# SELF-SUSTAINABLE SOLAR STREETLIGHT CHARGING

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# 1. Introduction

## 1.1 Objective

The goal of our project is to design and create a charging circuit for a portable, self-contained, self-sustaining and user-friendly streetlight that can be installed with minimal effort, independent of the power grid, and will function similarly to a commercial streetlight in providing light during periods of darkness.

The overall design of the streetlight will use a LED lighting fixture, powered by a rechargeable battery, which in turn will be charged via power produced by a solar panel. To make the streetlight's design user-friendly, it will include a subsystem which will monitor and transmit the battery's current power level. This will allow the user to always know how long they can expect the streetlight to continue running at any given time. The user will be able to use a mobile/web application in order to see data from this monitoring subsystem. Our project centres around building the charging circuit required for the battery to obtain power from the solar panel and will utilize an optimization technique called maximum power point tracking (MPPT). More specifically, our project will involve:

1) Identifying specifications for the solar panel and battery that best allow both of them to work together while still maintaining portability
2) Building appropriate hardware subsystems to ensure proper/smooth operation of the major components
3) Implementing a MPPT power conversion circuit that will maximise the efficiency of the charging system, allowing the battery to extract maximal power from the solar panel.

## 1.2 Background

Streetlights powered by electricity have been around for nearly 140 years, since arc lamps were first used for lighting streets in cities such as Paris and Los Angeles. While the lighting fixture used in these streetlights have changed near continuously over time - from arc lamps to incandescent bulbs to high-intensity discharge lamps to LED lights - the electricity used to power these streetlights has almost always come from the electrical grid. Directly using solar panels to power streetlights is hardly a new idea - numerous patents have been filed on the concept, including some as early as 1978 - but city-wide solar-powered street lighting is still limited to a few select urban regions around the world. There are three major reasons for this. Firstly, and most importantly, solar street lights have a very high initial setup cost compared to conventional streetlights. Secondly, using solar panels has various downsides, such as less power generated during shorter days (which coincide with longer nights, when light is needed the most) and requiring cleaning from dust, snow, etc in order to continue functioning effectively. Thirdly, the degradation over time of the battery's charge-discharge life cycle means the solar streetlight will either become less effective over time if not properly maintained.

## 1.3 High Level Requirements List

- The solar panel must be large enough to make the streetlight independent of the grid, yet small enough to be reasonably portable. It must have a total area less than 1250 $in^2$ and have both its length and width be under 50 inches.
- The battery must be able to obtain enough power from the solar panel to provide the full 40-50 Watts of electricity required to power the streetlamps LED light source for at least 2 days.
- The MPPT circuit should be capable of charging the lead-acid battery at 80% efficiency.

# 2. Design

## 2.1 Block Diagram

Fig. 1 represents the overall design for the solar streetlight at a high level, and consists of three major subsystems centered around the battery. The charging and discharging circuits together constitute the battery's charge cycle: the former involves storing electrical power generated by the solar panel into the battery, while the later involves using the power stored in the battery to power the LED light source as needed. The two circuits also involve additional components (such as an MPPT charge controller for the charging circuit, or a LED switch for the discharging circuit) required for controlling power flow, implementing safety measures, etc. The third subsystem, user monitoring, involves hardware components that measure the battery's remaining charge level and transmit this information via wifi, and a mobile/web application that receive this data and allow the user to find out the remaining battery life of the streetlamp.

Fig. 2 shows the circuit schematic for the MPPT charging circuit we plan to implement in this project, and comprises of the green 'Charging Circuit' subsystem within diagram 1. It implements voltage regulation, PWM generation, and current control. An additional buck converter and a battery charging IC (not shown in the diagram) can be added to the design to complete proper charging of the battery.

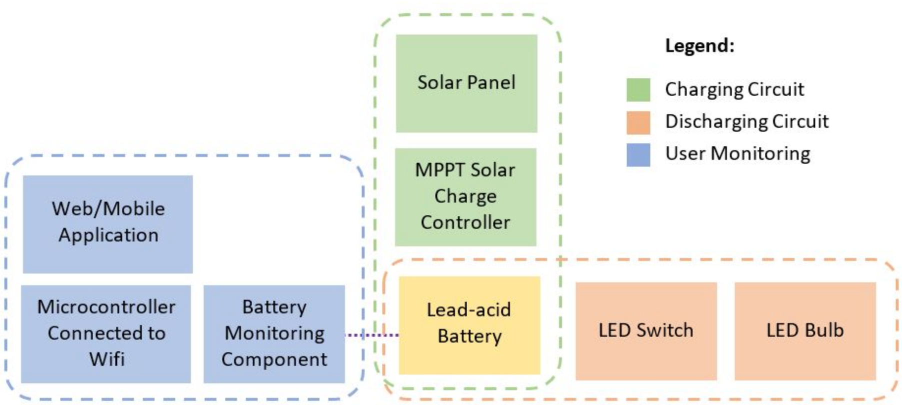


*Figure 1: A high-level block diagram showing the various components (solid blocks) and subsystems (dashed-line borders) of the overall streetlight design*

