costs by 100% since they would not draw any power from the grid, and would be self-contained and self-sustaining.

I. Introduction & Background

Street lights have provided a bright path for cars and pedestrians on the road to travel. Most street lights contain compact fluorescent lamps (CFL) or incandescent lamps, which prove to be inefficient in use of power and output of lighting compared to light emitting diodes (LEDs). Inefficiency brings upon many problems such as increased operational costs and decreases in reliability. CFLs and incandescent lamps are limited in output of lumens and cannot handle constant switching between on and off states which shortens the life cycle of these bulbs. CFLs also contain mercury, which is a toxic substance.

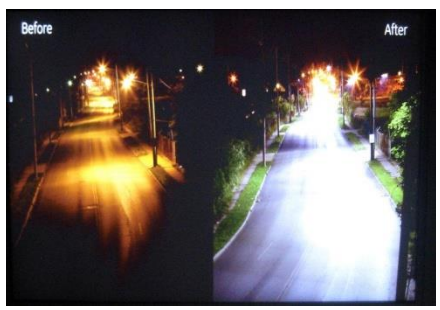

Figure 1. The lumen output difference between CFL and LEDs [1]

LEDs are a solution and introduce better efficiency, providing a cooler lumen color output, and also have a longer lifespan even with cycling. Yet, to simply switch out the CFLs and incandescent lamps out for LEDs will be costly and only provide a small improvement for the city.

The city would wait for the old CFLs and incandescent lamps to burn out before replacement. By waiting, it would be a slow weaning process to change to LEDs and defeat the purpose of improving the lighting system. Each fixture will be upgraded to be compatible to LEDs and this will be an inefficient process that will cost the city more money.

The contents of this project will provide a complete system that will prove to solve all the issues with the current street light status quo and also provide cities with a major upgrade per cost. The system will provide a self-sufficient street lamp lumen system that will allow cities to take streetlights off the power grid. The system itself is seen in Figure 2 and will contain four major components, a solar panel, battery, charging circuit, and a LED driver. The solar panel will charge the battery during daytime. As night falls, the system will not activate the LEDs until it senses an object, mainly a car or pedestrian, under its lumen system. The LEDs would track the object and only those LEDs that will provide the maximum range of lumen output will be turned on to efficiently use the power from the battery.

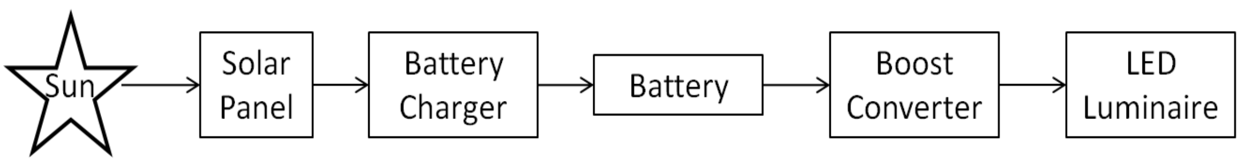

Figure 2. Block Diagram of Complete System

The LED luminaire is already built and can be seen in Figure 3, this project will focus mainly on the circuitry and components before the LED luminaire. Using knowledge of electronic circuits and power electronics, to build an efficient, self-sufficient street light system to be paired with the LED array.

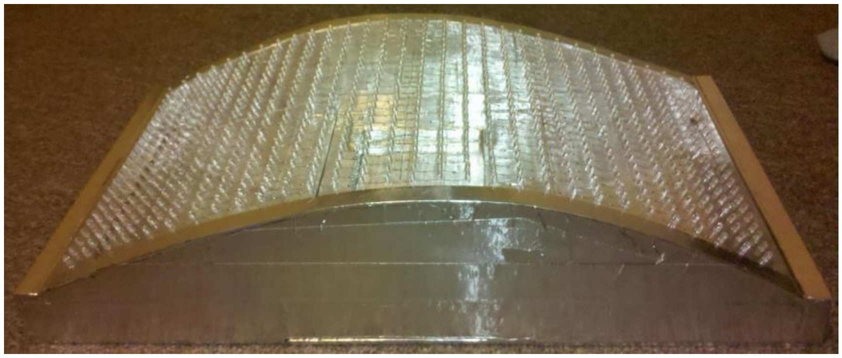

Figure 3. Completed LED array for LED Luminaire

By ensuring the battery is big enough to provide enough power to the lumens if they were to be on the entire night, the battery will be heavy and large in size. Therefore, the battery will need to be at the base of the street light. By placing it at the base, it would be safer to have it under the cement blocks and in a casing that will prevent further damage. Since the battery would likely be placed in an enclosure, a sealed lead acid battery is considered due to the reduced ventilation requirements needed as opposed to a non-sealed flooded lead acid battery. The solar panel will be mounted on top or behind the LED array to prevent shading which negatively affects the performance of solar panels, while also providing the best angle depending on location to receive the most sunlight and charge the battery quickly.

With self-sufficient street lights that will provide better efficiency, lighting, and a longer lifespan, the city will obtain a reasonable upgrade that will save them money in the long run. There is little to no maintenance needed for the street light system, only periodic cleaning of the solar panel and lens on the LED array and changing of the battery.

II. Requirements and Specifications

For this project, several requirements must be taken into account, as shown in Table I. The size and weight requirements are more for safety and cost, as the whole system is to be mounted on a light pole, and having a heavy system would be difficult and even dangerous to mount. The system budget was set by the funding provided by the Electrical Engineering department, and is also in place to try to keep the system as affordable as possible so that its use can be more widespread and used by more people.

Table I. Project requirements/specifications

Requirement	**Justification**
System will not require any external power sources aside from the PV electronics	The system is to be self-sustaining and powered only by sunlight
System must not be excessively heavy or large	System is to be mounted at street light height, so special considerations must be made.
System will cost at most $500	System must be kept affordable if it is to be used widely in cities.
System will be able to operate for two days without sunlight	System must take into account rainy days, or days that sunlight is not present

Table II. Charger Circuit requirements

Requirement	**Justification**
Charger Circuit will accept a wide range of voltage at the input	Charger Circuit has a PV at the input which will vary the amount of voltage and current input depending on exposure to solar radiation
Charger Circuit will regulate CV/CC	Charger Circuit must maintain a battery with a sufficient state of charge

Table III. Boost Converter Requirements

Requirement	**Justification**
Circuit will have an efficiency of at least 80%	Unnecessary losses will simply waste energy that could be powering the luminaire
Circuit will have a line regulation of at least 2%	Output voltage of the circuit should remain fairly constant to ensure LED brightness is constant regardless of battery voltage
Circuit will have a load regulation of at least 2%	Output voltage should remain constant regardless of the number of LED arrays powered on

III. DESIGN

The high level system block diagram can be seen in Figure 4. The system is built to power the LED Luminaire designed and constructed by Quanghuy Le[2]. For example, the battery was chosen to be 40Ah capacity since it can power the luminaire for 2 days without sunlight, which is a consideration made because during operation there may be some days with less than ideal sunlight, or little to none.

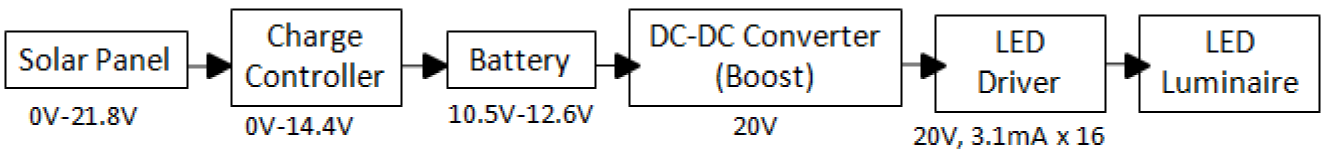

Figure 4. System Block Diagram with Approximate Output Voltages Labeled

3.1 LUMINAIRE BACKGROUND:

Since the luminaire has already been constructed and is the base for this project, the design process for the power system begins with the luminaire itself. The LED luminaire has 10 sections, each with 12 strings of 6 LEDs, each string having a current limiting resistor. With 10 sections and each section with multiple strings of LEDs, it is more efficient and protects from an entire section of LEDs from becoming inoperable if a single LED burns out. LEDs were chosen for the main source of lumen output since LEDs consume less power and have a longer lifespan than traditional incandescent.

The forward voltage of each LED is about 3 V, and since 6 LEDs are in series with each other, a source voltage of about 20 V is needed to ensure each LED receives an adequate voltage to properly function. A current limiting resistor is in series with each string of LEDs, and in each section of the luminaire there are 12 strings of 6 LEDs connected in parallel. The 12 strings make up

a single section of the luminaire total of 10 sections which was done so that each section could be independently controlled. The labeled picture in Figure 5 displays the separate sections. Each half of the luminaire (5 LED array sections) was measured to require at least 1.55 A of current for proper operation. These requirements will be taken into account with the design of the other system components.

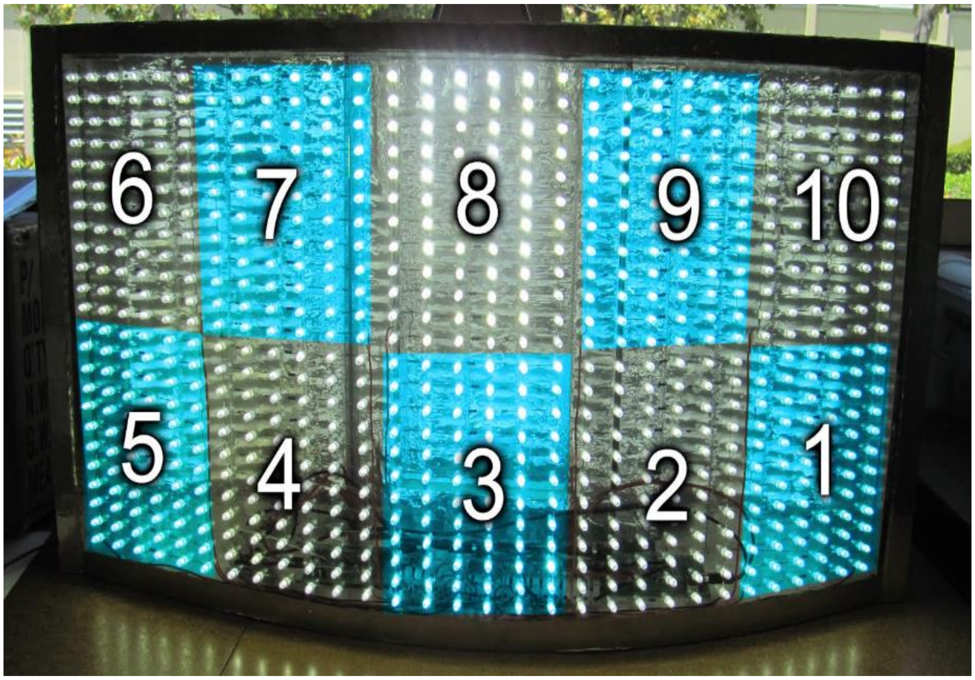

Figure 5. LED Luminaire with 10 Sections

3.2 BATTERY SELECTION:

The battery serves as the direct source of power for the LED luminaire. The energy storage function is especially important since the luminaire will be running at night, and the battery will be the sole source of energy to power it since the solar panel will be unable to provide power. A battery with a capacity rating of 40 amp hours was selected, which means the battery could theoretically provide 1 amp of current for 40 hours, or 5 amps of current for 8 hours and so on. A capacity of 40 amp hours was selected as it is desired to have the system be functional for at least 2

days without sunlight to account for cloudy days, without over discharging and damaging the battery.

