

Efficient Control Algorithm for a Smart Solar Street Light

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Abstract—This paper describes a model of a smart street light that can work autonomously, save energy and can be seamlessly integrated with the existing grid. The street light incorporates a Light Emitting Diode array and an ARM Cortex M0 based microcontroller, both of which are powered by a combination of a solar panel and battery pack. The microcontroller executes an astronomical time switch based estimation algorithm to determine the sunrise and sunset time daily. This is done using the Real Time Clock running on the controller along with the hard coded coordinates and time zone of any given location. Upon evaluation of the sun times, the controller can routinely regulate the lamp at sunrise and sunset. The algorithm operates with an accuracy of up to 10 seconds in its estimation of sun times. The controller also monitors the voltage from the battery at sunset and switches to mains to power up the LED array in case power is not enough. A coin cell is also connected to the controller to ensure RTC keeps on running in the scenario that battery is completely discharged and there is no power from the mains. The results conclude that the use of such a technology would provide high energy efficiency, increases the operating life and also proves to be cost effective as compared to prevalent lamp technologies. Analysis is performed using HOMER, a microgrid simulation software. The boundary conditions are set for Indian scenarios; however the result applies to many geographical locations.

Keywords— Battery chargers, Lighting control, Maximum power point trackers, Power control, Power system simulation, Renewable energy sources, Smart grids

I. INTRODUCTION

Lighting is one of the most important and expensive responsibilities of a city, and accounts for almost 10-38% percent of the expenditure on electricity[1]. Street lighting is a particularly critical concern for public authorities in developing countries because of its strategic importance for economic and social stability. 8–10% of the total lighting corresponds to outdoor lighting which includes street lights, traffic lights and parking lots' lighting [2].

Central Electricity Authority statistics have estimated gross energy consumption for public lighting to be 6.7 TWh in India for the years 2010-2011[3]. Inefficient lighting wastes significant financial resources every year, and poor lighting leads to unsafe conditions. Proper lighting improves visibility and can reduce fatalities and crashes with pedestrians as shown by studies done in [4]

and [5]. Energy efficient technologies and design also help to cut street lighting costs significantly.

An electric light source is a device, which transforms electrical energy, or power (in Watts), into visible electromagnetic radiation, or light (Lumens). The rate of converting electrical energy into visible light is called “luminous efficacy” and is measured in Lumens per watt.

Most urban and semi-urban cities and towns in India are still using a combination of fluorescent, Compact Fluorescent Lamps (CFL), High Pressure Sodium Vapor (HPSV) lamps or Metal Halide (MH) bulbs, which result in high energy expenditures and high maintenance costs. Outdated installations increase energy costs and new technology represents a large cost saving potential. Table 1 shown below presents a comparative study of various lighting technologies used. A relevant conclusion that can be drawn from the table is that Light Emitting Diodes (LED) provides an efficient solution considering their low power consumption, long life time, negligible maintenance and excellent colour rendering properties [6].

Annual energy cost is calculated using (1) where X is the cost, Ω is the wattage, H is the daily operating hours, K is the cost of electricity in kWh and N is the number of lamps considered.

$$X = (\Omega * H * 365 * K * N) / 1000 \quad (1)$$

With a valid assumption that the street lights are operated on a daily basis for 15 hours, and the number of lamps being 1000, table 1 also shows the cost incurred for lamps of different technologies.

The objective of the proposed LED lighting solution is to employ renewable energy resources for powering the lamps rather than the centralized grid and use control algorithms to further increase efficiency of the system.

This paper is organized as follows:

Section 2 provides the complete hardware architecture supported by explanations to justify all components used. Section 3 discusses the control algorithm and its implications on system performance. Section 4 describes the analysis of simulations and a comparative study of how system efficiency was affected using the underlying implemented algorithm. This section is followed by the conclusions.