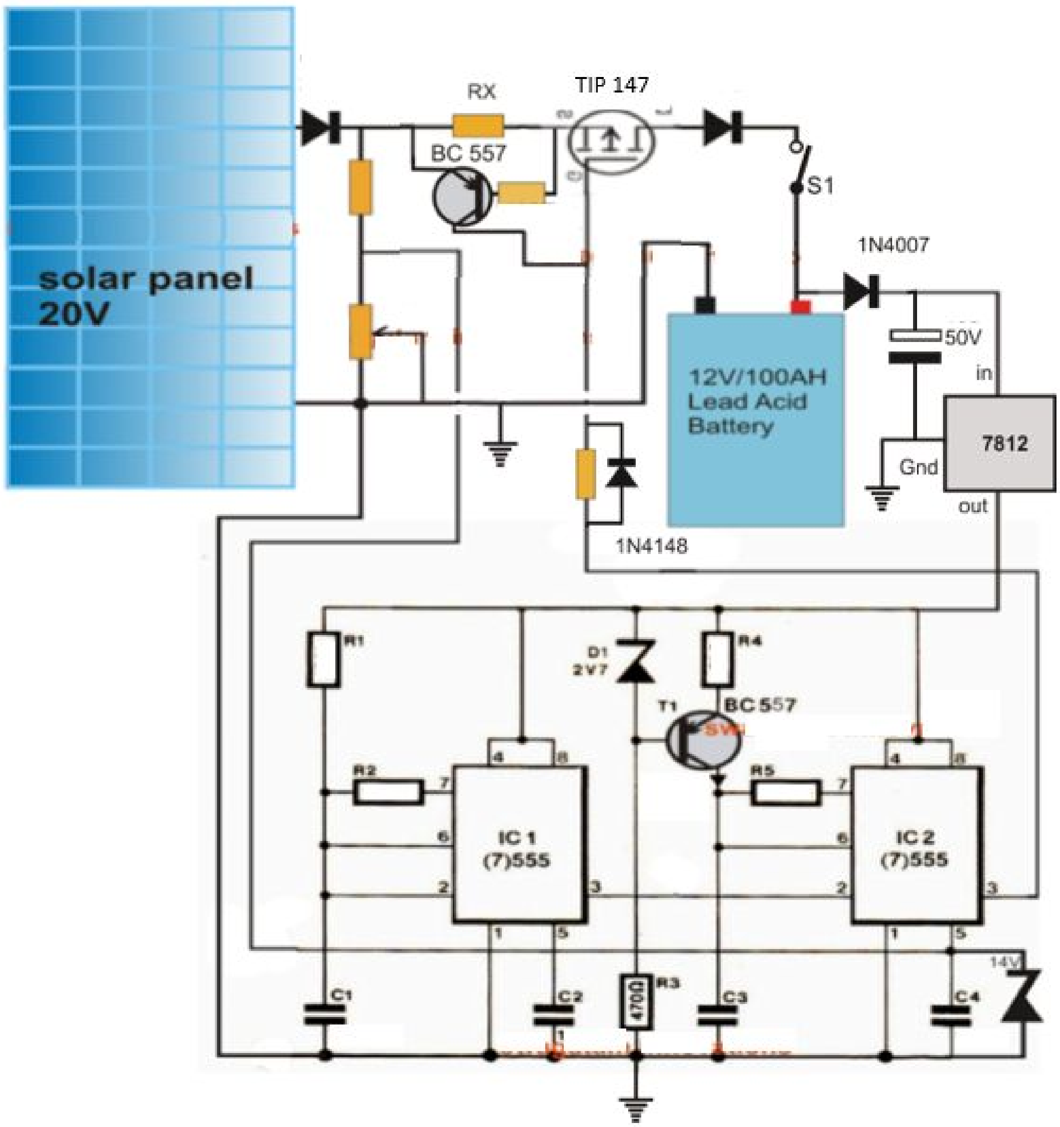


*Figure 2: A more detailed diagrammatic representation of the MPPT charging circuit, showing required components and the connections between them.*[17]

## 2.2 Block Design

### 2.2.1 Functional Overview

The Charging Circuit includes:

I. Solar Panel - The solar panel needs to produce enough power (around 80W-120W) to power the system and the LED. Additionally, because a high-level requirement is for the streetlight to be portable, the solar panel should be as small as possible while being large enough to generate sufficient power.