The PowerSonic PS-12400 sealed lead acid battery was chosen as it does not require regular maintenance, can be mounted at any angle without battery acid leaking, and for the reduced ventilation requirements. The latter is important if the battery is mounted into an enclosure to protect it from the environment. The battery's physical dimensions can be seen in Figure 6 and it is rather compact for a 40Ah battery, but the weight is the on the heavy side of 29.10 lbs. [3]

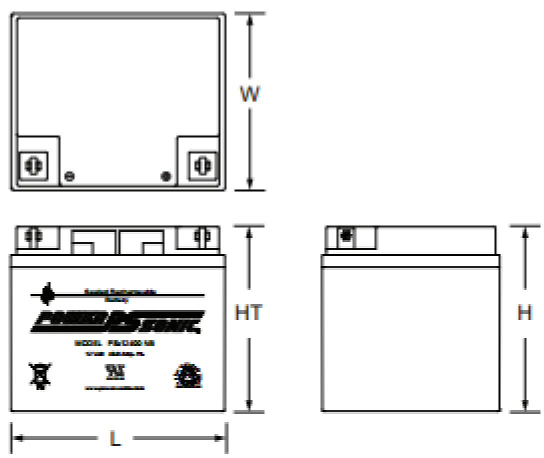

Figure 6. Battery Dimensions (L: 7.76in. W: 6.5in. HT: 6.69in.)

3.3 SOLAR PANEL SELECTION:

With the battery selected, the next step is to select a solar panel that can provide an adequate amount of energy to charge the battery in a reasonable amount of time. The solar panel provides the main method of generating electrical power by collecting solar radiation and converting it into direct current electricity, a method known as photovoltaics. For this system, the 40W 12V Crystalline PV module was selected because of its power output and physical dimensions as seen in Figure 7. Without a load, both open circuit voltage and short circuit current was

measured to be 17.2V and 2.35A respectively. The solar panel is the largest component of the system with the following dimensions: 20" x 26" 1.4" (W x H x D) and weighs about 13 Lbs [4]. A 40W solar panel was chosen to have the ability for a max charge rate of 2A, but in this system a charge rate of 1A was chosen so the solar panel did not have to operate near max ratings. Yet, 1A charge rate was more than enough to charge a 40 amp hour battery. Power consumption calculations have been made for the LED luminaire, and a requirement of about 200W-hr are required from the panel during the day, and the 40W solar panel meets this requirement[2]. Depending on sunlight conditions, the selected 40W solar panel can output anywhere between 0A to 2.35A[4]. Due to this variability, a charge controller is required to effectively protect and charge the battery.

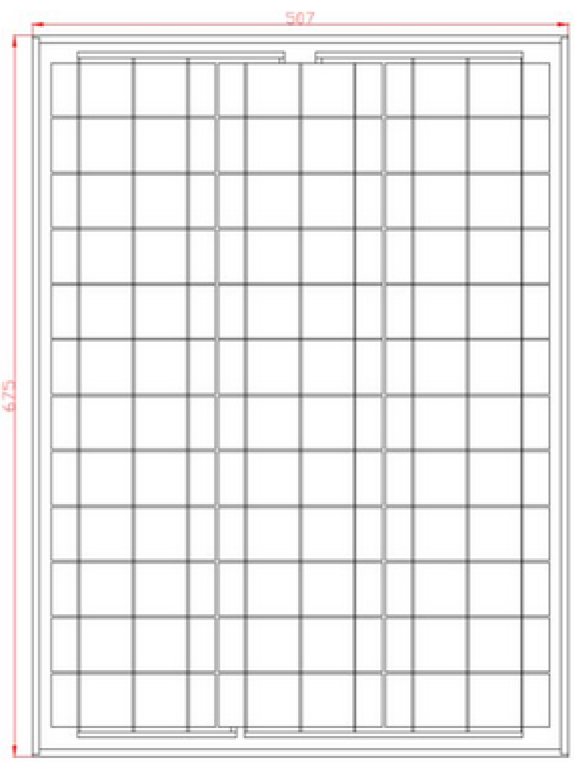

Figure 7. CDT Solar CDT-40w Panel Top View

3.4 Battery Charge Controller Design:

A battery charge controller is needed to ensure that the battery maintains a sufficient state of charge to be able to provide enough power to the luminaire for the entire night. We chose to use Linear Technology's LT3652 integrated chip which allows for maximum power point tracking (MPPT) technology to sample the output of the solar cells and ensure a linear output efficiency regardless of environmental conditions. The charge circuit will accept a large range of input voltage, 5V-32Vdc from the solar panel and output 10V-14Vdc at 1A to the battery. The rate of current charge to the battery can easily be changed to a maximum charge rate of 2A by replacing the value of Rsense (R1) from the 0.1Ω to 0.05Ω calculated with the equation:

$$R_{sense} = V_{sense} / I_{charge(max)}. \rightarrow R_{sense} = 100mV / 2A = 0.05\Omega.$$

A NTC (Negative Temperature Coefficient) thermistor on pin 8 of the LT3652 was used to allow for a failsafe against a major rise in temperature to the circuit. Charging will only occur if the NTC pin 8 reads a voltage between 0.29V to 1.36V. A rise or decrease in temperature could cause the NTC pin to be outside of the voltage range and the charging circuit will shut down.

The Linear Technologies 3652 Power tracking 2A battery charger IC has been selected since this application is relatively low power. The chip has many useful features which can be used for our application, such as adjusting the charge current if the solar panel's output voltage drops below a certain level, which is useful for maintaining high efficiency. The chip can also monitor battery voltage and enter a fast-charge mode when the battery's voltage drops below a specified voltage, or enter a slower trickle charge mode for when the battery is almost completely charged [5].

In this system, the charger programming was done with a three resistor feedback network at the BAT and V_{FB} pins. With a battery float voltage of 13.5V, resistors R5, R7, and R8 were calculated using the following equations:

$R8 / R5 = 3.3 / (V_{BAT(FLT)} - 3.3)$

For $V_{BAT(FLT)} = 13.5V$

R8 / R5 = 3.3 / (13.5 - 3.3) = 0.32

With R8 = 100 kΩ

R5 = R8 / 0.38 = 100k / 0.32 = 312500 (Chose 309k)

The divider equivalent resistance is

R5 || R8 = 100k || 309k = 75k

To have 250k equivalent resistance to the V_{FB} pin

R7 = 250k - 75k = 175k (Chose 174k)

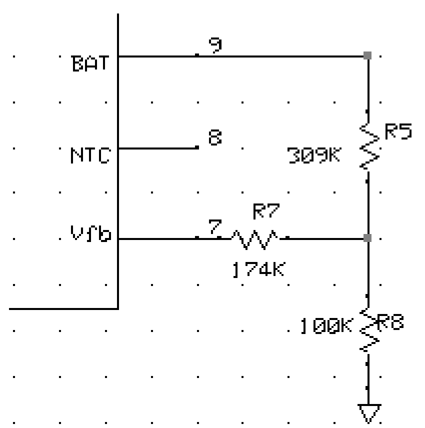

Figure 8. Three-Resistor Feedback Network

With the chosen resistors for the three resistor feedback network at the BAT and V_{FB} pins, the charger will be programmed to have a 3-stage charger, where it will fast charge at 1A with CC/CV up to 14.4V. Then, if charge current falls to 0.1A, charger will switch to 13.5V float charge mode. The Charger will return to 14.4V fast charge if battery voltage is below 13.2V and trickle

charge at 0.15A if battery voltage is below 10V. The LTspice simulated output current that shows a max charge of 1A can be seen in Figure 10.