TABLE I. Comparison of various lighting technologies

Lamp Technology	Average Wattage (W)	Luminous Efficacy (lm/W)	Lamp life in hours	Annual Energy Cost(\$)
High Pressure Mercury Vapor (MV)	239 W	35-65 lm/W	5,000	105,990.5
Metal Halide (MH)	311 W	70-130 lm/W	8,000	146,790.2
High Pressure Sodium Vapor	216 W	50-150 lm/W	15,000	95,790.6
Low Pressure Sodium Vapor	180 W	100-190 lm/w	15,000	79825.5
Low Pressure Mercury Fluorescent Lamp	147 W	30-90 lm/W	5,000	65,190
Energy-efficient Fluorescent Lamp	25 W	100-120 lm/W	5,000	11086.8
Light Emitting Diode	15 W	70-160 lm/W	50,000	6652.12

II. HARDWARE ARCHITECTURE

A. The Controller and Display Unit

The processor core chosen to run the on-board algorithm was the ARM CortexM0 based STM32F051R8 controller manufactured by STMicroelectronics [7]. The reason to have chosen this controller was the Real Time Clock (RTC) power domain functionality. This feature allows a separate battery supply to be connected to the RTC domain to ensure its continued operation even when the main controller supply is unavailable. When the controller encounters a power-on-reset, the RTC registers would have retained the current date and time information. Other peripherals that are being used include Pulse Width Modulation (PWM) for dimming the LED array during late night hours, Analog to Digital Conversion (ADC) to get the battery voltage, low power modes to save maximum energy during the day, USART for LCD interfacing and external interrupts. STM32F051R8 is an entry level CortexM0 microcontroller with multiple features. It's a highly popular processor chip with abundant design resources available. The Serial Wire Debug interface is used to program the controller.

A 2 X 16 LCD and a keyboard are also interfaced to display the current RTC time and battery voltage when a keyboard is used. The purpose of this is to check if the system is functioning properly at any time during its lifetime

B. Solar panel and Battery Setup

A solar photovoltaic (PV) is used to convert solar illumination into electrical energy. This energy powers a load at its terminal voltage. The electrical energy produced by the panel is used to charge a rechargeable battery. The interconnection of the solar panel and battery is effectively a DC-DC converter. A 100 watt

monocrystalline PV solar panel was used for this application along with a 12 V, 1kWh lead acid battery.

To ensure that the maximum power is drawn from the solar panel and battery is charged efficiently to achieve longer operating life, various control algorithms are implemented [8].

A Maximum Power Point Tracking (MPPT) algorithm is necessary to track the operating point of the solar panel to get maximum output from the battery. The operating point is the point where maximum power is delivered while varying the output voltage. An MPPT algorithm is required here because the power point optimum levels vary due to changing sunlight intensities and operating temperatures [9].

A lead acid battery is a member of a family of rechargeable batteries. Lead acid batteries are the preferred choice for solar applications as they have a faster charging rates and a higher energy density. Since the battery needs to charge and discharge at specific times, a battery charge discharge controller is necessary.

There is a wide variety of Integrated Circuits (ICs) in the market that implement MPPT and battery charging algorithms. One such IC is LT8490 which is a high voltage, high current buck-boost battery charge controller with maximum power point tracking [10]. The IC greatly reduces the effort in making circuits for the MPPT and charge controller algorithms.

C. LED Array and LED Driving Circuit

A 12V LED Driving circuit was made using the LM3464 IC which is a LED Driver with Dynamic Headroom Control (DHC) specially used in streetlight applications [11]. The DHC technology maximizes overall efficiency of the lighting system. It achieves this by adjusting the output voltage of the battery dynamically. Linear current regulation secures the output current, the LEDs and ensures system reliability. The driver also incorporates PWM dimming which provides the flexibility of brightness control.

D. Power Source Switching

A high efficiency AC-DC converter is connected with a relay in parallel to the battery. In the scenario that the battery does not have enough power, the controller sends a pulse to the relay which then connects the LED array to the mains through the converter. The State of Charge (SOC) of the battery is checked by the controller right before switching the lamp on at sunset using the ADC peripheral.