II. Lead-acid battery - The battery should keep the entire system continuously powered. The battery would take in current from the solar charge controller (below) that matched the solar panel's generated output to the battery's input. In particular, a sealed lead acid battery is preferred due to its low price, low maintenance, and reliability.

III. Maximum Power Point Tracking (MPPT) Solar Charge Controller - A solar panel by itself has a low rate of conversion efficiency, which is why MPPT is necessary. Maximum Power Point Tracking (MPPT) is an algorithm that will find, within the given conditions, the maximum power from a solar panel. The "maximum power point" is the voltage at which the solar panel produces this maximum power and varies with solar insolation and temperature.  Using MPPT allows for the maximum current from a solar panel to be acquired without changing the voltage of the solar panel. A buck converter may be utilized for eventually modifying the input current into the battery. Overall, the MPPT charge controller is needed for the streetlight as it allows the lamp to be efficient by getting the maximum available power from the solar panels and helps it be self-sustainable. There are several methods to implement an MPPT controller:

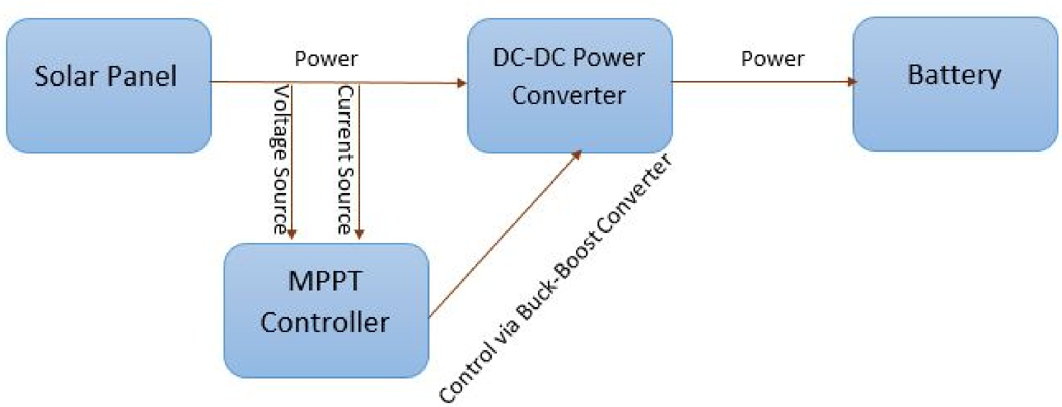

*Figure 3: An overview of how the MPPT Controller interacts with the solar panel and battery*

A. *Perturb & Observe* - This method allows for modification of the operating voltage and operating current of the solar panel until the maximum power is acquired. The MPPT charge controller compares the output of the solar panels with the battery voltage. After this, it calculates the best power that the panel can produce to charge the battery and then converts this into the best voltage to get maximum current into the battery. This is done by following the MPPT algorithm.