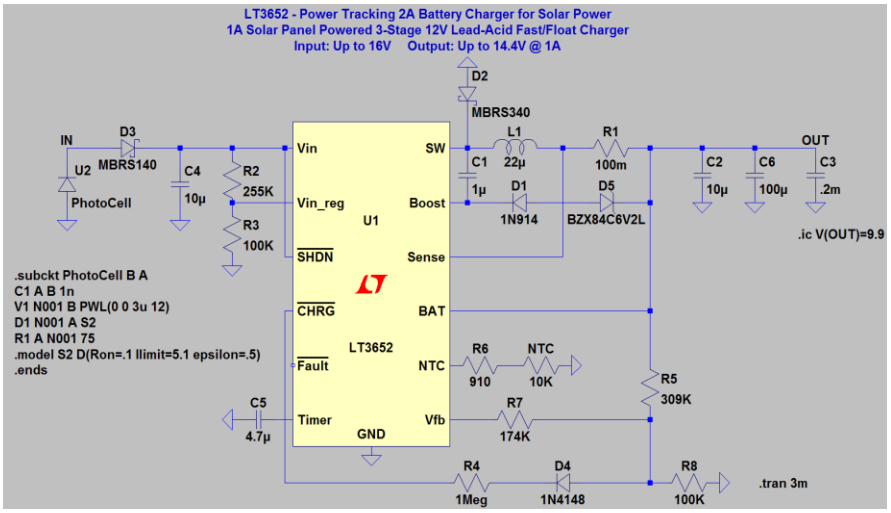

Figure 9. Schematic of Simulated Charger Controller Circuit

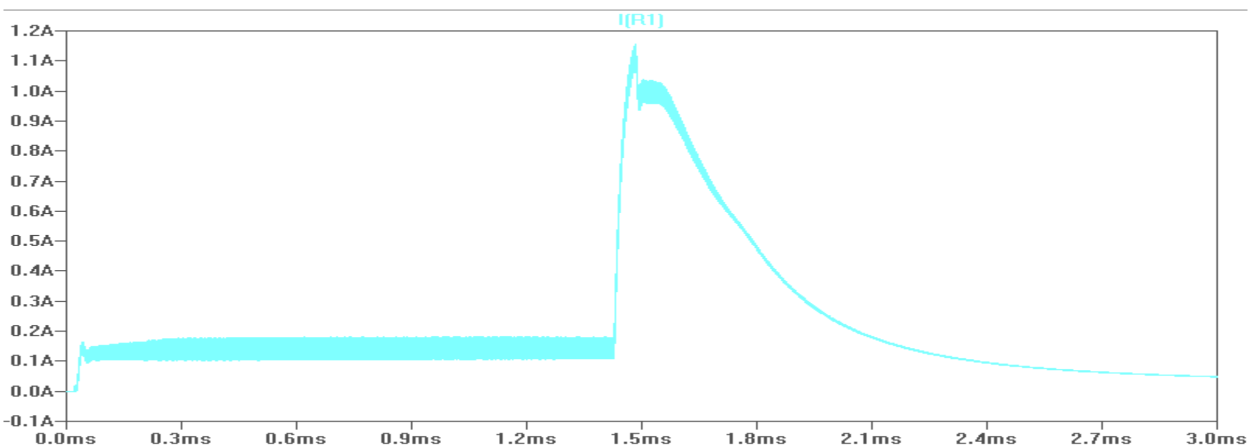

Figure 10. Simulated Charger Controller Output Current Waveform

3.5 Boost Converter Design:

The battery has a terminal voltage than can range from around 10V to 14V. However, the LED luminaire requires a constant 20V DC power source. If the LEDs were connected directly to the

battery terminals their brightness would decrease as the battery's stored charge decreases. To address this issue, a boost converter has been chosen to step up the battery's voltage to the 20V required for the LED luminaire.

One important design choice that has been made is that two separate boost converters are utilized as opposed to single converter to address possible reliability issues as well as to keep cost down. Each boost circuit controls half of the LED luminaire sections, so if in the event that one boost circuit breaks or malfunctions the luminaire would still be able to output light. Because the two boost circuits operate in parallel from one another, each circuit receives and outputs half the current than if a single circuit was used. As a result, costs were reduced as thinner wires and components with lower power ratings can be utilized. Also, there is less noise generated since the magnitude of current is reduced.

Taking these considerations into account, a pair LT3757 controller based boost converters have been chosen to power the luminaire, since the controller is able to receive a wide range of voltages and output the required 20V at 2A. Each boost converter is able to take in a voltage ranging from 8V to 16V, well beyond the range required for this application. The 2A current output is also sufficient to power half of the luminaire.

Boost converters are able to increase DC voltages by varying their duty cycle, or the amount of time their switch is on during the switching period. The transfer function for a boost circuit is as follows:

$$V_{out}/V_{in} = 1/(1-D)$$

As seen in the equation, if the output voltage is desired to be constant but the input voltage is variable, as is the case with the battery, the converter controller can compensate by altering the duty cycle. The LT3757 boost controller is able to monitor the output voltage via its

FBX pin which is presented in the integrated circuit (IC) pinout seen in Figure E-2. By altering the two resistors that form a voltage divider to keep the FBX pin in its correct operating range less than 6V, the output voltage can be programmed [6].

Vout = 1.6V*(1+R2/R1)

By using the above equation and selecting a resistance value of 200 kΩ for R2 to simplify calculations and part procurement, the necessary value for R1 is 17.4 kΩ. By using these values and simulating the circuit using Linear Technology's LTspice as seen in Figure 10, an output voltage of 20.013 V was achieved, which is adequate for the LED luminaire. The waveform for the output voltage is seen in Figure 12. Further simulations with an input voltage of 10V and 14V were conducted to simulate the battery voltage fluctuation, and outputs of 20.02V and 20.014V were measured via simulation, respectively.

$$Line\ Regulation = \frac{Vout_{high\ input} - Vout_{low\ input}}{Vout_{nominal\ input}}$$

By calculating load regulation using the equation above, a line regulation of about .03% or .0003 was obtained. This value is extremely low and is within a desired range, as the value denotes how much the output voltage changes with respect to the input voltage. Since the line regulation value is low, it can be assured that the output voltage will be constant and will ensure constant LED brightness. However, since it is a simulation that utilizes ideal components, the actual load regulation for the physical circuits is expected to be higher.

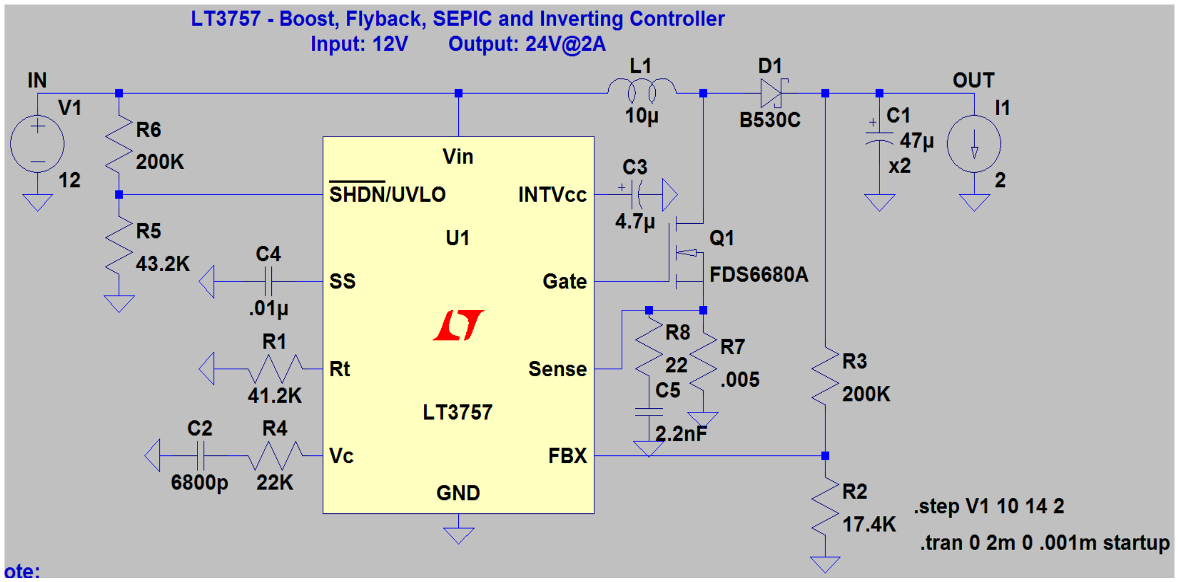

Figure 11. Simulated Boost Circuit

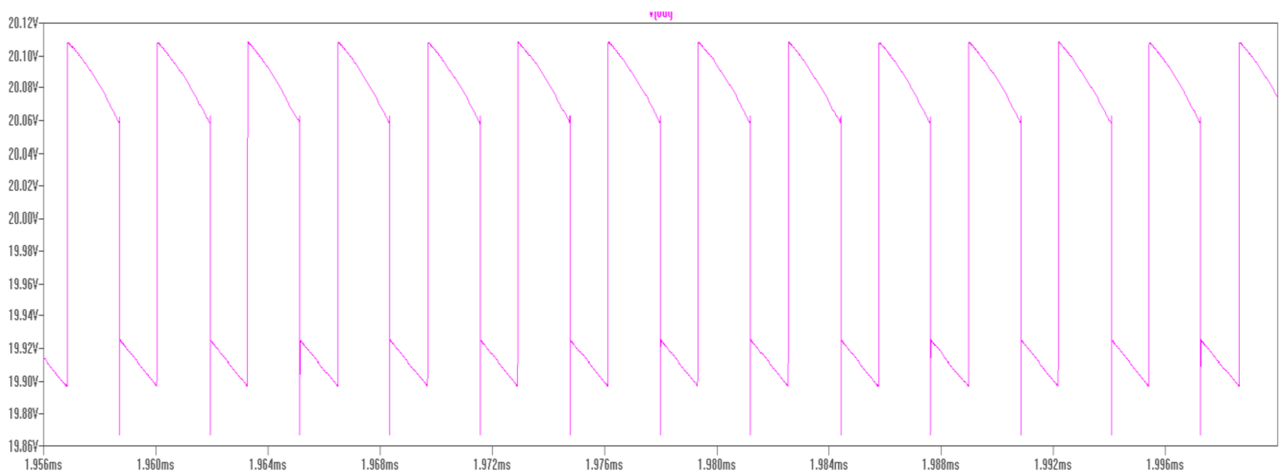

Figure 12. Simulated Boost Circuit Output Voltage Waveform

IV. Test Plans

4.1 LED Luminaire

The testing of the LED luminaire will first consist of a visual inspection for any solder joints that may have become broken or any possible short circuits. Once that has been completed the luminaire sections will be individually connected to a DC power source with current limiting capabilities for safety. By testing each section individually any open circuits or non-operational LEDs can be easily located and repaired.

4.2 Solar panel

With testing the solar panel, there are two things that need to be measured in order to ensure the panel is functioning properly. The first being open circuit voltage and the second being short circuit current. To measure open circuit voltage, the panel can be in the sunlight but care must be taken since the panel will be live when it is in sunlight and there is a possibility for electric shock. Once the panel is in the sun, a multimeter set to measure voltage can then be connected to the leads of the panel, and the open circuit voltage can be read and compared with the labeled open circuit voltage that the panel is rated for by the manufacturer.

For short circuit current measurement, on the other hand, the panel should be shaded when the ammeter (or digital multimeter set to measure current) is connected to the panel to reduce the risk of sparking or electric shock. Once the meter is connected, the panel can then be placed in sunlight and the short circuit current can be measured and compared with the rating put in place

by the manufacturer. If the open circuit voltage and short circuit current are both well within range of the manufacturer's marked ratings, the panel can then be deemed functional.

4.3 BATTERY

Without a functioning charger, it will be not be completely certain to determine the battery's capability to hold a charge. Aside from that fact, a visual inspection of the battery can help to determine that the battery is in good condition. Things to look for include: leaking acid, crystallization on the terminals, or physical damage such as cracks on the battery. These are all indicators that the battery has been damaged and if any of these are found on the battery, an exchange for a new battery must be made. The battery's open circuit voltage can also be measured using a multimeter. A voltage between 12 V and 13 V will be expected and indicate that the battery is healthy and has been charged.