III. CONTROLLER ALGORITHM

The algorithm running on the controller is responsible of three functions:

- (1) autonomously control the lamp to perform switching at sunrise and sunset
- (2) dimming of the lights during night time from 11:30 pm to 4:30 am
- (3) monitor battery voltage to switch between battery and mains to power up LED array.

To calculate the sunset and sunrise time, the controller needs to know geographical information of the location. The system input is the time zone and the date of operation. The location data is hard-coded into the controller and needs to be changed accordingly depending on where the street light is being installed. The date and time is retrieved from the RTC. The calculations from the algorithm are theoretically accurate to within a minute. Due to variations in atmospheric conditions such as temperature, pressure and composition the observed values may differ.

The algorithm can be divided into three parts which are:

- (1) One time initialization
- (2) The interrupt handlers
- (3) The main program loop.

A. One Time Initialisation

This part of the code gets executed when the controller gets powered up. Ideally, this executes only once assuming that the battery can sustain at least the controller. However, since the controller is chosen such that a backup supply from a coin cell can be given to the RTC domain, when the controller recovers from an unexpected shutdown, time and date information is not lost. Fig. 1 illustrates the basic state machine employed for the same.

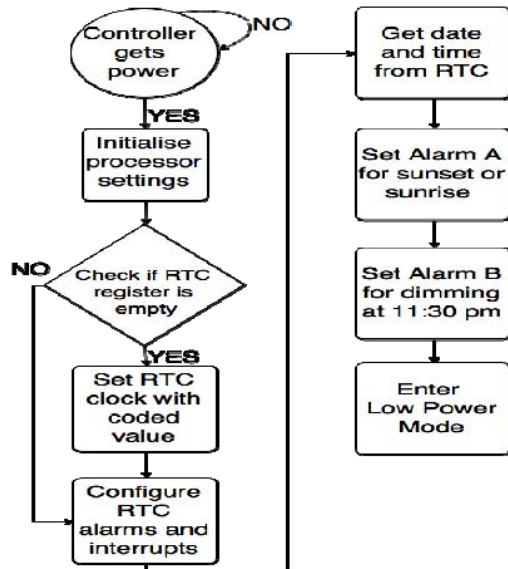


Fig. 1. Program execution state machine

Once the controller wakes up, it initializes the processor settings such as clocks and General Purpose Input Output (GPIO) pins being used for operation. The controller then checks if the RTC register has some data in order to make sure date and time do not get overwritten. In case the register is empty, the coded time and date get loaded into the RTC registers.

The RTC peripheral has an alarm feature that allows the controller to generate an interrupt whenever the set alarm time matches the current RTC time. Two such

alarms, alarm A and alarm B can be configured. Once the RTC alarm and interrupt settings are done, the controller fetches the date and time from the RTC registers, determines the next solar event and sets alarm A to the corresponding time. Alarm B is used to set the time for dimming the LEDs, which is in our implementation set to 11:30 pm.

Once the alarms are set, the controller enters a low power mode. ARM controllers have special low power operating modes that reduce the power consumption by switching off redundant modules. The register contents are however, preserved. The controller can exit the low power mode when an interrupt is generated; this is where the RTC alarm interrupts are used.

The low power mode is only employed during the day when the lamp is off as controller performs no function during this time.

B. The Interrupt Handlers

When the controller wakes up by the interrupt generated by the alarm, this part of the code gets executed. Once the interrupt line goes high, the controller goes to a specific memory location corresponding to that line known as the interrupt handler. The controller then sets some flags and clears the interrupt, having effectively serviced it. Two flags, Alarm_Sun and Alarm_Dim are used to indicate whether a solar event or a dimming event has occurred respectively. Fig. 2 shows the flow of control inside the handler.