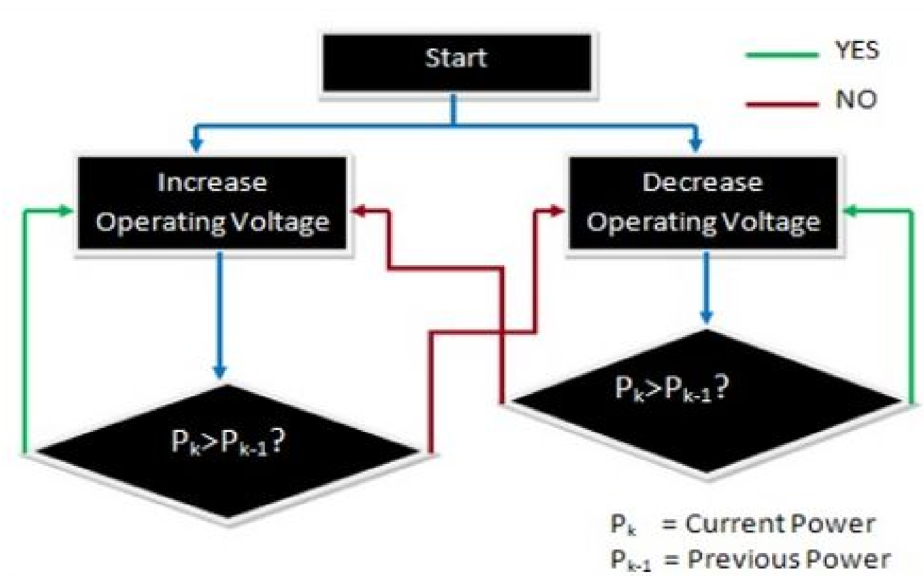


*Figure 4: Perturb and Observe algorithm flowchart*

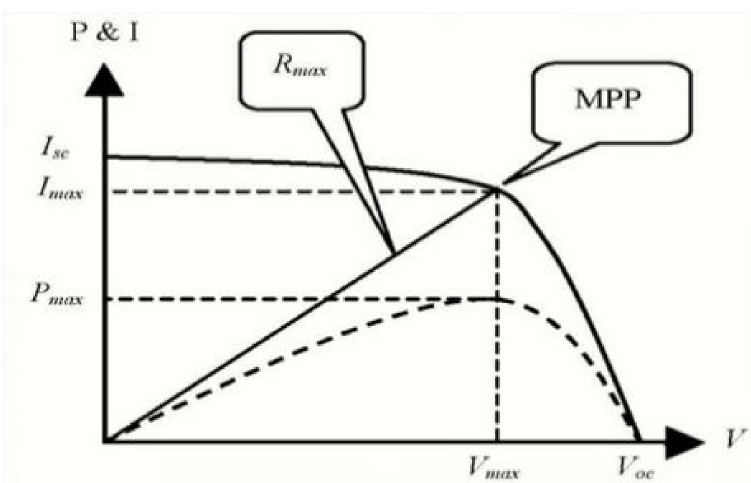


*Figure 5: The V-I and V-P characteristics of a solar panel. The MPP is the point the solar charge controller, using MPPT, tries to locate.*

B. Incremental Conductance: The slope of the power-voltage curve is 0 at the MPP, positive at the left of the MPP, and negative to the right. The incremental conductance takes this fact into account to find the MPP.