4.4 BATTERY CHARGE CONTROLLER

Once the solar panel and battery has been tested and assured to be functional according to specifications, the battery charge controller will be connected to both with the solar panel at the input and battery at the output. The solar panel will start out shaded to prevent any chances of electrical surge since the solar panel is live instantly when exposed to any solar radiation. A multimeter set to measure current will be connected in series from the output of the charge controller to the positive terminal of the battery. Then, the solar panel will slowly be exposed to solar radiation and the multimeter will be observed to see if the current will slowly increase and stop at a maximum current of 1A. A 1A maximum current charge current will prove that the charge

controller is regulating the input from the solar panel and have a constant current output of 1A needed to charge the battery.

4.5 Boost DC-DC Converter

Upon completion of the boost circuit, initial testing with a continuity tester will be made to ensure there are no short circuits and that all components are connected where they need to be. Once the circuit is confirmed to be assembled correctly, power can be input to the circuit using a bench DC power supply with current limiting capabilities for safety.

Testing will begin with the power supply set to the battery nominal voltage of 12 V and the circuit unloaded in order to measure the open circuit output voltage. The desired output voltage for the boost circuit is 20 V, and once that has been confirmed the testing of the circuit with a load on the output to draw current can commence.

In order to load the circuit an electronic load will be used to avoid using resistive loads which can get hot and can be safety hazards. Using the electronic load, each boost circuit will be loaded from 0.5 A to 2 A in 0.5 A increments with pauses between steps to avoid loading the circuit too quickly and causing damage to the circuit. Data such as the input and output voltage as well as input and output current will be recorded to assess the circuit performance via calculation of efficiency and line and load regulation.

V. Development and Construction

5.1 PCB Design and Component Physical Sizing

The system was to be as compact as possible, with the solar panel and LED luminaire being the biggest components. Therefore, the battery charger and boost converter circuits were to be small enough to fit inside the LED luminaire enclosure. Surface mount components were chosen to keep the size of the system small. Yet, the smallest surface mount component will have a 0603 (1608 metric) packaging to keep the components a practical size for handling and soldering. Along with surface mount components, the decision to design and have custom printed circuit boards (PCBs) for both circuits were due to ensuring neat layouts and to minimize noise. Custom PCBs will allow for large traces for connections between the components and having a dedicated ground plane will keep noise to a minimum. ExpressPCB's MiniBoardPro service has been selected for its fast turnaround time for three identical 3.8" x 2.5" PCBs with two layers, solder mask, and silk screen.

5.2 Component Rating and Tolerance Selection

Components were also chosen with consideration of voltage and current ratings. The input to the charger circuit had a voltage rating of 20 V and current rating of 3 A. The output of the charger circuit had a voltage rating of 12 V and 2 A. For the boost circuit, the components that were on the main power path such as the inductor, MOSFET, and diode were all slightly oversized to ensure proper operation. For example, the diode is rated for 40 V and 4 A forward current, which is more than enough for the application, but at the same time not oversized to the point where there

would only be unnecessary costs. The inductor is also rated for up to 10 A, which is also more than enough for the application but the oversizing was done to ensure that the inductor does not saturate and cause adverse behavior. For both circuits, 1% tolerance resistors were selected for the resistors used to select the output voltage for the boost, or the charging rate for the battery charge controller, as these are important functions for the system.

5.3 Connector Selection

Male jack and female plug connectors were the main connection terminals for the input and output of each circuit. The connectors were chosen because of the ease of use, with a plug and play application, and also to ensure there are no accidental shorts. Each male jack and female plug was rated to handle 24Vdc and 5A. The female plug can be seen in Figure 13 and the male jack can be seen in Figure 14.

Figure 13. Female Plug Connector [7]

Figure 14. Male Plug Connector [8]

5.4 Soldering of Surface Mount Technology Components

Soldering the surface mount components onto the custom PCBs was easy due to the use of a reflow oven. First, solder paste was conservatively placed on each solder pad on the PCB. Then, each component was placed in their responding solder pads. Lastly, by following the onscreen instructions on the reflow oven, the solder paste was heated to the point where it adheres to the solder pads and the component. The resulted PCB was completed populated by the components with clean solder connections. The completed boards for both the boost converter and charge controller can be seen in Figures 15 and 16, respectively.