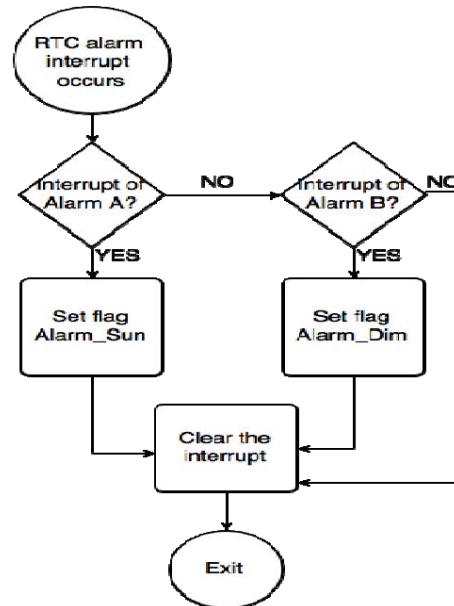


Fig. 2. Operation flow control diagram.

After the controller exits the handler, it enters the main loop. The flags set in the handler are used to make decisions in the main loop.

C. Main Program loop

When the controller is not in the low power mode, it continuously executes the main loop. This is the part of the code where battery monitoring, switching of the lamp and setting consecutive alarms happens.

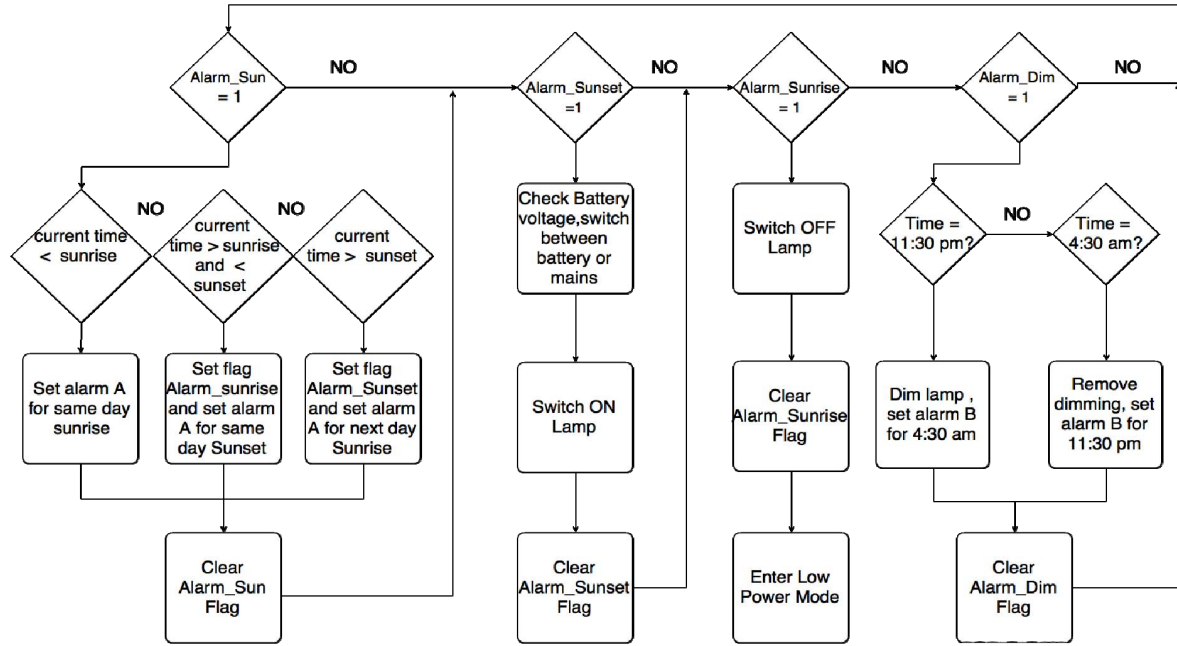


Fig. 3. Flag set decision chart

Four flags Alarm_Sun, Alarm_Dim, Alarm_Sunset and Alarm_Sunrise are used to monitor current state of the controller. Alarm_Sun and Alarm_Dim get set in the interrupt handler as mentioned in the previous section and are cleared here once they serve their purpose. Two new flags Alarm_Sunset and Alarm_Sunrise are used to dictate whether a sunrise or a sunset caused the alarm to generate an interrupt. Accordingly the lamp is switched on or off. The state machine model of the same is shown above in fig. 3.