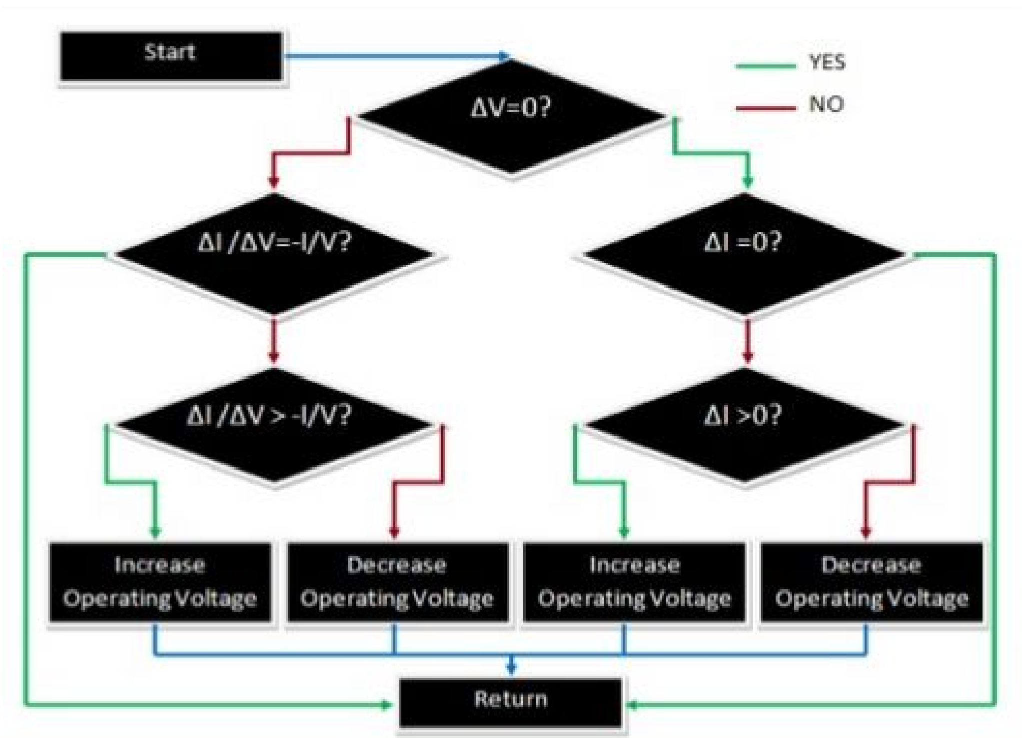


*Figure 6: Incremental Conductance algorithm flowchart*

C. *Fractional Open-Circuit Voltage*: This finds the Vmpp point with relation to Voc: Vmpp = k1Voc. Usually, k1 is between 0.71 and 0.78.
D. *Fractional Short-Circuit Current*: This method finds the Impp = k2*Isc. Usually, k2 is between 0.78 and 0.92
E. *PWM*: The premise of PWM for MPPT is to modify the width of the PWM based on the peak voltage input. There are two main stages of the design: an upper voltage regulator stage and a lower PWM generator stage. The PWM generator stage will utilize IC555s that will create the PWM, and the upper stage has a MOSFET and switch that will respond to the PWM info sent to it. The idea is to make the PWMs wider or narrower based on peak voltages and less wide otherwise. These PWMs are sent to the MOSFET that provides the required voltage to the battery. For example, during

the peak of sunshine in a day, the panel generates high voltage, causing the IC555 to allow for a larger duty cycle. This makes the MOSFET switched off for longer periods and on for shorter periods. When the sunshine is lesser, the duty cycle decreases so the MOSFET conducts more and the average current and voltage on the battery stay near the optimal values. This varies based on sunlight patterns. An important feature of this approach is that the battery remains stable, and the solar panel voltage will not be affected. A current control feature should also be added to prevent the battery from drawing too much current from the panel.

IV. Buck Converter - This steps down voltage and thus, increases current, from the input to output. This is essentially a DC to DC converter; it takes DC voltage from the solar panels, changes this into AC, and converts the voltage back to another DC voltage and current so that the solar panel matches the battery. A buck converter, as opposed to a boost converter, has been utilized because the battery voltage when it is fully charged (12V) is lower than the MPPT voltage of the solar panel (18V); a step down from the solar panel's voltage will be needed, not vice versa.

These above approaches were researched, and it was determined that each of these approaches were difficult to complete in the given timeframe. Initially, when choosing which approach to use for charging the battery, the MPPT algorithm mentioned above (A) seemed to be the most efficient for the system; however, it was also the most complicated. The PWM approach (E) is the best for the given time frame since it is capable of achieving 80% efficiency without a significant increase in complexity (which would have made it unfeasible). It is the approach we are going forward with. Our subsystems will be: the upper and lower stages of PWM, current control, and a buck converter if the other subsystems are completed. A lead acid battery charger IC may also be utilized for battery charging.

An MPPT circuit with a buck converter circuit allows for changing of current with response to the sun intensity levels. It is slightly different from the PWM workflow above (without the Buck Converter) The following equation, Vout = DVin, describes the relation between the voltage from the panel, the duty cycle, and the voltage from the buck converter. Vout can be changed by controlling the duty cycle of the buck converter or Vin. This means that when there is peak sunshine outside (Vin is high), the MPPT workflow will cause the PWMs to be narrower and allow the Vout to stay at the optimal level. When the sun intensity changes, again, the PWMs are widened so that Vout remains at the same level.