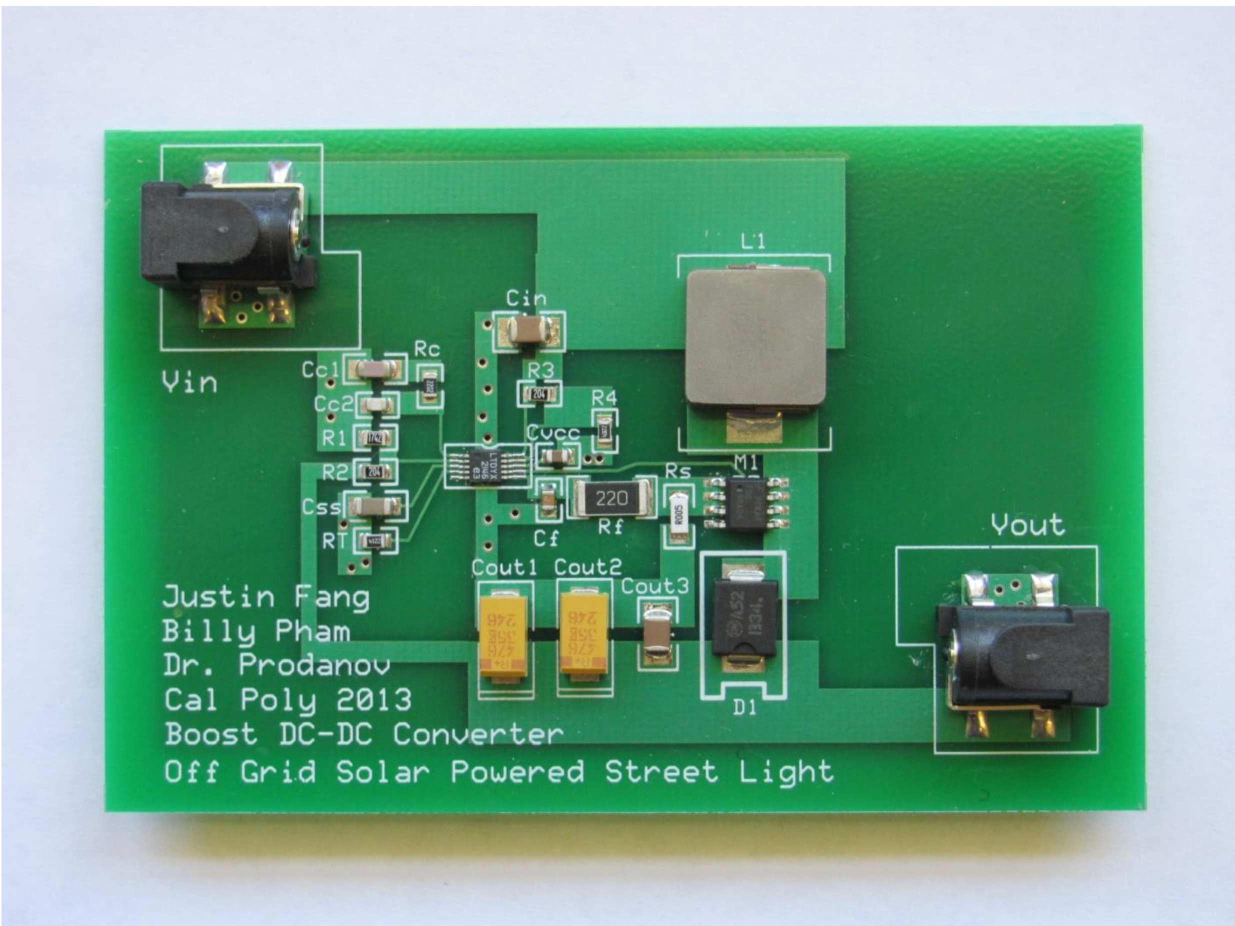

Figure 15. Completed Boost Converter PCB with Components Soldered

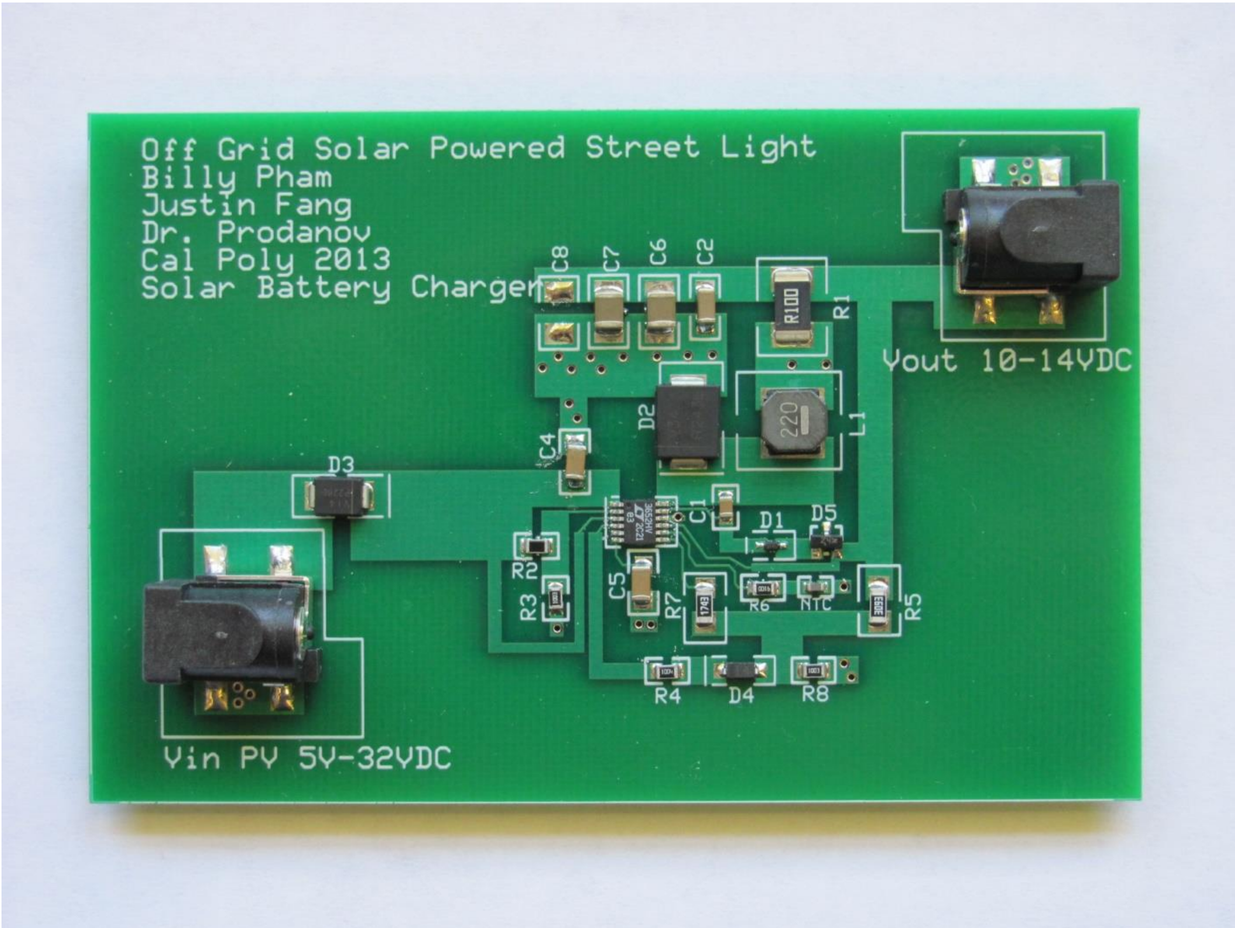

Figure 16. Completed Charge Controller PCB with Components Soldered

5.5 Distribution Block Selection

The distribution blocks selected for the system are screw based terminal blocks. Each connection point is connected electrically only to the terminal directly across from it. Each block is rated for 250 V and 30 A, well above the voltages and currents that will be utilized in the system. The screw based distribution blocks were selected for the ease of use and for the fact that connections can be broken and remade easily and securely without the use of solder. Distribution blocks with more outputs were used for the LED power rails, and allow switches to be implemented easily in future projects. Appendix G displays the hardware layout and the numbering of the

distribution blocks, as well as the corresponding LED array sections. Separate distribution blocks were utilized to keep the power and ground connections separated.

5.6 LED LUMINAIRE MODIFICATIONS:

The LED luminaire was modified with a small cut at the bottom of the door to allow four wires to pass through the luminaire, two wires from the solar panel into the luminaire and two wires from the distribution block inside the luminaire out to the battery. Each circuit and distribution block was attached to the inside of the LED luminaire with industrial strength Velcro. The Velcro provides for a repositionable and secure connection. Also, with the Velcro, there will be a small clearance from the bottom plane of the circuits from the LED luminaire surface to prevent possible shorts with the PCB traces.

VI. Integration and Test Results

6.1 Solar Panel Testing

Right out of the box, the solar panel was tested using a simple multimeter. Two criteria were tested for, open circuit voltage and short circuit current. The CDT 40W solar panel had factory specifications on the back of the panel which can be found in Figure 17. To test for open circuit voltage, the solar panel was placed away from direct sunlight because the solar panel is live once it receives any solar radiation. Then, a multimeter set to detect voltage was used, connecting the positive lead from the multimeter to the positive output from the solar panel and the negative lead to the negative solar panel output. Direct the solar panel into sunlight and the voltage measurement was observed. For short circuit current measurements, the same procedure was replicated, but this time, the multimeter was set to detect amperage. Both the open circuit voltage and short circuit current matched the solar panel's specifications.

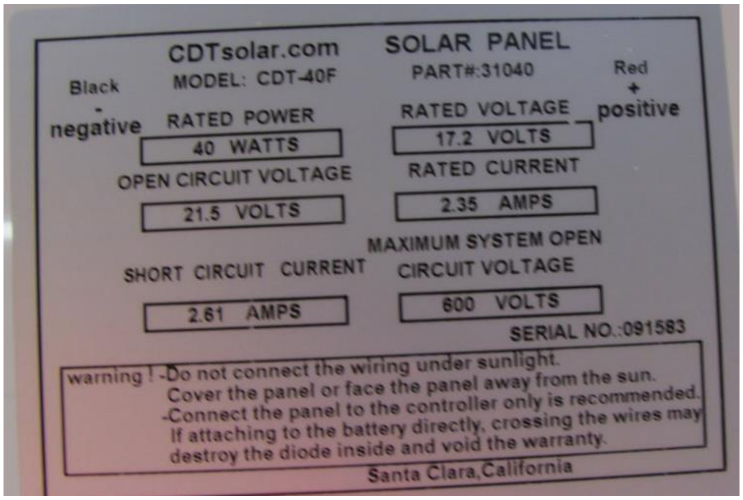

Figure 17. Solar Panel Specifications

6.2 Battery Inspection and Initial Testing

Upon obtaining the battery for the system, the battery underwent an inspection for signs of use or physical damage. The battery was free of any cracks or surface dents, and the battery terminals were clean and free of any leaking acid or crystallization. A measurement of the battery's open circuit voltage yielded a voltage of 12.6 V, which indicated the battery was holding its charge well and was kept at a good voltage level.

6.3 Charger Circuit Testing

The charger circuit was connected with the PV at the input and the battery at the output. The PV was kept shaded to prevent any chances of malfunction or sparks from a live PV. A multimeter was placed between the output positive wire of the charging controller circuit and the positive terminal of the battery to measure the current transferred to the battery. The resulted charge rate with the PV completely exposed was the maximum 1A charging rate as desired. The current was also varied depending on the amount of shading present on the solar panel, which confirmed the maximum power point tracking abilities of the circuit, as the circuit was compensating for the lower voltage of the panel and in turn, lowered the current to get the most power from the panel based on the conditions.

6.4 Boost Circuit Testing and Performance Assessment

The boost circuit measured performance data in Table IV. Input voltage was provided using a bench power supply and was varied to represent the range of voltages outputted by a lead acid battery. The circuits were loaded using an electronic load set to constant current of 2A to simulate

full load conditions. Line regulation, or how stable the output voltage is while the input voltage is varied, was calculated using the following equation:

$$Line\ Regulation = \frac{Vout_{high\ input} - Vout_{low\ input}}{Vout_{nominal\ input}}$$

Table IV. Measured Boost Circuit Performance

Input Voltage (V)	Input Current (A)	Output Voltage (V)	Output Current (A)	Power Loss (W)	Efficiency (%)	Line Regulation (%)
10	4.33	19.45	2	4.4	89.8	0.103
12	3.6	19.47	2	4.26	90.1	
14	3	19.47	2	3.06	92.7	

The line regulation was measured to be only a tenth of a percent, which indicates that the output voltage of nearly 20 V remains very stable over the range of input voltages likely to be output by the battery. Line regulation is important as it is undesirable for the voltage to vary greatly depending on the input voltage. For example, if the line regulation was very high, then it would be possible that some LEDs would dim or even shut off if the battery voltage dropped too low. Both boost converters functioned as expected with no problems. The circuits were tested using various loads from 0 A to 2 A in 100 mA increments, and the output voltage was maintained close to 20 V, which is satisfactory as the load on the circuits will vary as the number of powered LED sections changes. Although the output voltages were not 20 V exactly, the output voltage that was obtained is adequate to power the LEDs as a minimum of 18V was needed.

The load regulation was also calculated for the boost circuits. The data collected with an input voltage of 12 V is tabulated in Table V, and a load regulation of 2% was obtained using the equation:

$$Load\ Regulation = \frac{V_{out(low\ load)} - V_{out(high\ load)}}{V_{out(low\ load)}} \times 100$$

A low load regulation value is desirable as it indicates that the output voltage does not change as the output, or load, current varies. For the system, a low load regulation is required to ensure the LEDs do not dim as more sections are powered on.

Table V. Boost Load Regulation Data Collected With Input Voltage of 12V

Iout (A)	Vout (V)	Load Regulation (%)
0.1	19.87	2.00
0.5	19.79	
1	19.71	
1.5	19.61	
2	19.48	

The efficiency for the boost circuits were also measured, and are also found in Table IV. The efficiency stayed near or above 90% at full load, which is acceptable for a non-synchronous boost converter.

6.5 Luminaire Testing and Troubleshooting

The luminaire was powered by a DC power supply that was set to 20 V. Individual sections were powered up with the DC power supply to check for non-functional LEDs. If a non-functional LED was found, the LEDs around the non-functional LEDs were probed and moved around to see if a possible loose solder joint or connection was responsible and usually, it would be the case. After all broken strings or sections of LEDs were fixed, the boost converters were connected to the luminaire and powered on to see if all the LEDs were receiving sufficient power from the boost

converter circuits. However, during the testing it was discovered that holes would need to be drilled into the enclosure to allow the solar panel wires and the battery wires to enter the enclosure.

Testing with the boost circuits was successful and the luminaire was powered without problems. The luminaire was completely illuminated over the course of 2 hours and no problems were encountered. The luminaire became slightly warm as expected with the use of such a large amount of LEDs, but was nowhere near a temperature which would cause problems.

6.6 Complete System Testing

Once each of the components were tested, the complete system was connected following the wire list in appendix E and laid out as shown in appendix G. Once each component was connected to the overall system, the system was powered on using the battery disconnect switch. The boost converters provided adequate power to the luminaire, and there was no noticeable dimming of the LEDs as the battery discharged, or as all of the LEDs were powered on. The battery charge controller functioned as expected and charged the battery at 1 A, even while the boost circuits provided power to the LED luminaire.

VII. Conclusion

The off grid solar powered street light system is an attempt to explore the possible changes that can be made to the street light infrastructure that every city has to light the road for pedestrians and cars. This system can be used to save energy and lessen the carbon footprint that is left by the use of energy from the grid. The system is totally self-contained and only runs on solar power that can be renewed and regenerated for daily use. No major problems were encountered while putting each of the five components of the system together.

The solar panel and battery worked perfectly to specifications right out of the box. Both the charge controller and boost converter circuit was built with no difficulties and worked on the first try. The challenges of the two circuits were the layout of the components during the custom PCB design phase. Traces were to be laid out so none would be overlapped. For the charge controller circuit, the use of the bottom layer was needed to place a trace that would otherwise be impossible to incorporate all on the top layer plane.

The system ran as expected, with the solar panel charging the battery at a maximum charge current of 1A and the battery providing power, boosted to power the entire led luminaire. The LED luminaire would sometimes have rows that are non-functional, but the issue was easily fixed by re-soldering led joints that were loose or have broken over time.