As we can observe from the figure, once the Alarm_Sunset flag gets set, the controller decides whether to use the battery or the mains to power up the lamp depending upon the battery state of charge. The controller also enters low power mode after sunrise to ensure maximum power saving.

IV. RESULTS AND ANALYSIS

Annual hours of operation for any lamp are given by 15 hours a day for 365 days which comes out to be 5475 hours. Using the algorithm that calculates sunrise and sunset times for any given day, total night time hours were calculated for the year 2015, this comes out to be equal to 4439.86 hours.

Therefore, each lamp stays on 1000 hours less each year when using the sunrise and sunset time calculation for operation.

The next implementation was the dimming of the lights for 5 hours during late hours of the night (11:30 pm to 4:30 am) by 30% without compromising operation of the street lights. In such a scenario, street lights work at full power only for an effective of 3831 hours.

This leads to power saving of minimum of 2000\$ every year for 1000 lamps (on mains) and adds 6 months to the lifetime. A comparison of a simple led street lamp with a smart led street lamp is made in table 2.

This elucidates the increased efficiency of the system due to the control algorithm running on the controller.

TABLE II. Performance comparison analysis table

Technology	Simple LED Street Light	Solar LED Street Light with Efficient Algorithms
Parameter		
Wattage (W)	15 W	15 W with full intensity and 10 W with 30% dimming
Efficacy (lm/W)	70-160	70-160
Annual Hours of operation (hours)	5475	3831
Annual Energy Cost (\$)	6652	4655 (on mains) 0.0 (on battery)

To verify the system functionality, simulations for the PV output, battery charging and load dissipation were done in HOMER software. HOMER is designed to evaluate design options for both off-grid and grid-connected power systems for remote, stand-alone and distributed generation applications. HOMER is supported by the National Renewable Energy Laboratory (NERL) for energy system analysis.

The software requires geographical location in order to get solar irradiation data from the NASA surface meteorology and Solar Energy Database. The location entered is UTC + 05:30, Delhi. The magnitude of the bar chart in fig. 4 shows the average daily irradiation of all months in a year. The figure also shows a line graph which indicates the clearness index of every month.

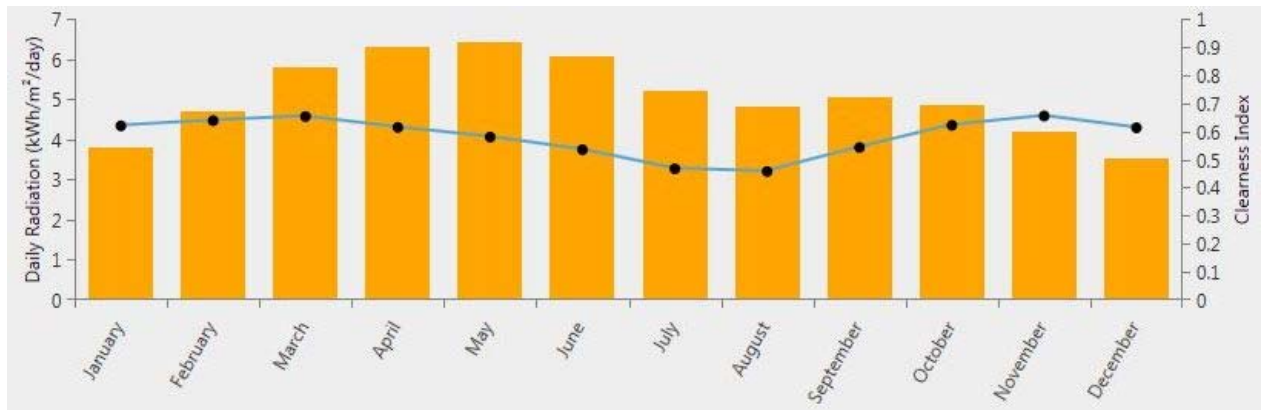


Fig. 4. Monthly average irradiance for a year.