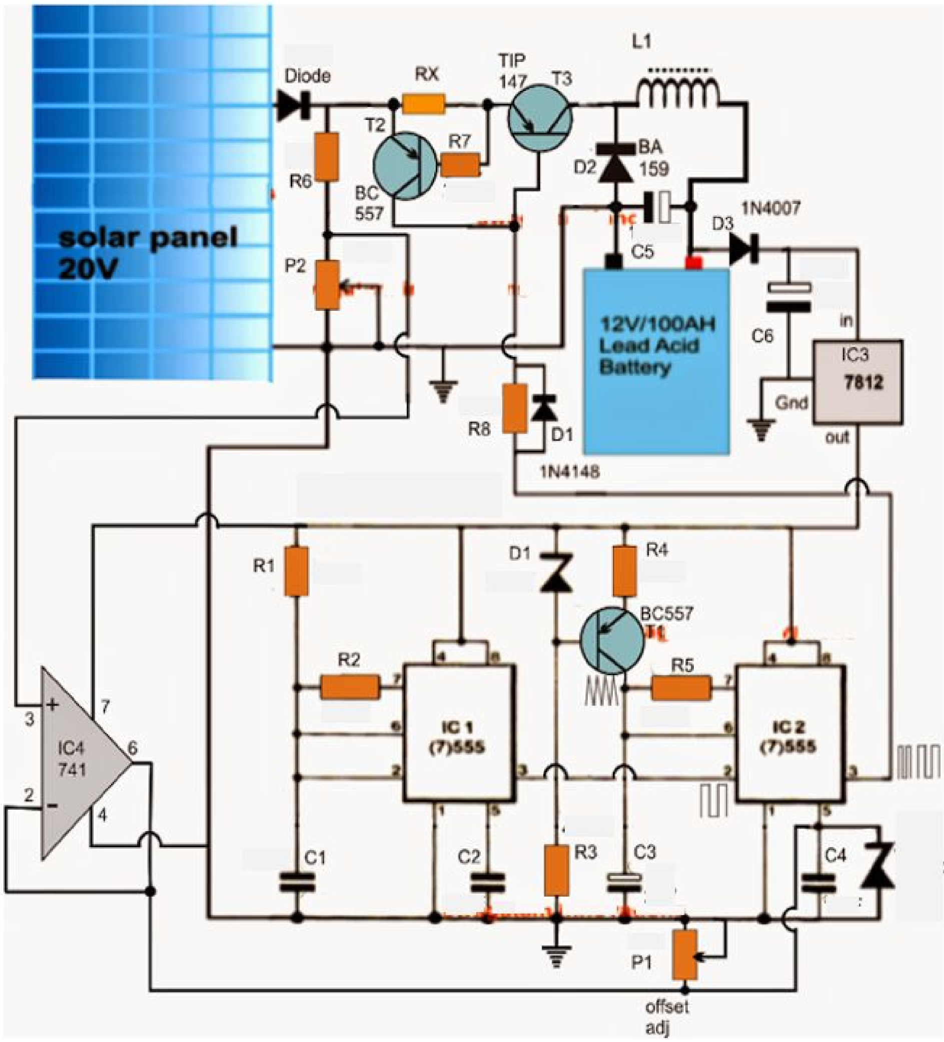


*Figure 7: Schematic of MPPT PWM with Buck Converter*

In particular, the MPPT will be most useful in the following conditions:

- Cold weather or cloudy days
- When the battery's State of Charge (SoC) is low

MPPT has an efficiency of around 80% in the conversion, though it may be lower in practice. In cold weather, solar panels work better, so the MPPT is needed to get the maximum power available. When the battery is mostly discharged, the MPPT algorithm can help adjust the voltage and current requirements so more current (given out by the buck converter) can be used to charge the battery.

## 2.2.2 Requirements & Verification

**Solar Panel**

| Requirements | Verifications |
| --- | --- |
| A. Wattage: 80W - 120W<br>B. Open Circuit Voltage: 20V - 24V<br>C. Minimum Operating Voltage: 18V<br>D. Area: Less than 55in * 30in * 5in | 1. Charge the Solar Panel under direct sunlight or in lab and connect it to the battery/load with the solar charger. Check that the battery/load gets charged/runs correctly.<br>2. Measure the open-circuit voltage with a voltmeter, ensuring that it is in the desired range.<br>3. Measure the dimensions of the solar panel using a tape. |

**Battery**

| Requirements | Verifications |
| --- | --- |
| A. Capacity: 90A-hr - 110A-hr<br>B. Nominal Voltage: 12V | 1. Discharge the battery at 15V/2.2A for 24 hours.<br>2. Use a voltmeter to measure the battery voltage. |

**Charge Controller**

| Requirements | Verifications |
| --- | --- |
| A. PWM MPPT Algorithm<br>B. The efficiency should be above 80%.<br>C. Output Voltage: 14V - 15V | 1. Connect solar panel to a half-charged battery using the charge controller.<br>2. Check the power generated by the solar panel and the power being injected into the battery.<br>3. Measure the Voltage with a Voltmeter while charging. |

**Lead Acid Battery Charger**

| Requirements | Verifications |
| --- | --- |
| A. Float Charging Voltage: 13.5V - 13.8V<br>B. Maximum Boost Charging Voltage: 14.7V<br>C. Charging Current: 6A - 8A | 1. Measure Voltage with a Voltmeter while charging the lead acid battery.<br>2. Measure Current with a Ammeter while charging the lead acid battery. |

### 2.2.3 Tolerance Analysis

One important detail which will greatly impact the performance of our MPPT circuit is the IV curve of the solar panel used. Typically, solar panels have an IV curve similar to that shown in Fig. 5 above, in the 'Functional Overview' section. In order to function properly, we need to be able to maximise the power we pull from it. As the conditions (weather, time, etc) change the IV curve keep changing as well and the maximum power range keeps changing. On building our circuit we need to find out what the tolerance of our circuit is to these factors.