The boost circuit was designed to have an output voltage of 20 V, but a voltage of about 19.5 V was measured as seen in Table V. Even though the voltage was not the desired 20 V, the 19.5 V was adequate for lighting the LEDs and no adverse effects were observed due to the lower voltage. The possible sources of the lower voltage could be because of the resistance of the traces, or the resistors used to select the output voltage. If greater efficiency is required in the future, synchronous boost converters can be implemented for efficiency gains of around 5%.

The system is operational, but there are plans to improve the design in the future. The size of the LED luminaire is rather large and is not practical. To be able to maintain the same high lumen output, but decrease the number of LEDs needed, high powered LEDs would be used. Also, the street light could incorporate a motion sensor that will operate the luminaire only when a pedestrian is detected under the system. Then, only the sections that will produce a maximum lumen output where the pedestrian is will be turned on. By having only selected sections turn on, the system will be able to save power and maintain a high charge on the battery to last through the whole length of the night even with a low charge time during the day due to bad weather or environmental obstruction of sunlight to the solar panel.

Solar powered technology is a great way to help power all the streetlights that are needed in cities. A simple system like the off grid solar powered street light can help reduce cost and provide an efficient way to provide safe lighting to the pedestrians that need it.

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APPENDIX A. SENIOR PROJECT ANALYSIS

Project Title: **Off Grid Solar Powered Street Light**

Student's Name: **Justin Fang & Billy Pham** Student's Signature:

Advisor's Name: **Dr. Vladimir Prodanov** Advisor's Initials: Date:

Summary of Functional Requirements

The Off Grid Solar Powered Street Light system can provide a bright path for pedestrians with the use of 720 LEDs. All the power the system needs will be generated by a 40W solar panel that will store its charge with a 40Ah sealed lead acid battery.

Primary Constraints

A major constraint from the system was the size of the LED luminaire. The luminaire is the main source of lumen output for the system, therefore, it must provide enough lumens to create a bright path for pedestrians. Yet, with the use of low powered LEDs, there needed to be too many LEDs. The LED luminaire was built before our contribution to the project, but if resources and time were permitted, high powered LEDs would have been used rather than low powered LEDs. This can lower the amount of LEDs needed for the luminaire and decrease size while maintaining a high lumen output and efficiency.

Yet, the inside of the LED luminaire was rather compact since the luminaire had a dome shape. The circuits were to be placed within needed to be small in size, so surface mount components were needed and this required custom PCBs to be designed. The custom PCBs required the most time, with research on component ratings and finding the right sizes and taking in

consideration of noise within the circuit. Some components needed to be closer to the main IC, while others were to be placed as far as possible to prevent noise.

Luckily no major difficulties were encountered, but that was due to the large amount of research and datasheet skimming to understand every components' contribution to the circuit to ensure the correct values were chosen to meet our specifications.

Economic

The project aims to benefit the Earth by reducing the consumption of Natural Capital. By using the readily available energy of the sun, resources are not consumed to power the street lights. The project will benefit Human Capital by providing new jobs involved with the manufacture and installation of the project. Over time, cities will save money by not having to pay for energy to power hundreds of street lights.

A majority of the costs come from the initial installation and retrofitting of existing street lights to the new self sustaining LED street lights. As with all sustainable energy systems, the initial cost is substantially higher than systems that use fuels, but over time the system pays for itself in energy savings. Costs will also arise with maintenance but with a well designed and installed system the project should not require frequent maintenance.

The original estimated cost of components was $500 but as the project was underway, it quickly grew to that amount and somewhat above. The final bill of materials is collected in Appendix B, tables B-I to B-III. The final total cost added up to be $636.86, over $100 what was estimated. Most of the cost came from the cost of the PCBs and the circuit components. Fortunately, there were no additional equipment costs accrued as the power electronics lab had a high power DC power supply with current limiting capabilities, as well as an electronic load. We were also

fortunate to gain access to the department's reflow oven which benefited us greatly in speeding up the soldering of the various circuits.

As of right now the project does not earn any money, but the system could easily be retrofitted into a cell phone charging station with the implementation of a Buck circuit to reduce and regulate the battery's voltage to 5V.

Timing

A motion sensor, a more refined LED luminaire and enclosure will be added in the future. As an estimate, the product could take another two years to be developed and refined to actually be sold to cities and used as a smart street light. The product would last as long as components that fail will be replaced, such as the solar panel, battery, and LEDs. The project took a combined time of about 4 months to be designed and produced while original projected . When design has been completed finalized, it will probably take a matter of a few months for production to begin and the system can be available for cities or organizations that will like a smart street light that will be powered solely by solar radiation. It will cost nothing to operate as it will be powered by a solar panel that harvests solar energy.

Environmental

Since the system is self sustaining and does not use grid power, the operation of the project would not contribute to the consumption of fossil fuels used during power generation in some plants. The LED street lights would be installed where existing street lights are already in place, which means no further impact to the environment would occur that has not already happened with the present lights. The system uses solar energy, which is a "free" source of energy. By harvesting the energy of the sun itself using the solar panel, no pollutants are generated other than

during the production of the panel itself. But hopefully the clean operation for years will offset any pollutants generated during production of the system.

The battery chosen can be recycled at battery centers, which ensures that the lead does not leach into the environment and harm any organisms. The project may reduce a city's light pollution as the light is not on all night, which may benefit animals that require the darkness of night.

Manufacturability

Manufacturability will be easy as the PCBs and components would already be designed. With the use of a reflow oven, the circuits can be made perfectly each time. The solar panel and battery will need to be bought from a source with the specifications of a 40W solar panel and 40Ah sealed lead acid battery. Then, all that is left is the connection of the wires which can be seen in the wire list of Table E-I.

Sustainability

The maintenance of the system will be easy. Major parts that will need to be replaced would be the LEDs in the luminaire, solar panel, and battery. The LEDs would be the hardest to replace as it is currently a large array of LEDs that are soldered together. Yet, if the luminaire was upgraded to high powered LEDs and the enclosure was to be made easily accessible and each LED had a specific slot to be plugged into, then the replacement of a LED would not be a problem. To be able to create such an enclosure, usage of stronger, more durable material than wood would cost more since it would need to be fabricated, but if it was produced in bulk, the cost will not be as high. Also, the weight would largely be reduced.

Ethical

During the design of the project, extra care must be taken to ensure all the components are properly sized. The project must also be properly manufactured and tested to ensure safe operation of the project, since streetlights are found very close to residential areas, if a street light were to be poorly designed or built and start a fire, the designers and manufacturers would be responsible. The potential for misuse is small for this project, as the street light itself has little to no potential of harming someone if it is properly installed.

Health and Safety

The project requires the use of printed circuit boards with components that need to be soldered, and lead free solder can be used to reduce the amount of lead that could leach into the environment or cause damage to the nervous systems of workers. The batteries are also quite heavy, so care must be taken by workers to not injure themselves. The batteries also contain sulphuric acid which can cause burns.

With the use of the project, the main safety concerns is that the panel and luminaire are securely mounted so they do not break free and fall, as in doing so a pedestrian or driver could be seriously injured. The battery should also be kept on the ground, as mounting something so heavy on a light post would be costly as well as dangerous. However, care must be taken to ensure the battery does have some ventilation as to not let a buildup of hydrogen gas to form.

Social and Political

The project addresses the need for more sustainable energies to be used in order to reduce the use of fossil fuels and the production of greenhouse gasses. The project impacts both the officials of cities as well as the citizens of the cities. Citizens and inhabitants of the cities gain the

benefit of not having their tax money pay for streetlights that are on all the time regardless of if they are needed or not, and at the same time gain the benefit of brighter streetlights that can improve the safety of pedestrians and drivers alike.

While the upfront costs of switching to a system like the one designed in the project may be higher, the overall savings will offset the initial cost. No inequities would be created, as everyone would benefit. Communities would receive better streetlights that would last longer than the current lights employed, meaning there would be no downtime of street lights.

Development

With the design of the charge controller and boost converter involving surface mount components on custom PCBs, a reflow oven was used. The reflow oven was a new tool that was used to help solder on the small surface mount components. By simply placing solder paste onto the solder pads on the PCB, components were populated onto the board and with the reflow oven, the circuits were brought to 270 degrees Celsius where the solder paste melts and the component is securely soldered onto the board. The resulting circuit is a cleanly soldered board compared to if it was hand soldered.

Appendix B: Parts List and Costs

Table B- I. Battery Charger Controller Parts List and Cost

Qty	Description	Value	Digikey Part Number	Designators	Cost
2	CAP CER 1UF 16V 5% X7R 0805	1uF Cap	399-8001-1-ND	C1	$ 0.60
3	CAP CER 10UF 16V 5% X7R 1206	10uF Cap	399-9309-1-ND	C2,C4	$ 7.50
2	CAP CER 4.7UF 10V 5% X8L 1206	4.7uF	399-5773-1-ND	C5	$ 2.48
2	CAP CER 100UF 16V 20% X5R 1210	100uF	587-3152-1-ND	C6	$ 4.50
2	RES 255K OHM 1/8W .1% 0805 SMD	255k ohm	P255KDACT-ND	R2	$ 1.26
3	RES 100K OHM 1/8W 1% 0805 SMD	100k ohm	P100KCCT-ND	R3,R8	$ 0.30
2	RES 1.00M OHM 1/8W 1% 0805 SMD	1Mega Ohm	P1.00MCCT-ND	R4	$ 0.20
2	RES 174K OHM 1/4W 1% 1206 SMD	174k ohm	P174KFCT-ND	R7	$ 0.20
2	RES 910 OHM 1/8W 1% 0805 SMD	910 ohm	P910CCT-ND	R6	$ 0.20
2	RES 309K OHM 1/4W 1% 1206 SMD	309k ohm	P309KFCT-ND	R5	$ 0.20
2	RES .10 OHM 3W 1% 2512 SMD	0.1 ohm	CRA2512-FZ-R100ELFCT-ND	R1	$ 1.08
2	INDUCTOR 22UH 1.9A 20% SMD	22uH	587-2082-1-ND	L1	$ 0.68
2	IC DIODE FAST SW 75V SOD-523F	Diode 1N914	1N914BWTCT-ND	D1	$ 0.34
2	DIODE ZENER 6.2V 225MW SOT-23	Zener BZX84C6V2L	BZX84C6V2LT1GOSCT-ND	D5	$ 0.30
2	DIODE SCHOTTKY 40V 3A SMC	Schottkey MBRS340	MBRS340TRPBFCT-ND	D2	$ 1.62
2	DIODE SCHOTTKY 40V 1A SMB	Schottkey MBRS140	MBRS140TRPBFCT-ND	D3	$ 1.20
2	DIODE SWITCH 100V 150MA SOD123	Diode 1N4148	1N4148WTPMSCT-ND	D4	$ 0.62
2	THERMISTOR 10K OHM NTC 0603 SMD	10k ohm Thermistor	490-2436-1-ND	NTC	$ 0.40
2	IC BATTERY CHARGER 2A 12-MSOP	LT3652	LT3652HVEMSE#PBF-ND		$ 14.52