A. PV Characteristics

A generic PV array is chosen with 100 Watt capacity with 13% efficiency. The PV output with and without an MPPT controller is shown in fig. 5. The distinguishing red peaks in the graph show how the implementation of MPPT has improved the power drawn from the PV array.

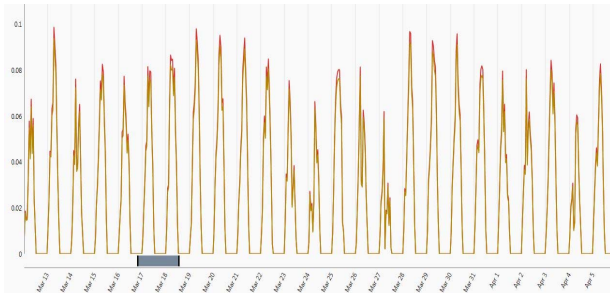


Fig. 5. Battery charging using MPPT control.

B. Load Characteristics

The data map of the load is shown in fig. 6. The figure can be viewed as three sections, uppermost section when dimming of the lamp takes place, next section when maximum power is drawn during peak night time traffic and finally the section when the lamp is turned off during the day.

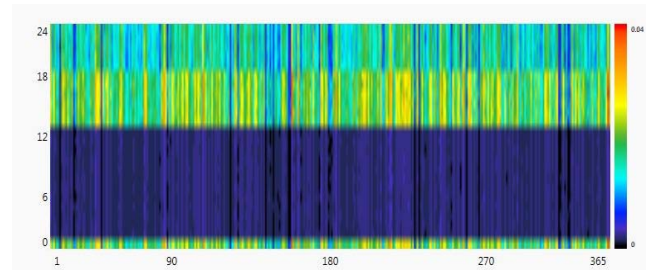


Fig. 6. Load side data map.

C. Battery Charging Characteristics

Simulations were carried out for multiple cases of initial State of Charge (SOC) of the battery. It was observed that less initial state of charge of the system does not affect the operation for a whole year. The battery SOC does not fall even below 40% throughout the year.

D. System Performance

Fig. 7 shows SOC of battery (red plot initially at 50%) and DC load power consumption (orange). Fig. 8 shows PV output (brown) along with battery SOC (red) for the July-August period. The least SOC is observed during the month of August at a value of 40%. As observed, the battery gets charged when the solar PV gives output and discharges when the lamp is switched on and solar panel output is unavailable.