# 3. Cost and Schedule

## 3.1. Cost

### 3.1.1. Labour Cost

| **Labourer** | **Salary/Hour** | **Hours** |
|---|---|---|
| Anirban Banerjee | $48.00 | 180 |
| Priya Mehta | $48.00 | 180 |
| Surya Teja Tadigadapa | $48.00 | 180 |

Total Labour Time = 540 Hours
Total Labour Cost = 540 hrs * $48.00 = $25920.00

### 3.1.2. Parts Cost

| **Description** | **Manufacturer** | **Quantity** | **Cost** |
|---|---|---|---|
| Solar Panel | Renogy | 1 | $139.99 |
| Lead Acid Battery | Renogy | 1 | $199.99 |
| 555 Timer IC | TI | 2 | $0.39 |
| 7812 Regulator IC | TI | 1 | $0.39 |

Total Parts Cost = $341.15

| **Total Man Hours** | **Total Cost** |
|---|---|
| 540 Hours | $26261.15 |

## 3.2 Schedule

| **Week Number** | **Surya** | **Priya** | **Anirban** |
|---|---|---|---|
| Week 1<br>Oct 15th | Work on calculations for charge controller.<br><br>Start designing the PCB layout. | Work on incorporating calculations and component specifications into schematic, finalize schematic. | Finalize component specifications.<br><br>Select and order required components. |
| Week 2<br>Oct 22nd | Order remaining components and test each component individually to avoid component failures. | Make any required changes to PCB to pass audit.<br><br>Help with component testing if needed. | Design the complete PCB layout.<br><br>Help with component testing if needed. |
| Week 3<br>Oct 29th | Begin testing each component on the circuit/PCB to make sure circuit is complete. | Assemble components on PCB (focusing on upper voltage regulating stage). | Assemble components on PCB (focusing on PWM generation stage). |
| Week 4<br>Nov 5th | Order any modified components.<br><br>Test any new modifications/new PCB's. | Test and ensure all requirements and verifications are met/verified. | Finalize PCB layout if any changes from original design |
| Week 5<br>Nov 12th | Set up a trial run with solar panel, PCB's, battery and bulb/load. | Solder components onto the PCB. | Start working on final project report. |
| Week 6<br>Nov 19th | Test Circuit from buck converter to the battery. | Test MPPT Circuit up until buck boost part. | Check on other teams progress and communicate if components can be combined. |
| Week 7<br>Nov 25th | Prepare Slide deck for presentation for Mock and Final Demo. | Create the demo setup making sure battery is semi charged and all systems are working as planned. | Interface with other team to ensure our systems perform correctly. |

# 4. Ethics and Safety

Of all the components in our project, the lead-acid battery has the greatest number of safety considerations.

- Lead-acid batteries are contain lead, a toxic metal, and sulphuric acid, a corrosive agent; and hance must be disposed of carefully.
- If lead-acid batteries are discharged too much or too fast, they can potentially be damaged.
- Certain temperatures and overcharging also cause lead-acid batteries to fail, requiring preventive measures to be taken. In some older models, extreme conditions can even result in the battery exploding.
- Lead-acid battery leakage has the potential to cause serious damage clothing and human skin, as well as other components such as wiring.

The manner in we will deal with this is by creating appropriate precautions to control how the battery is charged and discharged, as well as by monitoring the temperature of the battery and the entire circuit. The solar charge controller will control the voltage going into the battery, and the LED driver, although for the LED, controls also the rate of discharge of the battery. General electrical hazards exist as well. If the direct current produced by the solar panels is not properly converted to alternating current (if the circuits are not properly integrated), electrocution, fires and other such problems might occur. Also if the casing is not made well and the wires are not insulated properly it may cause issues in the functioning of the streetlight.

Another issue is that of the weather effects on our streetlight. It is intended for the streetlight to be self-sustainable and be placed outside without being attached to another device. If the attachment of the solar panels and components on the streetlight is not designed properly, it is plausible that high winds can loosen or even completely detach these solar panels or components and cause damage to nearby items or people (after all, the streetlight is expected to function in populated areas with people nearby). We must keep IEEE Ethics Code #1 ("*to accept responsibility in making decisions consistent with the safety, health, and welfare of the public...*") and ACM Code #1.2 in mind as our streetlight can affect people's safety if not constructed properly. Rain or the moisture in the air  can create mold, rotting, or corrosion, which can cause additional concerns if the streetlight is attached to a home or shed.  In the winter, snow is another issue to be considered. If the solar streetlight is not able to sustain the weight of snow piling up on it, as solar panels are generally quite light, the structure can collapse. To prevent weather-related issues, we will take preventive measures by creating a casing to encapsulate all sensitive components and insulate wires.