Table B- II. Boost Converter Parts List and Cost

Qty	Value	Digikey Part Number	Cost
4	10uH Inductor	541-1036-1-ND	$ 12.44
4	MOSFET	FDS6680ACT-ND	$ 3.80
4	Schottky Diode	MBRS340T3GOSCT-ND	$ 2.04
4	LT3757 IC	LT3757EMSE#PBF-ND	$ 17.60
6	Outcap (47 uF) tant	399-3905-1-ND	$ 13.80
6	In/outcap2 (10uF) cer	445-3946-1-ND	$ 3.72
4	4.7uF 16V cap	445-7640-1-ND	$ 0.96
4	6800pF cap (Cc1)	478-1502-1-ND	$ 2.40
4	0.1uF cap (Css)	587-1147-1-ND	$ 2.72
4	2.2nF filter cap Cf	399-8041-1-ND	$ 1.44
4	.005 resistor Rs	MCS1632R005FERCT-ND	$ 1.40
6	200k res (R3, R2)	RR12P200KDCT-ND	$ 0.66
4	17.4K res (r1)	RR12P17.4KDCT-ND	$ 0.44
4	22Ohm res (Rf)	A102515CT-ND	$ 0.56
4	22kohm res (rc)	RHM22.0KCHCT-ND	$ 0.40
4	41.2K res RT	P41.2KCCT-ND	$ 0.40
4	43.2K res R4	P43.2KCCT-ND	$ 0.40
4	100pF (cc2)	399-9150-1-ND	$ 0.64

Table B- III. All Other Parts List and Cost

Qty	Item	Cost
10	Male Jack Connectors	$ 18.90
10	Female Plug Connectors	$ 13.60
1	40W CDT Solar Panel	$ 152.32
1	40Ah Sealed Lead Acid Battery	$ 133.41
1	16 AWG Red Wire	$ 5.20
1	16 AWG Black Wire	$ 5.20
2	3 Circuit Distribution Block	$ 1.50
2	10 Circuit Distribution Block	$ 7.76
3	Charge Controller PCB	$ 92.70
3	Boost Converter PCB	$ 92.70

Appendix C: Schedule - Time Estimates

Milestone 1: List major components needed for project

Milestone 2: Design circuit and actual component values

Milestone 3: Design PCB layout for each major component

Milestone 4: Research for cheapest parts that will be compatible with design

Milestone 5: Order double the number of necessary parts

Milestone 6: Test each component for data sheet specified values of voltage and current

Milestone 7: Construct the circuit

Milestone 8: Test and debug

Milestone 9: Finalize circuit

Milestone 10: Place all components together

Milestone 11: debug and run

Milestone 12: Senior Project Expo Event

Table C- I. Milestone Task's Start Date and Duration

Task	Start Date (DD-Month-YY)	Duration (weeks)
Define Major Components	28-Sep-12	1
Design component values	1-Oct-12	5
Design PCB Layout per Component	29-Oct-12	2
Research Sells for Parts within Budget	10-Oct-12	0.5
Order Double the Parts	1-Nov-12	2
Test Each Component Upon Receiving for Datasheet Values	3-Dec-12	1
Construct Circuit	5-Jan-13	1
Test and Debug #1	12-Jan-13	2
Finalize Circuit	29-Jan-13	3
Place all Components on PCB	21-Feb-13	1
Test and Debug #2	3-Mar-13	2
Senior Project Expo Event	30-May-13	0

APPENDIX D: WIRE LIST

Table D- I. System Wire List and Connections

Guage	From	Color	To	Comment
16 AWG	PV out+	Red	Charger In +	
16 AWG	PV out -	Black	Charger In-	
16 AWG	Charger Out +	Red	Battery +	Distribution block 1
16 AWG	Battery +	Red	Boost1 In +	
16 AWG			Boost 2 In +	
16 AWG	Charger Out -	Black	Battery -	Distrubution block 2
16 AWG	Battery -	Black	Boost1 In -	
16 AWG			Boost 2 In -	
20 AWG	Boost1 Out+	Red	LED Array 1 +	Distrubution block 3
20 AWG			LED Array 2 +	
20 AWG			LED Array 3 +	
20 AWG			LED Array 4 +	
20 AWG			LED Array 5 +	
20 AWG	Boost 2 Out +	Red	LED Array 6 +	Distrubution block 3
20 AWG			LED Array 7 +	
20 AWG			LED Array 8 +	
20 AWG			LED Array 9 +	
20 AWG			LED Array 10 +	
20 AWG	Boost1 Out-	Black	LED Array 1-10 -	Distrubtion block 4
20 AWG	Boost Out -	Black		