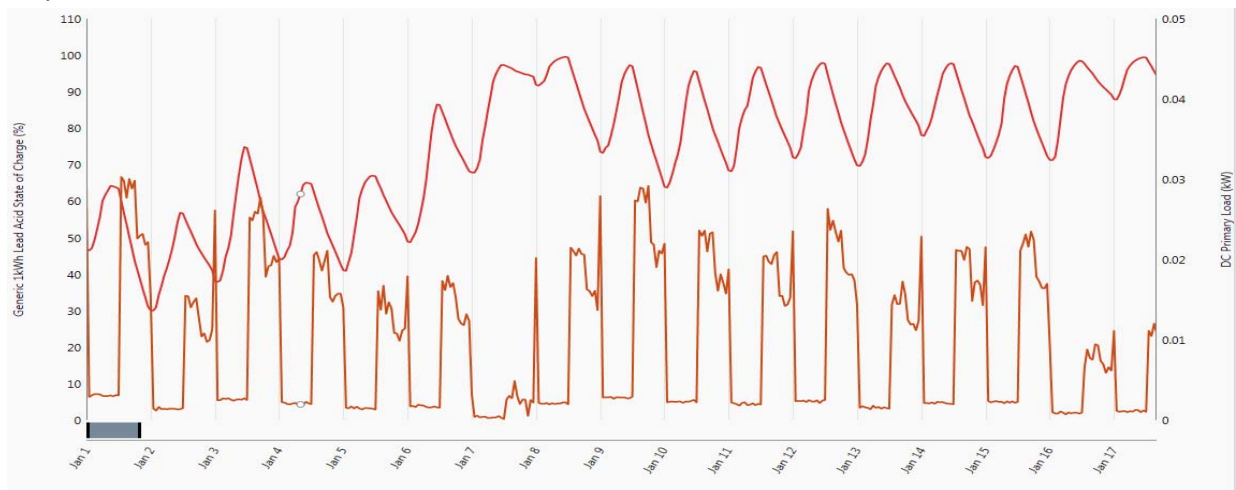


Fig. 7. Varying battery SOC and charging graph.

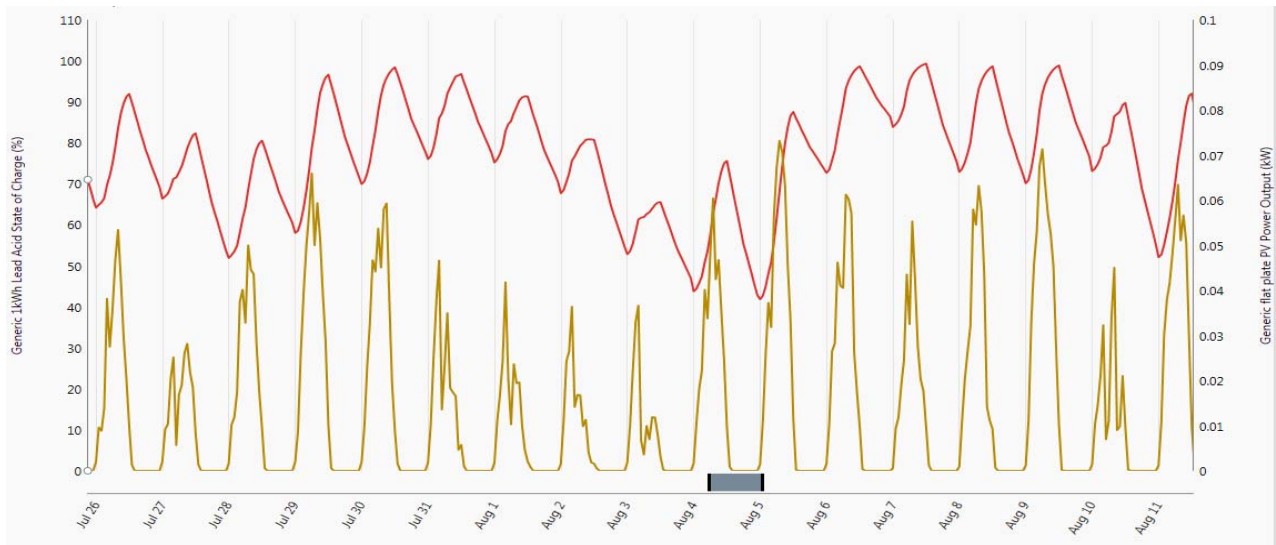


Fig. 8. PV output and battery SOC.

V. CONCLUSION

The smart LED lamp operates for 3831 hours as compared to 5475 hours for an ordinary LED lamp. This increases the operating life of lamp by 50% annually. That means a lamp that would operate for two years earlier would now operate for 3 years.

Simulation results reveal that entire system can operate on solar energy without switching to mains under normal circumstances. Use of renewable energy sources ensures 100% energy saving and no CO₂ emissions. The cost of energy saved can cover the cost of hardware requirements. The suggested solution also has an environmentally positive impact.

The proposed solution can also be extended to be used in other areas such as parking lots, shop floors and other commercial lighting areas where ample sunlight is present.

Mean Time before Failure (MTBF) of the system depends on the operating life of the individual components. Simulation results proved that the battery, LED lamp and the PV panel had a lifetime of 10, 23 and 25 years respectively, resulting in an MTBF of 10 years.

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