In order to mitigate the safety concerns regarding the use of a lead-acid battery, the first step we are taking is to precisely calculate the exact specifications required of our lead-acid battery so that we pick a model that is best suited to our project (as opposed to one that is too big or too small, which increases the risk of possible accidents due to overcharging/undercharging). We will also be carefully studying and following all safety precautions related to using, handling, storing and transporting lead-acid batteries as outlined in ECE 445's 'General Battery Safety' documentation, which can be found under the 'Safety Guidelines' section of the ECE 445 website (a link to the pdf document has been provided in the *References* section below). In order to protect against possible damage to wiring or sensitive components during general field operation of the streetlight, we will use an external casing built by the ECE machine shop to safely house all the components (including the lead-acid battery, which should further reduce any chance of harm to users or the environment in case of any accidents), and minimise the amount of external wiring in implementing our design. We will also ensure that the solar panel is firmly fixed in a stable orientation and has minimal risk of being loosened or detached from its position.

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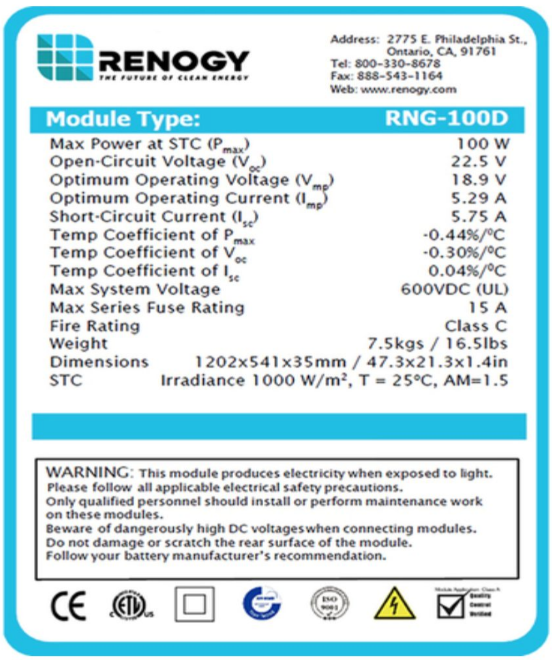
# 6. Appendix A: Battery Calculations

Calculation of the battery requirements and charge cycle required.

The solar panel's specifications are as follows:




Solar Panel:
Max Power: 100W
Efficiency: Unknown/Variable

LED Bulb:
Power: 33W
Voltage: 12V

Battery:
Rating: 100A-hr
Voltage: 12V

How to read the above figures:

Rating * Voltage = How much power the battery can hold on a full charge.
Therefore our battery can supply X W-hr of power.

Assuming we need to power our bulb for 12 hours every night (6:30pm - 6:30am). We need = led wattage*hours of power to run the led at full power through the night.
In our case we need 396 W-hr of power every night.

The power supplied by the solar panel varies based on climate conditions. At full power in an ideal setting with perfect conditions our solar panel can supply 100W-hr. If efficiency is 50% it can supply 50W-hr.

Now an important consideration with batteries is that they should not be completely discharged for a longer life. For our needs I was planning on not discharging the battery beyond 50%.

Example: For a 50 A-hr battery the cycle life is as follows. For our use case a cycle will be approximately a day (because we charge everyday because of the solar panel. So how much battery we use in a night is equal to our discharge %)

100% Discharge = 572 Cycles.
50% Discharge = 1485 Cycles.
30% Discharge = 2406 Cycles.

572 Cycles = ~1.5 years
1485 Cycles = ~4 years
2406 Cycles = ~6.5 years

For a good middle ground I think we should try and achieve less than 50% discharge daily. This means if we run our lamp for 12 hours a night we need 396 W-hrs of power. So to have achieved less than 50% discharge we need a battery with twice the capacity of this. Also we need to run the remaining power electronics on top of our lamp, so let's assume our power consumption for one night to be about 450W-hrs. This means our battery needs to be able to hold about 900W-hrs at least on a full charge. If we take a 100A-hr, 12V battery it can hold 1200W-hr's of power, which is perfect for us. With all inefficiencies that may encounter we should still be able to be well within this limit.

Now that we know we want our battery to have 100-hr, 12V specs and we know that per night at best we will use 450W-hrs of power lets see how fast can our solar panel charge the battery. Now since we don't want to go below 50% discharge, lets not take into consideration the first time we charge the battery completely. So now the battery hold 1200W-hrs and will lose 450-500W-hrs per night. Our main aim is to replenish this power that we consume every night. Our solar panel is capable of a theoretical maximum of 100W but we will always get far lesser out of it. At 80% efficiency we need ~6 hours to produce that energy. At 40% efficiency we need ~12 hours to produce that much energy. Our numbers will be more accurate once we know what the remaining electronics on our product are and how much energy they consume. The biggest variable though is how long it takes us to charge the battery, which we can only simulate.