APPENDIX E. IC LOCATION DIAGRAM

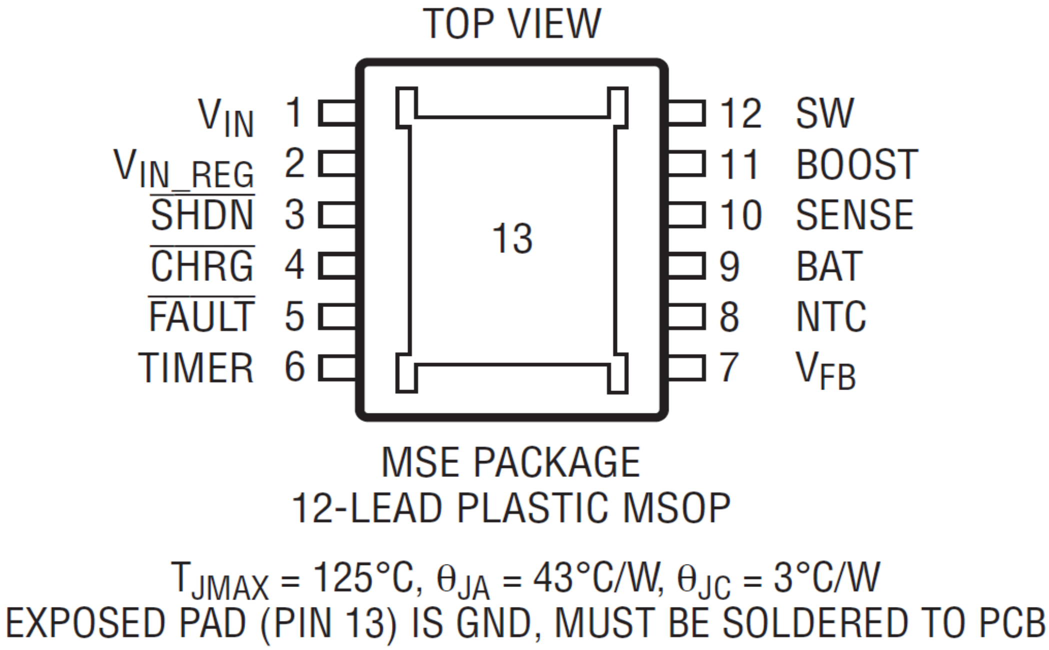

Figure E- 1. LT3652 Charge Controller IC Pinout

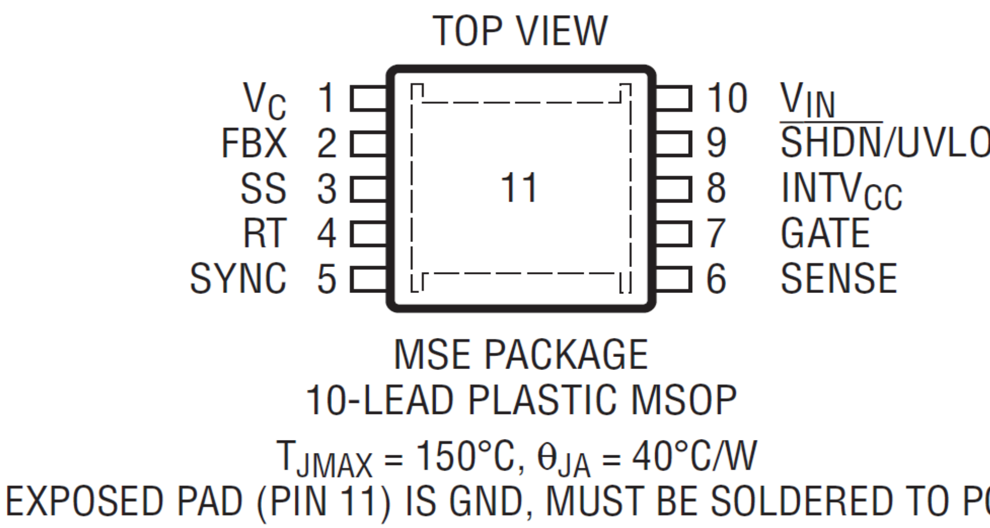

Figure E- 2. LT3757 Boost Converter IC Pinout

Appendix F: PC Board Layout

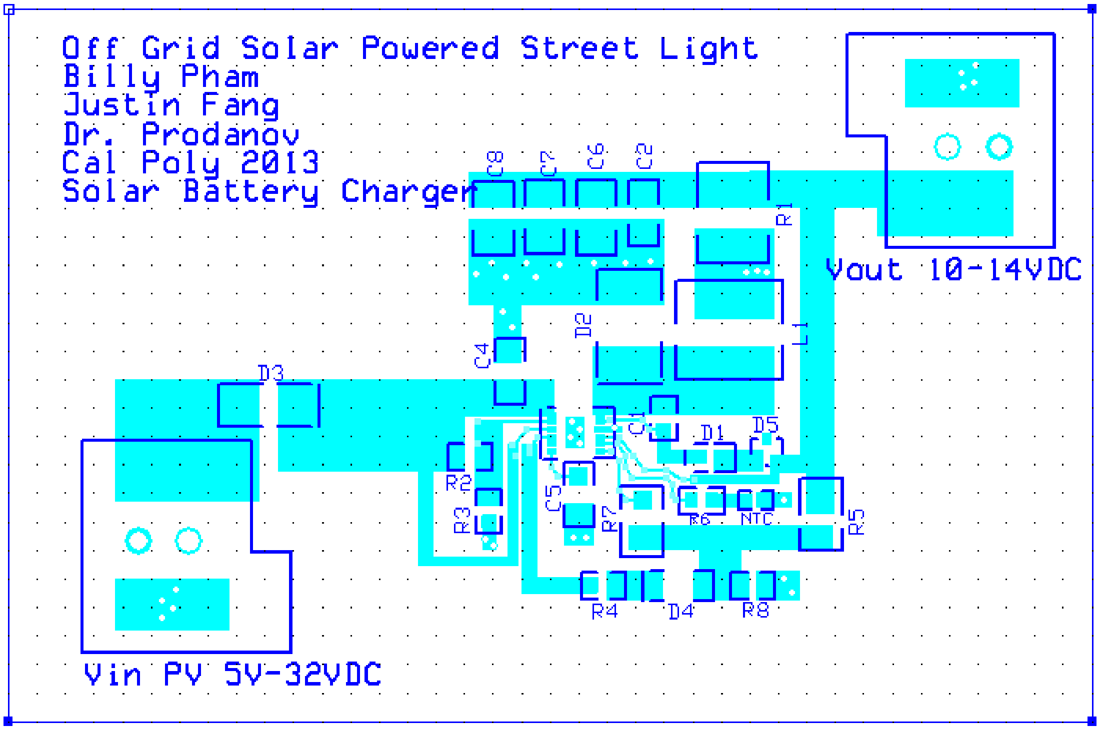

Figure F- 1. Solar Battery Charger PCB Layout Top Plane Design with ExpressPCB

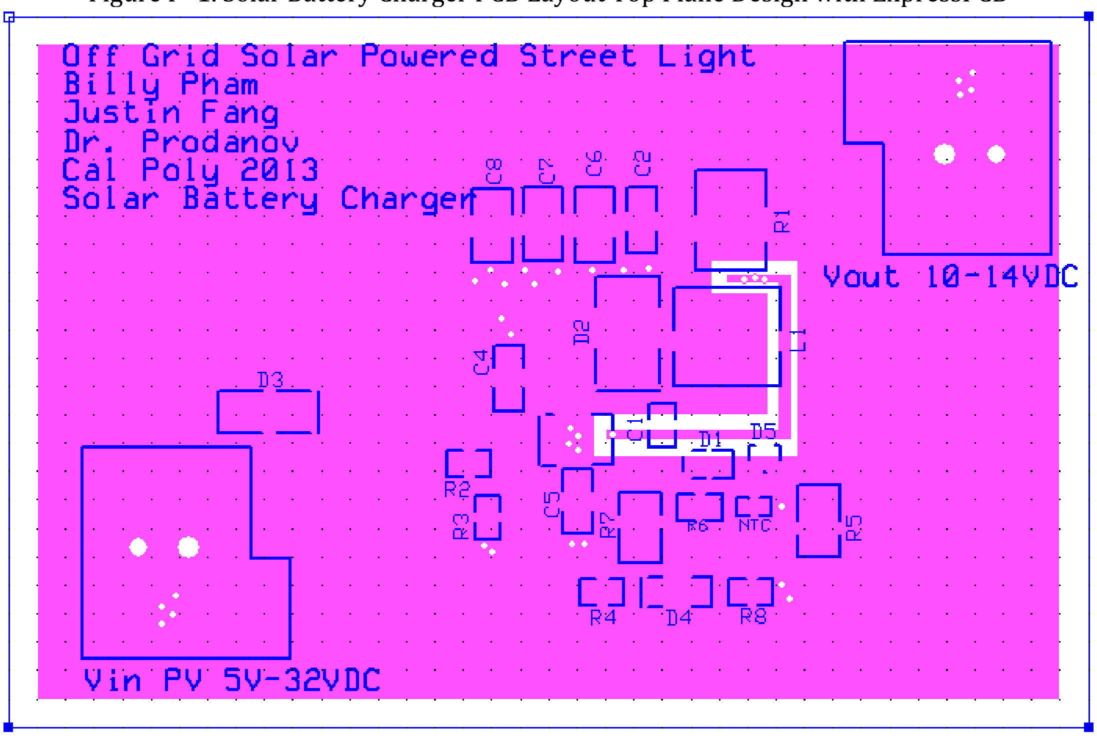

Figure F- 2. Solar Battery Charger PCB Layout Bottom Plane Design with ExpressPCB

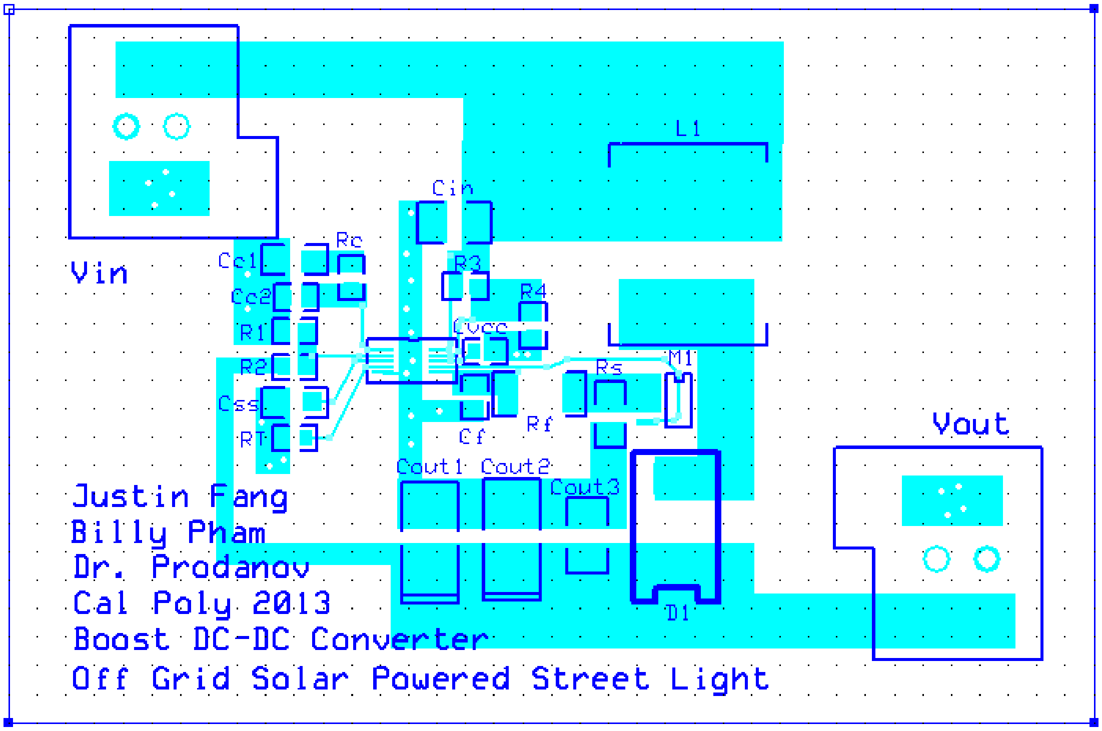

Figure F- 3. Boost DC-DC Converter PCB Layout Design with ExpressPCB

APPENDIX G. HARDWARE CONFIGURATION/LAYOUT

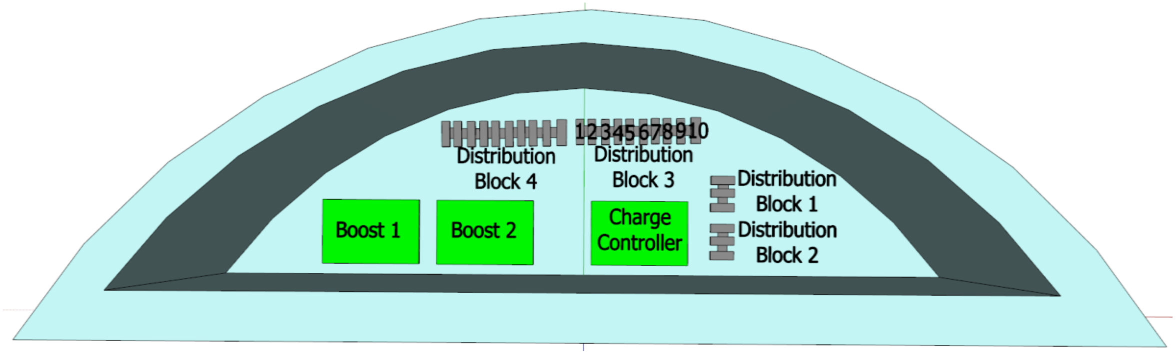

Figure G- 1. Luminaire Layout Viewed from Top

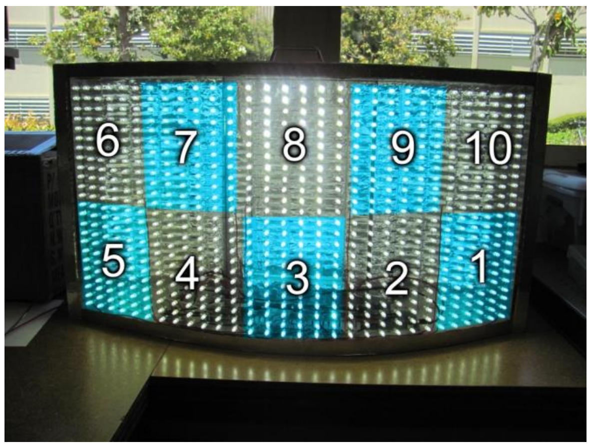

Figure G- 2. Luminaire LED Array Layout Viewed from Front

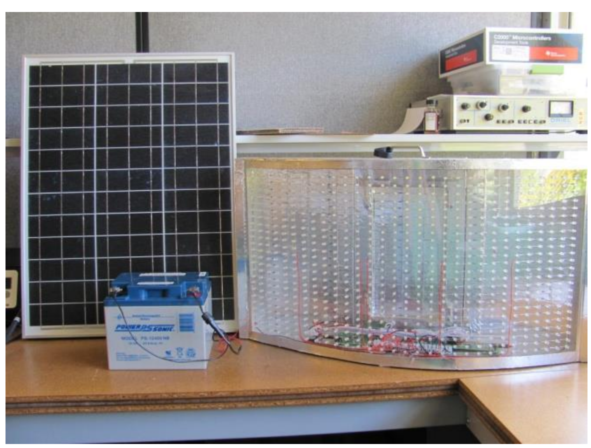

Figure G- 3. Complete System